Arbeitsbericht NAB 20-08

TBO Bülach-1-1: Data Report

Dossier X
Petrophysical Log Analysis

February 2021

National Cooperative
for the Disposal of
Radioactive Waste

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Dossier X Petrophysical Log Analysis

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Nagra Arbeitsberichte NAB ("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:
S. Marnat (data analyses, interpretation and writing)
J.K. Becker (project administration and writing)

Editorial work: P. Blaser, M. Storz and M. Unger

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

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Abbreviations

ANHYDR	Anhydrite weight percentage from MultiMin
APLC	Corrected neutron hydrogen index from APS (limestone matrix)
APS	Accelerator Porosity Sonde
B/E	Barns/Electron
BS	Drilling Bit Size
CALCITE	Calcite weight percentage from MultiMin
CALI	Caliper
CARBONATES	Carbonates weight percentage from MultiMin
CHLORITE	Chlorite weight percentage from MultiMin
COAL	Coal weight percentage from MultiMin
CONDNUM	MultiMin model condition number
CT	Conductivity in the formation
CT_PRED	CT prediction by MultiMin
CU	Capture Unit, unit for sigma
CXO	Conductivity in the invaded zone
CXO_PRED	CXO prediction by MultiMin
DENS	Bulk density
DENS_MIX_PRED	Dens_MIX prediction by MultiMin
DENS_MIX	Bulk density from wireline logs and core
DENS_MIX_INPUT	Array Monte-Carlo input for bulk density
DOLOMITE	Dolomite weight percentage from MultiMin
DRHO	Bulk density correction
DRY_CLAY	Dry clay weight percentage from MultiMin
dRRC	Rush corrected data
DWAL_WALK2	Dry weight fraction aluminium
DWAL_CALC	Dry weight fraction aluminium from core and ECS
DWAL_CALC_INPUT	Array Monte-Carlo input for DWAL_CALC
DWCA_WALK2	Dry weight fraction calcium
DWCA_MIX	Dry weight fraction calcium from ECS and core analysis
DWCA_MIX_INPUT	Array Monte-Carlo input for DWCA_MIX
DWFE_WALK2	Dry weight fraction iron
DWFE_MIX	Dry weight fraction iron from ECS and core analysis
DWFE_MIX_INPUT	Array Monte-Carlo input for WFE_MIX
DWSI_WALK2	Dry weight fraction silicon

DWSI_MIX	Dry weight fraction silicium from ECS and core analysis
DWSI_MIX_INPUT	Array Monte-Carlo input for DWSI_MIX
DWSU_WALK2	Dry weight fraction sulphur
DWSU	Dry weight fraction sulphur from ECS
DWSU_INPUT	Array Monte-Carlo input for DWSU
DTCO / DTC	Compressional wave slowness from far monopole mid frequency source compressional wave slowness
DTC_INPUT	Array Monte-Carlo input for DTC
DTC_PRED	DTC prediction by MultiMin
DTSM	Shear wave slowness from X-Dipole (90°) source
DTS	Shear wave slowness
DTS_INPUT	Array Monte-Carlo input for DTS
DTS_PRED	DTS prediction by MultiMin
ECGR_EDTC	Environmentally corrected Gamma Ray from EDTC
ECS	Elemental Capture Spectroscopy
EDTC	Enhanced Digital Telemetry Cartridge
EMS	Environment Measurement Sonde
FMI	Fullbore Formation Microimager
g/cm^3	Gram per cubic centimetre
GAPI	Unit of radioactivity used for natural Gamma Ray logs
GPCI	Geneva Petroleum Consultants International
GPIT	General Purpose Inclinometry Tool
GR	Total Gamma Ray
HALITE	Halite weight percentage from MultiMin
HDAR	Hole diameter from area
HDRA	Bulk density correction
HFK	Potassium concentration from HNGS
HFK_MIX	Potassium concentration from HNGS and core analysis
HFK_MIX_INPUT	Array Monte-Carlo input for HFK_MIX
HFK_MIX_PRED	HFK_MIX prediction by MultiMin
HI	Hydrogen Index
HNGS	Hostile Natural Gamma Ray Sonde
HRLT	High Resolution Laterolog array Tool
HSGR	HNGS Standard Gamma Ray
HTHO	Thorium concentration from HNGS

HTHO_MIX	Thorium concentration from HNGS and core
HTHO_MIX_INPUT	Array Monte-Carlo input for HTHO_MIX
HTHO_MIX_PRED	HTHO_MIX prediction by MultiMin
HURA	Thorium concentration from HNGS
HURA_INPUT	Array Monte-Carlo input for HURA
HURA_PRED	HURA prediction by MultiMin
ILLITE	Illite weight percentage from MultiMin
KAOLIN	Kaolinite weight percentage from MultiMin
KEROGEN	Kerogen weight percentage from MultiMin
LEH.QT	Logging Equipment Head with Tension
LQC_INDEX	Log Quality Control Index
MCFL	Micro-Cylindrical Focused Log
MHF	Micro Hydraulic Fracturing
MULT_QC	MultiMin analysis quality flag
MULTIMIN	Multi mineral and multi fluid analysis module in geolog software
mMD	Metre measured depth
MSIP	Modular Sonic Imaging Platform
NFUN	Number of MultiMin iterations
NHI	Neutron Hydrogen Index
NHI_INPUT	Array Monte-Carlo input for NHI
NHI_PRED	NHI prediction by MultiMin
NO_K_CLAYS	Not potassic clays weight percentage from MultiMin
NPHI	Corrected neutron hydrogen index (limestone matrix)
ORTHOCL	K-Feldspars weight percentage from MultiMin
p.u.	Porosity unit
PEF	Photoelectric factor
PEFZ	Photoelectric factor
PEFZ_INPUT	Array Monte-Carlo input for PEFZ
PEFZ_PRED	PEFZ prediction by MultiMin
PHI_PICNO	Core pycnometer porosity
PHI_WL1	Core water-loss porosity (105 °C) using bulk wet density
PHI_WL2	Core water-loss porosity (105 °C) using grain density
PHIE	Effective porosity
PHIE_ALL	Array Monte-Carlo output effective porosity

PHIT	Total porosity
PHIT_ALL	Array Monte-Carlo output total porosity
PLAGIO	Plagioclases weight percentage from MultiMin
PPC	Power positioning device and caliper tool
PYRITE	Pyrite weight percentage from MultiMin
QC	Quality Control
QUALITY	MultiMin analysis quality
QUARTZ	Quartz weight percentage from MultiMin
RCL	Reduced Composite Log
RHGE_WALK2	Matrix density from elemental concentrations
RHOG	Grain density from MultiMin
RHOG_ALL	Array Monte-Carlo output grain density from MultiMin
RHOS	Solids density
RHOZ	Bulk density
RHOZ_PRED	RHOZ prediction by MultiMin
RT_HRLT	HRLT true formation resistivity
RUGO	Borehole wall rugosity
RXOZ	Invaded formation resistivity filtered at 18 inches
SIDER	Siderite weight percentage from multimin
SIGF	Macroscopic cross section for the absorption of thermal neutrons, or capture cross section, of a volume of matter, measured in capture units [c.u.]
SIGF_PRED	SIGF prediction by MultiMin
SIGF_INPUT	Array Monte-Carlo input for SIGF
SILICATES	Matrix silicates weight percentage from MultiMin
SLB	Abbreviation for Schlumberger Logging Company
SP	Spontaneous Potential
STOF	APS Stand-Off Tracks
Swe	Effective water saturation
Swt	Total water saturation
TLD	Three-detector Lithology Density
TNPH	Corrected neutron hydrogen index (limestone matrix)
TOC	Total organic carbon [w/w or wt.-%]
U	Volumetric photoelectric factor [b/cc]
UBI	Ultrasonic Borehole Imager
v/v	Volume per volume

VCL	Volume of wet clay
VOL_ANHYDR	MultiMin volume of anhydrite
VOL_ANORTH	MultiMin volume of plagioclase
VOL_ANTHR	MultiMin volume of anthracite
VOL_CALCITE	MultiMin volume of calcite
VOL_CHLOR	MultiMin volume of chlorites
VOL_DCL	Volume of dry clay
VOL_DOLOM	MultiMin volume of dolomite
VOL_HALITE	MultiMin volume of halite
VOL_ILLITE	MultiMin volume of illite
VOL_ORTHOCL	MultiMin volume of potassic feldspars
VOL_SIDER	MultiMin volume of siderite
VP	Compressional waves velocity [m/s]
VS	Shear waves velocity [m/s]
VPVS	Compressional and shear waves velocity ratio
VPVS_INPUT	Array Monte-Carlo input for VP/VS
VOL_NO_K_DCL	Volume of not potassic dry clays
VOL_SILI	Volume of quartz and feldspars
VOL_MATRIX	Volume of matrix minerals
WT.-%	Weight concentration
W/W	Weight per weight, concentration
WANH_WALK2	Dry weight fraction anhydrite/gypsum
WCAR_WALK2	Dry weight fraction carbonate
WCLA_WALK2	Dry weight fraction clay
WEIGHT_ANHYDRITE	Array Monte-Carlo output anhydrite weight
WEIGHT_CALCITE	Array Monte-Carlo output calcite weight
WEIGHT_CARBONATE	Array Monte-Carlo output carbonates weight
WEIGHT_CHLOR	Array Monte-Carlo output chlorites weight
WEIGHT_COAL	Array Monte-Carlo output coal weight
WEIGHT_DCL	Array Monte-Carlo output dry clays weight
WEIGHT_DOLOMITE	Array Monte-Carlo output dolomite weight
WEIGHT_HALITE	Array Monte-Carlo output halite weight
WEIGHT_ILLITE	Array Monte-Carlo output illite weight
WEIGHT_KAOLIN	Array Monte-Carlo output kaolinite weight
WEIGHT_KEROGEN	Array Monte-Carlo output kerogen weight

WEIGHT_KFELDS	Array Monte-Carlo output K-feldspars weight
WEIGHT_NO_K_CLAYS	Array Monte-Carlo output no potassic clays weight
WEIGHT_PLAGIO	Array Monte-Carlo output plagioclases weight
WEIGHT_PYRITE	Array Monte-Carlo output pyrite weight
WEIGHT_QUARTZ	Array Monte-Carlo output quartz weight
WEIGHT_SIDERITE	Array Monte-Carlo output siderite weight
WEIGHT_SILICATES	Array Monte-Carlo output matrix silicates weight
WEVA_WALK2	Dry weight fraction salt
WPYR_WALK2	Dry weight fraction pyrite
WQFM_WALK2	Dry weight fraction quartz+feldspar+mica
WSID_WALK2	Dry weight fraction siderite
XRD	X-Ray Diffraction
µs/ft	Microsecond per foot (unit for sonic slowness)

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 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 Bülach-1-1 borehole.

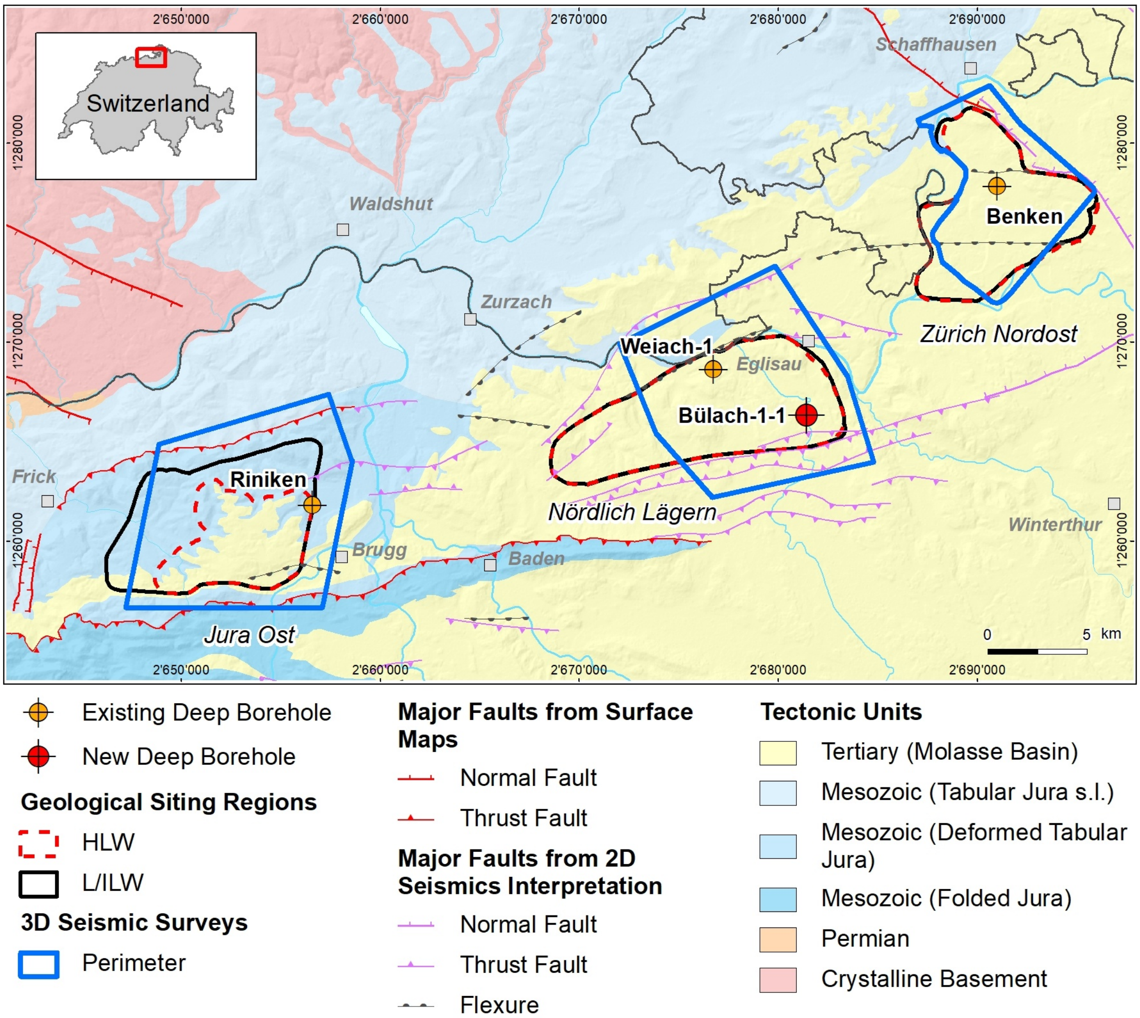

Fig. 1-1: Tectonic overview map with the three siting regions under investigation

1.2 Location and specifications of the borehole

The Bülach-1-1 (BUL1-1) exploratory borehole is the first deep borehole drilled within the framework of the TBO project. BUL1-1 is a vertical borehole. The drill site is located in the south-eastern part of the Nördlich Lägern siting region (Fig. 1-2). The borehole specifications are provided in Tab. 1-1. The lithostratigraphic profile and the casing scheme are shown in Fig. 1-3. Due to instabilities, the borehole was plugged back from 1'043.00 m to 918.70 m (*cf.* Dossier I). Resuming coring operations, a sidetrack was initiated with a kickoff point at 995.85 m. This sidetrack was labelled Bülach-1-1B (BUL1-1B). BUL1-1B reached the final depth of 1'370.19 m (measured depth MD core depth)[1]. For easier communication and labelling, the name BUL1-1 is generally used for the complete vertical borehole unless stated otherwise. Fig. 1-3 shows the combined lithostratigraphic profile of BUL1-1.

Tab. 1-1: General information about the BUL1-1 borehole

Location	Bülach (Canton Zurich / ZH), Switzerland
Siting region	Nördlich Lägern
Coordinates	2'681'446.028 / 1'266'298.472
Elevation	389.62 m asl (top of rig cellar)
Borehole depth	1'370.19 m MD core depth
Drilling period	15 April 2019 – 27 November 2019 (spud – rig release)
Drilling company	Daldrup & Söhne AG
Drilling rig	Wirth B 152t
Drilling fluid	Water-based mud with varying amounts of Pure-Bore®, Pure-Bore® ULV, soda ash, sodium bicarbonate, xanthan gum

[1] *Measured depth (MD)* below top rig cellar along borehole trajectory. In all dossiers, depth refers to MD unless stated otherwise.

MD core depth refers to the depth marked on the cores. Note that petrophysical logs have not been shifted to core depth, hence MD log depth differs from MD core depth. The depth shift between core depth and log depth is documented in Dossier V, Appendix E-1.

