Acoustic Borehole Televiewer - Raising the Bar in Geotechnical Site Investigation

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ABSTRACT: Coring and logging of boreholes plays an important role in geotechnical site investigations. Using an Acoustic Borehole Imager provides valuable information in addition to cores. Acoustic Image Logs provide detailed oriented structural information that can be exploited by powerful software. Very thin fractures and joints – hardly visible on the core – can be detected, as well as bedding planes. Dip, strike, aperture and type of these structural elements can be determined and displayed in rose and polar diagrams and histograms. A case study of a geotechnical exploration for a dam site project is presented together with core data. The benefits of combined evaluation of core and log data are discussed in detail.

KEYWORDS: Acoustic televiewer, Geotechnical site investigation, Oriented fracture analysis

1. INTRODUCTION

Image logging tools produce electrical, optical or acoustic images of the full circumference of the borehole wall (image logs). Compared to standard logs like e.g. natural Gamma logs or density logs image logs have a high resolution (5mm or less). The depth of penetration into the formation, however, is very small. Image logs are normally orientated to north, or in case of highly deviated wells or horizontal wells, to the highside.

Acoustic image tools use a rotating acoustic beam to record the amplitude and the travel time of an acoustic impulse reflected at the borehole wall.

The amplitude of the image log gives detailed structural information on bedding planes, fractures, faults, foliation, and grain size (Deltombe and Schepers, 2004; Schepers et al., 2001; Taylor, 1991). For geotechnical exploration it is important to notice that acoustic measurements are very sensitive to detect fractures in the rock. Additional information from other logs (such as core photos) enables discrimination between open and closed fractures. The lithologies can be determined from the core. This tool is typically run in conjunction with coring of the borehole.

Precise caliper logs (resolution 0.5mm or less) can be calculated from the travel time of the acoustic image logs. Borehole deformations and breakouts indicate regions of differential horizontal stress and allow to determine directions of minimum and maximum horizontal stress.
Specific for geotechnical applications acoustic scanner tools have the advantage that the amplitude level of the reflected impulse is directly related to the elastic properties of the rock. The relative change of rock quality (or rock hardness) can be derived directly from the amplitude image log. Acoustic image tools can be operated only in water/mud filled boreholes.

The correlation of the main structural features - like bedding planes, fractures, foliation, and schistosity - both from the borehole wall image and from the core image is the most reliable and cost-effective method of core orientation. Once the core is orientated all detailed structural evaluation of core data, and all laboratory measurements on cores to determine physical, hydrogeological and engineering properties can be assigned to true directions.

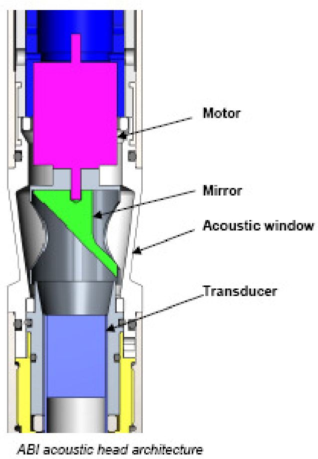
The existence of anisotropy and their effects are best studied on core samples, as anisotropy is normally not revealed by logs. Taking into account anisotropy can be essential for fluid flow calculations and rock stability assessments. Also, anisotropy has to be considered when measurements on rock samples are used to calibrate log responses and to derive lithological, hydrogeological and engineering properties from geophysical logs.

Compared to detailed but sparsely sampled core analysis, geophysical logs complementary offer the advantage of continuous information, determination of true in-situ properties, filling the gaps of core loss intervals, and providing information from cheaper percussion boreholes. Moreover, careful log interpretation can help to detect thin, weak layers that can have a major impact on rock mass stability, but are often not present in the core data.

