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Arbeitsbericht NAB 20-30

Petrophysical Log Analyses of Deep and Shallow Boreholes: Methodology Report

December 2020

S. Marnat & J. K. Becker

National Cooperative
for the Disposal of
Radioactive Waste

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

www.nagra.ch

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S. Marnat[1] & J. K. Becker[2]

[1] GPCI
[2] Nagra

KEYWORDS

Petrophysical log interpretation, core calibration, mineralogy, porosity, workflow, methodology, stochastic approach, MultiMin, deterministic approach, uncertainties, MSCL, Benken borehole, good hole intervals, bad hole intervals

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Abbreviations

Abbreviation	Unit	Description
a		Archie's coefficient
ABS		Absolute value
APLC	V/V	Array epithermal porosity limestone corrected
APS		Accelerator porosity sonde
BH_FLAG		Bad hole flag
BHT	Deg C	Bottom hole temperature
BS	IN	Bit size
C	W%	Mud filtrate salinity (in wt.-%)
CC	cc	cm^3
C1/C2	IN	Caliper from four-arms caliper tool
CALI	IN	Density caliper
CGR	GAPI	Uranium-free Gamma-Ray
CMR		Schlumberger's nuclear magnetic resonance
CONDNUM		Analysis Condition Number Tool
_COR		Suffix for mineral volumes recomputed considering no porosity
CORE_LOG		Flag indicating wireline logs replacement by core logs
CT	MHO/M	True formation conductivity
CTEMP	DEGC	Formation temperature (in degrees Celcius)
CW	MHO/M	Water conductivity
CXO	MH/M	Flushed zone conductivity
DCL		Dry Clays
DENS	g/cm^3	Bulk density
DEPTH	m	Measured depth
DRHO/DRH	g/cm^3	Bulk density correction
DSOZ	IN	Density computed stand-off
DT_MA	µs/ft	Matrix sonic compressional slowness
DT_FL	µs/ft	Fluids sonic compressional slowness
DT_CLAY	µs/ft	Wet clay sonic compressional slowness
DTC	µs/ft	Compressional sonic slowness
DTCO	µs/ft	Compressional sonic DTSM
S/F		Shear sonic slowness
DTC0_STC	µS/F	Compressional sonic slowness from Semblance processing
DTS	µS/F	Shear sonic slowness

Abbreviation	Unit	Description
DTSM	µS/F	Shear sonic slowness
DTSM_STC	µS/F	Shear sonic slowness from Semblance processing
DWCA_WALK2	W/W	Calcium concentration (dry weight)
DWFE_WALK2	W/W	Iron concentration (dry weight)
DWSI_WALK2	W/W	Calcium concentration (dry weight)
DWSU_WALK2	W/W	Calcium concentration (dry weight)
ECS		Elemental Capture Spectroscopy
ENPI	V/V	Neutron Porosity Corrected except for Formation Salinity
FMI		Formation Modular Imager
FPRESS	psi	Borehole hydrostatic pressure
g	m/s^2	Earth gravity acceleration
GR	GAPI	Gamma-Ray
GR_CLEAN	GAPI	Gamma-Ray of clean formations
GR_CLAY	GAPI	Gamma-Ray of clays
GR_SHALE	GAPI	Gamma-Ray of shales
GRC	GAPI	Edited Gamma-Ray
HMC	IN	Mud cake thickness
HSGR	GAPI	HNGS Standard Gamma-Ray
HFK	%	Formation Potassium Concentration
HTHO	ppm	Formation Thorium Concentration
HURA	ppm	Formation Uranium Concentration
LCAL	IN	Density caliper
LLD	OHMM	Laterolog Deep Resistivity
LLS	OHMM	Laterolog Shallow resistivity
m		Archie's cementation exponent
MTEM	Deg C	Mud Temperature
MSFL	OHMM	Flushed zone resistivity
MW	ppg	Mud Weight
n		Archie's saturation exponent
NFUN		Number of iterations of solution engine
NHI	V/V	Neutron Hydrogen Index
NMR		Nuclear Magnetic Resonance
NPHI	V/V	Neutron Porosity
PDF		Probability Density Function

Abbreviation	Unit	Description
PEF	B/E	Photoelectric Factor
PEFL	B/E	Long Spacing Corrected Photoelectric Factor
PHIE	V/V	Effective porosity
PHIT	V/V	Total porosity
PHIT_CLAY	V/V	Clays total porosity
PHIT_DET	V/V	Total Porosity from Deterministic Approach
POTA	FRACTION	Potassium content
_PRED		MultiMin suffix for predicted values
QUALITY		Analysis Quality
R75DegF	OHMM	Mud filtrate resistivity at 75 DegF
RCL		Reduced Composite Log
RD	OHMM	Deep Resistivity
RHGE	G/C3	Grain density (from ECS)
RHOB/RHOM	G/C3	Bulk density
RHOE	G/C3	Electronic density
RHOG	G/C3	Grain density
RHOS	G/C3	Solids density measured on core samples
RHOMA	G/C3	Matrix density from ECS
RLA1	OHMM	HRLA shallow resistivity
RLA0 to 5	OHMM	HRLA resistivity at various depth of investigations
RM	OHMM	Mud Resistivity
RMC	OHMM	Mudcake Resistivity
RMF	OHMM	Mud Filtrate Resistivity
RS	OHMM	Shallow Resistivity
RSOZ	IN	Resistivity computed stand-off
RT	OHMM	True formation resistivity
RT_HRLT	OHMM	HRLA true resistivity
RW	OHMM	Water Resistivity
RXO/RXOZ	OHMM	Flushed zone resistivity
SGR	GAPI	Spectral Gamma-Ray
SIGF	CU	Formation capture cross section
SIGM	CU	Formation capture cross section
SP	MV	Spontaneous Potential
STOF	IN	APS neutron computed stand-off

Abbreviation	Unit	Description
SWE	V/V	Effective Water Saturation
SWT	V/V	Total Water Saturation
TCMR	V/V	NMR total porosity
THOR	PPM	Thorium content
TMP	DegC	Borehole temperature curve
TNPH	V/V	Neutron porosity log
TVD	m	True Vertical Depth
U	B/C3	Photo-electric cross-section
UBI		Ultrasonic Borehole Imager
U_BndW	V/V	Bound water in the virgin zone
U_FreeW	V/V	Free water in the virgin zone
URAN	PPM	Uranium content
VCL	V/V	Volume of wet clay
VCL_HI	V/V	Maximum wet clay volume of shales
VOL_ANHYDR	V/V	Anhydrite volume fraction
VOL_ANH	V/V	Anhydrite volume fraction in core samples
VOL_CALCITE	V/V	Calcite volume fraction
VOL_CARB	V/V	Calcite + Dolomite fraction in core samples
VOL_CHLOR	V/V	Chlorite Fe volume fraction
VOL_CHLOR	V/V	Chlorite Fe volume fraction in core samples
VOL_CLC	V/V	Calcite volume fraction in core samples
VOL_DCL	V/V	Dry Clay volume fraction
VOL_DOL	V/V	Dolomite volume fraction in core samples
VOL_DOLOM	V/V	Dolomite volume fraction
VOL_ILL	V/V	Volume of Illite in core samples (XRD)
VOL_ILLITE	V/V	Volume of Illite (multimin interpretation)
VOL_KAOL	V/V	Kaolinite volume fraction in core samples
VOL_KAOLIN	V/V	Kaolinite volume fraction
VOL_KEROGEN	V/V	Kerogen volume fraction
VOL_KF	V/V	Orthoclase K volume fraction in core samples
VOL_MA	V/V	Quartz + Feldspars measured on core samples
VOL_ORTHOCL	V/V	Orthoclase K volume fraction
VOL_PYR	V/V	Pyrite volume fraction in core samples (XRD)
VOL_PYRITE	V/V	Pyrite volume fraction

Abbreviation	Unit	Description
VOL_QUARTZ	V/V	Quartz volume fraction
VOL_SID	V/V	Siderite volume fraction in core samples
VOL_SIDER_COR	V/V	Siderite volume fraction
VOL_WETCLAY	V/V	Wet Clay volume fraction
VP_VS		DTS/DTC
WCLA	W/W	Clay dry weight content
WCLA_WALK2	W/W	Clay dry weight content from ECS tool
ECS		Elemental Capture Spectroscopy tool
NMR		Nuclear Magnetic Resonance
WBM		Water Based Mud
WCL		Wet Clay
X_BndW	v/v	Bound water in the invaded zone
X_FreeW	v/v	Free water in the invaded zone
XRD		X-Ray diffraction

Abbreviations for computer-processed interpretation

Curve name	Unit	Description
_PRED		Predicted Values
_COR		Mineral Volumes Recomputed Considering No Porosity
BH_FLAG		Bad Hole Flag
CONDNUM		Analysis Condition Number
NFUN		Number of Iterations of Solution Engine
PHIE	V/V	Effective Porosity
PHIT	V/V	Total Porosity
PHIT_CLAY	V/V	Clay Total Porosity
PHIT_DET	V/V	Total Porosity from Deterministic Approach
QUALITY		Analysis quality
RHGE	G/C3	Grain density (from ECS)
RHOG	G/C3	Grain density
RHOS	G/C3	Solids density measured on core samples
TCMR_GH	V/V	Total Porosity (CMR) Good Hole
VOL_ANHYDR	V/V	Anhydrite volume fraction
VOL_ANH	V/V	Anhydrite volume fraction in core samples

Curve name	Unit	Description
VOL_CALCITE	V/V	Calcite volume fraction
VOL_CARB	V/V	Calcite + Dolomite volume fraction in core samples
VOL_CHLOR	V/V	Chlorite Fe volume fraction
VOL_CHLOR	V/V	Chlorite Fe volume fraction in core samples
VOL_CLC	V/V	Calcite volume fraction in core samples
VOL_DCL	V/V	Dry Clay volume fraction
VOL_DOL	V/V	Dolomite volume fraction in core samples
VOL_DOLOM	V/V	Dolomite volume fraction
VOL_ILL	V/V	Volume of Illite in core samples (XRD)
VOL_ILLITE	V/V	Volume of Illite (MultiMin interpretation)
VOL_KAOL	V/V	Kaolinite volume fraction in core samples
VOL_KAOLIN	V/V	Kaolinite volume fraction
VOL_KEROGEN	V/V	Kerogen volume fraction
VOL_KF	V/V	Orthoclase K volume fraction in core samples
VOL_MA	V/V	Quartz + Feldspars measured on core samples
VOL_ORTHOCL	V/V	Orthoclase K volume fraction
VOL_PYR	V/V	Pyrite volume fraction in core samples (XRD)
VOL_PYRITE	V/V	Pyrite volume fraction
VOL_QUARTZ	V/V	Quartz volume fraction
VOL_SID	V/V	Siderite volume fraction in core samples
VOL_SIDER_COR	V/V	Siderite volume fraction
VOL_WETCLAY	V/V	Wet Clay volume fraction

1 Introduction and objectives

During stage 2 of the "Sachplan Geologische Tiefenlager" (SGT), three potential siting regions (Jura Ost, Nördlich Lägern and Zürich Nordost) have been chosen for a detailed site investigation programme during stage 3 of the SGT to assess their suitability for the safe disposal of radioactive waste in Switzerland. Currently, a large-scale investigation programme is in place including drilling several deep boreholes to characterise the rocks of the Mesozoic (and partly also the upper Paleozoic) sedimentary sequence within the siting regions. An elaborate measurement and sampling programme will be performed, including the acquisition of petrophysical logs in the borehole and along cores and samples for laboratory measurements. In addition, logging and laboratory data from several already existing boreholes (deep boreholes as well as shallow geothermal boreholes so-called "Erdwärmesondenbohrungen" EWS) are available.

Next to other parameters, the mineralogy (and here especially the clay mineral content) and porosity of the rocks are of main importance for the site characterisation. This report presents the methodology used for the analysis of petrophysical logs for all existing and newly acquired data from boreholes to calculate the aforementioned mineralogical content and continuous porosity profiles.

The workflow presented here will be used for any subsequent log interpretation performed for Nagra in SGT stage 3 and will be referred to in each documentation of the interpretation results. If any deviation from this workflow is necessary, it will be explained in detail in the report(s) accompanying the log interpretation results.

The aim of the petrophysical log analysis is the elaboration of a continuous profile for formation porosities and detailed mineralogical compositions. The reliability of the interpreted data will depend on the quantity and quality of log datasets or any other continuous or non-continuous measurements suitable for the workflow presented here.

The log interpretation is calibrated on core data (mineralogy, porosity) – where available – which will also be explained in detail in the following chapters.

This methodology report will use data from a previous study from the Benken borehole to provide examples of the workflow. As such, it is not intended to deliver the results of the Benken log analysis results. Also note that the stratigraphy, especially formation names, used in the composite plots shown in this report in the examples from the Benken borehole has previously been revised and hence represents slightly outdated formation and member names.

Finally, most abbreviations used in this report refer to Schlumberger (SLB) mnemonics. Other logging contractors may use different abbreviations for their tools.

2 Definitions and available data and data preparation

2.1 Unknowns and definitions

Most scientific fields (here: petrophysics) have their own terminology and it happens quite often that this terminology is used slightly different between different fields of research. Hence, it is important that the exact definition of the "scientific slang" is known. In the following, the most important terms used in this report, and their petrophysical meaning, are shortly defined.

Wet shale: Clay-rich mud-supported rock, mixture of clay minerals, grains (e.g. quartz grains, usually silt granulometry), carbonates, water (includes e.g. clay and capillary bound water, see also below).

Capillary bound water: Water bound by interfacial tension and wettability at grain surface.

Clay bound water: Electrochemically bound water in clay interlayers and on clay mineral surfaces.

Wet Clay: Hydrous aluminium phyllosilicate minerals (e.g. kaolinite, smectite, illite, chlorite) including clay bound water. Wet clay is one of the main constituents of the wet shales.

Dry Clay: Wet clay minus clay bound water. Comparable to clay content from lab measurements on core samples (in wt.-%).

Fluid volume: Volumetric content in volume/volume (v/v) of all fluids (free water, capillary bound water and clay bound water, oil or gas).

Dry mineral volume: Volumetric content in volume/volume (v/v) of the pure minerals in the rock, free from their associated water. The sum of all minerals and fluids volumes equals 1.00 v/v (100 %).

Matrix: All minerals except clays and kerogen.

Total porosity (PHIT): Voids volume divided by rock volume, in volume/volume (v/v).

Effective porosity (PHIE): PHIT minus clay bound water volume (in v/v). Note that the capillary bound water, which is unmovable, is included in PHIE.