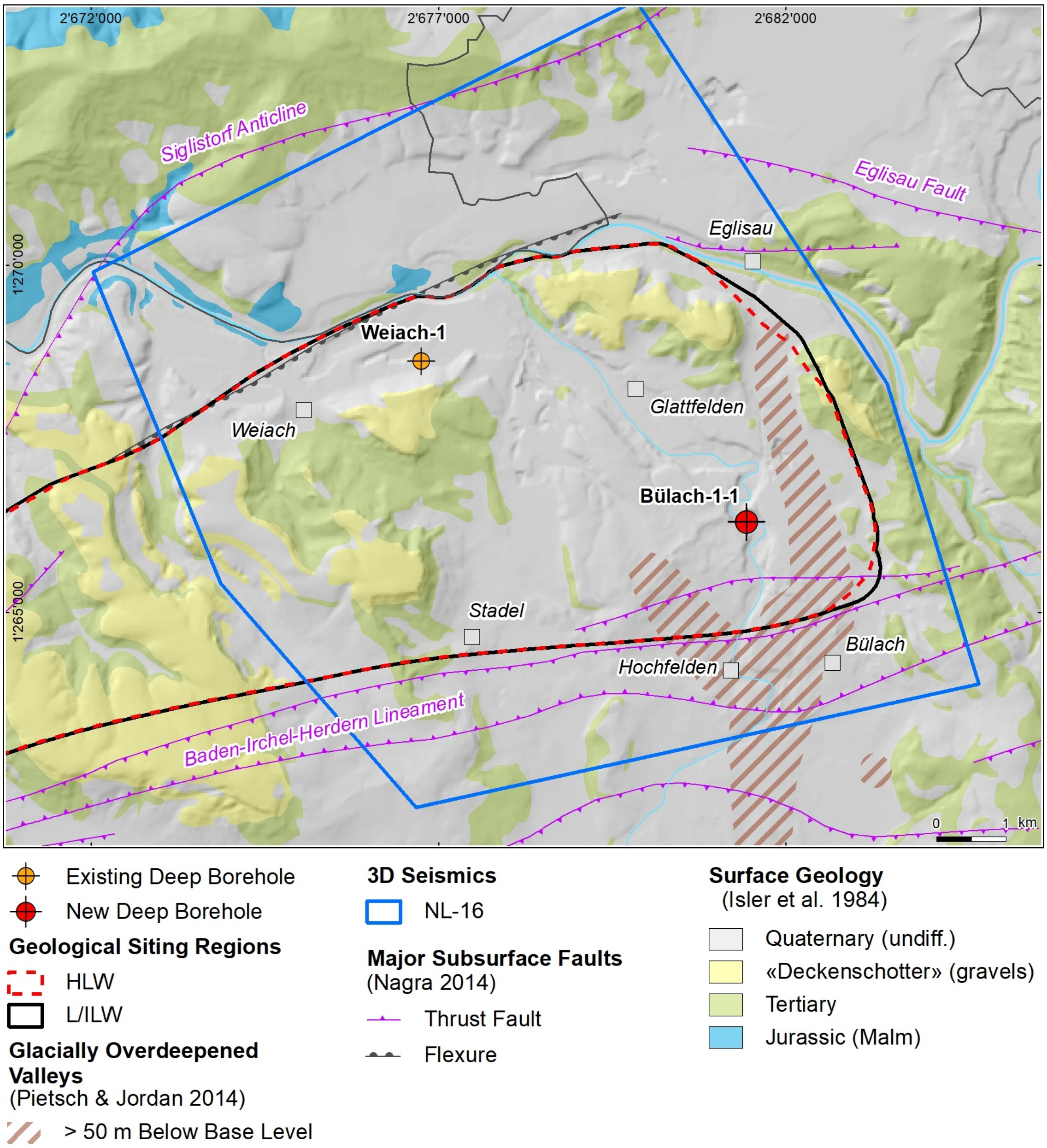

Fig. 1-2: Overview map of the investigation area in the Nördlich Lägern siting region with the location of the BUL1-1 borehole and the existing Weiach-1 borehole

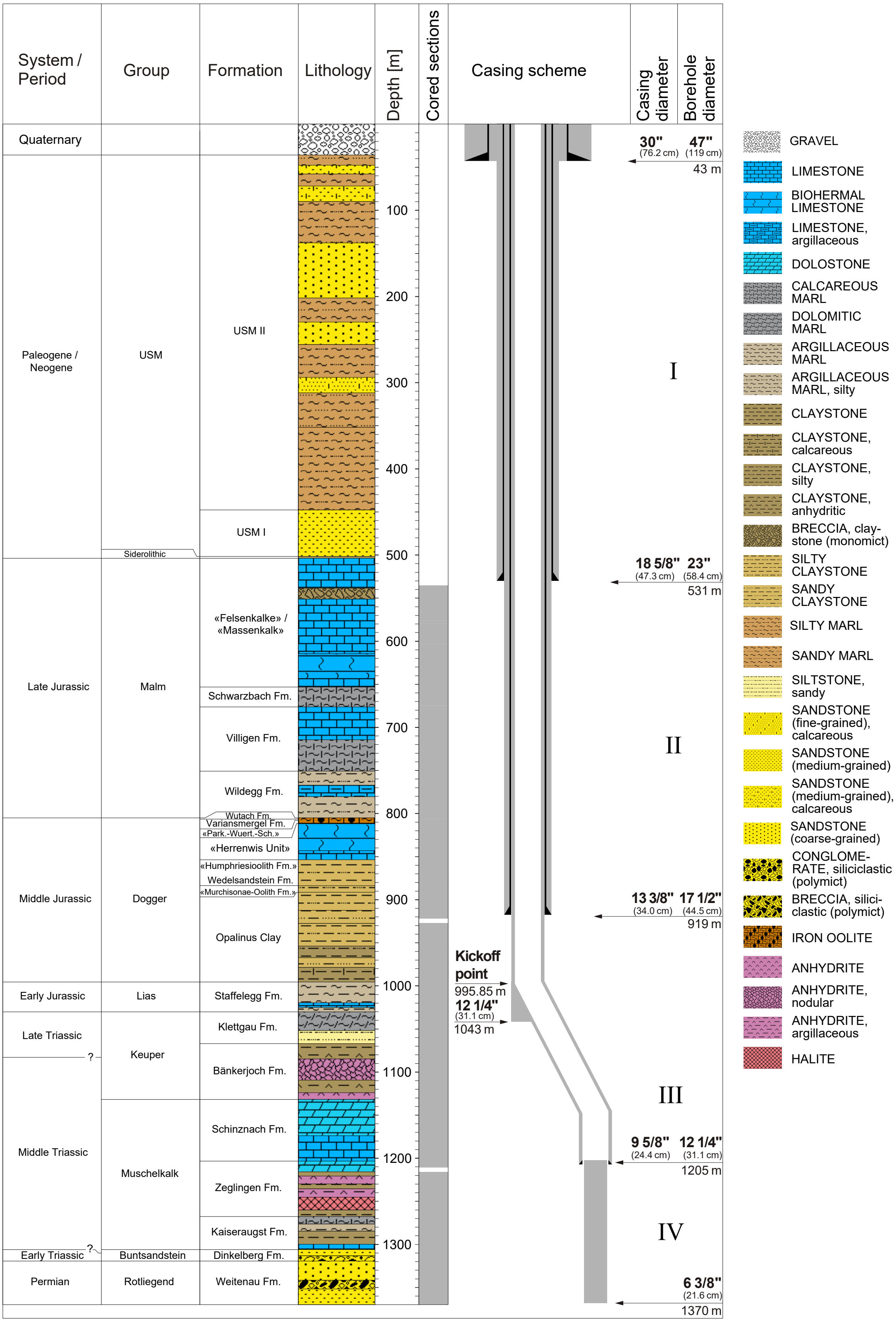

Fig. 1-3: Lithostratigraphic profile and casing scheme for the BUL1-1 borehole

1.3 Documentation structure for the BUL1-1 borehole

NAB 20-08 documents the majority of the investigations carried out in the BUL1-1 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. 1-2).

This borehole documentation aims at early publication of the data collected in the BUL1-1 borehole. It includes the majority 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 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. 1-2: List of dossiers included in NAB 20-08

Black marks the dossier at hand.

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

1.4 Scope and objectives of this dossier

The present report describes the results of the stochastic petrophysical log analysis performed in the BUL1-1 borehole. The detailed workflow for this analysis is described in a methodology report (Marnat & Becker, in prep.), here, only a very short summary is given. The petrophysical logs record a measurement every ½ foot (~ 15 cm). For the Multimineral Log Analysis (abbrev. MultiMin throughout this report), a mineral content is assumed at each of these measurement locations, either from prior knowledge or from mineralogical lab analyses. A theoretical log response from this assumed mineral content for each available petrophysical log is calculated and compared to the actually measured log. Using optimisation techniques, the difference (i.e. the error) between calculated log responses and actual measured petrophysical logs is minimised by adjusting the assumed mineral content. In case of gaps in the log-coverage of the borehole, data from a Multi-Sensor-Core-Logger (MSCL) is used to fill the gap. The same workflow, as shortly summarised above, is used with the MSCL data. Any deviation from this workflow is explained in this report.

The result of this analysis therefore are continuous profiles of the mineralogical content and other rock parameters (e.g. porosity) where the main aim of these calculations here were continuous profiles of the clay content and porosity.

The organisation of this dossier follows the necessary steps of the workflow. First, data is collected and, if needed, quality checks (QC) are performed. In addition, necessary pre-calculations concerning important environmental parameters are performed (Chapter 2). This is followed by the actual analysis of the data (Chapter 3) and a short description of results in Chapter 4. Chapter 4 also includes an estimation of the fit of the results to available data from lab measurements.

All depths in this report are reported as measured depths (MD) if not stated otherwise.

2 Data preparation

2.1 Used log data

The acquisition, QC (quality control) and generation of log composites of the petrophysical logs from the borehole BUL1-1 is described in more detail in Dossier VI, the raw data is also shown in Plate 1. Note that abbreviations in brackets in the list below are according to Schlumberger (SLB) mnemonics (as SLB was the log contractor responsible for the log acquisition). 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 and can be found elsewhere. The petrophysical logs used for this study are listed below:

- Caliper log (EMS/PPC – Environment Measurement Sonde / Power Positioning device and Caliper tool)

  The caliper log uses several arms (6 in this case) to continuously measure the borehole shape.

- Gamma Ray (GR, from the EDTC – Enhanced Digital Telemetry Cartridge)

  This log measures the naturally occurring radioactivity which can be used to determine the mineral content (mainly clay)

- Spectral Gamma Ray (SGR, from the HNGS – Hostile Natural Gamma Ray Sonde)

  This tool also measures the naturally occurring radioactivity. In addition to the total radioactivity, the tool is able to determine the amount (in ppm or wt.-%) of Uranium (U), Thorium (Th) and Potassium (K) in the rocks which can be used e.g. for clay typing.

- Neutron Hydrogen Index (NHI, from APS – Accelerator Porosity Sonde)

  The APS is a tool that can measure the porosity (or more precise the NHI) in water saturated formations. Usually, the corrected NHI is used (in this case corrected for limestone porosity). SLB refers to this corrected NHI as APLC (Near/Array Corrected Limestone Porosity). In addition, the APS can be used to determine Sigma (SIG), a measure to determine the water content and mineralogical characterisations.

- Density (TLD – Three-detector Lithology Density)

  TLD is a gamma-gamma density type logging tool using a radioactive source to determine the density of the rock. In addition, the TLD records the photoelectric factor (PEF or PEFZ) which can also be used to determine the mineralogy.

- Element Spectroscopy (ECS – Elemental Capture Spectroscopy)

  The ECS uses a radioactive neutron source to measure elemental concentrations in rocks and estimate the major matrix properties from them.

- Resistivity (HRLT – High Resolution Laterolog array Tool)

  The HRLT measures the true formation resistivity even in thinly bedded and deeply invaded formations.

- Sonic (MSIP – Modular Sonic Imaging Platform

  The MSIP measures the formation interval transit time, a measure of how fast seismic waves (compressional, shear and Stoneley waves) propagate through the formation.

An overview of the used petrophysical logs and their measurements in the borehole BUL1-1 is given in the Appendix in Plate 1.

Due to degraded borehole conditions, rat-holes and cased hole sections (see borehole report, Dossier VI), gaps in log data were observed in the following intervals:

- 0 – 535 m (technical logging in large hole, 23 inches)
- 921 – 1'007 m (see Fig. 2-1)
- 1'195.5 – 1'205 m

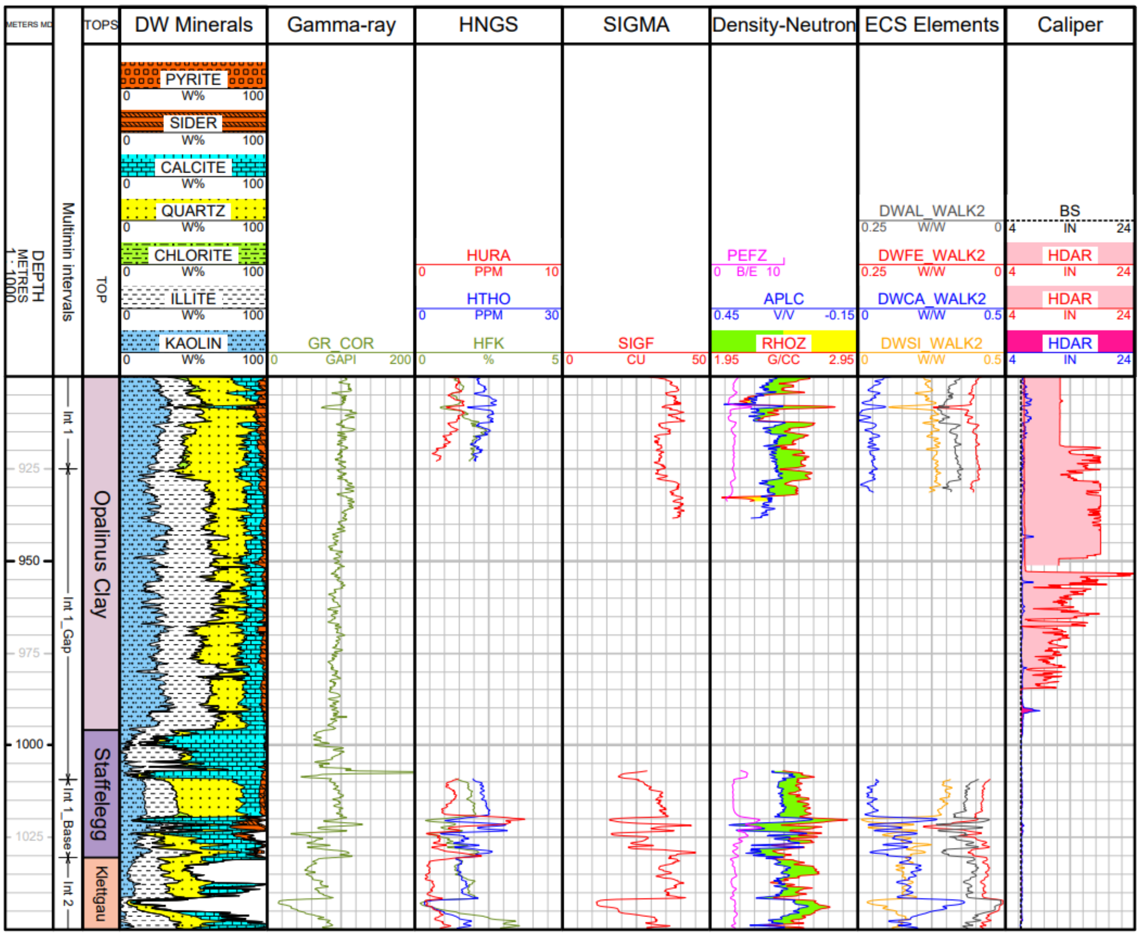

Fig. 2-1: Petrophysical log availability in the interval from 900 – 1'050 m in the borehole BUL1-1

Please note that ECS elements are displayed as measured (in weight/weight, w/w) and are hence not converted to wt.-% (weight percentage).

As previously mentioned, data from an MSCL-Scanner (see Section 2.3) was used in the two lowermost gap intervals. In the upper interval (0 – 535 m), only technical logging was performed which is not suitable for the log interpretation routines used here. However, this interval is only of minor interest in terms of formation characterisation for the geological disposal of radioactive waste and, hence, was disregarded completely.

2.2 Used core data

As previously mentioned, the MultiMin algorithm requires an initial assumption of the mineralogical content. For the calibration of the log interpretation, core data (mainly lab measurements of mineralogy, porosity and density) was used (see Dossier VIII for more details, some core data is shown in the Appendix in Plates 1 and 2). The available data includes XRD (X-ray diffraction) bulk mineralogy for 195 samples in the interval 538.45 – 1'203.3 m. The analysed minerals were quartz, K-feldspars, plagioclase, calcite, dolomite/ankerite, siderite, anhydrite, celestite, pyrite, clay minerals and organic carbon. In addition, 61 samples were analysed for clay typing (in the interval from 541.6 – 1'027.6 m): quantification of illite, smectite, kaolinite and chlorite endmembers. These weight percentages (wt.-%) were used to calibrate the MultiMin interpretation (mineral weight percentages).

Porosities and grain densities are also included and used for this study. The three measured porosities (water-loss porosity (105 °C) using bulk wet density, water-loss porosity (105 °C) using grain density and pycnometer porosity) were used and compared to the MultiMin total porosity (Phit (Φ_t)). The relative errors of these measurements are provided as well. For more details on the exact measurement procedures of these parameters see Waber (2020).

The difference between core and log depth has been reported in Dossier V and was applied to the core dataset so that core depth matches log depth. Part of the core data is also shown in the Appendix in Plate 2.

2.3 Used MSCL data

MSCL measurements from cores were available for parts of the borehole BUL1-1 (from 797.0 – 1'045.05 m). Measurements were performed in the interval of the host rock (Opalinus Clay) and its confining units. The following parameters were measured:

- Bulk density in g/cc
- Compressional (P) wave velocity in m/s
- Spectral gamma ray curves: potassium (K, %), thorium (Th, ppm) and uranium (U, ppm)
- XRF (X-ray fluorescence) elemental analysis: Iron (Fe), silicium (Si), calcium (Ca), aluminium (Al) and sulphur (S) are used for this study.

These data were used to fill in the petrophysical log gap from 938 – 1'007 m, as explained in more details in Section 2.4.2.

The MSCL data (also referred to as core logs in this report) covers the measured interval at variable sampling rates (0.02 to 0.10 m). The core logs were resampled to the composite log sampling rate (0.1524 m) using the convolution product with a triangular operator.

As with the used core data, a depth shift was applied according to values reported in Dossier V.

2.4 MultiMin input dataset preparation

The petrophysical composite log used as input for this study (see Dossier VI) represents a quality controlled, edited, corrected and merged dataset for all petrophysical logging data recorded in each section of the borehole. As mentioned earlier, some gaps in the coverage of the borehole with petrophysical logs occur. Hence, some additions to the data were performed, aiming at reducing the logging gaps or to increase the data redundancy, as explained in the two next sections. The original measurements and corrections of the petrophysical logs are reported in Dossier VI.

2.4.1 Sonic curve

In the Opalinus Clay (in the interval from 925 – 996.5 m), the wireline compressional sonic curve was missing in the composite log in parts of the borehole as during the QC of the petrophysical data it was deemed to be not suitable for usage (because of bad borehole conditions). Nevertheless, for the MultiMin log interpretation, an additional QC was performed on the raw data of MSIP Run 4.2.3 (see Fig. 2-2). The QC showed that the energy levels received by the tool in these intervals were sufficient to warrant a usage of the data in the MultiMin log interpretation. Hence, the compressional sonic curve (DT_OUT) was picked at the maximum energy received (red colour in Fig. 2.2) and merged to the input dataset of the MultiMin interpretation in the interval from 925 – 996.5 m.

