Structural characterization of hard rock formation using wireline borehole logging techniques in an open pit mine, Norway

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ABSTRACT
Detailed investigation of hard rock formations is very popular and relevant research area for a successful execution of geotechnical engineering projects such as tunnel and/or bridge construction works, fractured hard rock aquifer projects as well as open pit mines. In conjunction with the analysis of core samples, borehole logging techniques are commonly used for purpose in hammer and even in core drilled boreholes. The primary objectives of such logging works are to reveal structural characteristics of the hard rock formation, to identify fracture zones as well as to verify the level of compactness of rocks including level of weathering. A wide range of logging techniques are generally applied in order to successfully complete the objectives. A logging tool park including acoustic televiewer, optical televiewer, three-arm caliper, full waveform sonic, dual focused resistivity, natural gamma, spectral gamma as well as flowmeter and temperature tools is generally adequate to provide sufficient amount of information for a comprehensive interpretation. The complete logging suite was deployed in an open pit mine in Hauge i Dalane in South-Western Norway. Information obtained from the open pit mine effectively contributed to the completion of rock stability studies. Geophysical borehole logging and core logging results were also compared and revealed sufficient correlation. Even spectral gamma tool was run for checking the behaviour of Potassium, Uranium and Thorium (KUT) concentration variations at fracture zones in order to reveal additional information about presence of clay fillings. Experience shows that even the most conventional logging methods such as resistivity and full waveform sonic can provide sufficient information about the structural characteristics of hard rock formations.

Keywords: geophysical logging, televiewer, sonic, resistivity, spectral gamma

1 *INTRODUCTION*

The open pit mine is located in Sokndal Municipality in South - Western Norway. It is an open pit mine that produces ilmenite since 1960. The ilmenite ore body is considered as one of the largest in the world. The open pit has a length of about 2.8 km, while the depth today is at 240 meters. The width of the pit varies from 400 to 600 meters. Historically there have been numerous slope instability occurrences, particularly on the hanging wall slopes. In order to cope with these challenges, it was decided that a geotechnical model should be developed. The geotechnical model is the cornerstone of open pit design. It is comprised by four components, the geological, structural, rock mass and hydrogeological models. The development of geotechnical model will allow the definition of the geotechnical domains and the allocation of design sectors. These two steps are

fundamental for the preparation of the final slope designs.
Into this framework the compilation of structural model is of high importance, as it allows describing the geological media that is responsible for the stability conditions and the groundwater flow inside the rock mass. In the case of the open pit mine, the following data sources were used:

1) 3D ortho-rectified pictures were compiled for certain areas of the mine. Mapping of fractures took place, where dip/dip direction, persistence, spacing and aperture (in some cases) were recorded.
2) Aero photos of the mine area were taken during the summer of 2014. These aero photos were inserted into a GIS system, and mapping of all the lineaments inside the pit area was commenced.
3) Structural mapping of the drainage tunnels that are running the perimeter of the mine was made.
4) The structural data and information of geological environment were retrieved from 12 hammer-drilled and from 10 core-drilled boreholes. To cover this objective, a wide range of geophysical logging methods were applied including acoustic (ATV) and optical televiewer (OTV), spectral gamma, dual focused resistivity and full waveform sonic (FWS). In hammer-drilled boreholes, in addition to the sonic formation velocity, FWS data were also used to determine geo-mechanical parameters such as Poisson's Ratio, Shear Modulus, Young Modulus as well as Bulk Modulus with the use of average lithological density data determined in field laboratory. In the 12 hammer-drilled boreholes piezometers were finally installed. The total length of cores that were retrieved is 2285m. Structural data were also retrieved in all boreholes (both hammer- and core-drilled) with the use of optical and/or acoustic televiewer.