2. ACOUSTIC BOREHOLE IMAGER

2.1 Measurement principles

Acoustic borehole imager tools scan the borehole wall with a rotating acoustic beam. In the ABI40 (Fig. 1) manufactured by Advanced Logic Technology (ALT) the acoustic beam is rotated by a rotating mirror. The mirror is used to focus the beam such that maximum resolution is achieved at the borehole wall. The non-moving acoustic transducer first sends out a burst of acoustic energy and the reflected signals are then recorded. An acoustic image of the surrounding formation is produced by recording echoes of the acoustic signal generated at the interface between borehole fluid and rock. At each scan point the maximum amplitude and the corresponding travel time of the reflected signal is measured. The amplitude depends on acoustic impedance of the rock (P-wave velocity times density), while the travel time depends on borehole radius.



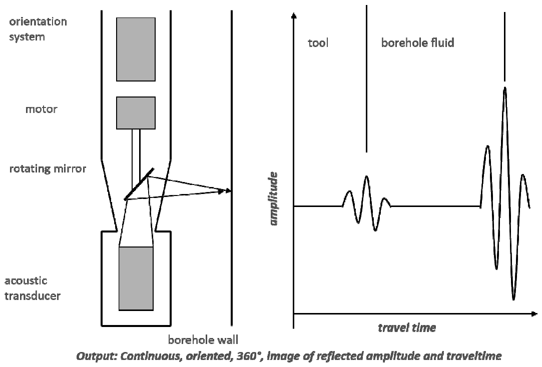


Figure 1a and 1b: Acoustic Image Measurement Principle

In the open hole two major reflections are observed (Fig. 1b): The first reflection is from the so-called acoustic window, where the acoustic energy penetrates from the inside of the tool into the borehole fluid. For a specific tool and a specific beam direction this reflection occurs approximately at the same time. The second reflection is from the borehole wall and can occur at any time beyond the first reflection time. Recording of amplitude and travel time of the reflection from the borehole wall has to be made by appropriate tool electronics. This is simple in the case depicted in Fig. 1b. But due to low impedance rock, irregularities of the borehole wall, mud conditions, and decentralisation of the tool, reflected amplitudes from the borehole wall can become very small. In this case, electronic noise, acoustic noise, and coherent acoustic noise (multiple reflected and scattered signals inside the transducer and the tool body) will limit the recording of reflections from the borehole wall.

Figure 2 shows the major reflections when the tool is used inside a PVC casing – the inside of the casing and the outside of the casing gives 2 additional reflections.

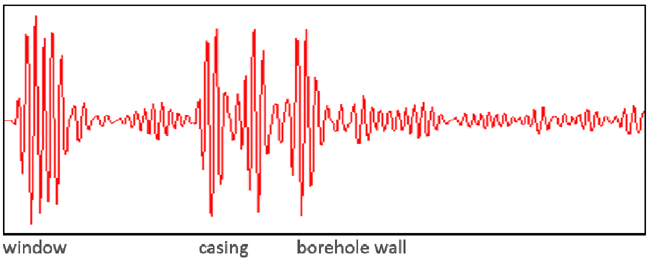


Figure 2: Reflection patterns of the acoustic borehole imager in a cased hole (signal strength is displayed along the Y-axis and travel time along the X-axis).

2.2 Data display

The results of borehole imager tools are best viewed as unrolled images which show the full circumference of the borehole wall in a planar display. An example of such a display is given in figure 3. Three different image logs (travel time, amplitude and 3D-image) are presented. The vertical axis is the depth along the borehole and the horizontal axis of each image is the direction starting with north on the left side and going over east, south, and west back to north. One may consider the unrolled image to be created by slicing the cylindrical borehole image along the north direction and rolling it out flat. In the 3D-image both the amplitude and travel time information can be combined as a 3D- column, or displayed as a 3D-column with constant radius, if due to borehole condition travel time data is poor. A plane intersecting the borehole appears in the unrolled image as a sine wave pattern. This is illustrated by figure 3 where data is displayed unrolled (centre) and as 3D-image (right).