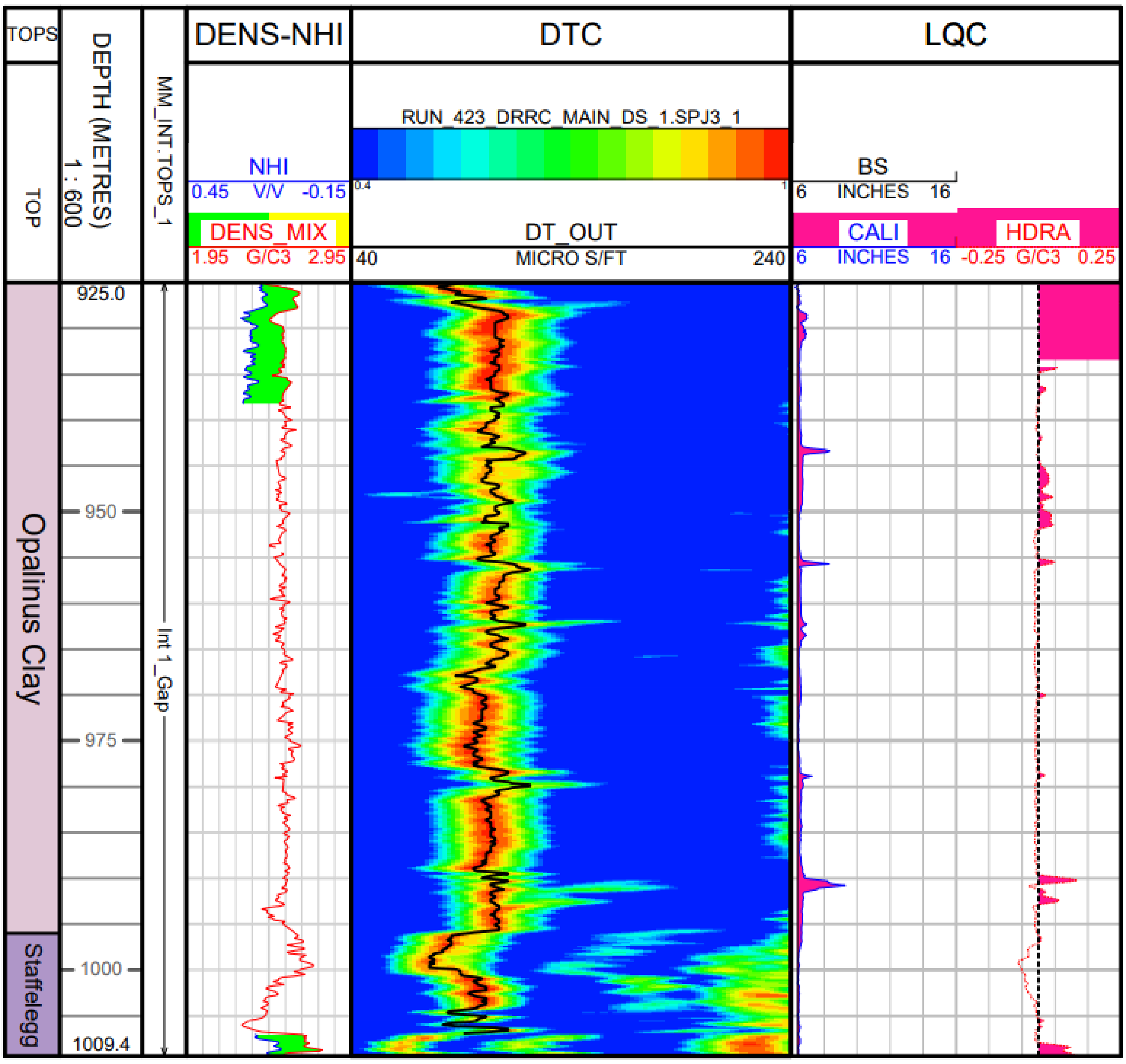

Fig. 2-2: Picking of the compressional sonic curve in the Opalinus Clay (in the interval from 925 – 996.5 m)

The signal shows fair levels of energy received by the tool, despite the poor logging conditions. Hence, the compressional sonic curve (DT_OUT) was picked at the maximum received energy (red color in track DTC). The arrival of the shear wave was not recorded in this interval.

A comparable logic was applied to MSIP Run 5.1.3 in the cased hole interval from 1'193.5 – 1'205.5 m (see Fig. 2-3). During the QC of the petrophysical data, the compressional sonic curve was neglected (as it was recorded in a cased hole; see Dossier VI). However, most of the other wireline logs are also missing in this short, cased interval and the compressional sonic curve and shear arrivals can give an important contribution to the determination between calcite and dolomite. Since fair energy levels have been recorded, shear arrivals were newly picked during this study (blue curve in Fig. 2-3) for the MultiMin interpretation. The two curves, compressional sonic curve (originally picked by SLB but later neglected because it was recorded in a cased hole interval) and shear arrivals (picked during this study), were merged into the input dataset for the MultiMin interpretation (see Plate 1).

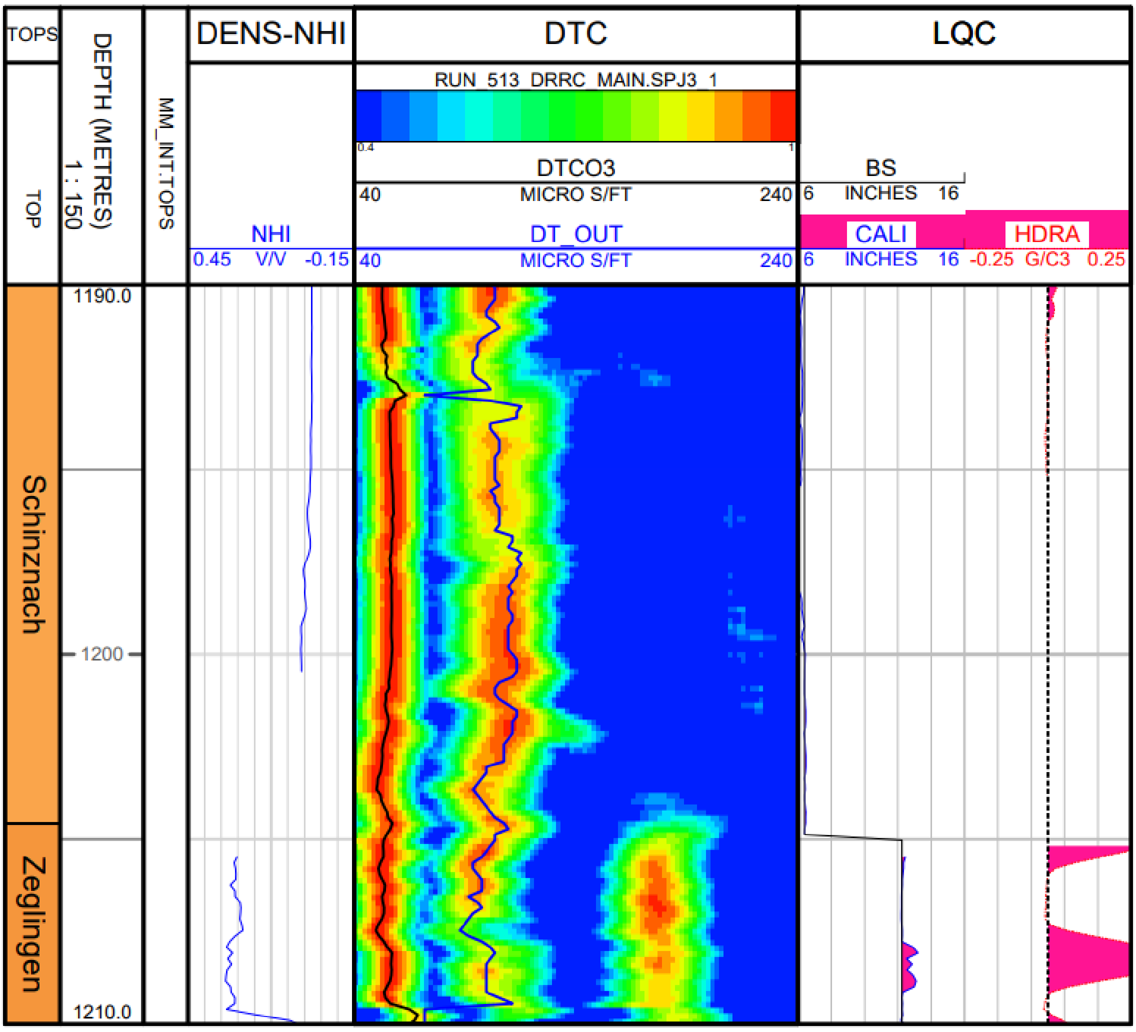

Fig. 2-3: Picking of the compressional sonic curve and shear arrivals in the interval from 1'193.5 – 1'205.5 m

Fair energy levels have been received for both, the compressional and shear arrival and hence were used for the MultiMin interpretation despite these curves beeing discarded in the original QC of the petrophysical data.

2.4.2 Use of MSCL data

As mentioned earlier, in the Opalinus Clay, the borehole was extremely enlarged (up to 30 inches against a nominal 6 3/8 inches hole size), resulting in invalid logs, mostly reading/measuring mud instead of formation. These petrophysical logs were removed from the composite log dataset detailed in Dossier VI leaving an insufficient data coverage in the interval from 921 to 1'007 m (Fig. 2-1). However, this interval was continuously cored and high-resolution acquisition of data using an MSCL scanner could be performed on the core samples. Measured parameters included the spectral gamma-ray, sonic compressional wave velocity, bulk density and XRF elemental composition.

The high-resolution MSCL measurements were cross plotted against the petrophysical logs where valid (Fig. 2-4 to Fig. 2-10). A correlation between MSCL and petrophysical logs was determined, allowing the replacement of bad or missing data in the petrophysical logs using the MSCL data: bulk density, potassium and thorium from MSCL SGR, silicium, iron, calcium, aluminium and sulphur from MSCL XRF. As the MSCL log correlation (even in the good hole sections) was poor for sonic and uranium contents, these two MSCL logs were not used in this study.

The aluminium content acquired from the ECS (Fig. 2-8) is not a measurement but an empirical processing from other elements (Si, Fe and Ca, all measured with the ECS). Therefore, it was decided to use the MSCL measurement as a guideline and to correlate the Al-content measured with the ECS log to the MSCL measurement (and not vice versa as for the other MSCL data).

Shown below are the cross plots in which the empirical laws were picked to compute the MSCL (or ECS in case of Al) curves.

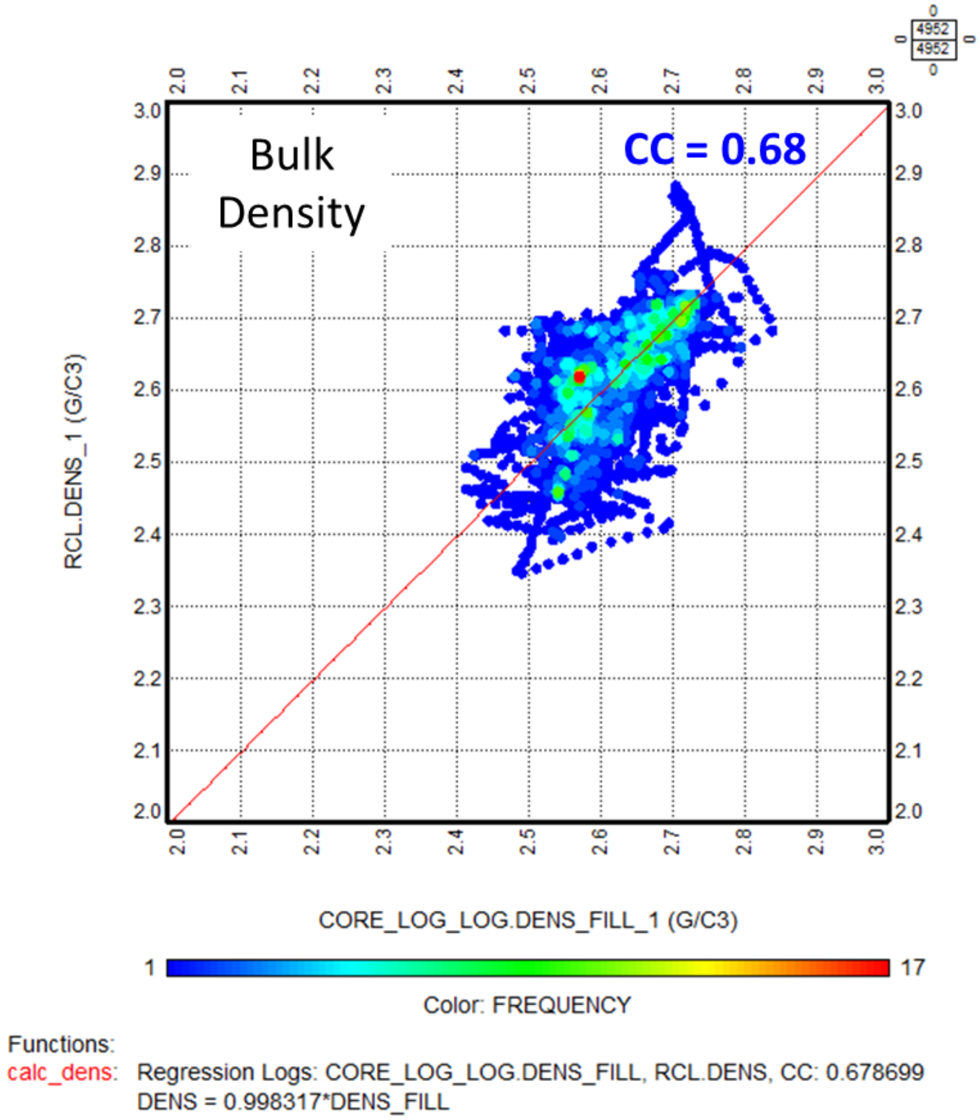

Fig. 2-4: MSCL bulk density log (x-axis) versus wireline density (y-axis)

The color coding shows the frequency of the data points.

The correlation is fair (cc = 0.68), the observed dispersion likely being related to the different conditions (in-situ for petrophysical logs and surface conditions for MSCL data), and possibly drying of the cores at the surface.

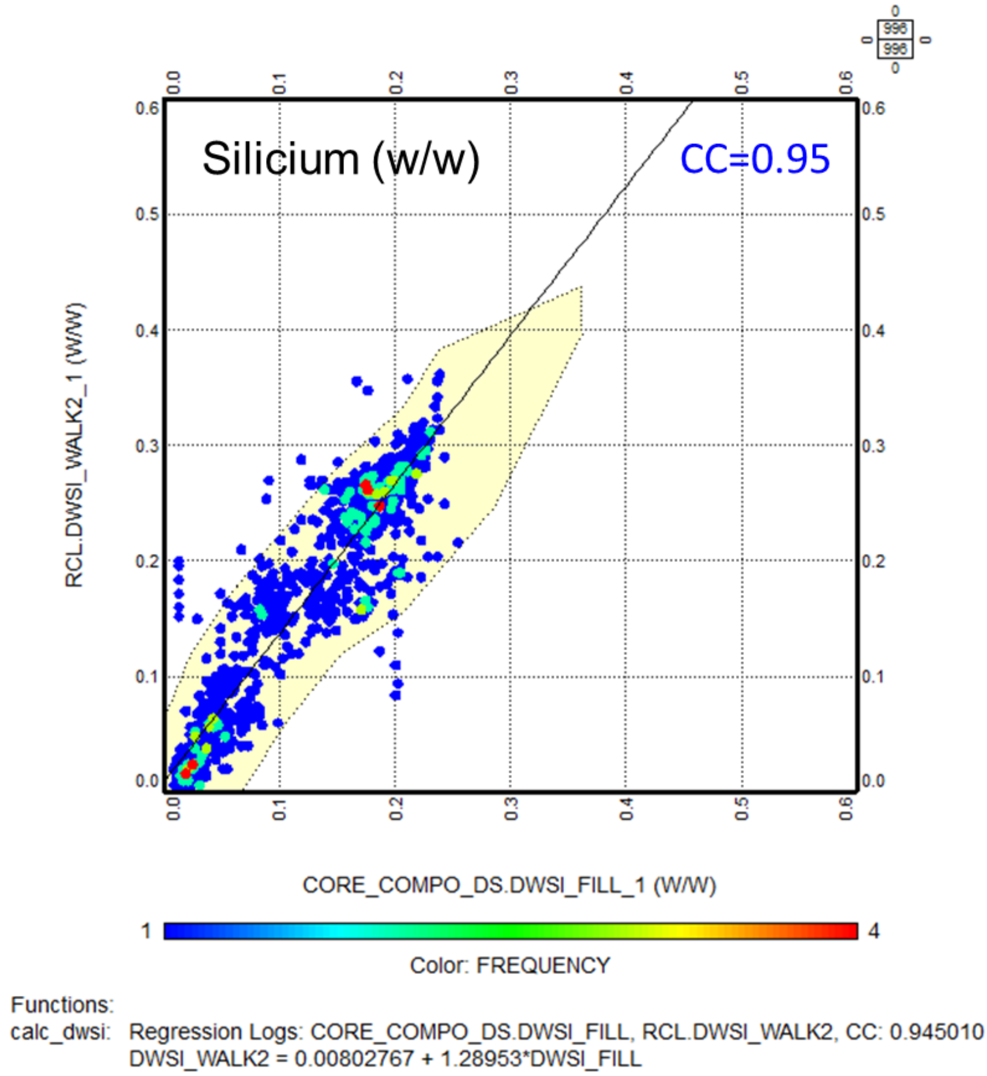

Fig. 2-5: MSCL silicium content log (x-axis) versus wireline ECS silicium (y-axis)

The yellow polygon represents the samples that were included in the regression; the dots outside the polygon are excluded as they are considered to be outliers/artefacts. The color coding shows the frequency of the data points.

The correlation between MSCL and wireline silicium measurement is very good (cc = 0.945). The MSCL silicium measurement reads lower than the ECS. As the reference data for this study are the wireline logs, this drift is compensated by the application of the regression named calc_dwsi.