By using the data from these four sources, the 3D structural model of the open pit can be compiled. The structural model is part of the geotechnical model, which is a vital part of an effective slope monitoring system. The purpose of this model is to reveal large-scale instabilities as well as local scale movements which are critical components for risk management practices in modern open pits (Panthi and Nilsen, 2006). Open-pit mines are typically enlarged until either the mineral resource is exhausted, or an increasing ratio of overburden to ore makes further mining uneconomic. When pits become larger and as they get deeper, the importance of understanding and controlling slope stability increases. This paper is intended to summarize and highlight the results and necessity of geophysical borehole logging works in an open pit mine by focusing on the acquired geophysical logging data sets regarding rock stability.

2 DRILLING IN TWO PHASES

Hammer drilling of 12 boreholes through the anorthosite – ilmenite-rich norite and diabase formations was completed between the end of April and beginning of June, 2014. Core drilling was completed by January, 2015. The name, length and elevation of each borehole are presented at Table 1 and 2.

Table 1 Hammer drilled boreholes

Drill sequence	Borehole ID	From	To	Length of Borehole (*m*)
1	TEL_F_01	234	-61	295
2	SKOG_F_02	235	105	130
3	SKOG_F_03	230	55	175
4	SKOG_F_04	245	75	170
5	SKOG_E_05	265	-60	325
6	SKOG_H_06	300	-60	360
7	SKOG_H_07	281	-79	360
8	SKOG_H_08	298	-62	360
9	SKOG_H_09	293	-67	360
10	TEL_H_10	206	-44	250
11	TEL_H_11	200	-40	240
12	TEL_H_12	200	-55	255
	TOTAL			3280

Table 2 Core drilled boreholes

Drill sequence	Borehole ID	From	To	Length of Borehole (*m*)
1	TEL_F_01_c	230	-40	270
2	TEL_F_02_c	230	-40	270
3	SKOG_F_03_c	185	-40	228
4	SKOG_F_04_c	200	-40	244
5	SKOG_H_05_c	230	-40	274
6	SKOG_H_06_c	238	-40	282
7	SKOG_H_07_c	185	-40	228
8	TEL_H_08_c	200	-40	244
9	TEL_H_09_c	80	-40	122
10	TEL_H_10_c	80	-40	122
	TOTAL			2285

3 GEOPHYSICAL BOREHOLE LOGGING AS VIRTUAL CORING

The primary objective of the interpretation of the acquired geophysical data was to reveal structural properties (fracture and joint mapping) of the formation as well as to determine geo-mechanical parameters (Poisson`s ratio, Young Modulus, Bulk Modulus, Bulk Compressibility, Shear Modulus) based on sonic P-wave (compressional wave) and S-wave (shear wave) arrivals with the aid of available density data. Fracture and joint mapping was performed by ATV and where it was feasible by OTV as well. The main objective was to combine both the ATV and OTV wherever it could be done to reduce the risk of misinterpretation of televiewer data. Cross plot log evaluation technique was applied in order to present and effectively evaluate the different type of logging data. Resistivity vs. fracture frequency and average aperture, magnetic field vs. resistivity, fracture frequency vs. P-wave velocity, resistivity vs. gamma ray (GR) and fracture statistics (fracture frequency and aperture) vs. geo-mechanical modulus cross plots were made in dedicated intervals for each borehole to reinforce the comprehensive interpretation. A common feature of fracture zone is the inhomogeneity of physical parameters that is sensitive to the variation in the level of compactness of rocks. These indicative physical parameters are resistivity, acoustic velocity and the calculated geo-mechanical parameters. Total gamma ray (TGR) log, Potassium (K) and Thorium (Th) concentration logs very well indicate the presence or the lack of clay deposits at detected joints or fractures. The main concept of the interpretation was determined and based on the results of the three main logging data sets such as resistivity, full waveform sonic as well as televiewer data in addition to the more conventional log types like three-arm mechanical caliper and gamma ray logs (Rigler, B., 2013; Rigler, B. and Varga, V., 2014); Rigler, B., 2015).