Total water saturation (SWT): Total volume of water divided by PHIT. Unless significant hydrocarbon content is apparent in a borehole, SWT = 1.00 v/v will be imposed.

Effective water saturation (SWE): Total volume of water divided by PHIE.

Log response: Value of a log reading of a fluid or mineral. For example, in case of the bulk density measurement, the tools are calibrated to a fresh water saturated limestone and the apparent bulk density is linearly correlated to the electronic density. This is slightly different from the true rock density: in a pure dolomite the apparent density is 2.85 g/cc, while its actual density is 2.87 g/cc.

Sigma log: Neutron capture cross-section, expressed in cu (capture units), for the absorption of thermal neutrons. It measures the ability of a material to capture thermal neutrons which largely depends on the water saturation and the mineralogy of the formation. The corresponding wireline curve is called SIGF.

2.2 Petrophysical wireline data in deep boreholes

In most of the deep boreholes, a large suite of petrophysical wireline logs was acquired (please note that abbreviations either refer to standards used in the oil- and gas-industry or are abbreviations used by Schlumberger, a logging-company):

- Caliper log (EMS/PPC, uses 6 arms to continuously measure the borehole shape)
- Total Gamma-Ray (GR, measures the naturally occurring radioactivity)
- Spectral Gamma-Ray (SGR, measures total GR and Potassium (K), Thorium (Th) and Uranium (U) concentrations)
- Sonic compressional and shear slowness (DTCO and DTSM, measures formation interval travel time, a measure of how fast seismic waves propagate through the formation).
- Resistivity at various depths of investigation (RT_HRLT – High Resolution Laterolog Array Tool, RLA0 to RLA5 – resistivity measurements at various depths of investigation, RXOZ – flushed zone resistivity)
- Bulk Density and Bulk Density Correction (TLD, determines rock densities)
- Photoelectric Factor (PEF or PEFZ, can be used to determine mineralogy)
- Neutron Hydrogen Index and Standoff (NHI, measure of porosity in water-saturated formations, standoff describes the distance between the external surface of the logging tool and the borehole wall)
- Neutron capture cross section (Sigma, SIGF, can be used to determine water content and mineralogy)
- Elemental Spectroscopy (ECS): element weight concentration and associated uncertainties (among others, DWSI_WALK2: Silica; DWCA_WALK2: Calcium; DWFE_WALK2: Iron; DWSU_WALK2: Sulphur). Magnesium (DWMG_MGWALK) is acquired with the MGWALK processing of the ECS in the most recent boreholes, it will be used in the low clay content sections. Some mineral volumetric contents are provided but are not used for this study as they are not raw data but already the result of a modelling with unknown parameters (as this modelling method is a company trade secret from SLB)
- Nuclear Magnetic Resonance (NMR, only available in parts of the Benken borehole, can be used to determine porosity)
- Spontaneous Potential (SP)

Other petrophysical wireline logs are also available in some of the deep boreholes (such as FMI, Formation Micro Imager) but are not used in the interpretation described here.

In addition to the petrophysical logs, most of the deep boreholes have extensively been cored and MSCL measurements (see section 2.4) and/or lab measurements from these cores (see section 2.5) are also available.

2.3 Petrophysical wireline data in shallow boreholes

In the shallow (usually geothermal) boreholes, only a reduced log suite is available for petrophysical interpretations:

- Total Gamma-Ray (GR)
- Sonic compressional slowness (DTCO)
- Deep resistivity (RES)
- Caliper (CAL)

As generally no cores are available for these shallow boreholes, lab or MSCL measurements are not available.

2.4 Multi-Sensor-Core-Logger data (MSCL)

The MSCL used in SGT E3 is capable of measuring petrophysical data on cores using the following sensors:

- Bulk density
- P wave velocity
- Magnetic susceptibility
- SGR
- Elemental concentration from X-Ray Fluorescence (XRF)

As the MSCL data is measured on cores (small measurement volume) while the petrophysical wireline logs are measured in a borehole (large measurement volume), the MSCL data must be "adjusted" to the wireline data before merging the two data types if needed. The workflow to merge them with petrophysical wireline data generally is as follows:

- Quality control of the MSCL logs, elimination of artefacts related to edges proximity (measurements taken close to the beginning/end of a core may measure a mix between core and air, i.e. measure less rock volume than in the middle of the core) and acquisition inside core barrel, if any.
- Detailed depth shift with petrophysical logs used as the depth reference; this is not expected to be a bulk shift.
- In intervals where both, petrophysical and MSCL data is available, determine a correlation between the two where both have good QC indicators. This is achieved by using cross plots or frequency histograms. The correlation between the two can be linear or nonlinear.
- Apply the correlation to the MSCL logs.
- Fill-in the gaps, or intervals with poor quality wireline logs with MSCL data and generate a flag called CORE_LOG (0 if petrophysical log, 1 if MSCL data). The intervals with MSCL data are also reported in a table in the interpretation report.
- Use the resulting mixed-origin log as an input for the petrophysical interpretation.

2.5 Core data

In addition to the petrophysical wireline and MSCL data, core data from lab measurements is available for some boreholes from different formations (mainly lab measurements of mineralogy, porosity and density). The available core data includes XRD (X-ray diffraction) bulk mineralogy, the analysed minerals generally are quartz, K-feldspars, plagioclase, calcite, dolomite/ankerite, siderite, anhydrite, celestite, pyrite, clay minerals and organic carbon. In addition, some core data on clay typing (illite, smectite, kaolinite and chlorite) may also be available. Next to the mineralogical information, porosities and grain densities usually are also available. Often, three measured porosities (water-loss porosity (105 °C) using bulk wet density, water-loss porosity (105 °C) using grain density and pycnometer porosity are measured. A detailed description of measurement protocols is given in Waber (ed. 2020).

When core data are available several parameters are compared:

- Porosity (unconfined), to be compared with the predicted total porosity (PHIT)
- Grain density, to be compared with the predicted grain density (RHOG)
- XRD mineralogy results to be compared with predicted mineral volumes

While the first two allow for a straightforward comparison (nevertheless with potential bias that will be discussed later in this chapter), the third one requires a conversion from XRD weight percentage (w/w or wt.-%) to MultiMin volumetric contents (v/v), as follows:

$$Mineral\ \left(\frac{v}{v}\right) = \frac{Mineral\ (\frac{w}{w})}{Mineral\ Density * Grain\ Density * (1 - Porosity)}$$

with

Mineral and Grain Densities in g/cc or kg/m^3

Mineral density is taken from published values (in this case from Schlumberger charts or default values from the used software), e.g. 2.71 g/cc for calcite.

Grain Density and porosity should be measured from the same plug on which the XRD was performed. Then the sum of all the mineral volumes from both cores and interpretations are normalised to 1.00 v/v.

The fact that core and log data are acquired at different scales must be taken into account:

- Core data are usually measured on sample plugs, these are, in the reference frame of a borehole, discrete measurements.
- Log data are continuous measurements with a vertical resolution dependent on the tool physics, generally transmitter to receiver distance, and lithology.

In case of significant heterogeneities, plug measurements are not supposed to match the log results, but a large number of plug measurements should.

2.6 Preliminary calculations and Neutron environmental corrections

All used petrophysical logs have previously undergone a full and detailed QA/QC process, hence no additional QC is necessary. Data loading and preparation is done using the software Paradigm Geolog (Version 19).

To perform the petrophysical log analyses using the Geolog software, environmental pre-calculations must be performed (using the Precalc module), including Neutron Hydrogen Index (NHI) environmental corrections. This is necessary because each logging tool has been characterised for standard conditions which are usually not met in the borehole (these corrections are a standard process and not a specific feature needed for the boreholes subsequently used with the workflow described below). Hence, corrections to the logging data must be performed.

The environmental pre-calculations include:

- the borehole temperature curve (from BHT (Bottom Hole Temperature) or continuous temperature measurements TMP). The temperature is not corrected, e.g. the used drilling fluid (mud) may be (much) warmer (or cooler) than the formation temperature so the temperature measurements may reflect the temperature of the borehole fluid rather than formation temperatures. Fortunately, as the objective of the log interpretations is not to compute hydrocarbon saturations where borehole temperature plays an important role, the impact of this approximation is minimal.
- the borehole hydrostatic pressure (FPRESS, from the mud weight):

  FPRESS = MW * g * TVD

  with

  MW = Mud Weight

  g gravity acceleration

  TVD represents the True Vertical Depth.
- the true formation conductivity (CT) and flushed zone conductivity (CXO, the flushed zone is the zone in the immediate vicinity of the borehole where borehole fluid has replaced the naturally occurring formation fluid) from RT (true formation resistivity) or RD (deep resistivity) and Rxo (flushed zone resistivity):

  CT = 1/RT and CXO = 1/RXO,
- the mud cake thickness (HMC):

  HMC = Maximum (BS-CALI)

  with

  BS = bit size

  CALI from the Caliper log
- the mud, mud filtrate and mud cake resistivities at depth (from log header information); the BATEMAN-KONEN equation (Bateman & Konen 1977) is used:

  $R75DegF = 0.0123 + 3647.5 / C^{0.955}$

  with

  R75DegF is the brine resistivity at 75 DegF

  C the salinity in weight percentage

- the Photoelectric Cross-section U:

  U = PEF * RHOE

  with

  RHOE as the electronic density

  RHOE = (Bulk Density + 0.1883) / 1.0704 (Serra & Serra, 2000)

  PEF (photoelectric factor, can be used to determine formation mineralogy)

The log environmental correction consistency is checked across all studied boreholes, even if the dataset has already undergone a rigorous quality control. In particular for the NHI, the following corrections must be applied, considering an APLC curve (Near/Array Corrected Limestone Porosity) from Schlumberger's APS tool (Accelerator Porosity Sonde, Schlumberger's chartbook 2005):

- Hole size: Caliper acquired during the APS run (if missing, caliper from Density run, TLD – Three-detector Lithology Density)
- Mud weight (per interval)
- Pressure and temperature from Precalc
- Formation salinity: as the neutron tool reads within the invaded zone, the formation salinity can be taken as a mix of salinity (or electric conductivity) of mud filtrate and formation water in the reservoir intervals.
- Standoff: 0.125 in (a correction factor to compensate for the distance between the tool and the borehole wall)

3 Stochastic and deterministic interpretation workflows

Depending on the amount of available information (i.e. petrophysical wireline logs and/or MSCL data), the data can be used to determine the mineralogy and porosity of the borehole. A standard technique to perform such a determination is the MultiMineral (MultiMin) approach (see section 3.2). However, if not enough information is available for a MultiMin interpretation, a more empirical, deterministic approach must be applied to the data (see section 3.1). It is also possible to mix both approaches: the stochastic MultiMin approach is applied where enough data is available while in parts with a reduced number of input data, the deterministic approach is used.

The number of input data depends on the type of borehole and/or on borehole quality. Shallow boreholes are usually drilled for geothermal applications (mostly for very small geothermal projects). Hence, the number of petrophysical wireline logs in such boreholes is limited to the very basic wireline logs. In deep, exploration type boreholes, a full suite of petrophysical wireline logs usually is available. Furthermore, bad borehole conditions (e.g. borehole breakouts) or false readings from wireline logs might reduce the number of available data and prevent the application of the stochastic MultiMin approach.

3.1 Deterministic workflow

The used deterministic workflow is shortly described below. First, the Wet Clay Volume VCL (Volume Clay) is computed using a linear volumetric Gamma-Ray equation (from the "MultiMin Technical Reference" of the Geolog Software):

$$VCL_{GR} = \frac{GR - GR\_CLEAN}{GR_{CLAY} - GR\_CLEAN}$$

with

GR_CLEAN refers to the reading of GR in an interval with 100 % sand (or as close to 100 % as possible)

GR_CLAY refers to a GR reading in an interval with 100 % clay (or as close as possible)

The GR curve used in this equation would preferentially be the CGR (Corrected Gamma Ray, a combination of potassium and thorium contents, uranium free GR) if an SGR was acquired.

The porosity (PHIE) depends on the previously calculated clay content and is evaluated using a linear volumetric equation as follows:

$$PHIE = \frac{DTCO - DT\_MA}{DT\_FL - DT\_MA} - VCL * \frac{DT\_CLAY - DT\_MA}{DT\_FL - DT\_MA}$$

with

DTCO – sonic compressional slowness
DT_MA – matrix sonic compressional slowness
DT_CLAY – wet clay sonic compressional slowness
DT_FL – fluid sonic compressional slowness
VCL – wet clay volume

If a mix between the different approaches (deterministic and stochastic) in the same borehole is to be performed, the parameters used for the deterministic workflow are calibrated to the MultiMin results in good hole intervals of the same borehole if possible, if this is not feasible no calibration can be performed.

3.2 Stochastic workflow (MultiMin)

The latest version of the Paradigm 19 Geolog software, embedding the stochastic log analysis module MultiMin, will be used for the interpretations. The MultiMin method uses the fact that each log measurement within a borehole is determined by the mineral and fluid content in the interval that it measures. If the mineral and fluid contents are precisely known, an exact theoretical log response can be calculated. The reverse approach is also possible, i.e., the petrophysical log measurements are known but the mineral and fluid content are unknown. Hence, assuming a mineral and fluid content in the interval and comparing the theoretical log response to the measured petrophysical logs, the actual mineral and fluid content can be determined. This is what Mayer & Sibbit (1980) proposed as an innovative approach to petrophysical log interpretation. They wrote log response equations to predict logging measurements and adjusted the mineral volumes used for the calculations to obtain and optimise the prediction of the logs. In 1986, Quirein et al. modified the equations and gave a linear, simplified form allowing faster computer processing. In 1990, Cannon & Coates incorporated core analysis results into the optimisation. The general set of equations used for the calculation of the theoretical log response and to reduce their error is given in section 3.2.1. The choice of fluids and minerals to be predicted is given in sections 3.2.2 and 3.2.3, respectively.

3.2.1 General set of equations

The most important equations used for the MultiMin interpretations are explained below (as defined in the "MultiMin Technical Reference", an unpublished software manual for the Geolog software).

Linear equations are used to predict the response of most of the logging tools (e.g. Bulk Density, Gamma-Ray, U, Sigma, ECS elements etc.). The general form of these equations can be written as:

$$\text{Predicted Log Response} = \sum_{k=1}^{n} \text{Vol}_{(k)} * \text{Endpoint(k)}$$

with

Vol $_{(k)}$: Fluid or mineral volume

Endpoint (k): Log Response of the fluid or mineral.