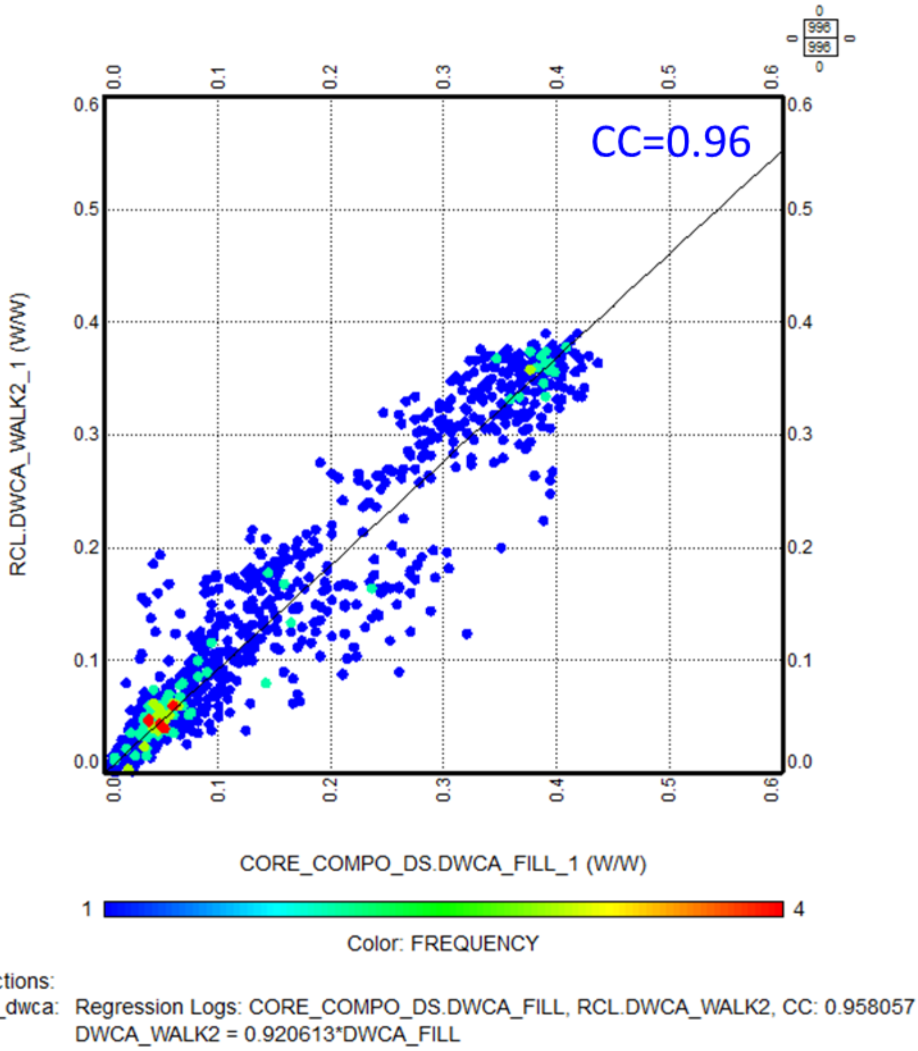

Fig. 2-6: MSCL calcium content log (x-axis) versus wireline calcium (y-axis)

The color coding shows the frequency of the data points.

The correlation between MSCL and wireline calcium measurement is very good (cc = 0.958). The MSCL calcium measurement reads slightly higher than the ECS, this drift is compensated by the application of the regression named calc_dwca.

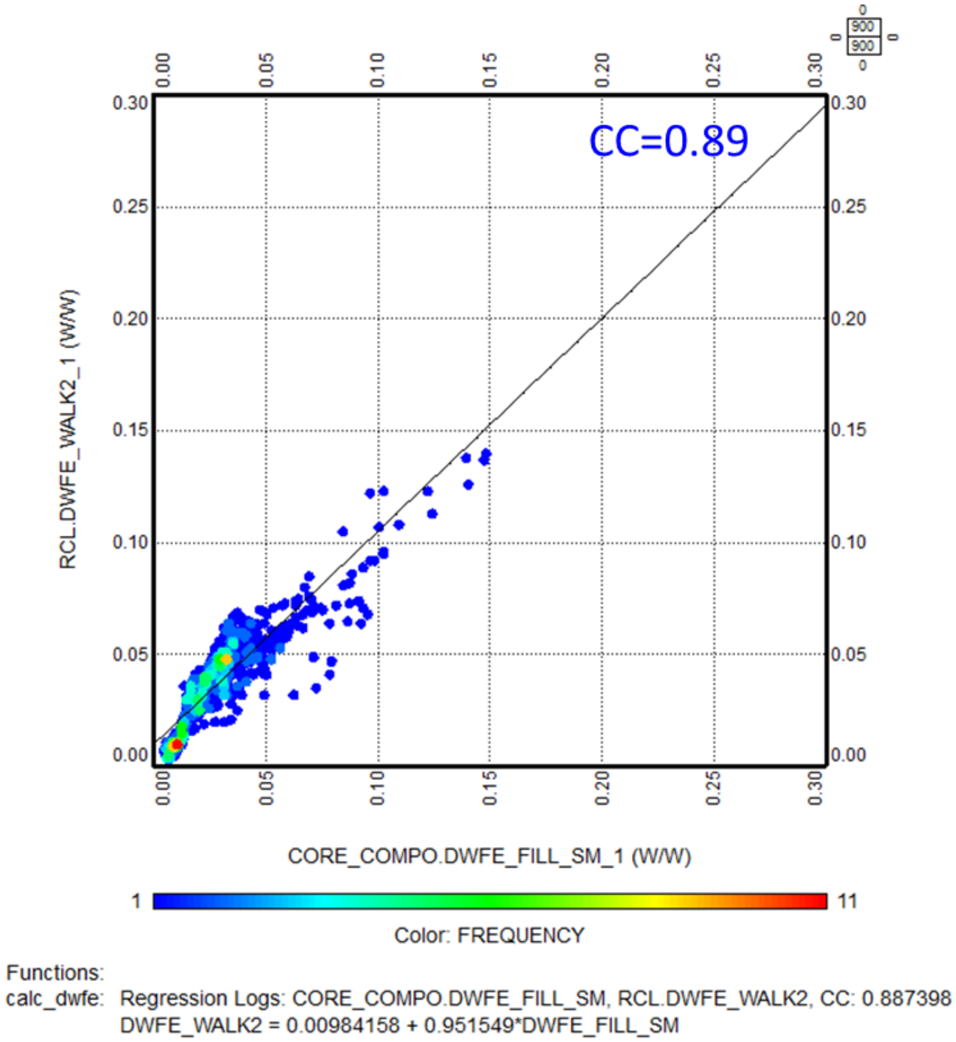

Fig. 2-7: MSCL iron content log (axis) versus wireline iron (y-axis)

The color coding shows the frequency of the data points.

The correlation between core and wireline iron measurement is good (cc = 0.887). The MSCL iron measurement read very close to the ECS, the drift is compensated by the application of the regression named calc_dwfe.

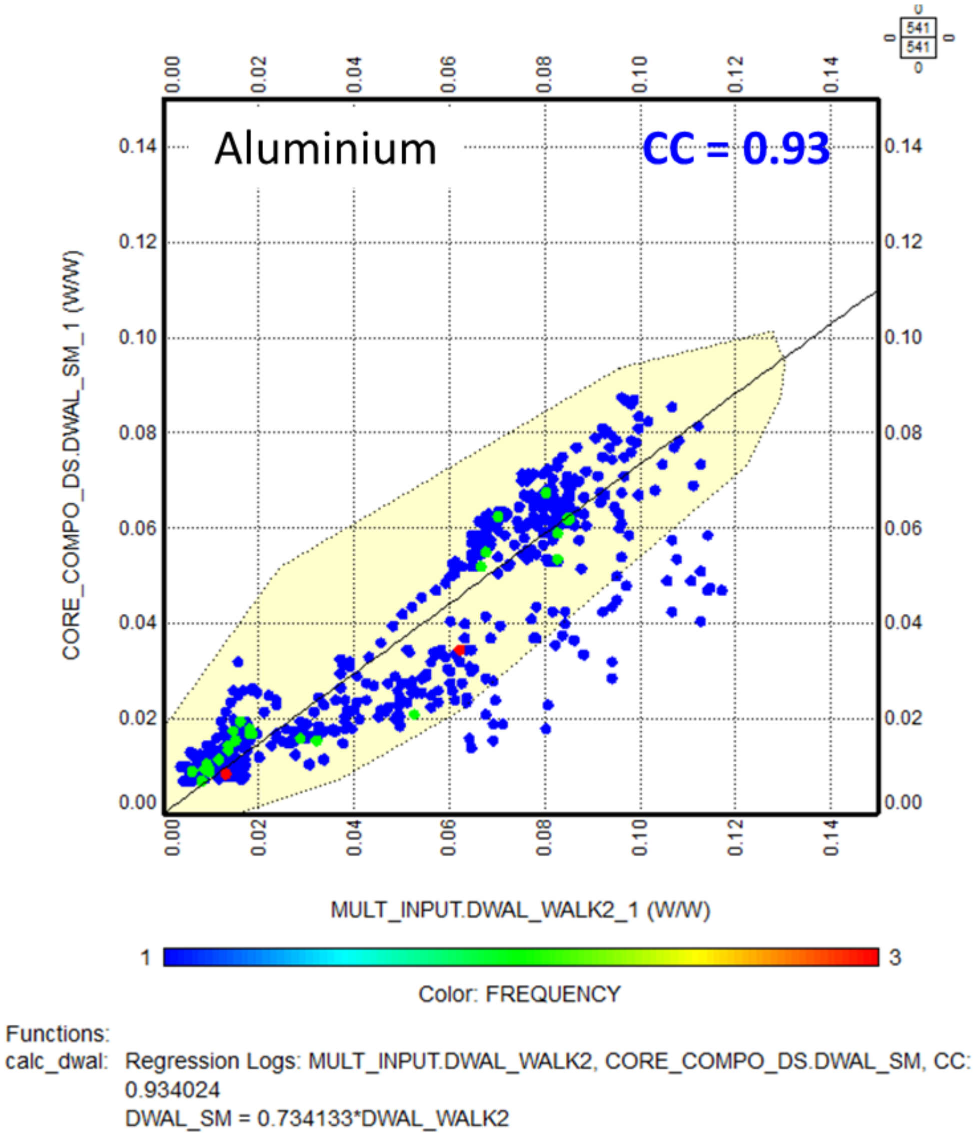

Fig. 2-8: Wireline aluminium (ECS) content log (x-axis) versus MSCL aluminium (y-axis)

The yellow polygon represents the samples that were included in the regression; the dots outside the polygon are excluded as they are considered to be outliers/artefacts. The color coding shows the frequency of the data points.

The correlation between MSCL and wireline aluminium measurement is very good (cc = 0.934). The ECS aluminium measurement reads higher than the MSCL.

In the gap interval, the core Al curve was found discontinuous; the gaps were filled with the data from DWAL_WALK2 from the petrophysical logs (Run 4.2.5). Since the Al content from the ECS is not a measurement per se (but is calculated from the ECS Fe, Si and Ca content), the ECS data was corrected using the CALC_DWAL regression (in contrast to the other elements where the MSCL data was corrected). An additional shift ranging from 0.035 to 0.065 w/w (weight/weight) was applied, based on expert judgement, to honour curve continuity. The resulting high-resolution curve was then upscaled to the petrophysical logs vertical resolution using a triangular convolution operator (0 1 2 3 2 1 0).

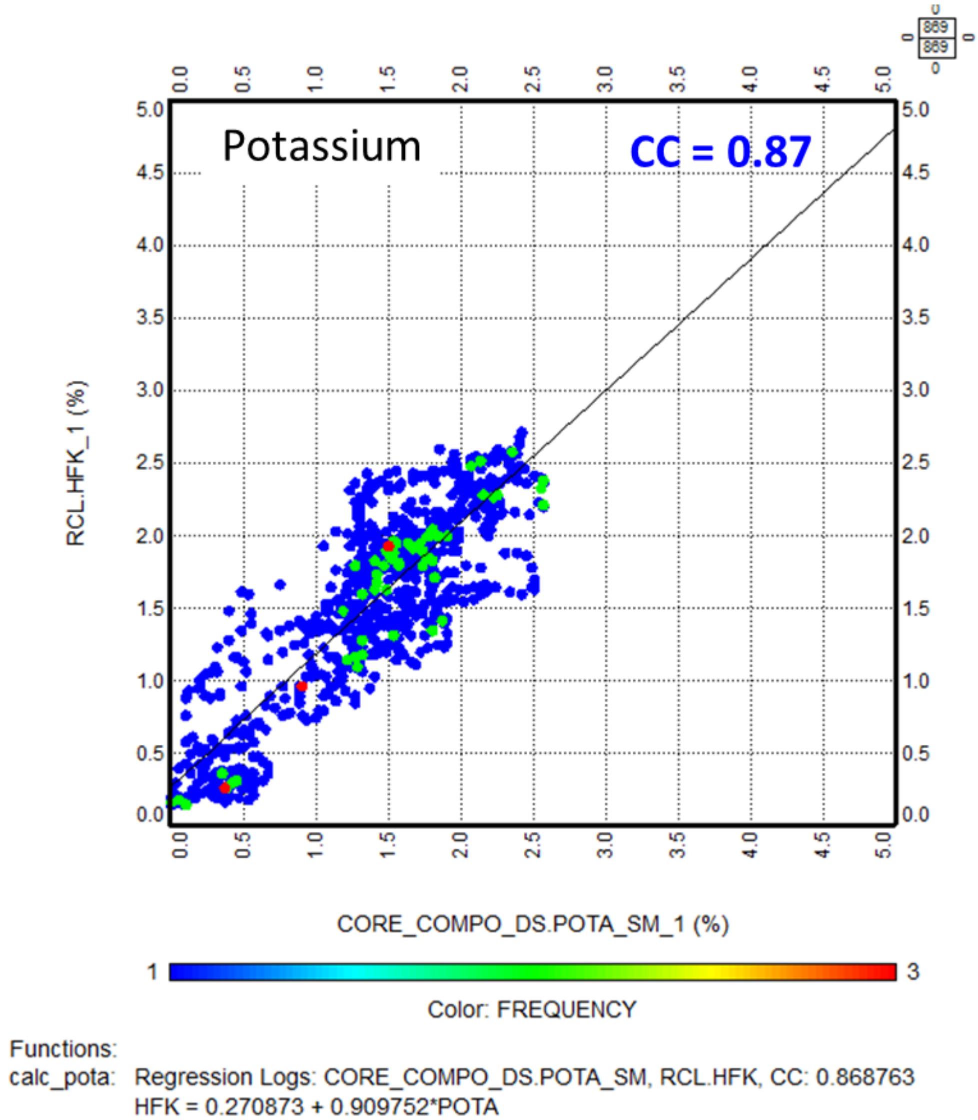

Fig. 2-9: MSCL potassium content log (x-axis) versus wireline HNGS HFK (y-axis)

The color coding shows the frequency of the data points.

The MSCL potassium was acquired with the MSCL spectral gamma-ray tool. The correlation between MSCL and wireline potassium measurement is good (cc = 0.869). The MSCL potassium measurement reads very close to SLBs HNGS tool, the drift is compensated by the application of the regression named calc_pota.

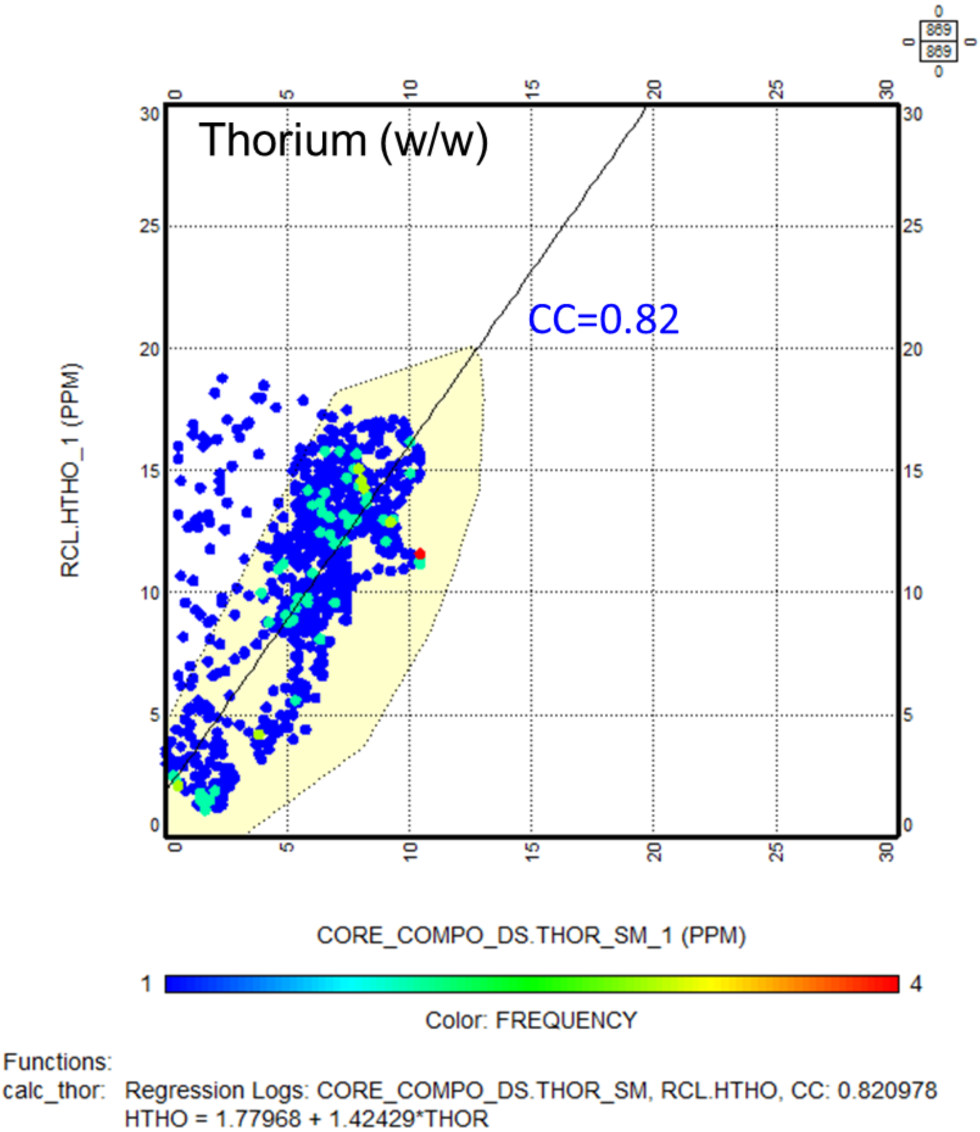

Fig. 2-10: MSCL thorium content log (x-axis) versus wireline HNGS HTHO (y-axis)

The yellow polygon represents the samples that were included in the regression; the dots outside the polygon are excluded.The color coding shows the frequency of the data points.

The MSCL thorium content was acquired with the MSCL spectral gamma-ray tool. The correlation between MSCL and the wireline potassium measurement is fair (cc = 0.821). The MSCL potassium measurement reads lower than the HNGS, the drift is compensated by the application of the regression named calc_thor.

Tab. 2-1 shows a summary of where (in which intervals) petrophysical logs have been replaced, or logging gaps were filled, with other data (sonic, see Section 2.4.1, or MSCL 2.4.2). While the missing petrophysical density logs could be replaced by MSCL-data without further adjustments, the other replacement data had to be edited, either using the regressions detailed in Figs. 2-4 to 2-10) or by adjustments to the respective curves due to the increased borehole diameter or due to petrophysical measurements acquired in a cased hole section. These adjustments are shortly reported in the column "Remarks / Formulation" in Tab. 2-1.

Tab. 2-1: Replacement of wireline logs with MSCL data

The column "Initial curve" represents the wireline curve with gaps or invalid intervals that was filled with data detailed in the "Replacing core log" column. Under remarks, the reasoning and in part the used adjustments of the data are given. Abbreviations in this table from SLB are: DEN – density, DWSI – silicium content from ECS, DWCA – calcium content from ECS, DWFE – iron content from ECS, DWAL – aluminium content from ECS, DTC – compressional wave from sonic log. Abbreviations from MSCL: DEN1 – density, Si, Ca, Fe, Al, Th, K – element contents from MSCL.