3.1 Full waveform sonic (FWS) logs

FWS data were acquired by a sonic tool, which is equipped with one transmitter and two receivers (3ft and 5ft). The wave trains are recorded by both receivers were processed and finally were cross correlated in order to derive the semblance image to interpret the acoustic formation P- and S-wave velocity. The P-wave and S-wave arrivals and slowness were interactively picked (Figure 1) as well (M. Bala, J. Jarzyna, 1996; R.E. Crowder, J.J. LoCoco and E.N. Yearsley, 1991; Barton, C. et al., 1989; S. Astbury & M.H. Worthington, 1986; N.O. Davis and T.M. Staatz) for the use of calculating the geo-mechanical parameters such as Poisson's Ratio, Shear Modulus, Young Modulus, Bulk Modulus and Bulk Compressibility. In

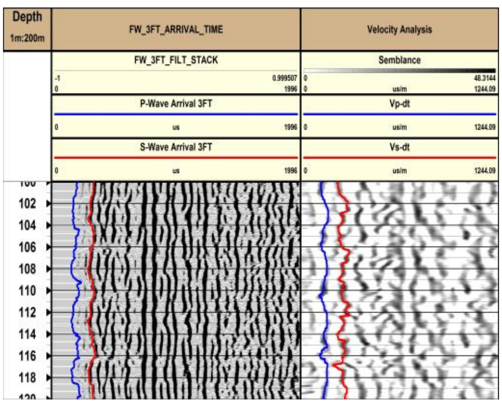

Figure 1 Picking P and S-wave arrivals and slowness values on full wave train and semblance logs

the mine, interpreted formation P-wave velocity values vary between 4000 and 9000 m/s depending on the level of compactness of rock as well as lithology. Acoustic wave propagation is very sensitive to the presence of joints, fractures and/or fissures. The acoustic wave velocity is proportional to the original state of the rock. Therefore, in the zones of weakness or tectonized zones the degree of decrease in velocity can be high. In the strongly fractured sections, the propagation velocity of P-wave (Vp) and S-wave (Vs) decreases (Figure 2) although the ratio Vp/Vs generally increases (Zilahi-Sebess, L., 2003). In high velocity rock formation at small fracture aperture just the opposite might happen, the Vp/Vs decreases with decreasing Vp velocity. All the interpreted fault or fracture zones and larger individual joints were identified on the resistivity log and the acoustic televiewer images as well. From the lithological point of view, acoustic P-wave velocity is generally very high along the entire logging sections, especially in the mother rock anorthosite. Anomalies on the sonic related parameter curves (Vp, Vs,

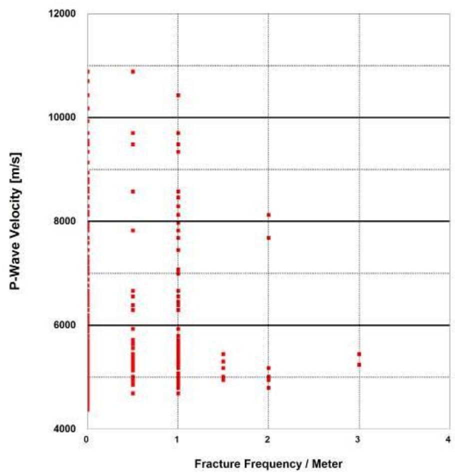

Figure 2 P-wave velocity vs. Fracture frequency / meter (FF/m)- Example from a hammer-drilled borehole

travel time, P-wave and S-wave arrivals as well as Vp/Vs and geo-mechanical modulus) are mainly related to structural variation (Figure 3) as well as level of compactness and weathering of rock rather than the lithology itself. Geo-mechanical parameters were calculated along the entire borehole sections based on the interactively picked P-wave and S-wave arrivals as well as density values that had been previously determined from lithological

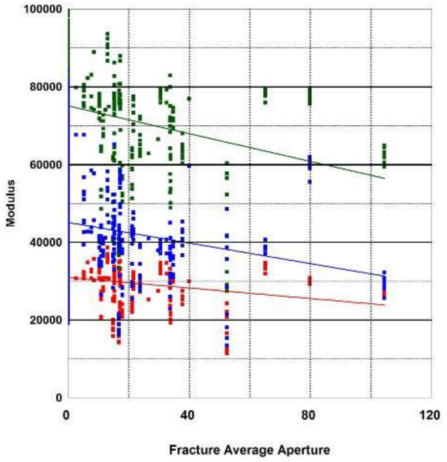

Figure 3 Fracture average aperture vs. Geo-mechanical modulus – Example from a hammer-drilled borehole; Green, blue and red are in respect to Shear modulus, Young`s modulus and Bulk modulus consecutively

samples, which had been taken from several locations in the area of open pit mine (Table 3). Lithological intervals were determined based upon acquired geophysical logs (Figure 4) and preliminary available geological information. Geo-mechanical parameters were calculated as described below (N.O. Davis and T.M. Staatz):