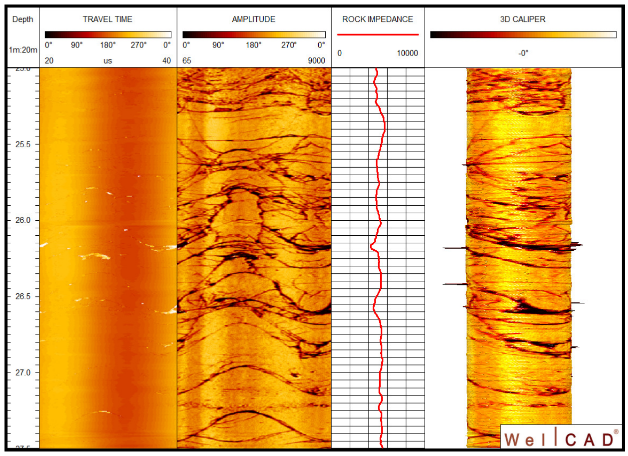


Figure 3: Typical Acoustic Borehole Imager data: travel time, amplitude, (calculated) acoustic impedance, and 3-D display of travel time and amplitude (depth in meters).

2.3 Travel time

The value of each measurement or data point of the left image log (travel time) of figure 3 corresponds to the travel time of the acoustic signal from the transducer to the borehole wall and back. The distance from the centre of the tool to the borehole wall can be calculated for each data point, given tool design and the velocity of the acoustic signal in the borehole fluid. The travel time log can be considered as a multi-finger caliper which in the case of Figure 3 would consist of 144 fingers. The addition of two opposite readings (180° apart) gives the caliper (diameter) of the borehole. This means that 72 caliper values can be calculated. The colour palette of the travel time log is chosen such that lighter colours (yellow) represent greater distances and darker colours (brown) smaller distances. In figure 3 the light and the dark stripes are opposite to each other. This indicates that the centre of tool is not moving exactly along the centre of the borehole (note that the travel time image of an oval bore hole would show two light and dark stripes). In the case of figure 3 the tool is about 3.5 mm out of the centre along an east-west direction. The resolution in distance of the ABI40 tool is 0.2 mm. For a detailed investigation of borehole shape (cross-section) it is helpful to remove the effect of tool decentralisation from the travel time image.

2.4 Amplitude

The value of each pixel of image log in the second column of figure 3 (amplitude) corresponds to the amplitude of the acoustic signal reflected at the borehole wall. The amplitude is influenced by the impedance of the rock within a small area which has approximately the size of the width of the acoustic beam which is applied to scan the borehole wall. Acoustic impedance is defined as density times P-wave velocity. The diameter of the acoustic beam of the ABI40 tool is around 3 mm. Despite the areal resolution of 3 mm, very thin fractures can be detected, because the rock fabric is destroyed within a small interval along the fracture plane. A destroyed rock fabric leads to a considerable drop in acoustic impedance.

No detectible reflection can be expected if fractures are open or if weak material has been washed out of fractures and joints. Of course, at those points travel time data is not correct.

2.5 Fracture Evaluation

Quantification of fractures (dip, strike, spacing, density, aperture, hydraulic conductivity) is important for geotechnical studies, since it reveals the tectonic history and hydraulics of an investigated area. The ALT WellCAD software offers powerful tools to pick structural information (joints, fractures, faults, bedding planes) from the amplitude and travel time image. The different structural features can be orientated to magnetic north or high side of the borehole. Within user defined depth intervals the structural data can be presented as tadpoles, polar- and rose diagrams, histograms and fracture densities (number of fractures per meter). See Figure 4.