Log	**Top** [m MD]	**Bottom** [m MD]	**Initial curve**	**Replacing core log**	**Remarks Formulation**
DENS	804.5	805.7	RHOZ	Den1	Badhole
	806.5	812.3	RHOZ	Den1	Badhole
	843.2	844.9	RHOZ	Den1	Badhole
	849.6	850.7	RHOZ	Den1	Badhole
	852.8	855.6	RHOZ	Den1	Badhole
	856.6	869.9	RHOZ	Den1	Badhole
	870.7	883.3	RHOZ	Den1	Badhole
	885.7	891.1	RHOZ	Den1	Badhole
	901.8	903.9	RHOZ	Den1	Badhole
	904.5	907.7	RHOZ	Den1	Badhole
	908.8	912.3	RHOZ	Den1	Badhole
	932.2	933.7	RHOZ	Den1	Badhole
	933.7	1'007	RHOZ Gap	Den1	Gap
	1'007	1'009	RHOZ	Den1	Badhole
	1'026.7	1'027.6	RHOZ	Den1	Badhole
	1'035.3	1'037.4	RHOZ	Den1	Badhole
	1'040.9	1'041.8	RHOZ	Den1	Badhole
DWSI	931.2	1'009.2	DWSI_WALK2 (Gap)	Si	1.29*Si + 0.00803
	944	946.2	DWSI_WALK2	DWSI_WALK2	DWSI_WALK2 + 0.12W/W
	967.5	969	DWSI_WALK2	DWSI_WALK2	DWSI_WALK2 + 0.08W/W
	994.6	996	DWSI_WALK2	DWSI_WALK2	DWSI_WALK2 + 0.07W/W
DWCA	931.2	1'009.2	DWCA_WALK2 (Gap)	Ca	0.921 * Ca
	944	946.2	DWCA_WALK2	DWCA_WALK2	DWCA_WALK2/10
	967.5	969	DWCA_WALK2	DWCA_WALK2	DWCA_WALK2/5
	994.6	996	DWCA_WALK2	DWCA_WALK2	DWCA_WALK2/5
DWFE	931.2	1'009.2	DWFE_WALK2 (Gap)	Fe	0.9515 * Fe + 0.00984
	944.2	946	DWFE_WALK2	DWFE_WALK2	DWFE_WALK2 + 0.03 W/W
	967.5	969	DWFE_WALK2	DWFE_WALK2	DWFE_WALK2 + 0.02 W/W
	994.6	996	DWFE_WALK2	DWFE_WALK2	DWFE_WALK2
DWAL	535.1	931.2	DWAL_WALK2	DWAL_WALK2	0.734 * DWAL_WALK2
	931.2	1'009.2	DWAL_WALK2	Al	Al, gaps filled by DWAL_WALK2, upscaled
	1'009.2	1'368.2	DWAL_WALK2	DWAL_WALK2	0.734 * DWAL_WALK2
HTHO	922.7	1'009.1	HTHO	Th	1.424 * Th + 1.78
	943.6	947	HTHO	HTHO Run 4.2.5	HTHO + 6
HFK	922.7	1'009.1	HFK	K	0.91 * K + 0.271
	944	946	HFK	HFK Run 4.2.5	HFK + 0.015
DTC	925	996.5	Missing	SPJ3 Run 4.2.3	CT_OUT picked from SPJ3 final validated
	1'086.2	1'088.1	DTCO	DTSM	0.518 * DTSM + 2.7 (DTCO not validated)
	1'1193.5	1'205.5	Missing	DTCO3	Run 5.1.3 final validated
DTS	1'193.5	1'205.5	DTCO	SPJ3 Run 5.1.3	DT_OUT picked from SPJ3 final validated

2.5 Preliminary calculations (Precalc)

As the wireline logs measure parameters under in situ conditions (e.g. temperatures depending on depth and temperature of the borehole fluid, infiltration of mud into the formation depending on the borehole fluid and its density etc.), these prevailing conditions in the borehole have to be taken into account to correctly predict/calculate the theoretical log response from the assumed mineral, porosity and fluid content at a certain depth. Continuous profiles of these environmental parameters were calculated using the Precalc module from the interpretation software Geolog. The main parameters used for the calculation of these environmental parameters are, for reasons of transparency and to be able to replicate exactly the analyses reported here, displayed in Tab. 2-2.

Tab. 2-2: Precalc parameters used in BUL1-1

Location	Mode	Comment	Unit	Name	6 3/8" RUN 2.X	6 3/8 RUN 4.2.X
Interval	In_Out	Option for formation temperature	ALPHA*8	OPT_FT	SONDE	SONDE
	In_Out	Option for reference	ALPHA*8	OPT_REF	DEPTH	DEPTH
	In_Out	Option for resistivity mudcake calc	ALPHA*8	OPT_HMC_RES	SRT	SRT
	In_Out	Option for salinity calculation	ALPHA*16	OPT_SAL	BATEMAN_KONEN	BATEMAN_KONEN
	In_Out	Option for form'n/hydro pressure	ALPHA*8	OPT_FP	MUD_DENS	MUD_DENS
	In_Out	Base of drilling mud	ALPHA*8	MUDBASE	WATER	WATER
	In_Out	Drilling fluid density	LB/G	DFD	9.08	9.58
	In_Out	Resistivity of mud sample	OHMM	RMS	0.71	0.73
	In_Out	Mud sample temperature	DEGC	MST	28.7	19.7
	In_Out	Resistivity of filtrate sample temperature	OHMM	RMFS	0.63	0.64
	In_Out	Mud filtrate sample temperature	DEGC	MFST	28.7	19.4
	In_Out	Resistivity of mudcake sample	OHMM	RMCS	0.94	1.01
	In_Out	Mudcake sample temperature	DEGC	MCST	28.7	20.1
	In_Out	Drilling bit size	IN	BS	6.375	6.375
Interval	Output	Salinity of mud	PPM	SALM	TOPS_PRECALC. SALM	TOPS_PRECALC. SALM
	Output	Salinity of mud filtrate	PPM	SALMF	TOPS_PRECALC. SALMF	TOPS_PRECALC. SALMF
Log	Input	Depth	METRES	DEPTH	DEPTH	DEPTH
	Input	Mud temperature from sonde	DEGF	MTEM	TEMP	TEMP
	Input	Caliper from nuclear/porosity	IN	CALI_POR	CALI	CALI
	Input	Caliper from resistivity/sonic	IN	CALI_RES	CALI	CALI
	Input	Density log	G/C3	RHO	DENS_MIX	DENS_MIX

Tab. 2-2: Cont.

Location	**Mode**	**Comment**	**Unit**	**Name**	**6 3/8" RUN 2.X**	**6 3/8 RUN 4.2.X**
Log	Input	Photo-electric factor	B/E	PEF	PEFZ	PEFZ
	Input	True formation resistivity	OHMM	RT	RD	RD
	Input	Flushed zone resistivity	OHMM	RXO	RXO	RXO
	Output	Formation temperature	DEGF	FTEMP	FTEMP	FTEMP
	Output	Formation/hydrostatic pressure	PSI	FPRESS	FPRESS	FPRESS
	Output	Mud resistivity	OHMM	RM	RM	RM
	Output	Mud filtrate resistivity	OHMM	RMF	RMF	RMF
	Output	Mudcake resistivity	OHMM	RMC	RMC	RMC
	Output	Mudcake from nuclear/porosity	IN	HMC_POR	HMC_POR	HMC_POR
	Output	Mudcake from resistivity/sonic	IN	HMC_RES	HMC_RES	HMC_RES
	Output	Photo-electric cross-section	B/C3	U	U	U
	Output	True formation conductivity	MH/M	CT	CT	CT
	Output	Flushed zone conductivity	MH/M	CXO	CXO	CXO

The full table with data for all runs is available in Appendix A.

The mud properties (mud density and resistivities) reported here were extracted from the validated SLB wireline log headers (see Dossier VI).

3 Petrophysical log interpretation

3.1 MultiMin interpretation

In the following, the petrophysical log interpretation and its results are shortly described. All necessary data treatment and environmental pre-calculations have been described in the previous chapters. Many qualitatively good wireline logs or replacement data from the MSCL were available in most of the borehole, allowing the computation of many unknowns (fluids and minerals).

Significant hydrocarbon shows were neither described by the mudlogging nor inferred from cores or petrophysical logs. Consequently, the formations were treated as water wet (i.e. with saline water as the pore fluid).

The main minerals were inferred from the XRD measurements on core samples and regional knowledge (XRD-data from previously drilled boreholes Weiach-1 and Benken-1 from Mazurek, 2017). Using the MultiMin approach, the mineral content for the following minerals were modelled:

- Clay mineral endmembers (kaolinite, illite, smectite and chlorites) and total clay mineral content
- Silicates: quartz, potassic feldspars, plagioclases
- Carbonates: calcite, siderite, dolomite/ankerite
- Evaporites: anhydrite, halite
- Organic carbon (kerogen)

These compounds were modelled depending on the available data. In case not enough data were available for a given interval (e.g. where data was missing and could not be substituted with other data), some minerals were merged to a pseudo-mineral to reduce the number of unknowns (see Marnat & Becker (in prep.) for more details).

Tab. 3-1 shows an example of the interpretation intervals, the available data and the MultiMin models used in each interval. The intervals are defined based on their general (expected) mineralogy. Interpretation intervals may be subdivided further, e.g. to respect a reduced data quality. The full table with all intervals is available in Appendix B.

Tab. 3-1: List of MultiMin models used in BUL1-1

The intervals (column Interval Name) may include several MultiMin models if some of the input data were of bad quality or the particular section of the interval required special assumptions due to its assumed mineralogy.

The column Cond Num stands for model condition number. Low values are typical for good mathematical models (below 4.00). Condition numbers above 4.00 highlighted in yellow correspond to fair models. See Section 3.2 for more information.

From [m]	To [m]	Interval [name]	Multimin models	Cond. num.	Description
504.0	551.5	Int 1	bul11_int1_top	3.20	Bad nuclear logs
551.5	804.5	Int 1	bul11_int1	3.05	All logs
804.5	805.3	Int 1	bul11_int1_bad-nhi	2.93	Desactivated APLC
805.3	806.5	Int 1	bul11_int1	3.05	All logs
806.5	807.5	Int 1	bul11_int1_bad_nhi	2.93	Desactivated APLC
807.5	810.5	Int 1	bul11_int1	3.05	All logs
810.5	812.0	Int 1	bul11_int1_bad_nhi	2.93	Desactivated APLC
812.0	854.5	Int 1	bul11_int1_Reef	4.12	Reefal facies
854.5	922.8	Int 1	bul11_int1	3.05	All logs
922.8	925.0	Int 1	bul11_int1_bot	2.74	All logs
925.0	953.9	Int 1_Gap	bul11_int1_gap1	3.63	Logs mosty from core
953.9	954.5	Int 1_Gap	bul11_int1_gap2	3.78	Density gap
954.5	1'009.3	Int 1_Gap	bul11_gap1	3.63	Logs mosty from core
1'009.3	1'030.4	Int 1_Base	bul11_int1_base	3.30	All logs
1'030.4	1'057.7	Int 2	bul11_int2_Final	4.34	All logs in Triassic
1'057.7	1'058.9	Int 2	bul11_int2_bh	4.77	Bad hole (BH_FLAG=1)
1'058.9	1'066.2	Int 2	bul11_int2_Final	4.34	All logs in Triassic
1'066.2	1'118.3	Int 2	bul11_int2_bh	4.77	Bad hole (BH_FLAG=1)
1'118.3	1'189.0	Int 2	bul11_int2_Final	4.34	All logs in Triassic
1'189.0	1'195.0	Int 2	bul11_int2_bot1	3.82	Phase bottom$
1'195.0	1'200.5	Int 2	bul11_int2_bot2	4.48	Phase bottom$
1'200.5	1'205.5	Int 2	bul11_int2_bot3	3.31	Phase bottom$
1'205.5	1'206.6	Int 2	bul11_int2_bot4	2.79	Phase bottom$
1'206.6	1'260.5	Int 3	bul11_int3_salt	1.62	Halite layer
1'260.5	1'270.3	Int 4	bul11_int4_gh	3.05	Incl. anhydrite
1'270.3	1'274.0	Int 4	bul11_int4_nos	2.52	No sulphur
1'274.0	1'277.5	Int 4	bul11_int4_gh	3.05	Incl. anhydrite
1'277.5	1'304.1	Int 4	bul11_int4_nos	2.52	No sulphur
1'304.1	1'319.5	Int 5	bul11_int5_top	3.28	Base Triassic

Tab. 3-1: Cont.

The column Cond Num stands for model condition number. Low values are typical for good mathematical models (below 4.00). Condition numbers above 4.00 highlighted in yellow correspond to fair models. See Section 3.2 for more information.

From [m]	**To** [m]	**Interval** [name]	**Multimin models**	**Cond. num.**	**Description**
1'319.5	1'358.5	Int 5	bul11_int5	3.24	Permian clastics
1'358.5	1'367.6	Int 5	bul11_int5_bottom	3.18	Less logs at bottom
1'367.6	1'369.0	Int 5	No model		Not enough logs

Given the sometimes limited data availability and number of core samples in the short interpretation intervals, an inverse linear modelling of the MultiMin endpoints could not be attempted in BUL1-1. Therefore, mineral and fluid endpoints were manually optimised to both reduce the difference between measured and predicted logs and match the core mineralogy and porosity. Greatly simplified, an endpoint can be regarded as a factor that is used to calculate the theoretical log response for each mineral (e.g. if it is assumed that the endpoint for the density of quartz is 2.7 g/cc, a mineral content of 100 % quartz should result in a density of 2.7 g/cc of the predicted density log. For a detailed explanation see Marnat & Becker, in prep.).

Based on expert judgement, an uncertainty value for the petrophysical logs was estimated and used to adjust the weight given to the respective log in the MultiMin computation. Again greatly simplified, if the uncertainty values are large, the corresponding log response will be predicted in the MultiMin interpretation, but it will not be used in the process of error minimisation and hence has no impact on the result of the MultiMin interpretation (for more details see Marnat & Becker, in prep.). High uncertainty values often apply to the Sonic curves, the PEFZ and the electrical conductivities.

The detailed parameters for all the MultiMin models are available in tables in Appendix C.

3.2 Bad hole treatment and quality of results

The quality of the MultiMin interpretation relies in part on the quality of the input data. However, it also relies on the number of available curves and the number of unknowns (i.e. minerals) that need to be calculated. Hence, several quality indicators exist that either are informative about the quality of the input data (LQC-Index), the definition of the mathematical model (CONDNUM, NFUN) or the quality of the interpretation results (MULT_QC and QUALITY).

3.2.1 Indicator for input data quality (LQC_INDEX)

Bad hole indicators are frequently calculated from some of the available wireline logs. They can be used as a quality measure of the data. In this report, a bad hole indicator was calculated using the caliper log, the bulk density correction, Density-Neutron cross plots and borehole wall rugosity. A similar indicator is reported in Dossier VI.

During each wireline logging, the borehole shape is determined using a caliper log. If the borehole shape deteriorates far from the bit size (BS) and bit shape (usually circular), some (or all) of the wireline logs may measure biased data, because the distance between the log and the borehole wall is too large. In that case, the response of a considerable amount of borehole fluid is measured by the tool and the measurements represent more the petrophysical parameters of the borehole fluid than of the formation. A log quality control flag (LQC_INDEX) was generated using the indicators listed below. Each triggered indicator adds a value of 0.25 to the LQC-Index. Hence, the value of the LQC-Index must be between 0 and 1 (and can only have values of 0, 0.25, 0.5, 0.75 or 1).

- DRHO > 0.025 g/cc

  DRHO (bulk density correction) is a correction of the bulk density measured with a gamma-gamma type logging device (here APL). If this correction factor is larger than 0.025 g/cc, the indicator is triggered.

- CALIPER > 1.15 * Bit Size

  If the measured (largest) diameter of the caliper log is larger than 1.15 times the bit size, the indicator is triggered.

- Density-Neutron crossplot

  If the values of the respective measurements are outliers (e.g. because they were measured in intervals with an enlarged borehole), this indicator is triggered (see also Dossier VI, Appendix B, Sheet Badhole Flags)

- Borehole wall rugosity > 0.4 in

  Borehole wall rugosity is a qualitative description of the roughness of the borehole wall (measured by rapid changes of the borehole diameter with depth). The indicator is triggered at values above 0.4 in.

3.2.2 Indicator for the mathematical model (CONDNUM and NFUN)

CONDNUM

The CONDNUM stands for model condition number. Low values are typical for good mathematical models (below 4.00). Condition numbers above 4.00 correspond to fair models. A list of CONDNUMs for the different MultiMin interpretation intervals is given in Tab. 3-1. Please note that CONDNUM is not a proxy for the quality of the calculated output but only for the definition of the mathematical model to calculate the said output.

NFUN

NFUN indicates how many iterations were required to fulfil the constraints imposed by the available data where fewer numbers of iterations are indicative for a more robust model. NFUN is also shown in Plate 1. Please note that NFUN, as CONDNUM, is not a proxy for the quality of the calculated output but only for the definition of the mathematical model to calculate the said output.

3.2.3 Indicator for the MultiMin interpretation results (MULT_QC and QUALITY)

MULT_QC

The MultiMin results were not edited in BUL1-1 (e.g. less reliable data were not removed from the interpretation results), but an integrative MultiMin QC flag was generated (MULT_QC) combining several of the aforementioned quality indicators to inform the data user of potentially invalid results. As this flag relies on the availability of lab measurements, it is only available where a respective lab measurement is available. The MULT_QC flag relies on expert judgement and can have values of 2, 1 or 0 based on the three different scenarios detailed below:

- Suspicious porosity spikes occur and are correlated to an LQC-Index above or equal to 0.5, the quality curve (displayed in Plates 1 and 2, see below) shows values above 2 and the MultiMin results do not match the core measurements: MULT_QC = 2. A value of 2 in MULT_QC corresponds to most likely unreliable data.
- Suspicious porosity spikes occur but with an acceptable LQC_Index (0 or 0.25) and MultiMin quality curve values below 2: MULT_QC = 1. This value indicates that results can/should be used for the characterisation of the formation but should be treated with caution as the interpreted results are not a perfect fit with the available data.
- Otherwise, MULT_QC = 0. Interpreted results are reliable and can be used to characterise the formation.