Poisson's Ratio:

$$\sigma = (0.5*(t_s / t_c)^2 - 1) / (t_s / t_c)^2 - 1 \quad (1)$$

Shear Modulus:

$$\mu = \rho_b / t_s^2 \quad (2)$$

Bulk Modulus:

$$k = \rho_b*(1/t_c^2 - 4/3*t_s^2) \quad (3)$$

Young's Modulus:

$$E = 2\mu(1 + \sigma) \quad (4)$$

Where t_s is shear (S) transit time in (μsec), t_c is compressional (P) transit time in (μsec) and ρ_b is bulk density in (g/cm^3)

In most cases, in each borehole, the value of modulus decreases with increasing fracture density and aperture as well as with decreasing degree of compactness of rocks.

Table 3 Density values determined in field laboratory (Rigler, B. and Varga, V., 2014)

Lithology	Density [g/cm3] (Provided by Titania AS)
Anorthosite	2.7
Ilmenite	3.3
Diabase	2.92
Ilmenite	3.2
Ilmenite Fresh	3.3

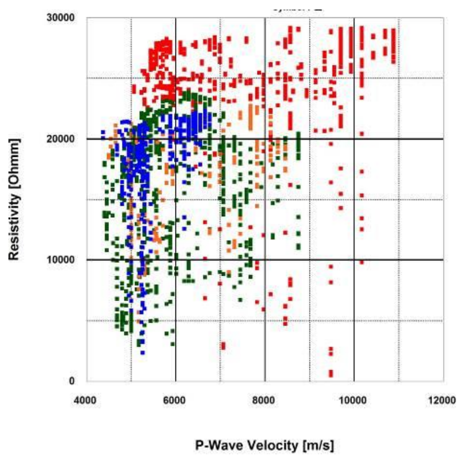

Figure 4 Lithological intervals were determined with the aid of geophysical logging data – Example from hammer-drilled borehole; Red, blue, green and orange are in respect to Norite Zone Nr.1, Anorthosite, Norite Zone Nr.2 and Diabase dyke consecutively

3.2 *Dual Focused Resistivity (DLL3) logs*

By the fact that dual focused resistivity tool is designed for focusing the injected current towards the formation by guard electrodes, DLL3 is an effective tool for the identification of thin bedding layers, consequently, for detecting the presence of small scale discontinuities such as fractures and joints. In the open pit mine, resistivity values vary within a wide range between a couple of hundred and maximum detectable 30000 Ωm along the entire logging section. Because the fresh rock itself is a non-conductor, joints or fractures and level of weathering of rock are the reasons for large reduction of resistivity readings. The main reason of this large reduction is the large variation in the degree of weathering of rocks (Danielsen, B.E., Madsen, H.B., 2013), the fracture frequency as well as the size of aperture of fractures or joints (Figure 5). The presence of clay deposits in the joints may also affect the magnitude of subsidence in resistivity. "Fissures representing a porosity of only 0.1% in the measured rock volume reduce the