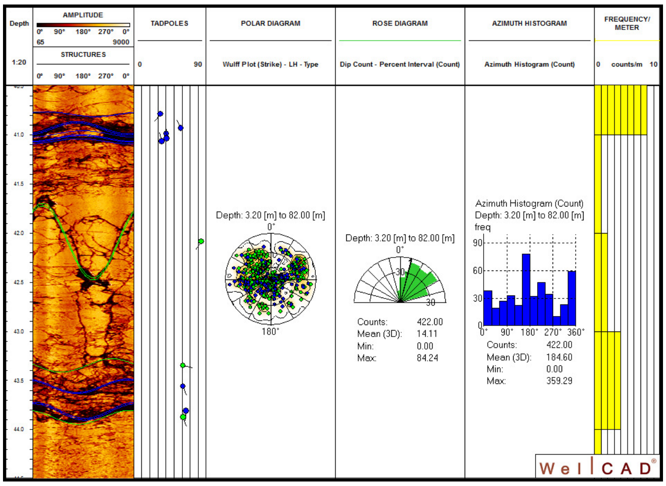


Figure 4: Typical Acoustic Borehole Imager data with polar and rose diagrams, and fracture density (depth in meters).

2.6 Rock Impedance

High impedance of the rock is reflected by large amplitudes (light yellow) and low impedance by small amplitudes (dark brown).

The acoustic amplitude is given in relative units. The amplitude image properly describes the variation of acoustic impedance of rock along the borehole. True values of the reflection coefficient at the borehole wall can be calculated if additional information from other logs (Density and Full Wave Sonic) or from measurements on core samples is available.

The rock impedance log is determined as follows: The median value of the amplitude image log (with 144 data points) is calculated, resulting in 1 impedance value per depth interval. Then, on the resulting impedance log a 10-point moving average filter is applied to create the final impedance log.

Figure 5 shows a rock impedance log which was calculated from the amplitude log on the left. The impedance log is displayed as a curve simultaneously underlain by a colour code which uses the same colour palette as the amplitude log. This display makes the distribution of hard and weak rock evident.

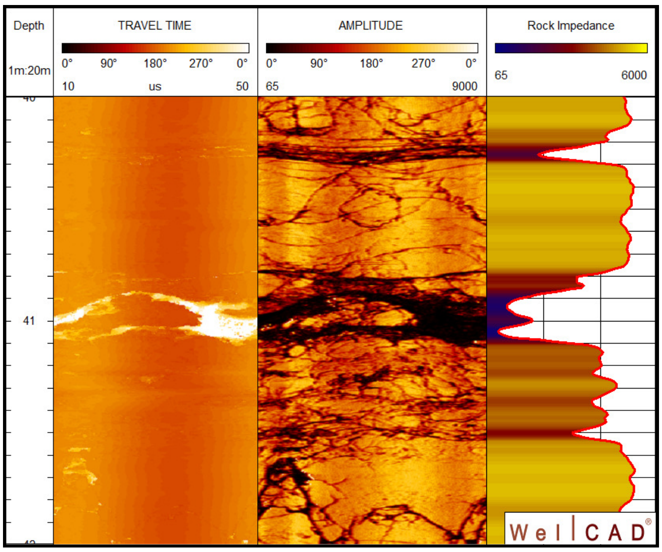


Figure 5: Presentation of a Rock Impedance derived from acoustic scanner images (depth in meters).

3. CASE STUDY

3.1 Introduction

The aim of the geotechnical exploration is a feasibility study for a dam project in Malaysia.
The geology in the area consists mainly of sediments and meta-sediments, ranging from conglomerates to sandstone and meta-sandstone, to siltstone and mudstone.
The reasons for using the Acoustic Borehole Imager (next to coring the borehole) are the following:

1. Determine the general dip direction of faults and fractures in the area
2. Determine fracture density in the area
3. Determine the average aperture of the fractures in the area

3.2 Field example 1: Different sandstones and conglomerate with vugs

Coarse grained sandstone with open fractures and fine grained sandstone with no fractures in the upper section, and conglomerate in the lower section (Figure 6).
Vugs aligned the fractures are visible between 12.0m and 12.4m and at 14.3m. Conglomerate starts at 12.9m. A major vug is visible at 14.3m.