Endpoints are defined as the log response of a given petrophysical log for the pure fluid or mineral. For example, the endpoint of a pure quartz to a density log could be 2.7 gg/cc. Endpoints can be evaluated using different approaches:

- From charts and books: The logging companies provide the interpreter with the theoretical log responses for the main minerals and fluids. For water, the endpoints are computed from the salinity. For hydrocarbons, the density at the measured/estimated temperature and pressure in the borehole is used.
- From log responses in pure or mixed mineralogy: looking at cross-plots or histograms.
- From calibration of log data to core measurements.

The workflow for picking endpoints will be described in more details using the example of data from the Benken borehole in chapter 4.

The results of the MultiMin interpretations are impacted by the endpoint values. Increasing the endpoint for a given mineral will decrease the computed volume of this mineral (to keep a good prediction). As MultiMin is a global optimisation process (see incoherence function below), changing the endpoint of one mineral will modify the computed volumes of all other investigated minerals. The interaction between all endpoints and associated uncertainties can be quite challenging to manage when dealing with many unknows and many logs. In case an endpoint is to drastically modified, the log predictions would not be achievable.

Non-linear equations are required for the correct prediction of some logging tools. In the following, a set of used equations is presented.

True conductivity: Several industry standard equations are available, e.g. Archie (for clean formations), Indonesia and Dual Water (shaly rocks). Ideally, in clay-rich formations the Dual Water should be used to account for clay minerals apparent conductivity, as this parameter can be assessed on both cores and petrophysical log measurements. Water apparent conductivity can be derived from the logs according to the F*Ct versus QVN crossplot (F is the Formation Factor, Ct the true rock conductivity and QVN the clay bound water saturation) or computed from core CEC measurement (Ventre & Levallois 2001).

It is likely that in most of the Nagra boreholes, no hydrocarbon must be modelled, and the CXO and CT equation (Archie non-linear) is used with a very high uncertainty, hence with a low weight. In case a borehole shows a significant hydrocarbon accumulation, the choice of the equation will depend on the available data.

$$CT = 1/a * PHIT^{m} * SWT^{n} * CW$$

with

CT: Formation electrical conductivity

a: Archie coefficient, usually a = 1.00

PHIT: Total porosity of the formation

m: Cementation exponent, often close to 2.00

SW: Water Saturation

n: Saturation Exponent, often close to 2.00

CW: Formation water electrical conductivity

Neutron Hydrogen Index (NHI): The responses of Neutron tools are non-linear with respect to the fluid and mineral volumes. The effect of this non-linearity can be seen on the logging operators Density-Neutron charts where the matrix lines are not straight. This is since the apparent matrix value depends on the porosity of the rock. The formulation of this equation, as implemented in MultiMin, is:

$$PHIT = a + b * NHI + 10^{(c + d * NHI)}$$

with

PHIT: Total Porosity of the rock

NHI: Neutron Hydrogen Index

a, b, c and d: coefficients depending on the Neutron Tool used, coefficients are taken from a database provided by the logging contractor (here SLB) and implemented in MultiMin Paradigm 19.

Sonic DTC: linear Wyllie or non-linear Raymer-Hunt-Gardner (Raymer et al. 1980). In Nagras boreholes, the Wyllie equation will be used.

Wyllie equation:

$$DTC = (1 - PHIT) * DT\_Solids + PHIT * DT\_Fluid$$

Raymer-Hunt-Gardner equation:

$$V\_Log = (1 - PHIT)^{C\_EXP} * V\_Solids + PHIT * V\_Fluid$$

both with

C_EXP: Acoustic tortuosity exponent, 2.00 by default

DTC: Formation acoustic compressional slowness from Sonic

DT_Fluid: Fluid compressional slowness

DT_Solids: Solids compressional slowness

V_Log: Formation acoustic velocity

V_solids: Solids acoustic velocity

V_Fluid: Fluid acoustic velocity

Velocity (m/s) = 106 / compressional slowness (ms/m)

3.2.2 Error minimisation

Once theoretical log responses have been calculated using linear or non-linear equations reported in previous chapters, the error can be determined individually using the following equation:

$$Error = \frac{Measured \log - Predicted\ log}{Uncertainty}$$

The denominator uncertainty here is comparable to a weight that can be given to the log based on expert judgement. These uncertainty values can be manually adjusted:

- In case of a low reliability of a curve, for example due to a bad hole interval. The value can be increased for the curve not to influence the computation. For example, if the bulk density is greatly affected by adverse borehole conditions, its uncertainty can be set to 1'000 g/cc, greatly reducing its influence on the overall computation.
- In case the petrophysicist wants to reduce the influence of a given curve. If all the logs were acquired in excellent conditions, the petrophysicist may not wish the Sonic DTC to influence the results as the nuclear tools should be preferred; then the uncertainty on DTC can be set at 1'000 microseconds/foot to greatly reduce its influence on the overall computation.
- In case the petrophysicist needs to modify the equilibrium of the model to give a higher relative influence for a tool compared to the others. The uncertainty on some will be decreased to give a higher weight, while it will be increased for the remaining logs.

If the theoretical (predicted) log response is a mathematical function of the mineral (or fluid) volumes, then one can write:

$$Error^2 = \left[\frac{Measured\ Log - Predicted\ Log_i}{Uncertainty}\right]^2 \quad for\ i = 1\ to\ n\_vol$$

with

i: i^{th} volume

n_vol: Number of modelled volumes

One of the major advantages of the MultiMin approach is that all petrophysical logs and the respective theoretical log responses are used simultaneously, i.e. using the incoherence function given below, the sum of all errors for a given mineral content can be calculated.

$$Incoherence\ Function = \sum_{k=1}^{n\_log} \mathrm{Error}_{(k)}{}^2$$

with

n_log: Number of logs

By (slightly) varying the assumed mineral and fluid content, the incoherence of the solution can be minimised, resulting in an adequate representation of mineral and fluid content using only the measured petrophysical logs. The importance of the uncertainty of the logs used to calculate the error now is also immediately apparent. A very small error (due to a high uncertainty) of one specific log will have (almost) no impact on the assumed mineral or fluid content when it is slightly varied to reduce the result of the incoherence function.

It is now also apparent why a number of logs indicative for different parameters (mineralogy, fluid content, porosity, density etc.) are needed. E.g., if only one log for the determination of the clay content, one log for the density and another log for the porosity would be available, using the MultiMin method the clay content and porosity could be determined, but not any other minerals (e.g. quartz, carbonates etc.). Generally, the more specific logs are available, the more precise the calculated mineral and fluid content will be, even more so if redundant logs (e.g. GR and SGR) are available.

3.2.3 Choice of fluids

Formation water is always present in the rocks. At a given temperature and pressure, it is fully characterised by its salinity, which allows computing all log responses. The water salinity would preferentially be taken from water sample analyses. In case none are reported, an apparent water salinity can be computed:

- from the deep resistivity logs (Archie equation with a = 1.00 and m = 2.00)
- or from the spontaneous potential curve (required: mud filtrate resistivity)

In porous and permeable rocks, mud filtration occurs: the rock is invaded by the water fraction of the Water Based Mud (WBM) called mud filtrate. The mud filtrate properties are inferred from the log headers.

In case significant hydrocarbon volumes are suspected from the mudlogging or the logging data, oil or gas are introduced in the models as additional unknowns. Oil volume or gas volume are computed, together with SWT and SWE showing values below 1.00 v/v.

In some intervals, significant organic matter (Kerogen) is present and will be modelled from the logs provided that a sufficient log dataset was acquired (advanced elemental spectroscopy is normally required, but the Uranium concentration from Spectral GR can be used as well).

3.2.4 Choice of minerals

The list of minerals to be modelled by MultiMin within a studied interval depends on two drivers:

- The minerals actually present in the formations
- The available logs (with good quality), giving the ability to model mineral volumes

In Nagra's project, clay minerals are almost always present and must be modelled. Depending on the log availability (e.g. Spectral GR and elemental spectroscopy), clay typing (i.e. quantifying the proportion of different clay minerals) can be attempted. In case a reduced log dataset is available, only one generic clay volume (representing all clay minerals) is computed. Accordingly, different matrix minerals (including cements) present in the formations are introduced in the MultiMin models if the log dataset allows their quantification.

As an example, a siderite volume can be computed if a full dataset, including iron content, is available.

The main matrix and cement minerals to be modelled are:

- Quartz
- Feldspars (potassic orthoclases and plagioclases)
- Micas (generally modelled with the clay volume)
- Carbonates (Calcite, Dolomite/Ankerite, Siderite)
- Anhydrite
- Halite

In case the log acquisition is insufficient, some minerals can be merged to a pseudo-mineral to reduce the number of unknowns:

- Quartz with plagioclases and orthoclase
- Calcite with dolomite and siderite
- All matrix and cement minerals together and all clay minerals together

In case a pseudo-mineral is modelled as the mixture of several minerals, the endpoint of this mixed mineral is computed as a constant volumetric mixture of several (n) minerals:

$$Pseudo\ Mineral\ Endpoint = \sum_{i=1}^{n} \text{Endpoint\_Mineral(i)} * \text{Vol\_Mineral(i)}$$

For example, considering a pseudo-mineral defined by 80 % calcite and 20 % dolomite, with a calcite bulk density response at 2.71 g/cc and dolomite bulk density response at 2.85 g/cc:

Pseudo-mineral bulk density endpoint = 0.8*2.71 + 0.2 * 2.85 = 2.738 g/cc

3.3 Quality indicators

The indicators described below are designed to help with the formal quantification of the MultiMin models and output quality. The Condition Number (CONDNUM) and NFUN refer to the mathematical robustness of the model, i.e. its ability to correctly evaluate the minerals and fluids volumes with the available data. The LQC-Index is calculated from parameters such as borehole shape and hence gives a measure of the input data quality. The borehole condition can have a large effect on input data quality and hence on the choice of fluids and minerals to be modelled:

- In case of washouts, the tool sensors are not close enough to, or in contact with, the borehole wall anymore. The sensors read a large amount of drilling mud in addition to the formation signal.

  The pad tools and the nuclear tools are very sensitive to washouts: Density, Micro-Resistivity, Neutron. The Elemental Spectroscopy and Sigma measurements are slightly more robust to moderate washouts, while the Sonic and Deep Resistivity are often almost unaffected. In case of large washouts, the Gamma-Ray readings will be attenuated.

- Breakouts: the borehole is enlarged mainly in one direction, usually parallel to the minimum horizontal stress. Unfortunately, some tools tend to self-orientate in this orientation where the borehole is enlarged and therefore are affected by the breakouts.

- Rugosity: Borehole wall small-scale irregularities results in varying tool stand-offs which affect the pad-tools readings. The bulk density measurements are very affected.

- Spiraling, corkscrew effect: In a deviated borehole, its dip and azimuth are varying in a periodic manner with a short wavelength (a few meters generally). The logging tools offset varies periodically and cannot be corrected.

Finally, the analysis quality (output curve called QUALITY) refers to the MultiMin model results. It is important to note that QUALITY is only a measure of the fit between the input data and the interpreted result. It does not take input data quality into account. Hence, even when the input data is of very low quality, the QUALITY may indicate a very good fit between predicted and measured logs.

3.3.1 Condition number

The condition number (CONDNUM) quantifies the quality of the MultiMin model and not of the interpretation results. It can be calculated for the whole model or on depth-by-depth basis. It varies with depth as temperature and pressure increases cause parameter changes, and changes as different models are used.

A model will have a high quality if, in a number of tool dimensional space, the measurements distinctly discriminate the mineral and fluid volumes.

The condition numbers normally range from two to ten, the lower the number, the better the model.

The following orders of magnitude for the condition number mean, from a mathematical standpoint:

- < 4.00: Good model
- 4.01 to 5.00: Fair model
- 5.01 to 6.00: Poor model
- 6.01 to 10.00: Bad model, likely unworkable
- > 10: Failed model, cannot be run

However, the condition number is only a mathematical indication of model quality and it should be treated as such. Although it is desirable to compose a model with a condition number as small as possible, a small CONDNUM only ensures that the model is well defined (in a mathematical sense) and not that the results of the model are of high quality/low uncertainty. The real proof of the analysis are the calculated results after optimisation.

3.3.2 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 said output.

3.3.3 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 input 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.

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
- 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.

3.3.4 Quality

The Quality index tests if the set of observed measurements and the set of predicted measurements are part of the same population. At a value of QUALITY less than one, the modelled accuracy is within 95 % compared to the original measurements, and therefore the analysis is of good quality. If this 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.

3.4 Core calibration

The calibration of the petrophysical log interpretation can be done in two ways, potentially complementary:

- Manual fine-tuning of the endpoints and curve uncertainties to improve the match between predicted results and the core measurements in terms of porosity and mineral content. The endpoints and uncertainties adjustment are done while keeping or improving the log curves prediction, in other words keeping or decreasing the "Quality" indicator.
- Using the "NIMBLE" module of Paradigm 19 Geolog. NIMBLE stands for "Numeric Inversion Modeling By Linear Equations" (Paradigm's acronym). It solves the inverse problem for a given model within an interval. The MultiMin endpoints are calibrated from a representative core dataset, considered as "hard data". The methodology is applicable to linear equations only; non-linear equations like the Neutron Hydrogen Index cannot be solved with NIMBLE.

The recommendation from Paradigm is that the Nimble modelling should be "vastly over-determined", meaning that much more samples than modelled equations are required, the more the better obviously. On top of over-determination, a good facies representation is advised, avoiding sampling bias. This means that the spacing between core samples can/should be irregular.

4 Stochastic log interpretation application to examples (deep boreholes)

While the theoretical basis of the MultiMin approach has been outlined in Chapter 3, some of the concepts of the MultiMin method are best explained in detail using an example. In Chapter 4, the full workflow to apply the MultiMin method to the Benken and in part Bülach-1-1 boreholes is detailed using (and extending) the general concepts described in Chapter 3. Please note that the exercise of log interpretation shown below is not meant as a documentation of the MultiMin interpretations from the boreholes but just as an example for the general steps and concepts of the stochastic MultiMin interpretation.

4.1 Selection of consistent analysis intervals and modelled minerals, fluids, logs and parameters

The first step of the workflow is selecting consistent analysis intervals in terms of:

- *Mineralogy*: for example, an evaporitic interval will not be mixed with a sand-shale section but split in two. This approach supposes that the interpreter already has preliminary information about the mineralogical content of the studied interval, from reference boreholes, geological context, mudlogging data (e.g. calcimetry) or log responses. In the example of the Benken borehole, the principal minerals expected in any given formations are well described from the regional knowledge, e.g. core XRD measurements. This can be cross-checked with the petrophysical log responses.
- *Fluids*: Large formation water salinity changes must be reflected by different MultiMin models. In case hydrocarbon legs are found, they must be treated with different models where special attention must be paid to the water saturation parameters. In this case, these methods and parameters will be reported in the borehole interpretation report.