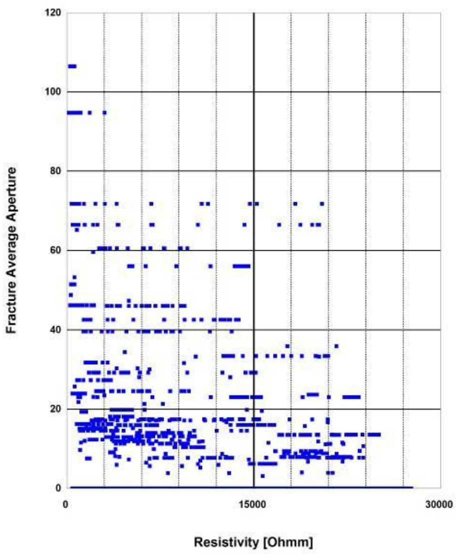

Figure 5 Resistivity vs. Fracture average aperture from a hammer drilled borehole

apparent resistivity of rock to about 1000 Ωm, thus it causes at least one order of magnitude decrease in resistivity compared to fresh rock – while the rock's density are practically unchanged – thus resistivity shows the presence of fractures in a strongly blown up form." (Zilahi-Sebess, L., 2003). Resistivity blown up and its phenomena can be observed at almost each single interpreted joint in each borehole. The highest resistivity and velocity values belong to very compact, fresh rock. Fresh ilmenite is non-conductive (Lohva, J. and Lehtimäki, J., 2005), this is why it has a resistivity range between 20000 and 30000 Ωm (limited by the detectable maximum of DLL3). Diabase has a slightly lower resistivity between 10000 and 25000 Ωm. Resistivity of anorthosite varies within a very similar range compare to the resistivity of diabase.

3.3 *Acoustic and Optical televiewer logs*

A combination of ATV and OTV logs is always recommended for a reliable fracture mapping. This is due to by the fact that OTV images might easily be misinterpreted in the lack of acoustic caliper and amplitude data. Minor fractures may not be found on an optical image but might be found on an acoustic caliper log and vica versa, bedding planes or foliations might be seen more confidently on an OTV log than on an ATV log. Due to limitations of OTV logging (e.g. opaque borehole fluid), acquisition very often does not even allow us to obtain a good quality optical image (Figure 6).

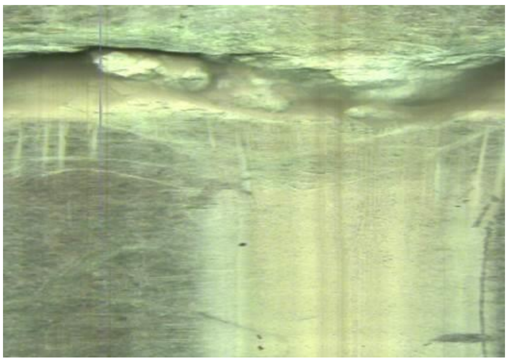

Figure 6 Cascading flow on OTV image – cascading material shades structure details on the image log

On an outstretched cope of borehole image (amplitude, transit time, acoustic caliper or optical) the intersection of a fracture plane generally appears as a sinus wave (Williams, J.H. and Johnson, C.D., 2004). Interpretation of both the ATV and OTV images were completed by using this concept (Figure 7). The dip and azimuth of fractures were determined and corrected by borehole deviation and are referred to true north after the application of magnetic declination correction. Fracture frequency per meter (FF/m), average aperture and RQD logs were derived from interpreted structural information obtained by televiewer logging.

Table 4 Classification of fractures (Duncan C. Wyllie and Christopher W. Mah, 2010)

Term	Aperture [mm]	Majority
Tight	0	Minor
Very Narrow	0-6	
Narrow	6-20	
Moderately Narrow	20-60	Major
Moderately Wide	60-200	
Wide	200-600	
Very Wide	600-2000	
Cavernous	>2000	

Majority of all individual fractures were also determined by using a classification method (Table 4). Magnetic field data were also acquired and recorded by the three axis magnetometer, which is installed in the televiewer tool body. The magnetic data are mainly used for structure orientation and borehole deviation purpose but it could be used for

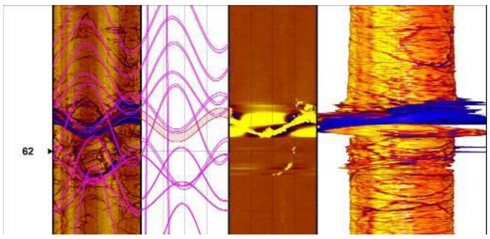

Figure 7 ATV log example from a core drilled borehole

evaluating the lithology (Figure 8), especially to identify Norite (ilmenite-rich rocks). It is important to note that from lithological point of view the recorded magnetic field data can only be evaluated as a relative anomaly in contrast with the magnetizability, which is usually acquired as magnetic susceptibility data. The higher magnitude of magnetic field shows the highest values in norite (ilmenite ore) and relatively high values in diabase dyke. Anorthosite was not observed as a magnetic body due to relatively low magnetic field readings (Rigler, B., 2013).