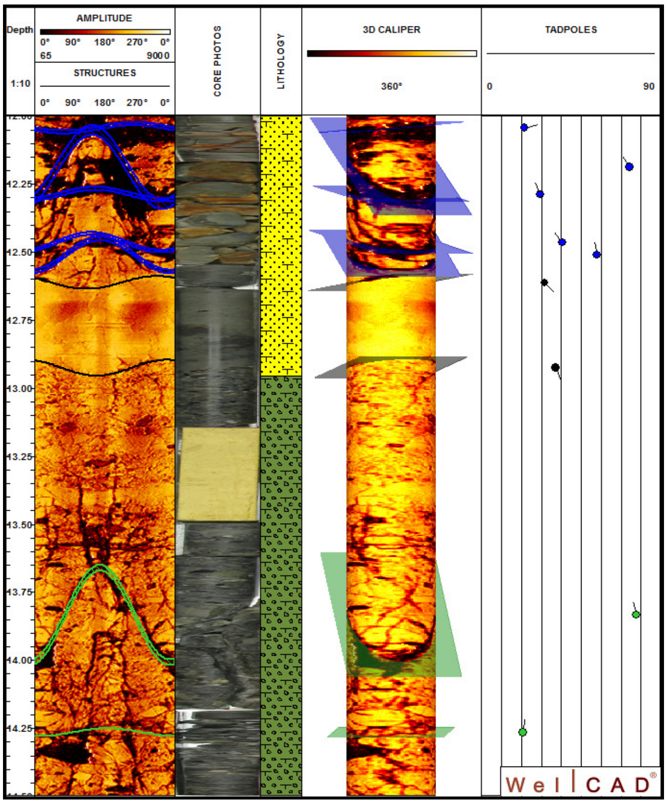


Figure 6. Different sandstones and conglomerate with vugs (depth in meters).

3.3 Field example 2: Core loss in a conglomerate with a steeply dipping facture

Conglomerate in the upper section, and medium to coarse grained sandstone in the lower section (Figure 7).
There is core loss in the upper conglomerate, but nevertheless the ABI40 image quality is good. Some major, steeply dipping joints are clearly defined in the image log. According to rock impedance log rock quality is good outside the region of major joints.
Transition conglomerate/sandstone is at 17.6m.

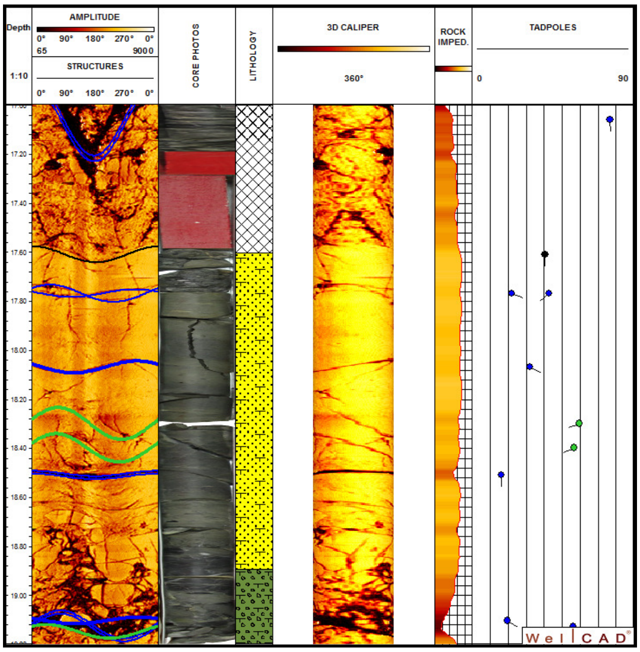


Figure 7. Core loss in a conglomerate with a steeply dipping facture (depth in meters).

3.4 Field example 3: Cyclic layering of conglomerate and sandstone

Within the conglomerate there are many thin fractures with opposite directions (Figure 8).
The sandstone sections show nearly no fractures.