  In the normal case (no hydrocarbons), the saturation equation parameters (mostly cementation factor m and water salinity) will be set to obtain SWT and SWE ≈ 1.00 v/v.
- *Log acquisition*:
  1. Possibly different types of Neutron tool
  2. Acquired log dataset: the model must be adapted to the available logs, the number of possible unknowns being increased or decreased
  3. Bad hole intervals: same as for point 2, but less unknowns can be modelled with less valid logs

The intervals will not always reflect the stratigraphic formations: for example, two formations with similar mineralogical assemblages and log acquisition would be treated with a single model.

Dedicated MultiMin models should be applied in each interval. For example, the Benken borehole was subdivided into the intervals shown in Tab. 4-1 based on the availability of petrophysical logs and formation mineralogy.

Tab. 4-1: Intervals for MultiMin analysis of the Benken borehole

Interval	From	To	Description	Logs	Salinity	DT Water
	m	m			ppm eq. NaCl	µs/ft
1	94.0	199.0	Molasse: shales, clatics, carbonates	SGR, Density, NHI, Pef, SIGF, Res, Sonic	10000	203
2	199.0	565.0	Malm - Dogger: carbonates, shaly	SGR, Density, NHI, Pef, SIGF, Res, Sonic	7200	201.5
3A	565.0	627	Opalinuston: shales, complex mineralogy	SGR, Density, NHI, Pef, SIGF, Res, Sonic, ECS	7200	198
3A_BH	627.0	649.0	Opalinuston: shales, complex mineralogy	SGR, Density, NHI, Pef, SIGF, Res, Sonic, ECS: bad hole	7200	198
3B	649.0	692.0	Lower Jurassic: shales, carbonates	SGR, Density, NHI, Pef, SIGF, Res, Sonic, ECS	7200	198
4	692.0	813.0	Triassic-Keuper: shales, dolomites, anhydrite	SGR, Density, NHI, Pef, SIGF, Res, Sonic, ECS	33000	191.5
5	813.0	948.0	Triassic-Muschelkalk: carbonates, shales, evaporites	SGR, Density, NHI, Pef, SIGF, Res, Sonic	299000	172
6	948.0	983.0	Triassic-Muschelkalk-Buntsandstein: sand, shales	SGR, Density, NHI, Pef, SIGF, Res, Sonic	67400	187
7	983.0	1007.0	Basement			

A list of model runs and the available/used data (logs) for the respective intervals shown in Tab. 4-1 for the Benken borehole are shown in Tab. 4-2.

Tab. 4-2: List of MultiMin models and available data in the Benken borehole

Several models may be necessary in a single interpretation interval depending on input data quality. Note that the ECS data acquired in a cased hole is not considered usable for quantitative log interpretation here (because of its attenuation in the cased section).

From	To	Good Hole	Bad Hole	Stratigraphic	Available petrophysical logs										QC logs		
m	m	Multimin Model	Multimin Model	Intervals	SGR	NHI	RHOB	PEF	SIGF	ECS	CT	CXO	DTC	DTS	Caliper	DRHO	STOF
94.0	199.0	benken_gh_int1	benken_bh_int1	USM, Tertiary	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
199.0	565.0	benken_gh_int2_final	benken_bh_int2	Malm, Dogger	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
565.0	649.0	benken_gh3a_final	benken_bh3a_final	Opalinuston	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
627.0	649.0		benken_3a_bh_opal	Opalinuston	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
649.1	631.0	benken_gh3b_final	benken_bh3b_opal	Lias	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
631.1	813.0	benken_gh_int4_final	benken_bh_int4	Triassic down to Gipskeuper	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
813.1	947.9	benken_gh_int5_final	benken_salt_int5	Oberer & Mittlerer Muschelkalk	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	No
948.0	983.0	benken_gh_int6_final		Unterer Muschelkalk & Buntsandstein	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	No

The number of modelled minerals depends, among other factors, on the number of valid logs in a given interval. As an example, where no SGR thorium and potassium content logs are available, it is not possible to discriminate illite from kaolinite or smectite: in this case, a single clay is modelled.

In the good hole intervals of the Opalinus Clay section of the Benken borehole, many minerals could be modelled:

- Quartz+Plagioclases (called Quartz, named QTZ_PLAGIO)
- Orthoclase
- Calcite+Dolomite (called Calcite, named CLC_DOL)
- Siderite
- Kaolinite+Smectite (called Kaolinite, named KAOL_SMEC)
- Illite+Micas (called Illite, named ILL_MICAS)
- Chlorites (called Chlorite Fe, named CHLORITES)
- Pyrite
- Kerogen

Tabs. 4-3 and 4-4 display the detailed minerals, fluids, logs and parameters used for the models applied to the Opalinus Clay in the Benken borehole. In these tables, "BndW" stands for Bound Water, "FreeW" for Free Water, X means the invaded zone and U the virgin zone (not invaded/ flushed).

A row is dedicated to the weight applied to each log, called "uncertainty" in the MultiMin software. Occasionally very high weights (uncertainties) up to 1'000 or 10'000 are used to disable a curve from the computation but keeping its prediction by MultiMin as a QC indicator. This means that the specific curve will not impact the computation (no constraint on the predicted curve) but will still be predicted. However, in the example given in Tabs. 4-3 and 4-4 below, DTC is not used in the good hole as there are other logs giving better/more precise data than the Sonic log. In bad borehole conditions however, the Sonic (DTC in Tab. 4-4) in turn is much more reliable than the density measurements for example and therefore used for the interpretation while DENS is not.

Tab. 4-3: benken_gh3a_final model parameters for the Opalinus Clay in good hole conditions

Condition number: 3.63		Multimin Model: benken_gh3a_final (Opalinuston)														
Mineral	Name	Dens	NHI	DTC	U	THOR	POTA	URAN	CT	CXO	SIGF	DWCA	DWFE	DWSI	DWSU	PEF
Fluids	in model	g/cc	v/v	µs/ft	B/C3	ppm	%	ppm	MH/M	MH/M	CU	W/W	W/W	W/W	W/W	B/E
Uncertainty		0.0264	0.014	10000	0.32	0.50	0.20	1.0	1000	1000	1.1	0.010	0.0036	0.0100	0.005	10
Method		LINEAR	APLC	WYLLIE	LINEAR	LINEAR	LINEAR	LINEAR	Archie non linear	Archie non linear	LINEAR	LINEAR	LINEAR	LINEAR	LINEAR	LINEAR
Quartz&Plagioclases	Quartz	2.641	Model	50.200	4.881	1.500	0.500	0.100	0.000	0.000	4.445	0.001	0.000	0.650	0.000	1.829
Orthoclase K	Orthoclase K	2.570	-0.006	53.490	8.710	2.500	15.000	0.150	0.000	0.000	15.340	0.001	0.010	0.450	0.000	2.900
Calcite&Dolomite	Calcite	2.715	0.000	48.800	13.620	1.000	0.100	0.010	0.000	0.000	7.008	0.300	0.001	0.002	0.000	5.100
Siderite	Siderite	3.960	0.184	43.800	72.200	1.000	0.100	0.010	0.000	0.000	50.000	0.003	0.650	0.002	0.000	15.000
Illite	Illite	2.793	0.230	105.00	6.000	25.000	10.000	2.000	0.000	0.000	92.800	0.006	0.050	0.200	0.000	5.000
Kaolinite&Smectite	Kaolinite	2.630	0.180	105.00	7.000	52.500	0.250	1.600	0.000	0.000	46.300	0.006	0.009	0.190	0.000	2.400
Chlorites	Chlorite Fe	3.420	0.250	105.00	40.000	13.900	0.130	1.800	0.000	0.000	57.200	0.002	0.100	0.106	0.000	6.300
Pyrite	Pyrite	4.987	-0.019	37.610	82.220	0.000	0.000	0.000	0.000	0.000	90.000	0.000	0.465	0.000	0.535	17.000
Kerogen	Kerogen	1.200	0.500	130.00	0.200	0.000	0.000	10.00	0.000	0.000	400.00	0.000	0.000	0.000	0.000	0.000
X BndW		1.001	0.998	198.00	0.409	0.000	0.000	0.000	0.000	0.572	22.160	0.000	0.000	0.000	0.000	0.000
X FreeW		1.001	0.998	198.00	0.409	0.000	0.000	0.000	0.000	0.572	23.080	0.000	0.000	0.000	0.000	0.000
U BndW						0.000	0.000	0.000	1.445	0.000	0.000	0.000	0.000	0.000	0.000	0.000
U FreeW						0.000	0.000	0.000	1.445	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Water properties	Rw	0.75	Ohm.m	at	77.0	Deg F										

Tab. 4-4: benken_bh3a_final model parameters for the Opalinus Clay in bad hole conditions

Condition number: 3.38		Multimin Model: benken_bh3a_final (Opalinuston)														
Mineral	Name	Dens	NHI	DTC	U	THOR	POTA	URAN	CT	CXO	SIGF	DWCA	DWFE	DWSI	DWSU	PEF
Fluids	in model	g/cc	v/v	µs/ft	B/C3	ppm	%	ppm	MH/M	MH/M	CU	W/W	W/W	W/W	W/W	B/E
Uncertainty		1000	1000	2.0	1000	0.50	0.20	1.0	1000	1000	1.1	0.010	0.0036	0.0104	0.010	0.2
Method		LINEAR	APLC	WYLLIE	LINEAR	LINEAR	LINEAR	LINEAR	Archie non linear	Archie non linear	LINEAR	LINEAR	LINEAR	LINEAR	LINEAR	LINEAR
Quartz&Plagioclase	Quartz	2.641	Model	50.400	4.881	1.500	0.500	0.100	0.000	0.000	4.445	0.001	0.000	0.650	0.000	1.829
Orthoclase K	Orthoclase K	2.570	-0.006	53.490	8.710	2.500	15.000	0.150	0.000	0.000	15.340	0.001	0.010	0.450	0.000	2.900
Calcite&Dolomite	Calcite	2.715	0.000	48.800	13.620	1.000	0.100	0.010	0.000	0.000	7.008	0.300	0.001	0.002	0.000	5.100
Siderite	Siderite	3.960	0.184	43.800	72.200	1.000	0.100	0.010	0.000	0.000	50.000	0.003	0.650	0.002	0.000	15.000
Illite	Illite	2.793	0.230	105.00	6.000	25.000	10.000	2.000	0.000	0.000	92.800	0.006	0.049	0.200	0.000	5.000
Kaolinite&Smectite	Kaolinite	2.630	0.180	105.00	7.000	52.500	0.250	1.600	0.000	0.000	46.300	0.006	0.009	0.190	0.000	2.400
Chlorites	Chlorite Fe	3.420	0.250	105.00	20.500	13.900	0.130	1.800	0.000	0.000	57.200	0.002	0.110	0.106	0.000	6.300
Kerogen	Kerogen	1.200	0.500	130.00	0.200	0.000	0.000	400.0	0.000	0.000	30.000	0.000	0.000	0.000	0.000	0.000
X BndW		1.001	0.998	198.00	0.409	0.000	0.000	0.000	0.000	0.572	22.160	0.000	0.000	0.000	0.000	0.000
X FreeW		1.001	0.998	198.00	0.409	0.000	0.000	0.000	0.000	0.572	23.080	0.000	0.000	0.000	0.000	0.000
U BndW						0.000	0.000	0.000	1.445	0.000	0.000	0.000	0.000	0.000	0.000	0.000
U FreeW						0.000	0.000	0.000	1.445	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Water properties	Rw	0.75	Ohm.m	at	77.0	Deg F										

The model parameters are displayed here as an example of parameters used in the Benken borehole, these parameters must be adapted in other boreholes.

4.1.1 Non-Clay mineral endpoints

Once interpretation intervals based on formation mineralogy and the minerals to be predicted/ interpreted have been defined, the theoretical log response of each pure mineral to be predicted has to be determined, in other words, the endpoints of each mineral to be predicted have to be defined.

The MultiMin endpoints for non-clay minerals are selected using MultiMin defaults from Herron & Matterson (1993), defaults from Schlumberger (1997), the Element Mineral Rock Catalog from Serra (1990) as well as cross-plots/histogram analyses. Further adjustments are occasionally done to fine-tune the log curves prediction to minimise the "Quality" output curve.

4.1.2 Clay mineral endpoints

The clay mineral endpoints can be chosen in the same way as the non-clay mineral endpoints but as the chemical composition of clays is quite variable, this would imply a large uncertainty.

An alternative way is picking the endpoints directly from the log response, considering a simplified clay model with potassic and non-potassic clays (Fig. 4-1). The workflow of picking endpoints is shortly detailed below using the example of the density and neutron logs of existing data from the Benken borehole in the Opalinus Clay section (Fig. 4-2):

- The significant presence of potassic clay minerals is checked in the potassium-thorium cross-plot (Fig. 4-1). Only if both types of clays are present in significant amounts is it possible to determine between these two clay types using the MultiMineral method and only then endpoints for both types of clays need to be determined. Otherwise, these two clay minerals would be grouped into one pseudo-mineral and only one endpoint would be needed for the calculations.
- The Density-Neutron cross-plot is displayed, the Potassium from SGR being the color map of the log points (Fig. 4-2).
- The Wet Shale Potassic (WSH_K) clay-rich endpoint is picked close to the high Potassium content points (orange color on the plot), to its right (highest Neutron Hydrogen Index for highest clay mineral content) and to the bottom (lowest effective porosity (free water porosity)).
- The non-Potassic Wet Shale (WSH) endpoint is picked with the same logic in lower Potassium content points (yellow to green), but the dots on the very right are neglected, considered as partly reading mud.
- Fixed points for matrix and water are needed to determine the Wet Clay and the Dry Clay points. The density of water is close to 1 (computed using Schlumberger's Gen-7 charts from Schlumberger's chartbook 2009, resulting in values close to 1.00 g/cc and 1.00 v/v for salinity below 10'000 ppm equivalent NaCl.) and hence lies in the upper right corner of the cross plot in Fig. 4-2. The matrix density is taken from prior knowledge and has no porosity, hence, it lies towards the lower left corner of the cross plot in Fig. 4-2 (please note that it has a slightly negative NHI. This is correct since NHI was calibrated for a limestone matrix so clastic matrices with no porosity usually range between -0.01 to -0.03).