3.4 Spectral gamma logs

Spectral gamma data was acquired in

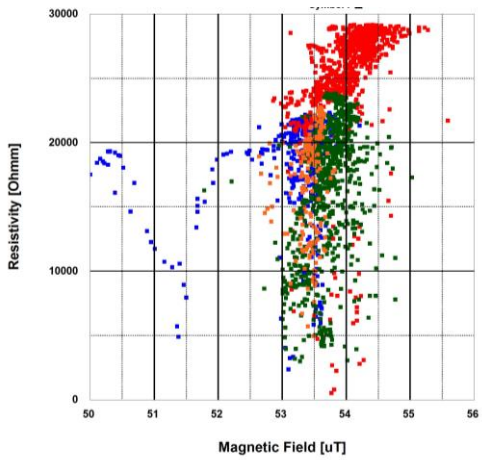

Figure 8 Resistivity vs. Magnetic Field crossplot showing red, green, orange and blu in respect to Ilmenite fresh, Ilmenite poor, Diabase and Anorthosite consecutively

order to calculate the K [%], U [ppm] and Th [ppm] concentrations, which were determined by using the coefficients and formula provided by tool master calibration results. It has been observed that thorium concentration is normally very low along the entire logging sections. The presence of Potassium (K) and the elements of Uranium (U) series dominate. Where potassium is present on the log, thorium concentration decreases but uranium is generally present together with potassium and shows linear relationship with the potassium concentration log. It means that total gamma ray (TGR) as a physical parameter is not suited for making a distinction between norite (ilmenite) and anorthosite. Total gamma as well as KUT concentration logs were very indicative when it comes to the identification of a large Diabase dyke, which had run through the open pit mine. TGR significantly increases at fractures or joints, where clay deposit to be present. These gamma anomalies are mainly caused by the presence of potassium, which is a very good indicator of clay mineral deposits. At the joints where gamma anomalies are not observed, clay is probably not present.

4 CORE LOGGING

Core logging is one of the fundamental techniques used to obtain geotechnical information and despite the fact that advanced geophysical techniques were used, it was decided that core-logging should still be performed. The actual logging process remains a manual operation that gives a hand-on experience of the geo material, which can be evaluated by the engineering geologists or geo technicians. The main purpose of geotechnical logging of solid core is to divide the core into geotechnical similar intervals (domains), then ascribe geotechnical to each domain (Read, J. and Stacey, P., 2010). The following parameters were collected:

- From, To
- Rock Type/lithology
- Fracture frequency per meter
- Rock quality designation (RQD)
- Total core recovery (TCR), which measures the total length of the core recovered, including broken zones, against the total length of the core drilled, expressed as a percentage (Read, J. and Stacey, P., 2010).
- Solid core recovery (SCR), which measures the total length of solid core, excluding pieces smaller than the core diameter, against the total length of the core drilled.
- Weathering Index, which describes the effect of weathering and/or alteration on the geo material. The ISRM (ISRM, 1978) based method was used in describing the weathering/alteration effect.
- Strength index, which represents the field estimate of the uniaxial compressive strength (UCS) of the intact core.
- The number of joint sets at each meter of core length.
- For each joint the joint alteration number (Ja) was recorded. This number is part of the Q-system (NGI, 2013) and it is used to describe the joint infilling and the roughness.
- Roughness of the discontinuity surfaces, by using the joint roughness coefficient values (ISRM, 1978).