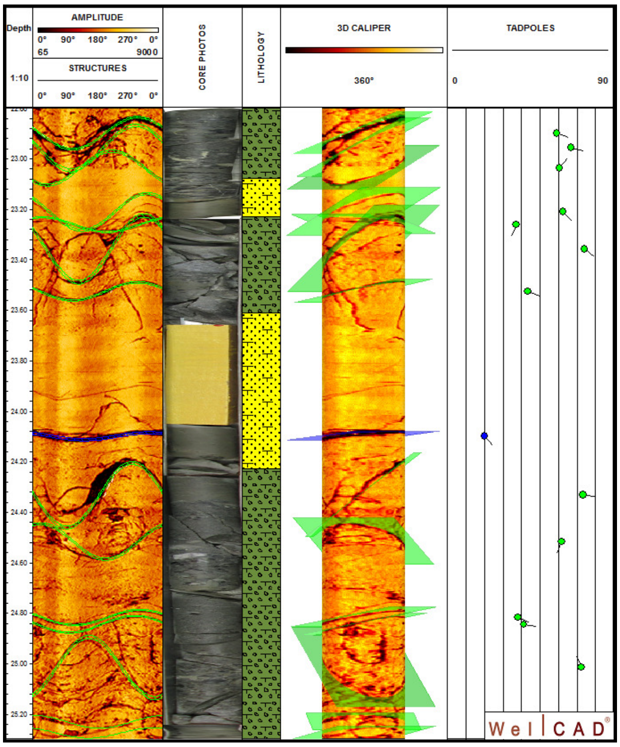


Figure 8. Cyclic layering of conglomerate and sandstone (depth in meters).

3.5 Field example 4: Conglomerate with very coarse gravel and highly fractured sandstone

In the upper conglomerate elongated gravel is visible between 48.0 and 48.5m (Figure 9). Rock quality of conglomerate and sandstone is equally good, but opposite to the field example 3, here, the conglomerate has nearly no fractures whereas the sandstone layer reveals many steeply dipping fractures.

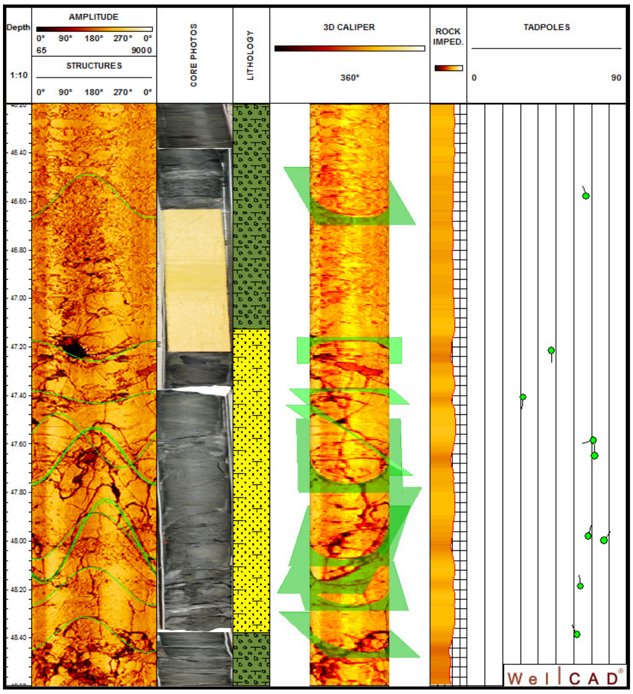


Figure 9. Conglomerate with very coarse gravel and highly fractured sandstone (depth in meters).

3.6 Field example 5: Core loss in a highly permeable sandstone

The lower section of the sandstone is of poor rock quality and there is a core loss of 0.8m (Figure 10).