QUALITY

In addition, a quality curve is shown in Plates 1 and 2. This curve is an indication of how well the observed measurements from wireline logs and the predicted results are part of the same population. At a value of QUALITY less than one, the calculated accuracy is within 95 % compared to the original wireline logs and therefore the analysis is of good quality. If the value is consistently above one, log measurements are not well honoured by the predicted curves, hence the analysis must be regarded as less robust.

Please note that the quality curve only compares the results of the MultiMin interpretation with the petrophysical logs and does not take data quality of the petrophysical logs (e.g. in bad hole sections) or lab measurements into account. The only indicator combining information on input data quality and interpretation result is the MULT_QC indictor detailed above.

4 Results of the calibrated stochastic log interpretation

In the following, the main results of the stochastic log interpretation are summarised. Plate 1 shows the measured wireline logs together with the calculated output from the MultiMin approach. The main results in terms of mineral content and porosity are displayed in Plate 2 as continuous curves. Plate 2 also shows the available lab measurements (from core data).

The aim of this chapter is not a detailed description and characterisation of the sedimentary sequence based on log interpretation results, but rather gives a more general description of the data and a general characterisation of the stratigraphic system or groups shown in Plate 2. Section 4.1 compares the interpretation results with core data giving an overview on the robustness of the interpreted mineralogical content in the borehole. Section 4.2 gives a general characterisation while Section 4.3 gives a more detailed description of calculated parameters in the Opalinus Clay.

4.1 Comparison of interpretation results with core data

Below, the MultiMin interpretations are compared to the mineralogical (bulk) and petrophysical measurements (porosity).

Due to the log database constraints and the need for robust mathematical MultiMin models (i.e. condition numbers ideally below 5 for fair to good models), the number of modelled minerals had to be adjusted. For the sake of easy comparison, the minerals had to be grouped:

- Quartz and feldspars (plagioclase and orthoclase) are grouped into a single pseudo mineral (called QF-Silicates in Plate 2).
- Different clay minerals were computed when possible (kaolinite – smectite together, chlorites: not potassic clays, called NO_K_DCL, and illite). All clay minerals were added to a (total) clay content (DCL). Plate 2 only shows the total clay mineral content.
- Comparable to the clay minerals, different carbonate minerals were also calculated (calcite, dolomite and siderite). In Plate 2, next to the total amount of carbonates (called carbonates), also calcite and dolomite are displayed as the latter two can be used to distinguish between some formations, especially below the Opalinus Clay.

Figs. 4-1 to 4-6 show crossplots between mineral weight percentages from cores (X axis, from XRD lab analyses) and interpretation results from MultiMin (Y axis). All available data are displayed together, covering the interval from the «Felsenkalke»/«Massenkalk» to the Schinznach Formation.

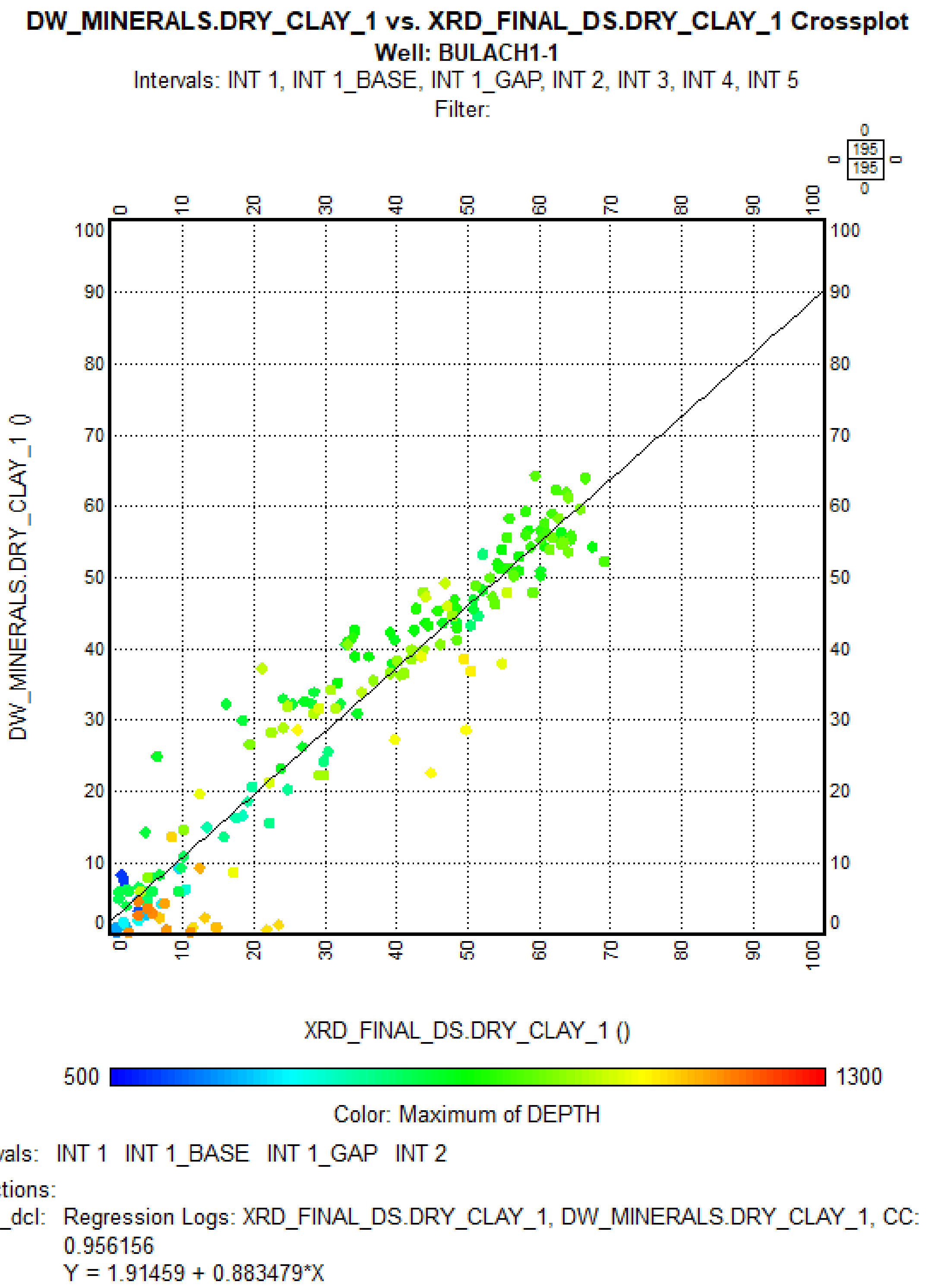

Fig. 4-1: Volume of dry clay compared to core XRD data («Felsenkalke»/«Massenkalk» to the Schinznach Formation)

The MultiMin dry clay volume is very well correlated to the core XRD data, although slightly underestimated (cc = 0.96).

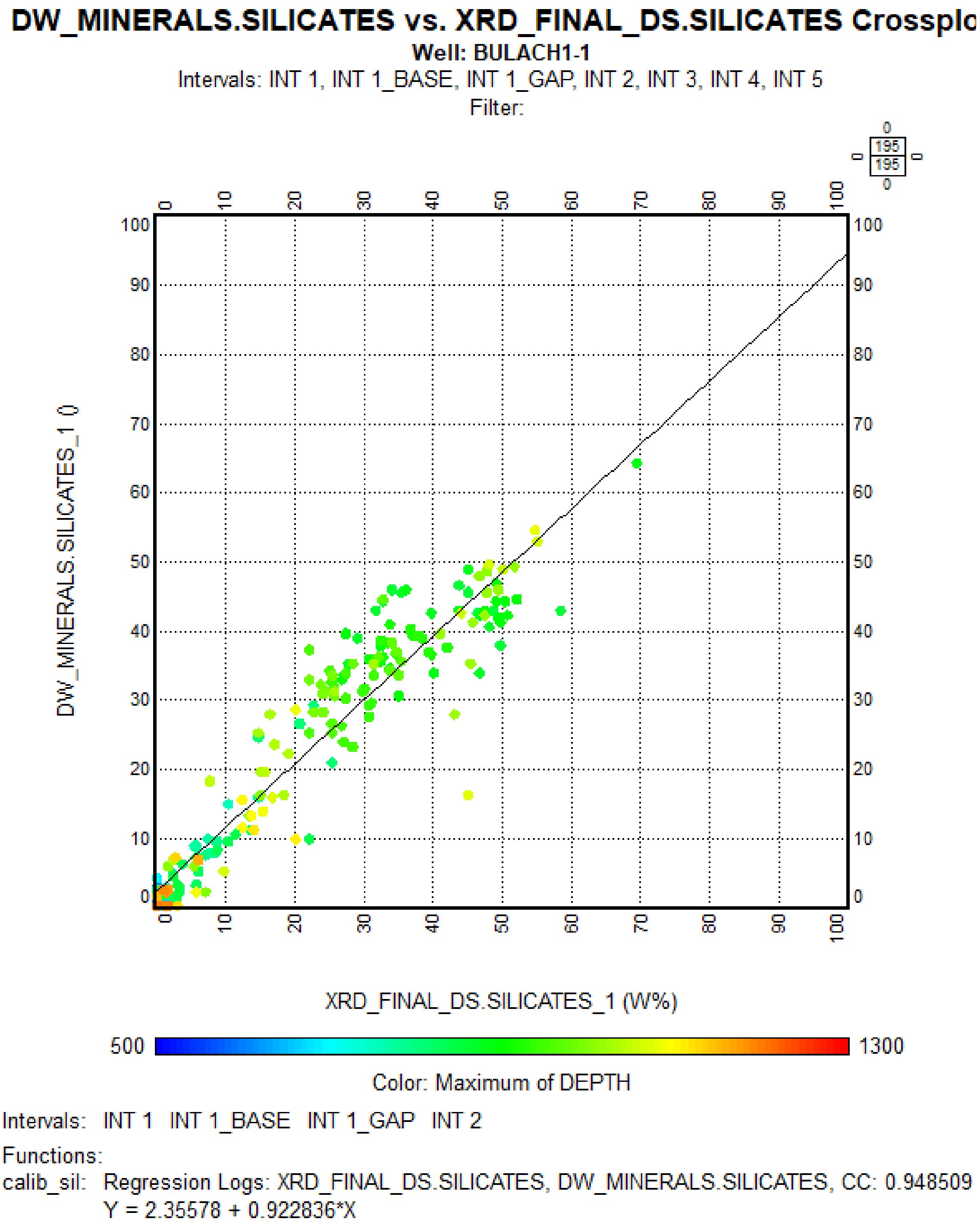

Fig. 4-2: Volume of QF-silicates compared to core XRD data («Felsenkalke»/«Massenkalk» to the Schinznach Formation)

The QF-silicates are the sum of quartz and feldspars. The calibration to core XRD data is very good (cc = 0.95).

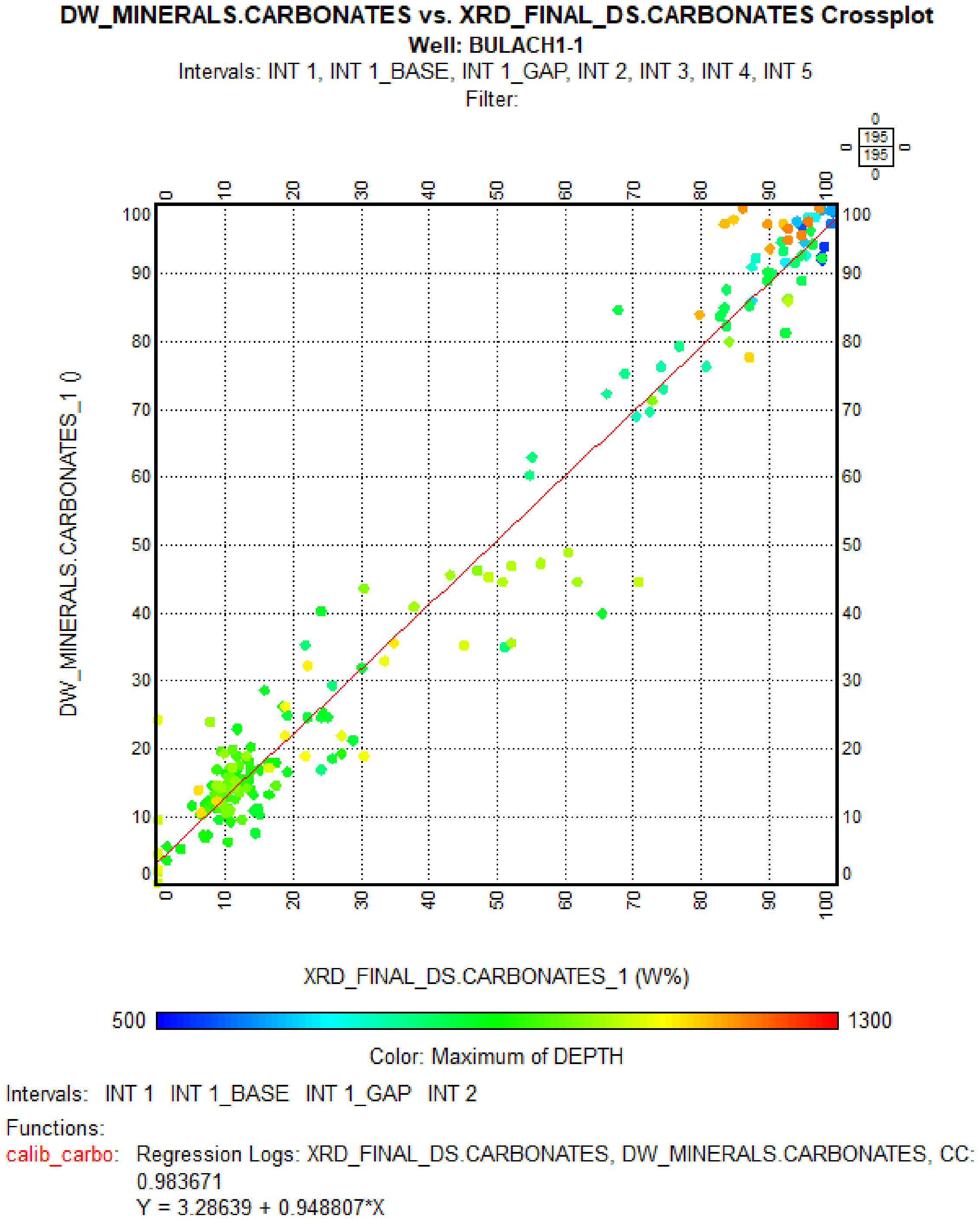

Fig. 4-3: Volume of carbonates compared to core XRD data («Felsenkalke»/«Massenkalk» to the Schinznach Formation)

The carbonates include the calcite, dolomite and siderite content. The calibration to core XRD data is very good (cc = 0.98), despite a few outliers and local heterogeneities.

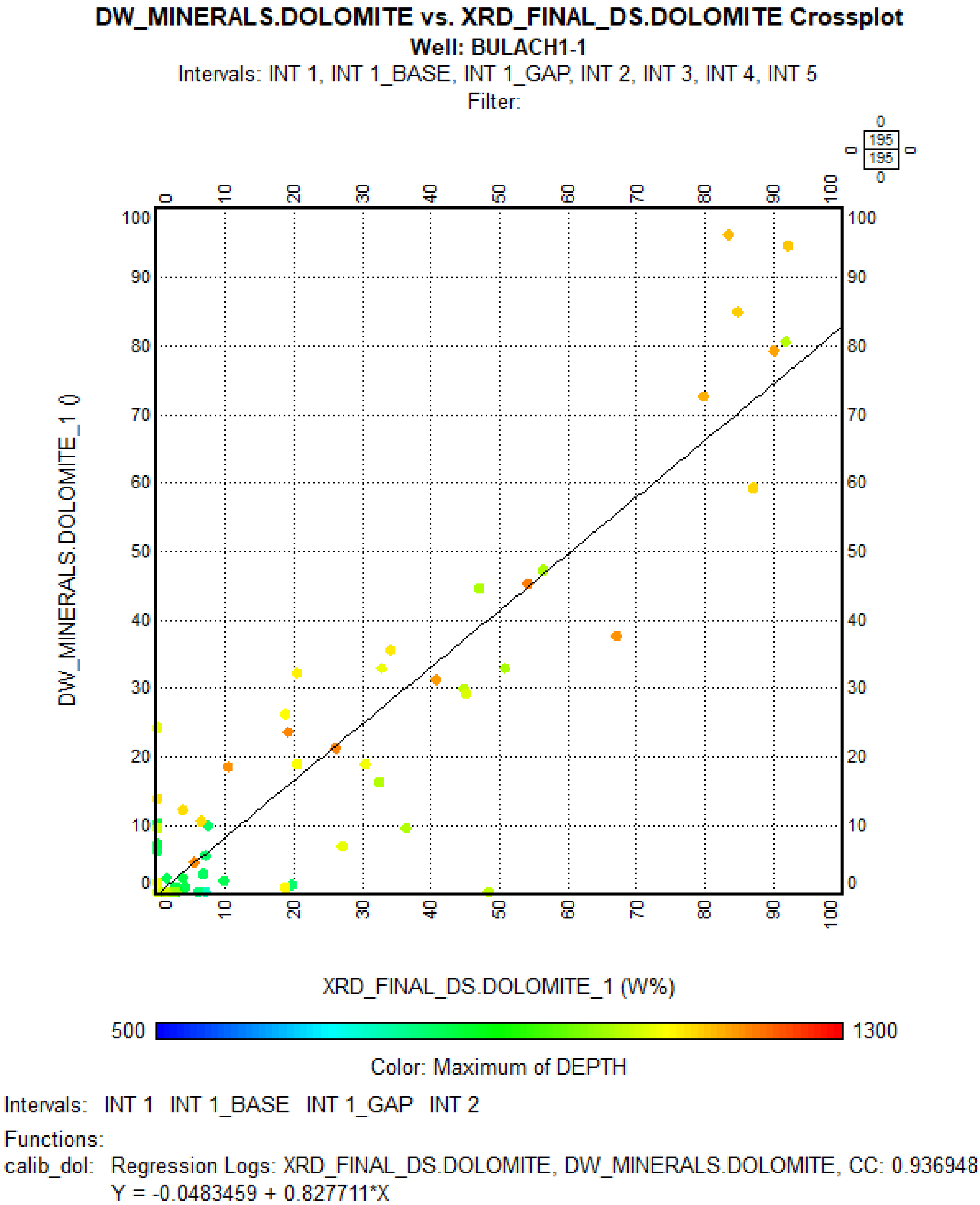

Fig. 4-4: Volume of dolomite compared to core XRD data («Felsenkalke»/«Massenkalk» to the Schinznach Formation)

The dolomites are mostly located in the Triassic, within complex mineralogical settings including anhydrite. The calibration to core XRD data is fair (cc = 0.94).