5 COMPARISON OF TELEVIEWER AND CORE LOGGING DATA

A correlation between the results from televiewer and core logging data was attempted. The parameter chosen to evaluate the degree of relationship between the two methods was the fracture frequency per meter (FF/m) as well as RQD. The results from core logging were obtained by visual inspection of every interval in the core box, considering the real length of the run, and not the recovered core. In practice there are some runs that show a partial length of the total core only, i.e. 0,95m in a 1 meter run, as shown in Figure 9. All the observed fractures observed were recorded, no matter that they were open or not. Comparison of

Figure 9 Actual core box. It is possible to see that the core stored in a 1m run is not always the full length, as it is clear in the lower three runs

core and televiewer logging results was performed in five boreholes. The results normally show a very good correlation, with location of anomalies at same depths and an overall contour that matches correspondingly. Figure 10 represents an example from SKOG_F_03_c borehole in the interval from 38 to 68m. The location of FF/m and RQD anomalies are almost identical on both type of logs. It is also observed that between 49m and 65m, anomalies follow each other with good level of correlation.

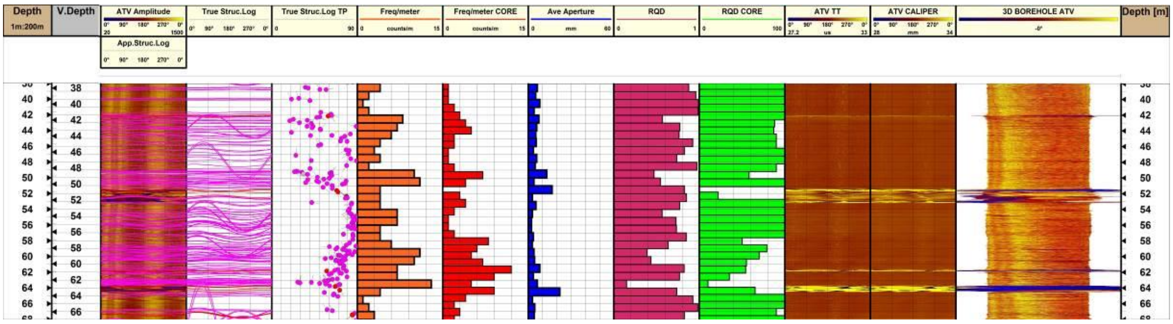

Figure 10 ATV structure logs and statistics including FF/m and RQD logs for comparison of televiewer and core logging data

The reliability of these data sets are just as good as these logs can be used for making decisions on the zones of hydraulic tests or the depths where piezometers could be placed.

6 CONCLUSIONS

Apart from some additional information (TCR, SCR, UCS) given by core sample analysis, the combination of televiewer and other geophysical logging methods on its own provides an overall picture and adequate amount of information about rock quality, structure details, lithological variations as well as geo-mechanics. Televiewer logs supplies with high confidence not only the fracture statistics (e.g. FF/m) but structure orientations as well. Resistivity logs provided very valuable information about level of weathering and compactness of rocks in addition to a valuable support on fracture mapping. In addition to formation velocity, sonic logs provided an overall and reliable picture about the geo-mechanical properties of formation rocks. Apart from Poisson`s ratio, the geo-mechanical modulus parameters are not as accurate as it was determined in laboratories by using core samples. This is mainly because of the restricted availability of formation density information. This might have been improved by running a gamma-density tool as an additional logging service. Due to the method of hammer drilling in very hard formation sections, roughness of borehole walls also made the determination of geo-mechanical parameters little uncertain since sonic data quality is highly affected by the roughness of borehole wall as well. Geo-mechanical parameters were very well estimated anyway and provided a valuable overview about the level of compactness of the rock formation. Gamma logs (both spectral and total gamma) also appeared to be very valuable in terms of identification and determination of lithological intervals, presence of clay at fracture zones as well as depth correlation. Spinner flowmeter logging (R. E. Crowder and K. Mitchell, 2002) was also performed in dynamic and static mode in order to reveal any potential water flow at detected fractures zones or joints. In addition to the geo-technical analysis, geophysical logging results were also provided valuable inputs for hydraulic (single and double packer testing). The description of these works is outside the scope of this paper.

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