- The corresponding Wet Clay points (WCL_K and WCL) are computed by a linear extrapolation from the Matrix and Shale points. The main unknown at this stage is the maximum wet clay content of the wet shale, which should be calibrated on cores. Having no information from cores implies assuming the value from experience: 0.75 to 0.80 v/v. In Benken, the most argillaceous shale was measured with 0.78 v/v wet clay content. Hence, the Wet Shale endpoint is located at 78 % of the distance between the matrix and the Wet Clay point. By determining the remaining 22 % distance, the endpoint for Wet Clay can be picked.
- The Dry Clay points (DCL_K and DCL) are extrapolated from the Wet Clays and the Water point. The extrapolation is based on clay porosity, which is approximated from the total shale porosity from the logs (for example from regional data or NMR log if available) and the assumption that all the water is clay bound water (in other words, PHIE = 0.00 v/v). An average clay porosity of 0.20 v/v was used as a starting point in Benken. This figure may be changed in the future founded on additional core or logs measurements.

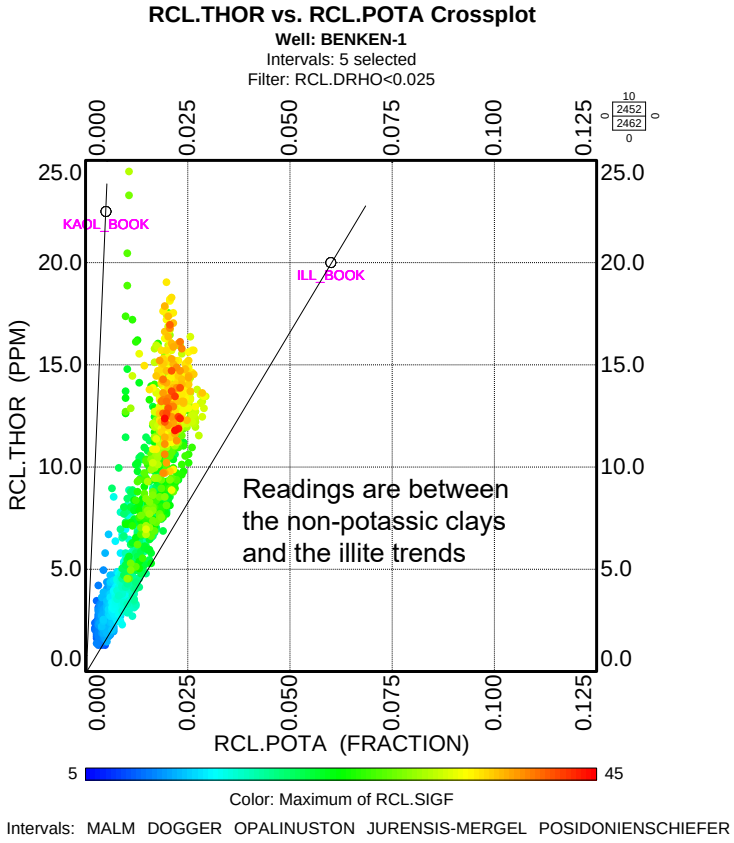

Fig. 4-1: Thorium versus Potassium from HNGS (spectral gamma-ray tool) in Benken

The thorium and potassium contents are measured using a spectral gamma-ray tool, in this case the HNGS tool from Schlumberger.

In case no SGR is available, or no significant potassic clays can be identified, a single clay endpoint is picked.

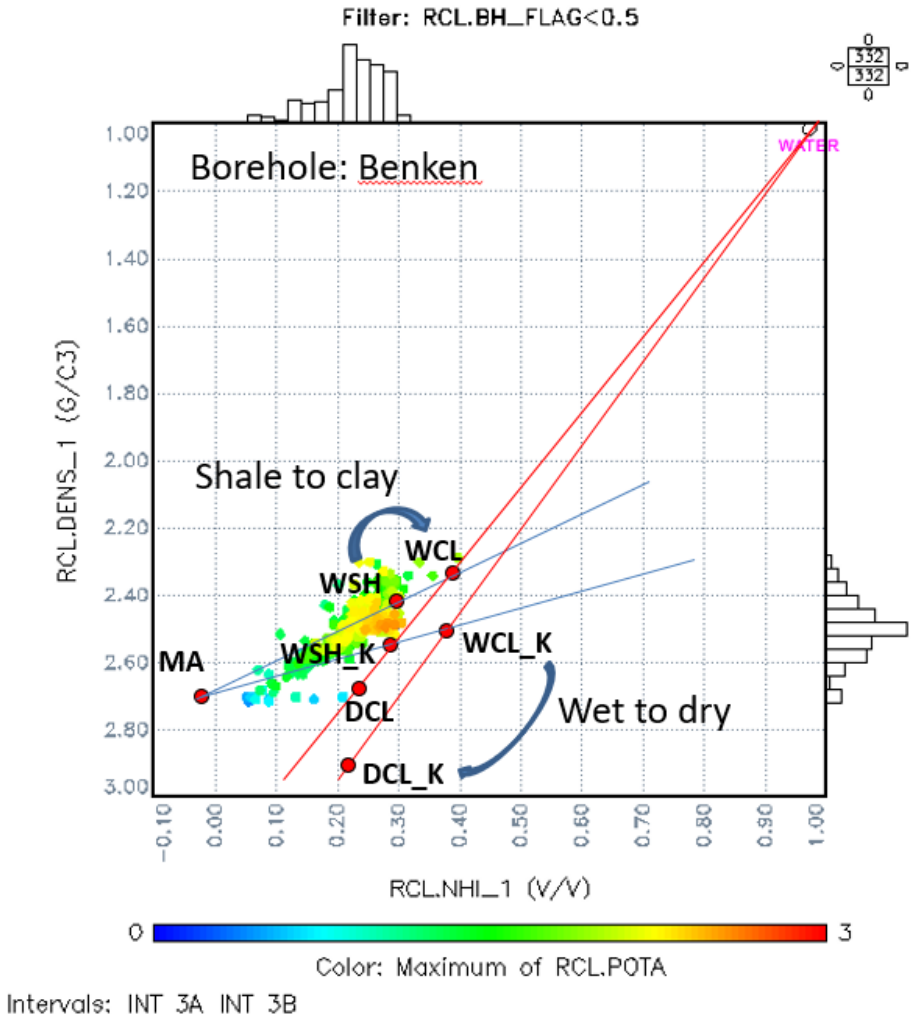

Fig. 4-2: Clay endpoints picking in the Den-NHI cross-plot

The wet shale points (WSH and WSH_K points) are first interpreted in the shale density-neutron region. A matrix point (called MA) is inferred from log data and the regional knowledge (e.g. core mineralogy in regional boreholes).The wet clay points are then extrapolated from the matrix to wet shale straight line (e.g. MA-WSH), assuming the wet clay content of the shale. The final step is the extrapolation of the dry clay points (DCL and DCL_K) on the fluid (WATER) to wet clay points straight line (e.g. WATER – WCL), assuming a wet clay porosity.

The clay endpoints for the other logs are also defined using statistics from the logs. For example, for the Sigma curve (SIGF, provides an additional equation for mineralogy and fluid determination), the following steps are performed:

- Picking the wet shale endpoint (P 99 of the histogram distribution, see Fig. 4-3): for example, 44.1 cu (capture units, units of measurement for Sigma).
- Extrapolate (linear) wet shale to wet clay assuming the wet shale clay volume and the matrix sigma:

$$Wet\_Clay\ Sigma = \frac{WSH_{Sigma} + Matrix_{Sigma} * (VCL\_HI - 1)}{VCL\_HI}$$

with

VCL_HI: Wet Shale Clay Volume

If VCL_HI = 0.78 v/v and Matrix_Sigma = 4.74 cu then wet clay sigma = 55.2 cu

- Extrapolate (using a linear volumetric equation as per the MulitiMin Technical Reference) wet clay to dry clay assuming the wet clay porosity (PHIT_clay) and the water sigma:

$$Dry\_Clay\ Sigma = \frac{Wet\_clay\ Sigma - PHIT\_Clay * Sigma\_water}{1 - PHIT\_clay}$$

Assuming PHIT_Clay = 0.20 v/v and Sigma_water = 22 cu then the Dry_Clay Sigma = 63.5 cu

- If potassic clays are identified using the potassium/thorium cross-plot (see Fig. 4-1 for the Benken borehole), compute the sigma endpoint for potassic and non-potassic clays using the MultiMin defaults for kaolinite (non-potassic, 20.12 cu) and illite (potassic, 40.56 cu) and assuming a single non-potassic over potassic clays ratio.

Assuming the same content of potassic and non-potassic clays would lead in this example to 87.1 cu for potassic and 43.2 cu for non-potassic clays.

The same workflow can be applied to U (B/C3), PEF (B/E), THOR (ppm) and URAN (ppm). The endpoints are kept reasonably consistent between juxtaposed intervals.

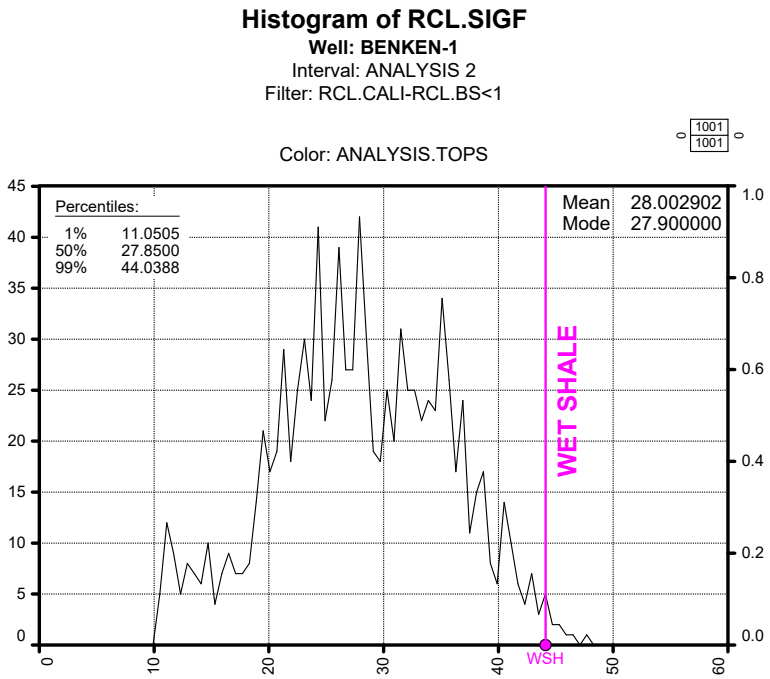

Fig. 4-3: Sigma frequency histogram in the borehole Benken for Jurassic and Triassic lithology

Sigma can also be used to determine the clean endpoint of calcite towards the lower end of the histogram, with values close to 10 to 11 cu (using P1). This value is significantly higher than the published theoretical endpoint for calcite (7.2 cu), suggesting the presence of high Sigma minerals (e.g. siderite, pyrite).

The ECS (Elemental Spectroscopy) Silicium, Calcium, Iron and Sulphur endpoints for clay minerals are taken from the Element Mineral Rock Catalog (Serra 1990):

- Illite: DWSI = 0.2331 W/W, DWCA = 0.0056 W/W, DWFE = 0.0491 W/W, DWSU = 0.00 W/W
- Kaolinite: DWSI = 0.2143 W/W, DWCA = 0.032 W/W, DWFE = 0.004 W/W, DWSU = 0.00 W/W
- Smectite: DWSI = 0.2415 W/W, DWCA = 0.117 W/W, DWFE = 0.0204 W/W, DWSU = 0.00 W/W
- Chlorites: DWSI = 0.1055 W/W, DWCA = 0.0018 W/W, DWFE = 0.10 W/W (range 0.08-0.316 W/W), DWSU = 0.00 W/W

These endpoints can be fine-tuned to improve the prediction quality of predicted curves.

4.1.3 Fluid endpoints

As fluids also have a large influence on the measured logs and may make up an important amount of the rock volume, the choice of fluids and their respective endpoints is also important. Most of the fluid endpoints are computed by MultiMin using the environmental parameters from Precalc and the fluid properties (water salinity, hydrocarbon density)

The following equations for water are used by MultiMin, with density in kg/m3 and salinity in ppm:

- Hydrogen Index = (Density * (1 – 0.000001 * Salinity ppm)) / 1000
- The apparent water density is computed according to the MultiMin Technical Reference (unpublished).
- Resistivity is computed using the Hilchies (1984) equation, accounting for salinity and temperature.
- Capture cross-section (Sigma) is taken from Schlumberger's chart Gen-12 (from Schlumberger's chartbook 2009).
- The water sonic slowness is computed from salinity, temperature and pressure using the chart from Serra & Serra (2000) (Fig. 4-4).

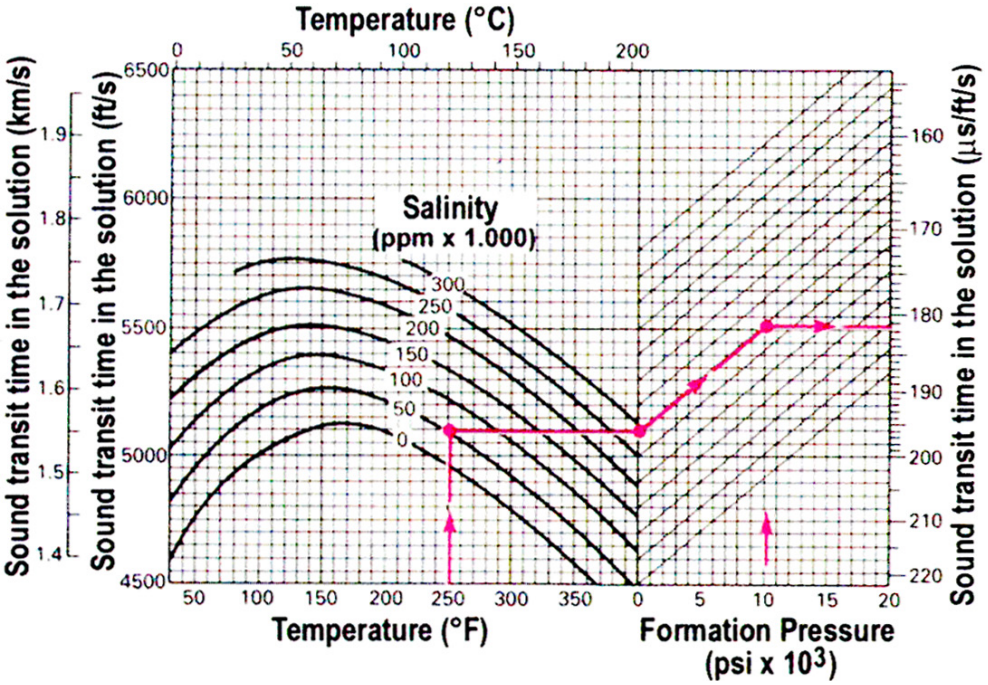

Fig. 4-4: Water sonic slowness from its salinity, temperature and pressure

It is unlikely that hydrocarbons are encountered in significant amounts in Nagra boreholes. Nevertheless, in case hydrocarbons are found and must be modelled, the following equations for oil are used by MultiMin:

- Hydrogen Index = 0.009 * (Density * (4 – 0.0025 * Density))/(16 – 0.0025 * Density)
- Apparent Density is computed using Vasquez & Beggs (1980).