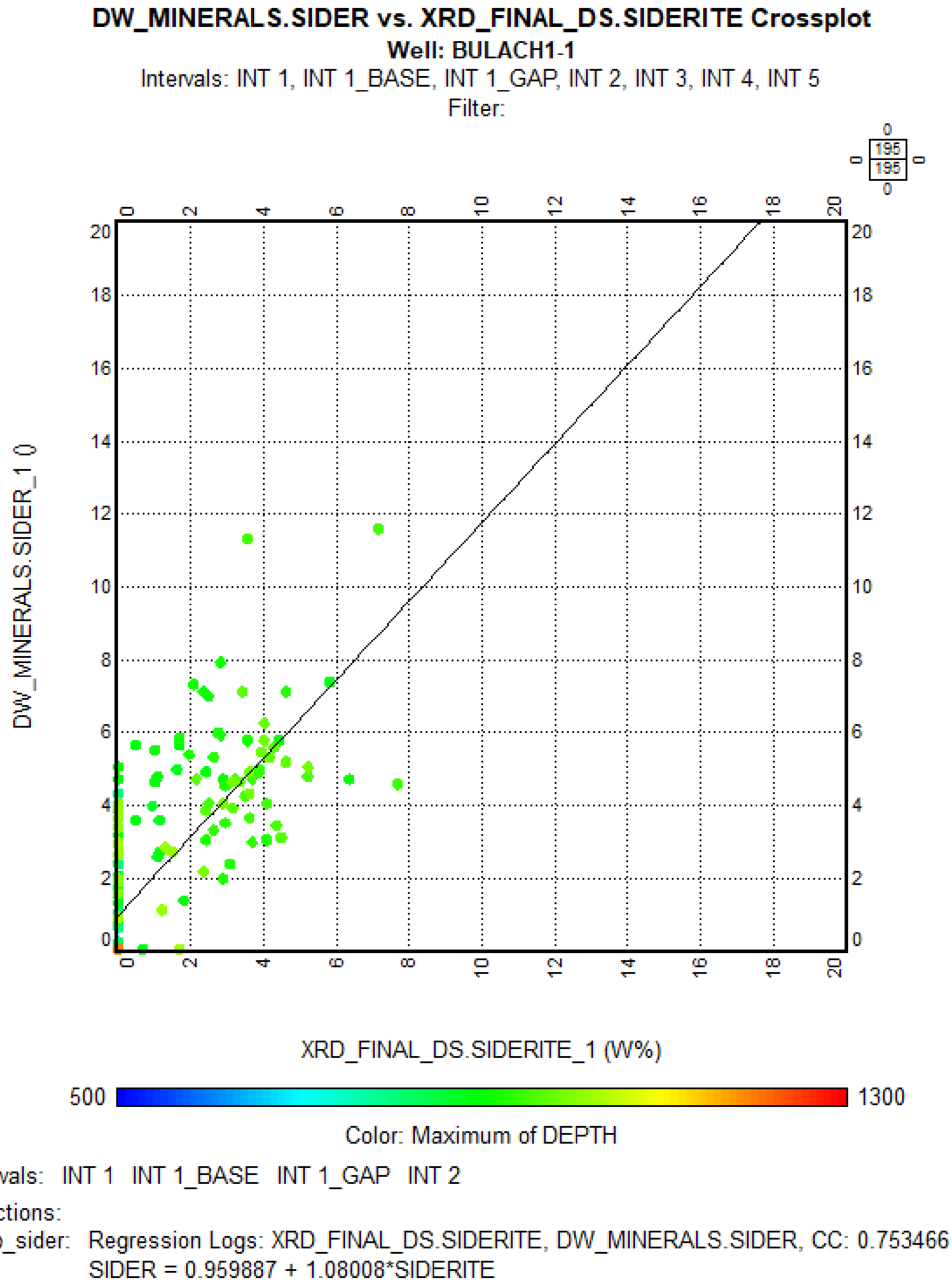

Fig. 4-5: Volume of siderite compared to core XRD data («Felsenkalke»/«Massenkalk» to the Schinznach Formation)

The range of the siderite volume is accurately predicted but the detailed match to core could not be achieved with the available data set (cc = 0.75).

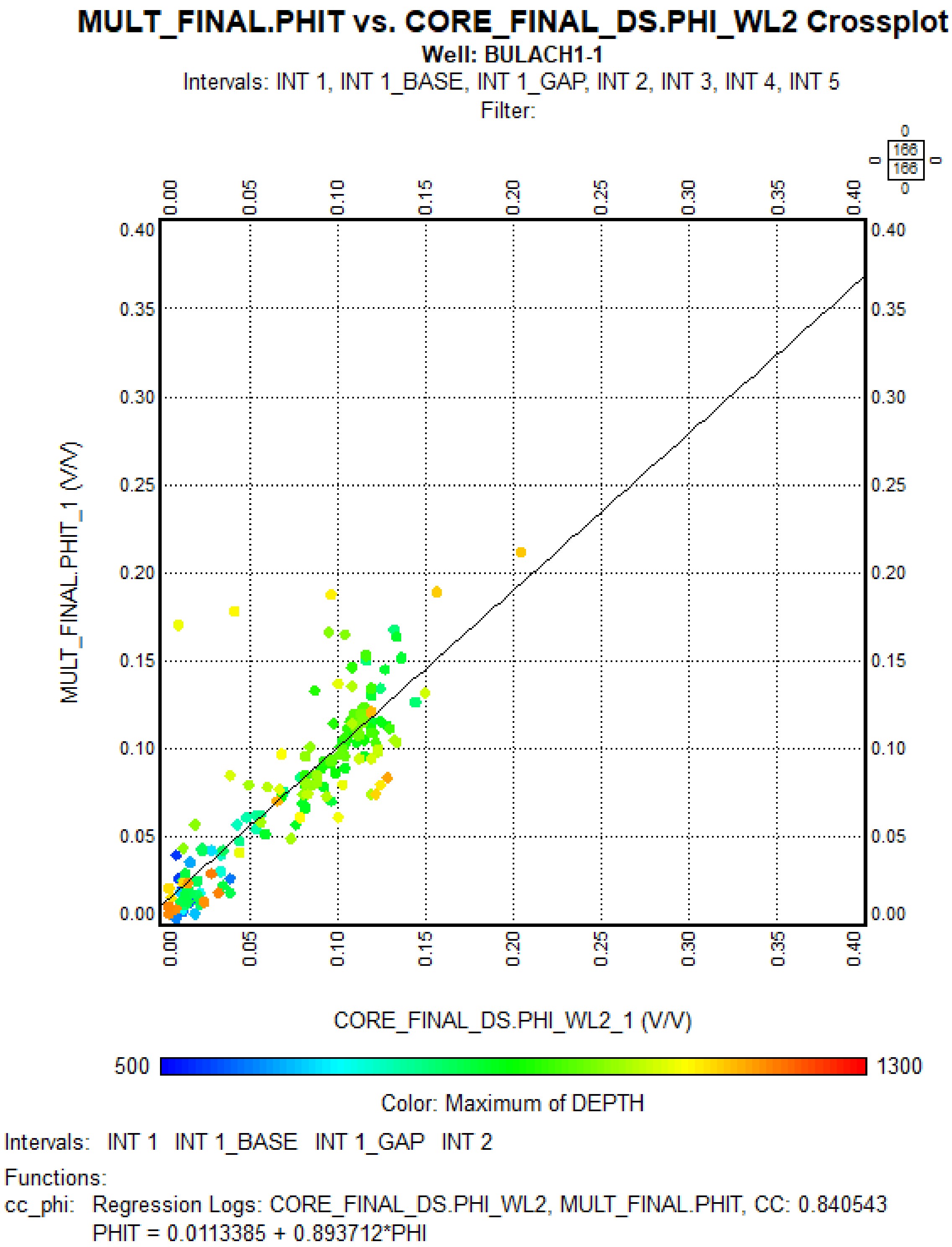

Fig. 4-6: Percentage of porosity compared to core XRD data («Felsenkalke»/«Massenkalk» to the Schinznach Formation)

The lab porosity used for the comparison was water-loss porosity (105 °C) using grain density, at ambient conditions, i.e. no confining stress was applied during measurements. Therefore, cores and logs measurements are not fully equivalent as the logs evaluate in situ, wet formations. Nevertheless, the correlation between MultiMin and lab porosity is fair (cc = 0.84), MultiMin porosity slightly underestimates core porosity.

4.2 Main results of the core-calibrated log analyses in the borehole BUL1-1

The main aim of the MultiMin interpretation were continuous curves of porosity and clay content of the borehole BUL1-1. Several other minerals have been determined (mainly QF-silicates and carbonates). Below is a summary of the main parameters of clay, carbonate, QF-silicate content and porosity for each system/group.

If not stated otherwise, clay content is used senso lato meaning that clay content is used as a general term for the total clay mineral content of the formation (i.e. the sum of all clay minerals). Carbonates and QF-silicates are also used sensu lato where carbonates are regarded as the sum of all carbonate minerals (calcite, dolomite and siderite) while QF-silicates is used synonymous for the sum of quartz (senso stricto) and feldspars.

Malm (504 – 805.28 m, «Felsenkalke»/«Massenkalk» Schwarzbach Formation, Villigen Formation and Wildegg Formation):

As expected, carbonates are the main constituents in the formations of the Malm, the mean carbonate content is 89.3 wt.-% (median of 94.5 wt.-%). Lithological changes (e.g. at group boundaries) are sometimes reflected in a sharp negative peak (i.e. decreasing carbonate content) but in general variance of the carbonates in the Malm is low. Only towards the base of the Malm (e.g. calcareous marl of the Villigen Formation and the more argillaceous marls of the Wildegg Formation) show a slight decrease of carbonates leading to a mean carbonate content in the Wildegg Formation of 71.2 wt.-% (median is also 71.2 wt.-%). The carbonate content in the Malm is dominated by calcite as no dolomite was calculated for this group.

The QF-silicate content in the Malm is very low (mean of 3.3 wt.-%, median of 1.1 wt.-%). The more clay-rich lithologies (e.g. Schwarzbach Formation or parts of the Wildegg Formation) show a slightly increased QF-silicate content (Mean/median of the Schwarzbach Formation: 5.3/ 4.7 wt.-%, Wildegg Formation: 10.4/9.8 wt.-%).

The clay content in the Malm generally shows the same characteristics as the QF-silicate content. Generally, the clay content is low (mean of 7.3 wt.-%, median of 4.5 wt.-%) with locally higher values in the more argillaceous intervals (e.g. parts of the Villigen or Wildegg Formations). In the Wildegg Formation, the maximum clay content is close to 39 wt.-% with a mean and median of 18.4 wt.-%.

Total porosity in the Malm ranges between 0 and 27 % (mean of 3.4 %, median of 2.3 %). Some porosity peaks occur, especially in the claystone interval in the upper part of the «Felsenkalke»/«Massenkalk» and also in the Schwarzbach and Wildegg Formations. These must be treated with caution as they might represent artefacts due to a reduced data quality in these intervals.

Dogger (805.28 – 995.85 m, Wutach Formation, Variansmergel Formation «Parkinsoni-Württembergica-Schichten», «Herrenwis Unit», «Humphriesioolith Formation», Wedelsandstein Formation, «Murchisonae-Oolith Formation», Opalinus Clay):

The boundary between the Malm and the Dogger is clearly marked by a sharp increase of the clay content and a sharp decrease of the carbonate content to the Wutach Formation.

The carbonate content in the Dogger is generally low, with a mean of 34 wt.-% and a median of 18.2 wt.-%. However, these general values mask the fact that e.g. the «Herrenwis Unit» has a very high carbonate content (mean and median of 87.8 wt.-% and 88.6 wt.-% respectively), while the other units/formations only have much lower carbonate contents. Again, the carbonate content is dominated by the occurrence of calcite with the exception of the «Herrenwis Unit» where a (very low) dolomite content was calculated.

The QF-Silicate content in the Dogger ranges between 0 to 64 wt.-%. Again, the mean and median values (23.9 and 24.4 wt.-%) are heavily influenced by the «Herrenwis Unit» which has a very low QF-silicate content (mean and median of 4.7 reps. 3.6 wt.-%) and also the Wutach Formation (mean/median: 4.8/4.2 wt.-%). The other formations are in the range between 15 and 40 wt.-%.

The clay content in the Dogger follows the aforementioned trends where the «Herrenwis Unit» has a very low clay content (mean and median of 7.5 resp. 6.3 wt.-%) while the rest of the group has clay contents up to 60 wt.-%. The Opalinus Clay in the Dogger certainly is the formation with the highest clay content ranging between 28 and 76 wt.-% (mean and median of 52.5 resp. 54.2 wt.-%) where the upper part of the Opalinus Clay (to ca. 928 m depth) has a lower clay content than the lower part.

Total porosity of the Dogger also is very different between the different units. While the «Herrenwis Unit» shows very low porosities (mean and median of 3.2 resp. 2.3 %), the rest of the Dogger formations have much higher porosities of around 10 – 15 %. Some porosity spikes occur reaching values of more than 25 % but these must be regarded as artefacts from the MultiMin interpretation due to a reduced data quality in some sections.

Lias (995.85 – 1'030.51 m, Staffelegg Formation):

The formation boundary from the Opalinus Clay (Dogger) to the Staffelegg Formation (Lias) is characterised by a sharp drop of the clay content and a sharp rise of the carbonate content.

The carbonate content of the Lias reflects the lithology where the upper parts (Gross Wolf down to Grünschholz Members) and lowermost parts (Beggingen and Schambelen Members) have a relatively high carbonate content (up to 86 wt.-%) while the central part (Frick Member, from 1'009 – ~ 1'020 m) has a relatively low carbonate content (between 14 and 20 wt.-%). As in the previous groups, the carbonate content is dominated by calcite, no dolomite content has been calculated.

The QF-silicate content shows the reverse of the carbonate content. While the upper (Gross Wolf down to Grünschholz Members) and lower parts (Beggingen and Schambelen Members) show a relatively low QF-silicate content (between 2 and 30 wt.-%) while the central part (Frick Member) shows QF-silicate contents in the range of 40 wt.-%.

The clay content in general ranges, with exceptions, between 30 – 45 wt.-%. Lower clay contents are indicative for boundaries between members, especially to the Grünschholz Member where the clay content is around 10 wt.-% only.

The total porosity in the Staffelegg Formation ranges between 2.5 and 22 % with relatively uniform values (around 8 %) in the Frick Member and highly variable values in the rest of the formation. Some of the high values reported here may be artefacts from the MultiMin interpretations due to reduced input data quality.

Keuper (1'030.51 – 1'132 m, Klettgau Formation, Bänkerjoch Formation):

In the Keuper, the top part of the Klettgau Formation (Gruhalde Member down to the Gansingen Member) is characterised by carbonate contents between 30 – 92 wt.-% (the latter represents a peak at the top of the Seebi Member) while the rest of the group (lowermost part of the Klettgau Formation and most of the Bänkerjoch Formation) shows lower carbonate contents ranging from 10 – 20 wt.-%. Exceptions occur in the lowermost part of the Bänkerjoch Formation in the anhydrite interval where the carbonate content reaches 60 wt.-%. Cabonate is dominated by dolomite with frequent occurrences of calcite.

The QF-silicate content again is somewhat the reverse of the carbonate content. Where the carbonate content is high, the QF-silicate content is low. The Ergolz Member (lowermost part of the Klettgau Formation) shows very low carbonate contents (0 – 15 wt.-%) while the QF-silicate content ranges between 10 and 58 wt.-%.

The clay content generally seems to be uncorrelated with the carbonate and QF-silicate contents. It ranges between 0 and 61 wt.-% with a mean of 27.6 wt.-% (median of 28.7 wt.-%). However, due to the presence of dolomites (for some logs, the endpoints of dolomites and clay are almost the same, hence the mathematical model cannot easily determine between the two) and the sometimes bad borehole conditions (meaning less reliable input data especially in the lower part of the Keuper, the fit between the lab measurements on cores and the calculated values from logs is not very good.

Muschelkalk (1'132 – 1'306.17 m, Schinznach Formation, Zeglingen Formation, Kaiseraugst Formation):

The boundary from the Keuper to the Muschelkalk is marked by a sharp increase of the carbonate content which here is dominated by dolomite.

While the upper part of the Muschelkalk (Schinznach Formation) uniformly shows very high carbonate contents (mean of 92.4 wt.-%, median of 95.6 wt.-%), the lower formations (Zeglingen Formation and Kaiseraugst Formation) show much lower carbonate contents (mean/median of 22.3/10.6 wt.-% resp. 30.4/27.7 wt.-%). In the upper part of the Schniznach Formation (Asp Member and Stamberg Member), the carbonate content is dominated by dolomites while in the lower parts of the Schinznach Formation (Liedertswil Member and Leutschenberg + Kienberg Members), the dolomite content gradually decreases while the calcite content gradually increases. The lowermost part of the Muschelkalk (Zeglingen and Kaiseraugst Formations) are characterised by the occurrence of anhydrite or, in more general terms, evaporites.

With the exception of a slight peak of QF-silicate and clay content in the uppermost part of the Muschelkalk (Asp Member), the respective mineral content is very low in the Schinznach and Zeglingen Formations (mean/median of clay minerals in the Schinznach Formation including the Asp Member: 4.7/3.5 wt.-%, in the Zeglingen Formation: 9/5.7 wt.-%. Mean/median of QF-silicate in the Schinznach Formation: 2.2/0.6 wt.-%, in the Zeglingen Formation: 2.2/0.5 wt.-%). In the lowermost Kaiseraugst Formation, QF-silicate (mean/median: 27.1/29.1 wt.-%) and clay content increase (mean/median: 30.3/35.1 wt.-%).

Total porosity in the Muschelkalk is very variable and ranges between 0 and 24 %. It is lowest in the «Salzlager» (part of the Zeglingen Formation, values of up to 2 %) and highest in the upper parts of the Schinznach and Zeglingen Formations (reaching values of up to 20 %).

Buntsandstein (1'306.17 – 1'319.63 m, Dinkelberg Formation) and **Rotliegend** (1'319.63 – 1'370.19m, Weitenau Formation):

The boundary from the Muschelkalk to the sandstones of the Buntsandstein and Rotliegend is characterised by a sharp increase of the QF-silicate content and a sharp decrease of the carbonate and clay contents.

The carbonate content of these two groups is very low and ranges between 0 and 20 wt.-% (mean/median for the Buntsandstein: 6.6/5 wt.-%, for the Rotliegend: 5.1/4.9 wt.-%). Carbonate is not dominated by either calcite or dolomite as both minerals occur.

The QF-silicate content is uniformly high though slightly higher in the Buntsandstein (mean/median of 85.4/86.5 wt.-%) than in the Rotliegend (mean/median: 75.5/77.7 wt.-%).