Nevertheless the quality of the ABI40 image is excellent. The thin low amplitude layer in the upper section and all low amplitude layers in the lower section are dipping into the same direction. Main parts of this sandstone can be described as skeleton sandstone as a result of water circulation, which has washed out thin clay veins.

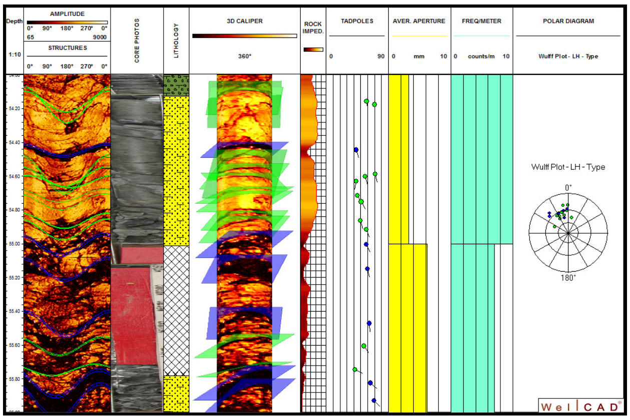


Figure 10. Core loss in a highly permeable sandstone (depth in meters)

3.7 Fracture Analysis

Figure 11 gives an overview of the fractures in the borehole. The polar diagram and the histogram show that there is no major dip direction in the borehole.

The rose diagram shows that the dip varies between 0° and 85° with an average dip of 44°.

The average number of fractures per meter over the borehole is just below 5, with the number of fracture per meter in 1 meter intervals are displayed in Figure 11.

The average aperture of the major fractures over the borehole is just over 7 mm per fracture, with the average aperture of the major fractures per meter in 1 meter intervals are displayed in Figure 11.

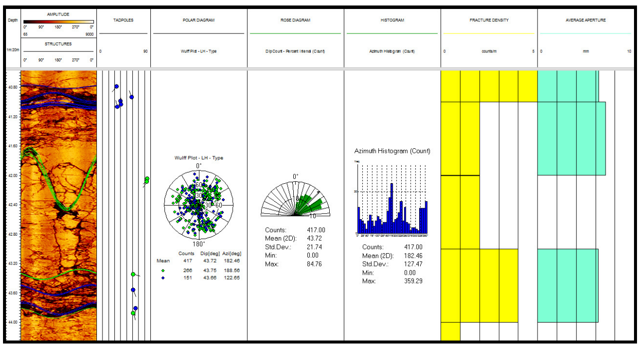


Figure 11. Polar and rose diagram, histogram, fracture frequency and average fracture aperture

4. CONCLUSIONS AND RECOMMENDATIONS

The evaluation of ABI40 logs provided critical information about dip and dip direction of fractures and bedding planes. Also, fracture frequency, fracture aperture and rock impedance all come from the image logs. This information is not available from the core data. Interpretation of ABI40 image logs is not possible without core data, but it may not be necessary to core the whole borehole, once the image logs are calibrated with the core photos, leading to substantial cost reduction.

When a combined interpretation of core data and borehole logs is made, a crucial point is exact depth matching of all data. The above described sequence of conglomerate and sandstone with variable shale content is not well reflected by the ABI40 image logs. In this case, depth matching can be improved if a gamma ray tool is mounted on top of the ABI40 tool and an additional gamma ray log is recorded. From the gamma ray log the shale content of the rock can be calculated to better depth match the logs with the core data.

5. REFERENCES

Deltombe J.-L. and Schepers R., 2004. New developments in real-time processing of full waveform acoustic televiewer data, Journal of Applied Geophysics 55, 161-172.

Schepers R., Rafat G., Gelbke C., Lehmann B., 2001. Application of borehole logging, core imaging and tomography to geotechnical exploration, Intl. J. of Rock Mechanics and Mining Sciences 38, 867-876.

Taylor T.J., 1991. A method for identifying fault related fracture systems using the borehole televiewer, SPWLA 32nd Ann. Symp. Trans., Paper JJ, 1-19.