The following equations for gas are used by MultiMin:

- Hydrogen Index = 0.0022 * Density
- Apparent Density is computed using the workflow detailed in Dranchuk et al. (1974).

4.1.4 Log uncertainties and curve predictions

A key parameter for a MultiMin model is the uncertainty value for a given input curve. Assigning a large uncertainty decreases the relative weight of the curve, as more flexibility is given to its prediction.

A comparison of curve predictions and log measurements in the Benken borehole using uncertainties shown in Tabs. 4-3 and 4-4 for the Opalinus Clay section is shown in Fig. 4-5.

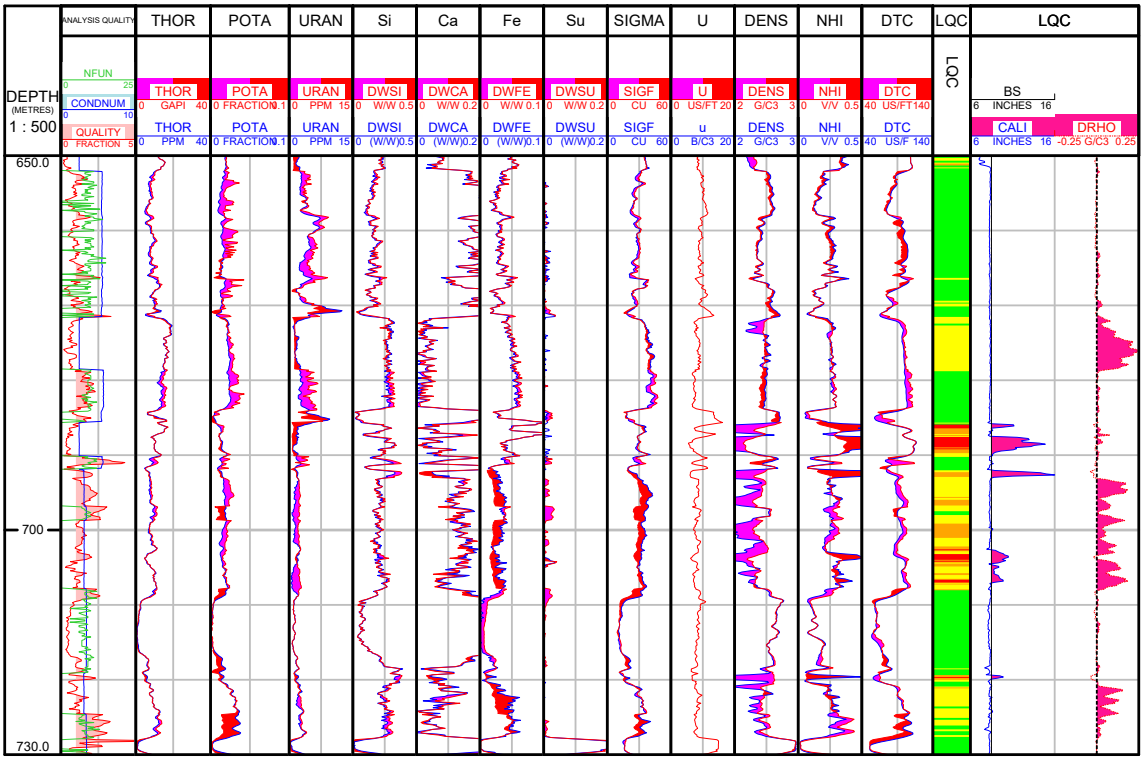

Fig. 4-5: Curve predictions in the Benken borehole

Red curves – Predicted, blue curves – actual log values. Red and purple fill to highlight differences.

4.1.5 Comparison of predicted data with core data

Some log interpretations will have to be performed without core data as none is available (e.g. for shallow boreholes), hence no comparison can be performed. An example for uncalibrated results in the Benken borehole is presented in Plate 1. If core data is available, the data can and will be used, an example of results from an interpretation using core data for the Benken borehole can be found in Plate 2.

Fig. 4-6 shows an example comparison of core results measured in the lab to MultiMin mineral content from the Benken borehole in the main zone of interest. The main minerals (from Mazurek 2017) were well predicted: total clays, matrix, calcite, siderite. The clay typing remained imperfect, the chlorite volume not being well quantified.

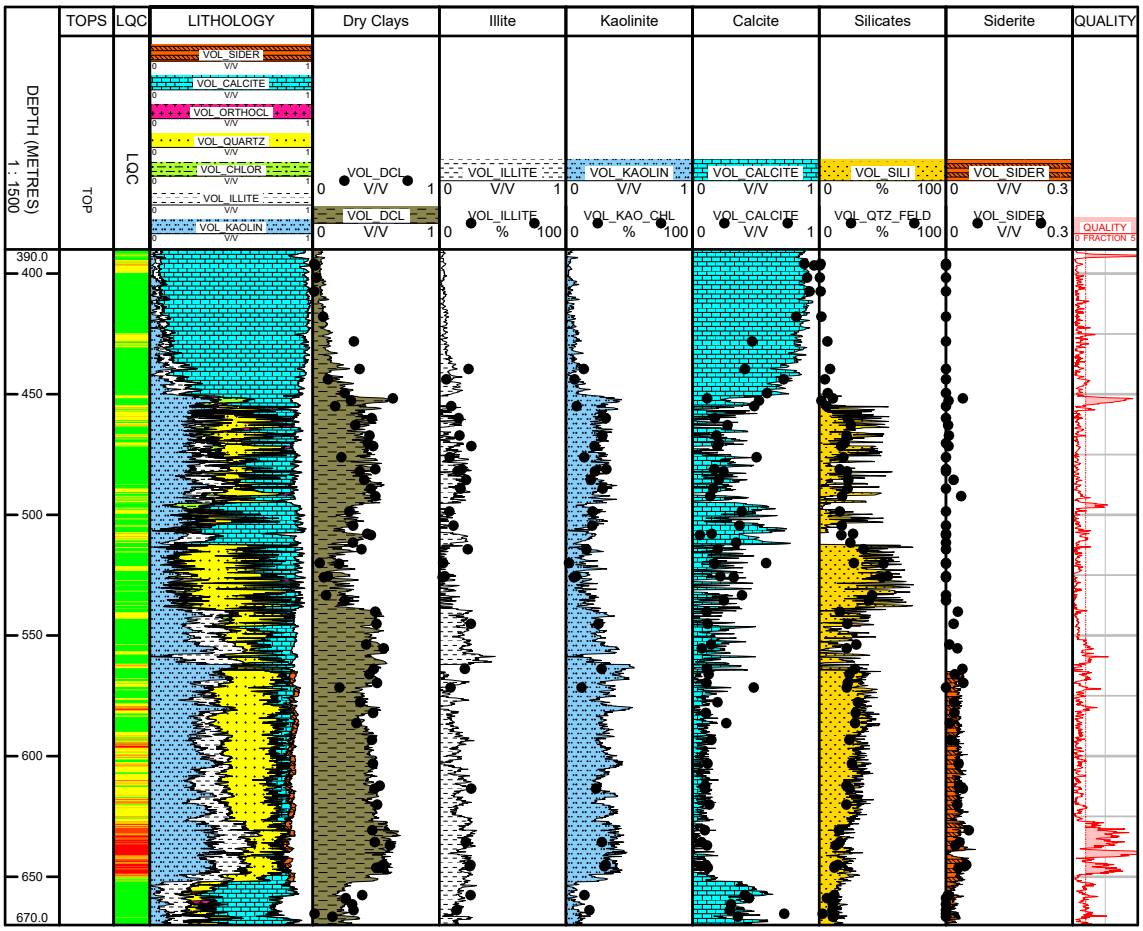

Fig. 4-6: Core-calibrated mineralogy in the Upper and Middle Dogger and Opalinus Clay of the Benken borehole

From left to right: Mineral content / Computing intervals / Formations names / Depth / TVDSS Dry Illite content / Dry Kaolinite+Dry Smectite content / Dry Chlorite content / Dry Clay Content / Quartz + Plagioclase content / Orthoclase content / Calcite + Dolomite content / Siderite content. All the mineral contents are volumetric.

Another way to compare core and MultiMin mineralogical contents is to convert the MultiMin minerals volumes to dry weight percentages, using the following equation:

$$Mineral\ \left(\frac{w}{w}\right) = Mineral\ \left(\frac{v}{v}\right) * \frac{Mineral\ Density}{\frac{Grain\ Density}{1 - Porosity}}$$

Then the sums of all the mineral weights from MultiMin output are normalised to 1.00 w/w. Fig. 4-7 shows an example comparison of core results measured in the lab to MultiMin mineral content from the Bülach-1-1 borehole.

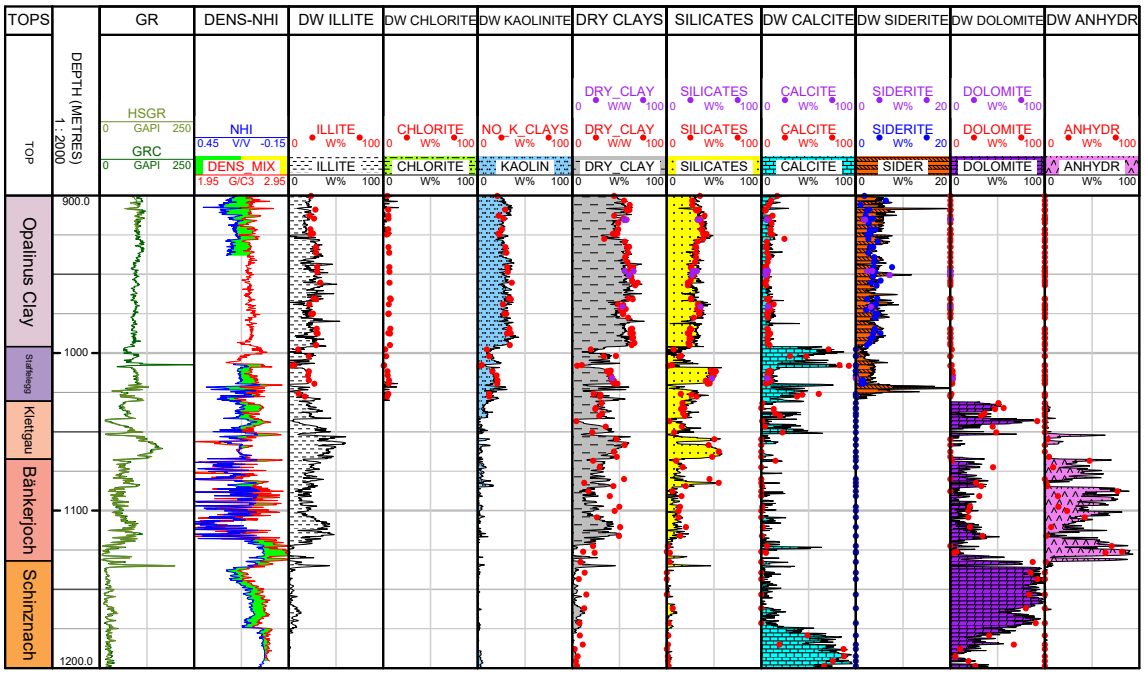

Fig. 4-7: Core-calibrated mineralogy in borehole Bülach-1-1

From left to right: Formation names, depth, Gamma-ray, neutron-density, Illite wt.-%, Chlorite wt.-%, Kaolinite wt.-%, Dry Clays wt.-%, Matrix Silicates wt.-%, Calcite wt.-%, Siderite wt.-%, Dolomite wt.-%, Anhydrite wt.-%.

An example of a comparison between the final log interpretation and core measurements is shown in Figs. 4-8 – 4-10 for the Benken borehole. The difference in measurement scales between logs (continuous readings investigating a large volume) and core (discrete measurement on small size plugs) should be accounted for in heterogeneous formations.