The clay content in the Buntsandstein (mean/median: 7.9/6.8 wt.-%) is slightly lower than in the Rotliegends (mean/median: 19.4/16.7 wt.-%). The Rotliegend includes a slightly more clay-rich section at the top of the Weitenau Formation.

Total porosity in the Buntsandstein and Rotliegend ranges from 1 to 17 %, mean and median of both groups are very comparable (Buntsandstein: 9.5/10.1 %, Rotliegend: 10.3/10.4 %) though the variability in the Buntsandstein is higher than in the Rotliegend.

4.3 Main results of the core-calibrated log analysis in the Opalinus Clay

The main results in terms of total clay content, mineralogy and total porosity for the main focus interval (Opalinus Clay) are shortly described in this section. Figs. 4-7 to 4-13 show some general statistical values of the MultiMin analysis results within the Opalinus Clay.

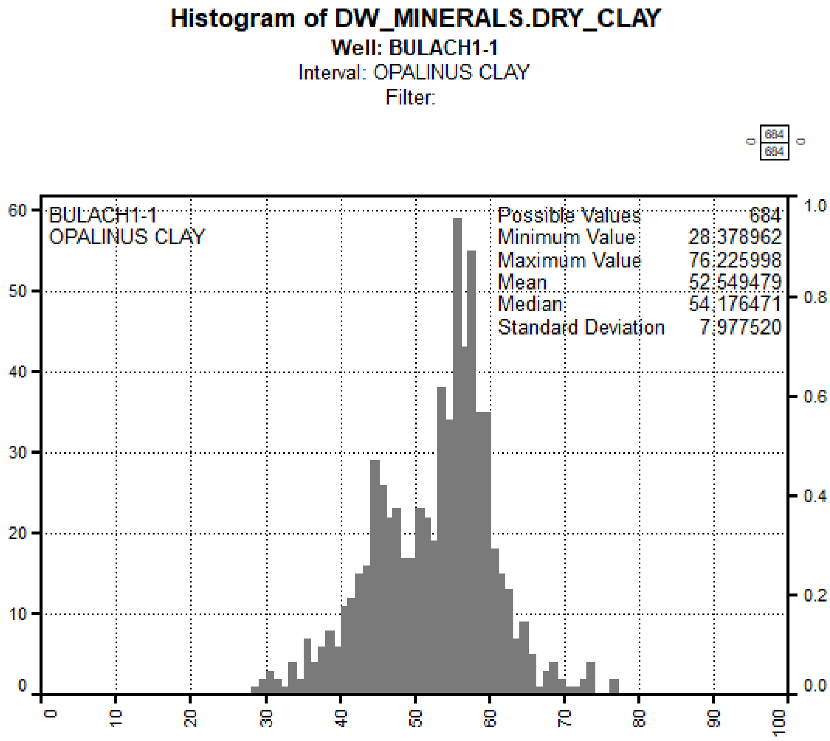

Fig. 4-7: Dry clay weight percentage frequency histogram in the Opalinus Clay

In the clay-rich Opalinus Clay, the mean and median dry clay contents are close to 52.5 and 54.2 wt.-%. The distribution is bimodal, the lowest clay content being in the shallowest part of the Opalinus Clay roughly in the interval from 891 to 928 m.

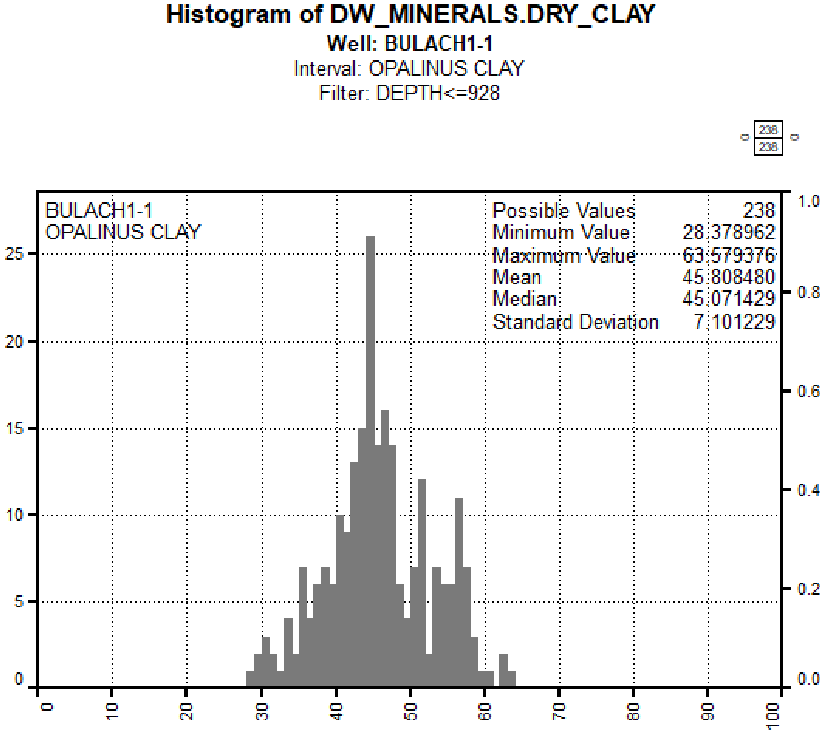

Fig. 4-8: Dry clay weight percentage frequency histogram in the upper section of Opalinus Clay (above 928 m)

In the upper part of the Opalinus Clay (above 928 m), the mean and median dry clay content are close to 45.8 and 45.1 wt.-%. The top part of the formation is less argillaceous.

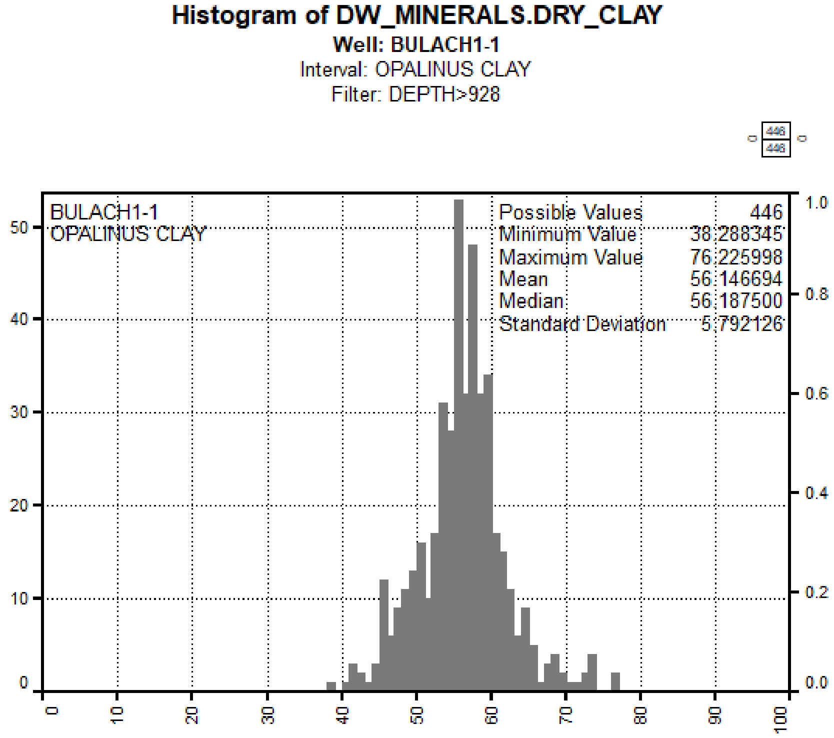

Fig. 4-9: Dry clay weight percentage frequency histogram in the lower section of Opalinus Clay (below 928 m)

The bottom part of the Opalinus Clay (below 928 m), is more argillaceous: the mean and median dry clay content are close to 56.1 and 56.2 wt.-%.

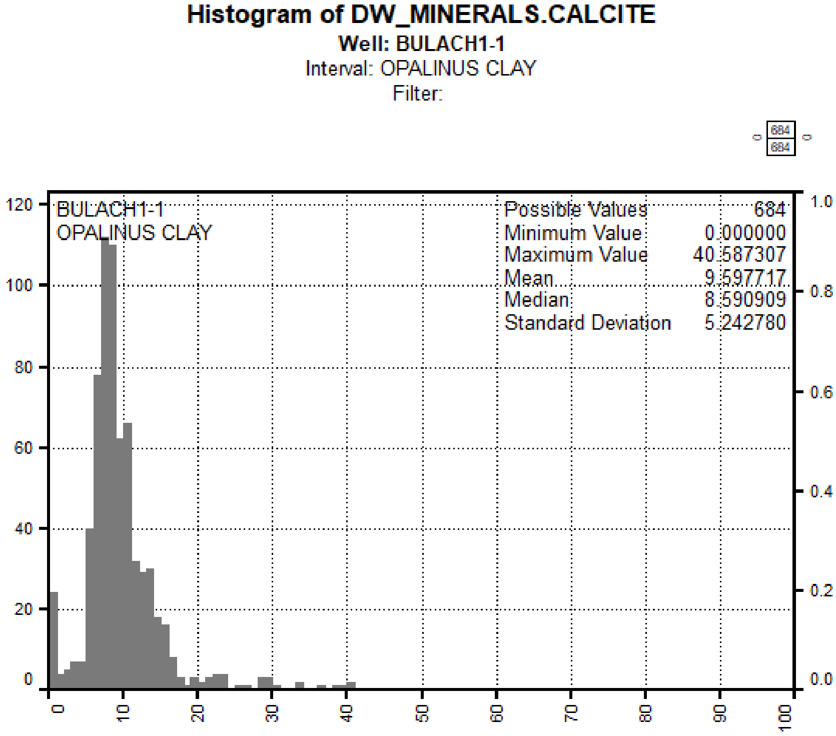

Fig. 4-10: Calcite weight percentage frequency histogram in the Opalinus Clay

The mean and median calcite content are close to 9.6 and 8.6 wt.-%. The maximum values are up to 40 wt.-%, i.e., corresponding to thin, calcite-rich layers. In case these layers are thinner than the log resolution, the maximum calcite content would be higher than computed.

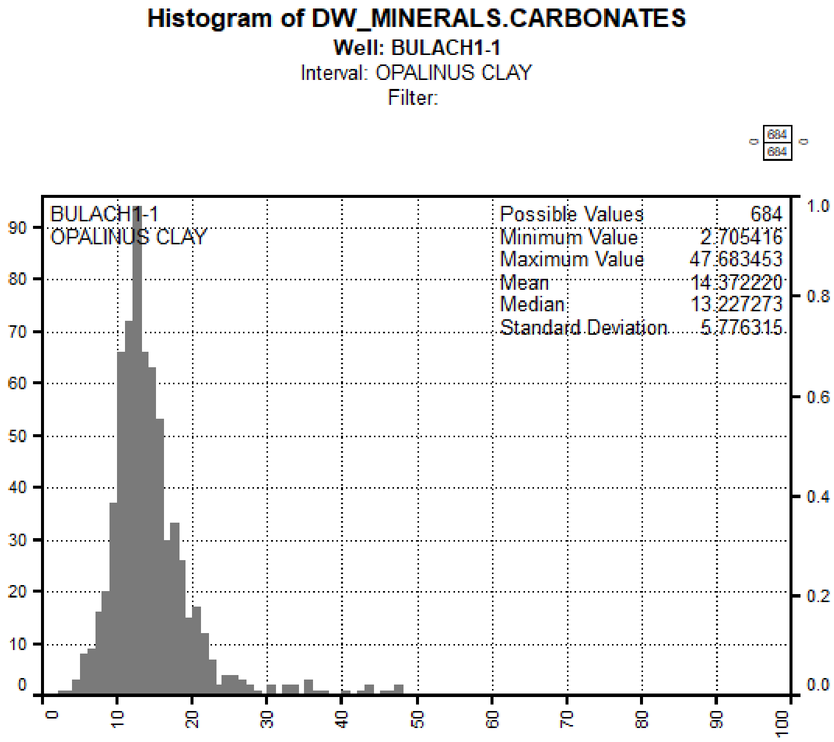

Fig. 4-11: Carbonates weight percentage frequency histogram in the Opalinus Clay

The mean and median carbonates (calcite, dolomite and siderite) content are close to 14.4 and 13.2 wt.-%.

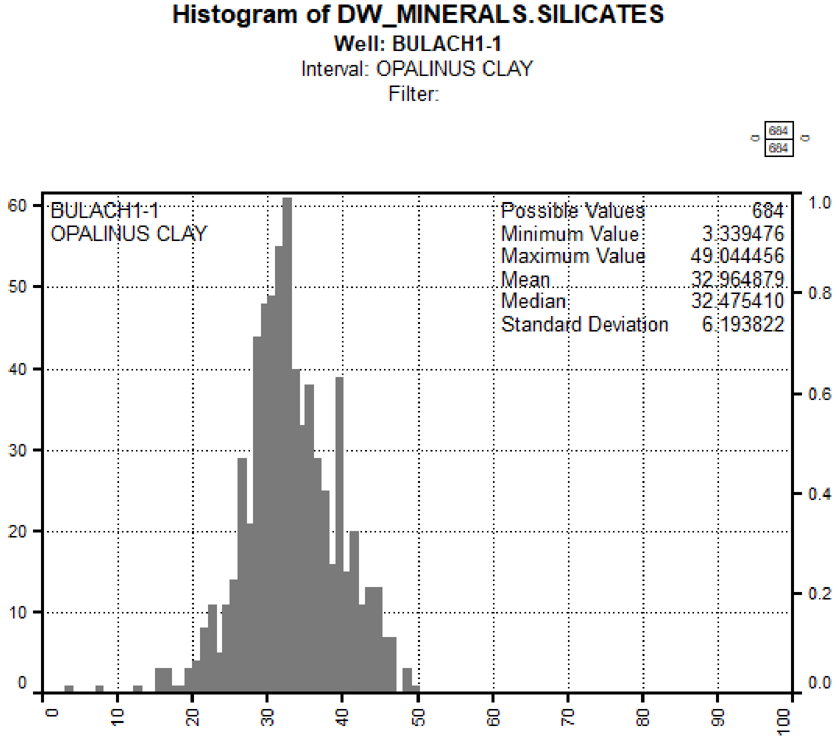

Fig. 4-12: QF-silicates (quartz and feldspars) weight percentage frequency histogram in the Opalinus Clay

The mean and median QF-silicates (quartz, plagioclases and potassic feldspars) contents are close to 33 and 32.5 wt.-%, much higher than the carbonates (close to 14 wt.-%).

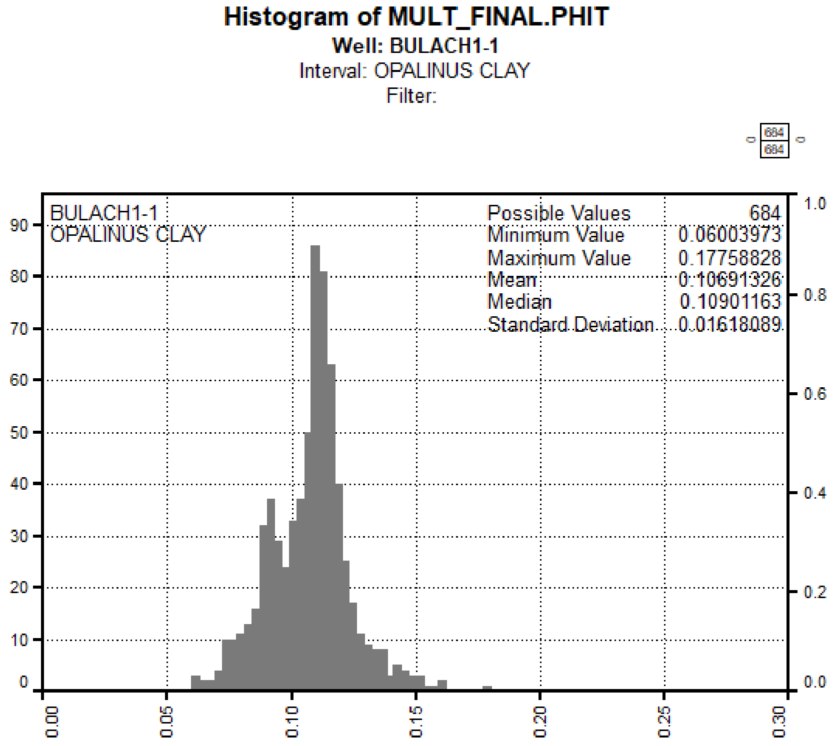

Fig. 4-13: Total porosity frequency histogram in the Opalinus Clay

The mean and median total porosities are close to 10.8 %.

5 Summary

The MultiMin interpretation was successfully applied in the borehole BUL1-1 using the Paradigm Geolog MultiMin software (see Appendix Plate 1 and 2). On the basis of available petrophysical logs and formation mineralogical contents, several specific MultiMin interpretation intervals were designed. Some of these intervals needed to be further subdivided due to e.g. borehole conditions to ensure the best possible MultiMin interpretation result. Especially in the large wireline acquisition gap from 923 to 1'007 m, MSCL data was used, in particular the results of the elemental analysis (XRF), bulk density and spectral gamma-ray (mainly thorium and potassium). The addition of the MSCL data allowed a detailed log interpretation even within the logging gap(s).

Core data from lab measurements were also available so that the mineralogical content and other parameters (e.g. density and/or porosity) were known at several points along the borehole. These core data included bulk rock XRD mineralogy, clay mineralogy, pycnometer and water loss porosity, and grain density. The core data was used as a starting parameter set for the MultiMin interpretation where available.

The mineralogical MultiMin interpretation results were converted to weight percentages for a straightforward comparison with core XRD measurements. In general, the comparisons showed a very good agreement between the mineralogy (and porosity) from the MultiMin interpretation and the core data. Only in the lower part of the borehole, where considerable amounts of dolomite are present and the borehole conditions were not ideal, the clay content calculated from the MultiMin method deviates from the available XRD measurements, mainly in the Bänkerjoch and Schinznach Formations. QF-silicates and carbonates show a good agreement with core data throughout the borehole even in the lowermost units.

The continuous curves from the MultiMin interpretation can be used to characterise the different formations (and hence members) occurring in BUL1-1. Interestingly, based on the MultiMin interpretation results, the Opalinus Clay can further be subdivided, based on the total clay content, into an upper and lower part where the upper part has a slightly lower clay content than the lower part. In addition, boundaries between formations (and also between members) are often clearly marked by a decrease or increase of clay-, QF-silicate and/or carbonate content. The carbonate-rich formations can further be characterised according to the occurrence of dolomite (replacing calcite), especially in the lower part of the borehole (in the lithostratigraphic units of the Keuper and Muschelkalk).

6 References

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