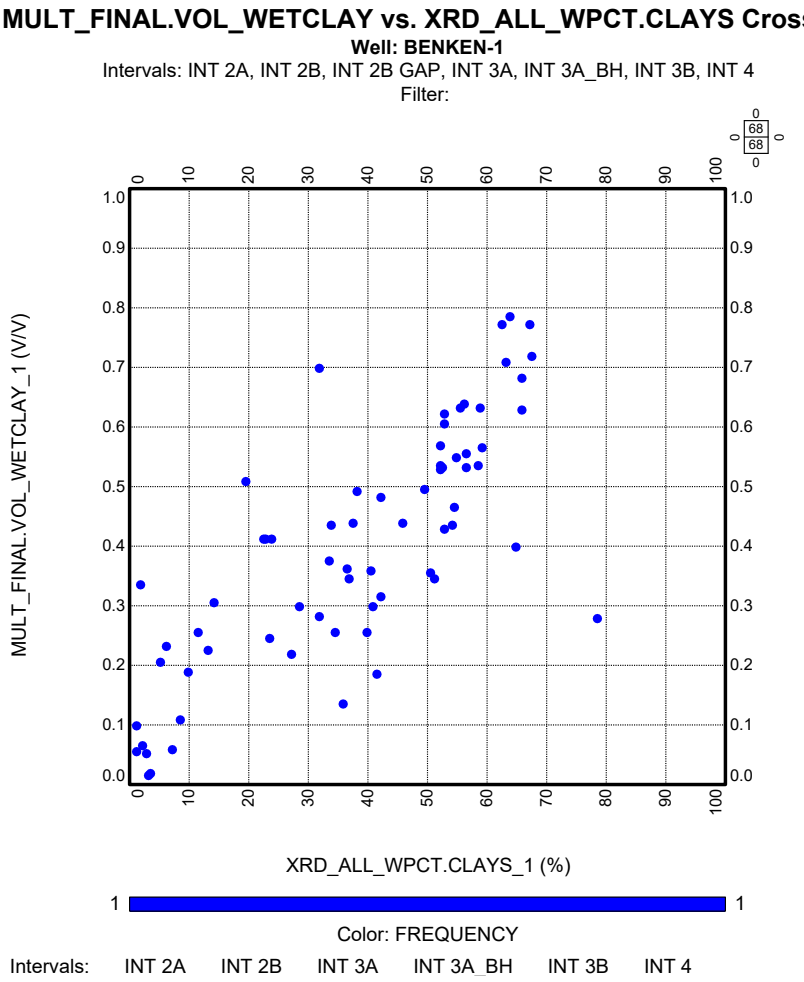

Fig. 4-8: MultiMin Clay volume vs. XRD Dry Clay W/W in the Benken borehole

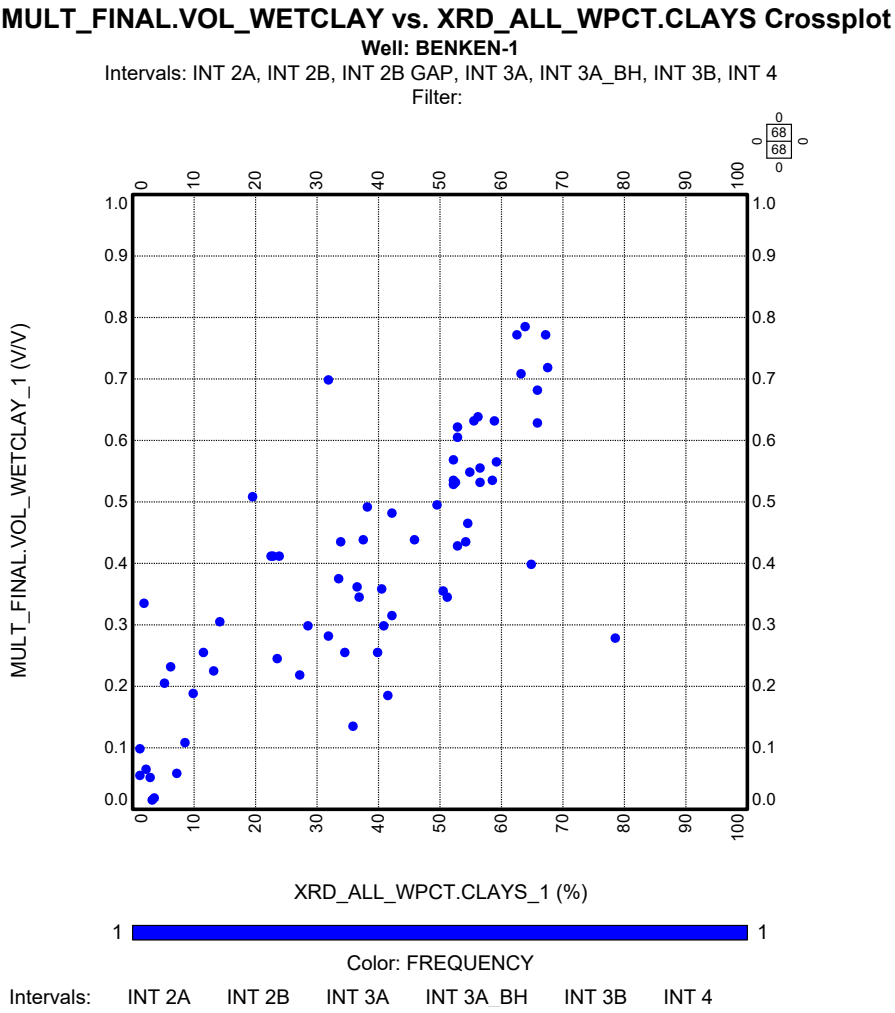

Fig. 4-9: MultiMin Dry Kaolinite & Smectite volume vs. XRD Dry Kaolinite & Smectite W/W in the Benken borehole

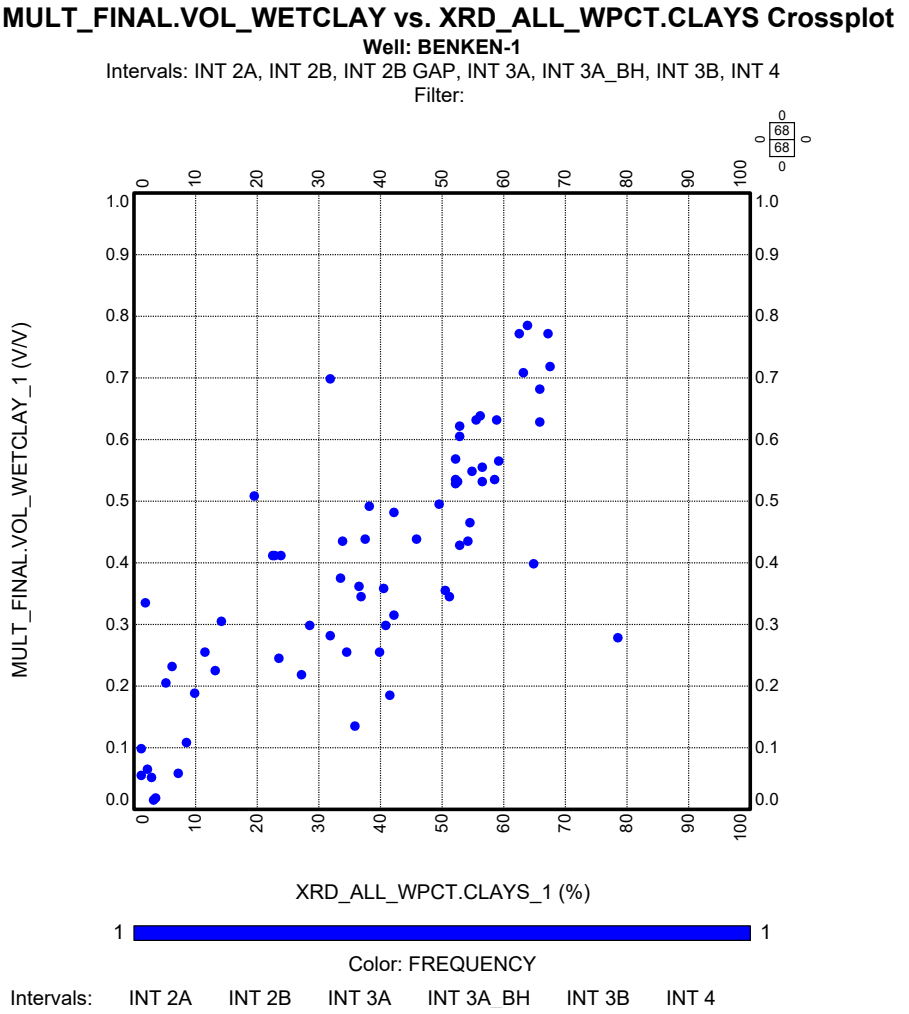

Fig. 4-10: MultiMin Quartz & Feldspars volume vs. XRD Quartz & Feldspars W/W in the Benken borehole

4.2 Bad hole intervals

In some intervals in the Benken borehole, log quality is affected by borehole conditions. In intervals with very large washouts, where the Gamma-Ray is attenuated by the mud and cannot be used for clay volume computation, empirical relations between the remaining logs and the clay volume can be calibrated in valid reference intervals. The output clay volume is then used as an input in the dedicated MultiMin model.

An example for this approach is shown in Fig. 4-11 for the base of the Opalinus Clay in the Benken borehole where large washouts (caliper saturated at 19" in a 8 ½" hole) made the GR curve unusable. An empirical VCL function of RD was derived in the surrounding formations (see Fig. 4-11), then applied in the bad hole interval with a good match to the core XRD data (see Fig. 4-12).

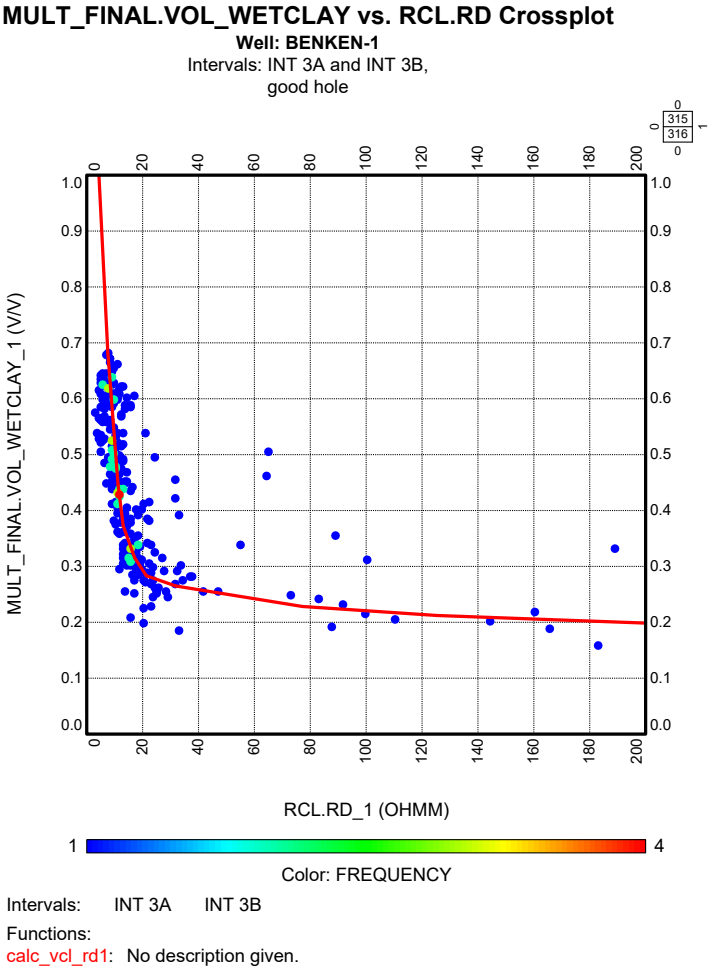

Fig. 1-11: Wet Clay Volume versus Deep Resistivity in the Interval 3 of the Benken borehole (good hole)

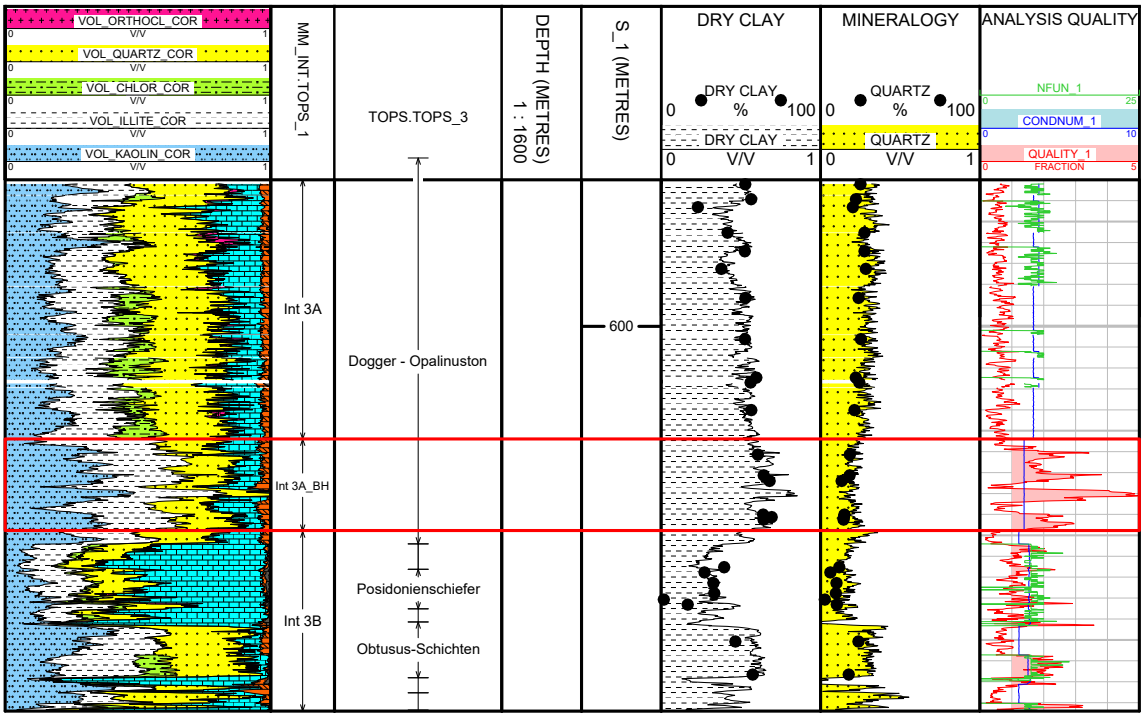

Fig. 4-12: Core to MultiMin mineralogy comparison in the Benken borehole (bad hole)

In case the log data are not sufficient for clay typing (i.e. where the SGR is not valid), a fully deterministic sequential workflow could be substituted for the stochastic approach. A mixed stochastic-deterministic approach may be considered as well: clay typing from MultiMin and porosity from the deterministic workflow.

5 Deterministic log interpretation application to examples (shallow boreholes)

As for the previous chapter, the example detailed here is not meant to document the interpretation results but rather to show the general workflow described in Chapter 3 using the example of the shallow borehole EWS Baden-Allmend. In general, a reduced suite of logs was acquired in the shallow boreholes: total Gamma-Ray, full wave Sonic (compressional and shear wave slowness) and deep resistivity. An example for available data in the shallow borehole EWS Baden-Allmend is shown in Tab. 5-1.

Tab. 5-1: Available data in the shallow borehole EWS Baden-Allmend

Curve	From m MD/RT	To m MD/RT	Curve name	Source file M-files or other	Environmental corrections	Normalization Formula
GRC	0.0	235.2	GR_ABF	27523_EWS-Baden-Allmend.dlis	No information provided	
RD	39.1	235,9	FEL	27523_EWS-Baden-Allmend.dlis		
DTC	39.0	236.2	DTP	27523_EWS-Baden-Allmend.dlis		Converted to µs/ft Depth shift to GR_ABF
DTS	39.0	236.2	DTS	27523_EWS-Baden-Allmend.dlis		Converted to µs/ft Depth shift to GR_ABF
CAL_X	31.1	236.4	CAL_X	27523_EWS-Baden-Allmend.dlis		
CAL_Y	31.1	236.4	CAL_Y	27523_EWS-Baden-Allmend.dlis		
FTEMP	25.6	237.0	TEMP	27523_EWS-Baden-Allmend.dlis		

No core data is available for EWS Baden-Allmend. In general, no core data is to be expected for shallow boreholes.

In the deep boreholes, very good correlations were found in the Jurassic between the deep resistivity, the sonic compressional slowness and the wet clay volume. Unfortunately, these same logs in the Jurassic Opalinus Clay have significantly different ranges in the deep and shallow boreholes, preventing an application of empirical laws determined in the deep boreholes to data from the shallow boreholes.

For example, the deep resistivity in the deep boreholes in Opalinus Clay is generally below 10 Ohm.m, while it is almost always above this value in the same formation in the shallow boreholes (see Fig. 5-1).

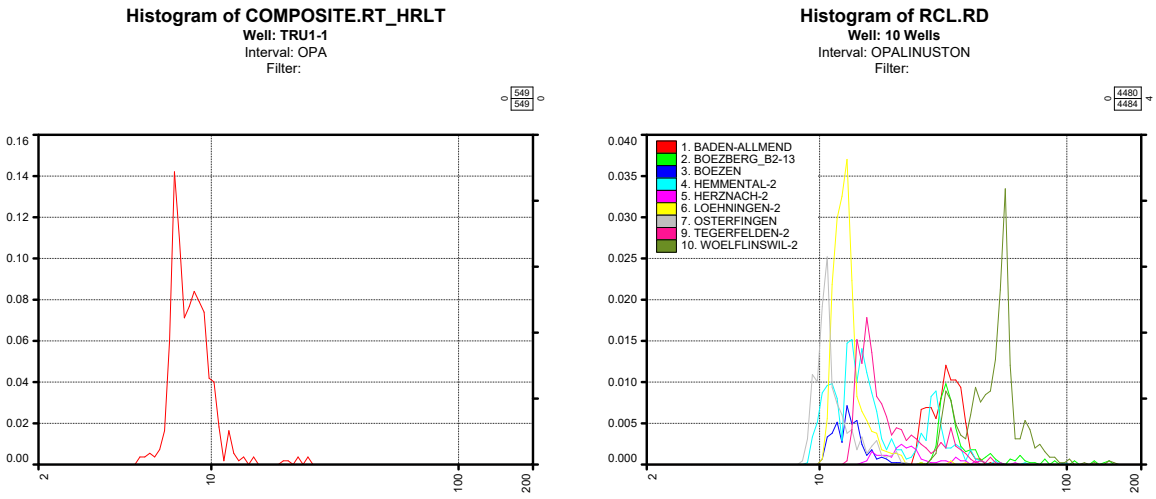

Fig. 5-1: Deep resistivity frequency histogram in Opalinus Clay comparing Trüllikon-1-1 (left) and ten shallow boreholes (right)

As neither the deep resistivity nor the compressional sonic slowness empirical clay volumes can be calibrated, the Gamma-Ray must be used for clay volume computation. The main difficulty is computing an accurate clay volume as the Gamma-Ray readings, even with full environmental corrections, are never fully characterised. This means that two different GR tool types, reading the same formation in the same borehole, will record slightly different values.

Therefore, the following (uncalibrated) sequential deterministic workflow will be applied here:

- The Wet Clay Volume (VCL) is computed using the same linear volumetric equation described previously:

  VCL_GR = (GR – GR_CLEAN) / (GR_CLAY – GR_CLEAN)

  The clean endpoint is initially computed as the P01 of the GR distribution but can be slightly further adjusted. As an unlimited VCL is first computed, slightly negative values are locally acceptable (in clean limestones) to account for the statistical variations of the Gamma-Ray measurements.

  A shale endpoint is initially picked as the P97 of the GR distribution. The maximum value often corresponds to a special mineralogy rather than shales, e.g. high kerogen content rocks (uranium rich) or heavy mineral rich layers. This shale endpoint is iteratively adjusted while computing the porosity, as explained later in this chapter.

  The wet clay endpoint is computed using the following formula:

  GR_CLAY = (GR_SHALE – GR_CLEAN) / VCL_HI + GR_CLEAN

  As already discussed, VCL_HI = 0.78 v/v in the Benken borehole. The clean and clay endpoints must be adjusted on a well by well basis.

- The porosity is computed with the linear volumetric Wyllie equation using the sonic compressional slowness (see section 3.1). The following compressional sonic endpoints will initially be used:

  – DT_FL: The water compressional slowness will be computed from the water salinity, temperature and pressure as shown in Fig. 5-2 In the shallow boreholes, DT_FL = 198 μs/ft.

  – DT_MA: the matrix minerals DT will vary in the shallow boreholes. A minimum value 49 μs/ft will be used in the clean limestones (calcite) and a maximum 53.5 μs/ft in the shaliest sections of the Opalinus Clay (mostly calcite and silicates). The matrix DT will be controlled by the following empirical linear law:

    DT_MA = 53.5 – (0.78 – VCL) / 0.78 * 4.5 limited between 49 and 53.5 μs/ft

  – DT_CLAY: the starting point for DT_CLAY will be 125 μs/ft and can be further adjusted to achieve PHIE close from 0 v/v in the shales.

  – VCL: the wet clay volume is computed during the first interpretation step from GR.

As DT_CLAY is computed from VCL, an iterative process will be performed to better adjust the GR_CLAY and DT_CLAY endpoints.

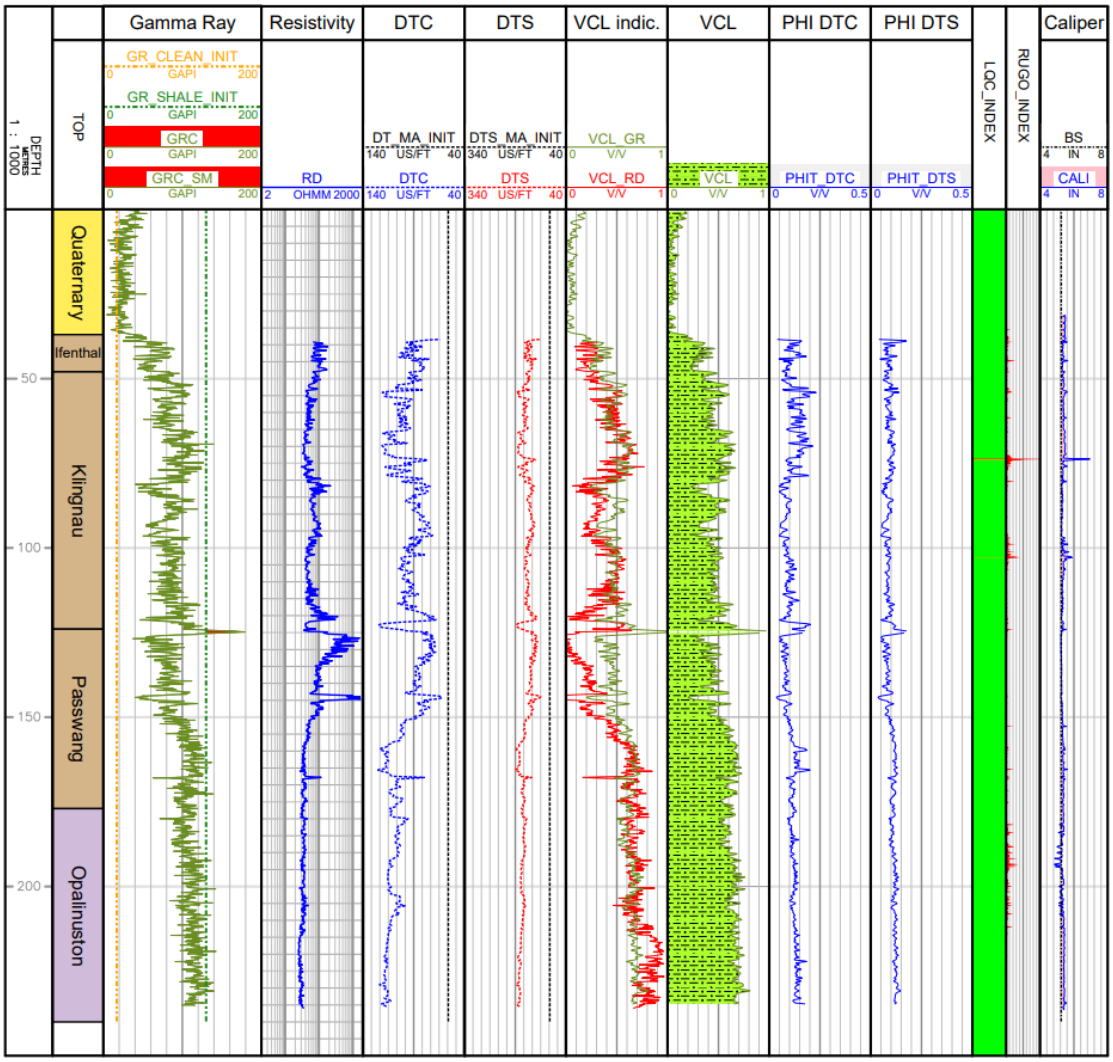

Fig. 5-2: Example of deterministic log interpretation in the EWS Baden-Allmend borehole

The _init values correspond to minimum/maximum values given previously in the text (e.g. GR-CLEAN_INIT/GR_SHALE_INIT refer to the values P01/P97).

This methodology will be propagated to all shallow boreholes.

6 Comparison of deterministic and stochastic interpretation results

A comparison of deterministic versus stochastic (quicklook) results in the Bülach-1-1 borehole is shown in Fig. 6-1. The dots are the laboratory XRD (X-Ray Diffraction) and porosity measurements on plugs (Mazurek et al. 2020). The column MULT_DCL displays the MultiMin dry clay wt.-% and the core XRD, while the column on its right, DET_DCL, shows the deterministic dry clay wt.-% and the core XRD.

Similarly, the columns Mult. PHI and DET. PHI compare the stochastic and deterministic total porosities, together with the core measurements. The results are close to each other in terms of clay volume and total porosity, and close to the core measurements.

In general, the primary method for the log interpretation will be the stochastic MultiMin approach, using the deterministic workflow only in zones of extreme washouts where the stochastic approach is not deemed reliable or where not enough data for the stochastic workflow is available.

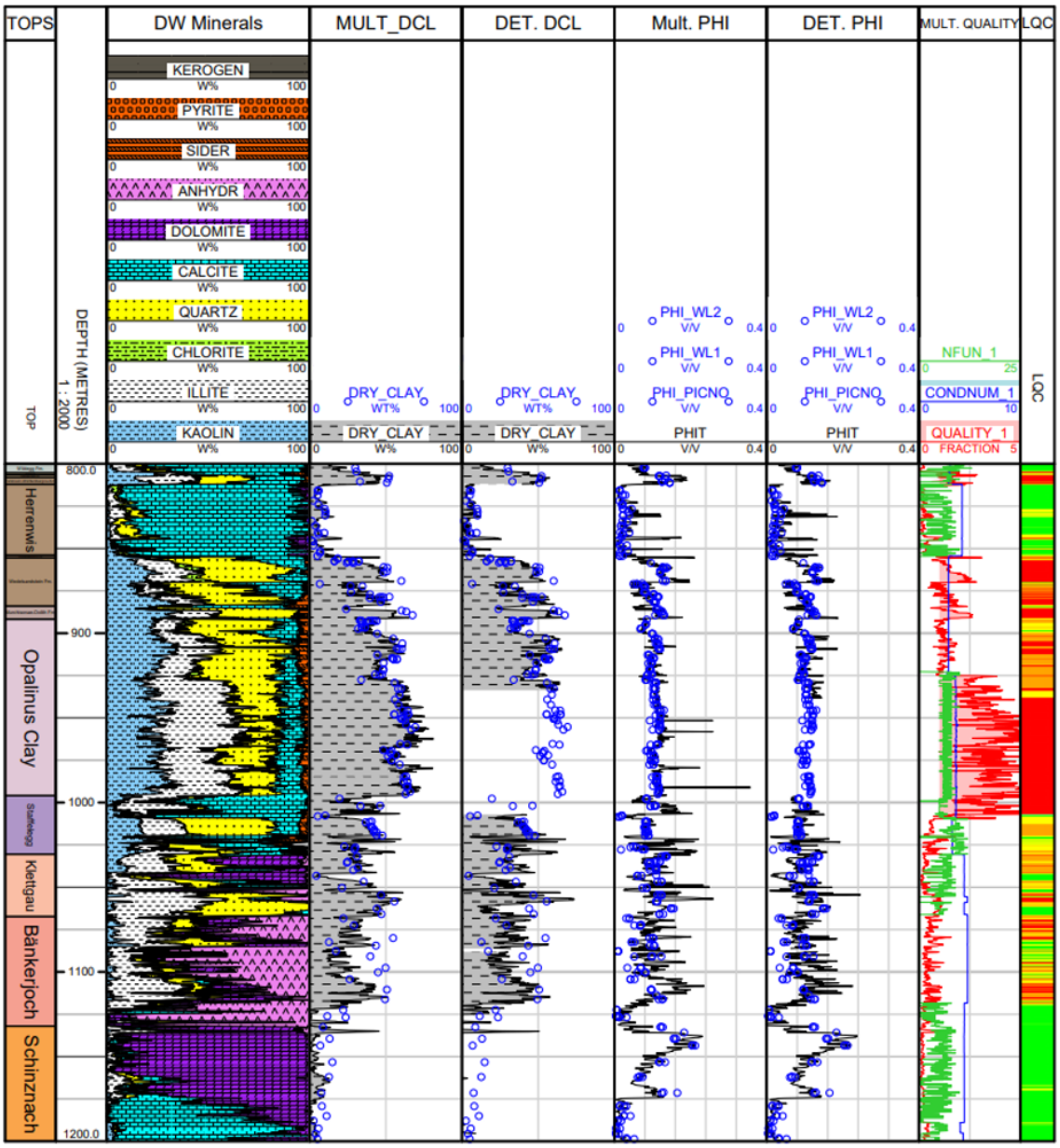

Fig. 6-1: Comparison between deterministic and stochastic results in Bülach-1-1

Mineralogy (DW Minerals – Dry Weight Minerals) from the log interpretation is compared to mineralogy from lab measurements. In addition, several lab porosity measurements are available: PHI_WL2 – Waterloss porosity using bulk wet density, PHI_WL1 – Water loss porosity using buld wet density and PHI-PICNO – pycnometer porosity, see Mazurek et al. (2020) for details. The last tracks include quality indicators (NFUN, CONDNUM, QUALITY and LQC).

7 Summary

This report describes the general workflow for the interpretation of petrophysical wireline logs and additional data (such as lab measurements and MSCL data) to determine formation mineralogy and porosity. In a first step, the availability and quality of data determines the applied procedures. If sufficient, good quality data is available, the stochastic MultiMin approach can be used. This approach uses the petrophysical wireline logs and, if available, MSCL data to calculate theoretical log responses from an assumed mineral content (from prior knowledge, e.g. lab measurements). If not enough sufficient data is available (e.g. in the shallow boreholes), a more empirical, deterministic approach of log interpretation must be used.

While the stochastic approach (MultiMin) is capable of calculating several parameters (mineralogy and porosity) and, depending on the data, even can be used for clay typing, the deterministic approach can only determine a very basic parameter set (usually total clay mineral content and porosity). The two approaches can be combined, e.g. in bad hole intervals the deterministic approach is used while in good hole intervals the stochastic approach is preferred.

In summary, both approaches can be used to determine several formation parameters and interpreted results mostly show a very good fit with lab measurements.

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