FRACTURED BEDROCK INVESTIGATION BY USING HIGH-RESOLUTION BOREHOLE IMAGES AND THE DISTRIBUTED TEMPERATURE SENSING TECHNIQUE

*G. Radioti, S. Delvoie, J.-P. Radu, F. Nguyen, and R. Charlier
University of Liege
Chemin des Chevreuils 1
Liege, Belgium
*(*Corresponding author: gradioti@ulg.ac.be)*

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ABSTRACT

In order to investigate the fracturing of the bedrock and its possible heterogeneous distribution in situ, four boreholes equipped with double-U geothermal pipes of 100 m long were installed on the campus of the University of Liege (Liege, Belgium) over a surface area of 32 m². The bedrock, which starts at a depth approximately of 8 m, is quite fractured and consists mainly of siltstone and shale interbedded with sandstone.

Different geophysical methods are applied at two different phases, after drilling the boreholes and after injecting the grouting material. The first approach consists in lowering an ultrasonic borehole imager (borehole televiewer; Zemanek, Glenn, Norton, & Caldwell, 1970), an instrument that acts as an ultrasonic transducer and receiver, into the boreholes to obtain high-resolution, continuous images with 360° coverage of the local geology and fracturing. Moreover gamma-ray logs of the four boreholes are obtained and inclinometry is conducted.

After drilling the boreholes fiber optic cables are attached along the pipe loops and the double-U pipes are installed inside the boreholes. Then the grouting material is injected. The second approach consists in measuring the temperature along the fibers by applying the Distributed Temperature Sensing technique (Soto, Sahu, Faralli, Bolognini, Di Pasquale, Nebendahl, & Rueck, 2007). A laser pulse is injected into the optical fiber and the temperature along the fiber is determined by the intensity of Raman stokes and anti-stokes reemitted signals. Temperature evolution is measured during hardening of the grouting material. Local maxima of the temperature curve are probably due to a local lower thermal conductivity and/or a local larger quantity of grouting material due to gathering of fractures.

A detailed fracture characterisation (position, opening, orientation, dip angle) is obtained based on the acoustic signal travel time and amplitude. The fractures are characterised by the same dipping and orientation but significantly vary in number and location in the four boreholes, despite the close distance between them. Gamma-ray data and observation of the cuttings during drilling result in rock identification through depth as well as in determination of the layer dipping. The inclination of the four boreholes tends to be perpendicular to the dipping. The combination of the two geophysical methods as presented provides information useful for the hydro-thermo-mechanical behaviour of the bedrock. The contribution of the thermal behaviour of borehole heat exchangers to bedrock investigation will be further studied by conducting Distributed Thermal Response tests (Fujii, Okubo, & Itoi, 2006). During the tests we will measure the temperature variation thanks to the installed fiber optics. These data will allow us to correlate any anisotropic thermal behaviour to the geological characteristics. The available information could be used for a detailed numerical model.

KEYWORDS

Fracture detection, Layer dipping, Bedrock heterogeneity, Ultrasonic borehole imager, Distributed Temperature Sensing technique

INTRODUCTION

Four boreholes equipped with double-U geothermal pipes (borehole heat exchangers) of 100 m long were installed on the campus of the University of Liege (Liege, Belgium) over a surface area of 32 m². The boreholes, of a diameter of 135 mm, were drilled by using a DTH hammer bit (destructive drilling technique). In order to investigate the fracturing of the bedrock and to characterise it we applied two different geophysical methods, the borehole televiewer logging method and the Distributed Temperature Sensing technique. These methods were applied at two different phases, after drilling the boreholes and after injecting the grouting material respectively. They provided high-resolution data which in combination with drill cuttings observations result in a detailed fracture characterisation and rock identification.

The objective of this paper is to investigate the contribution of the applied procedure to bedrock heterogeneity knowledge. Outcrop observation or investigation of only one borehole results in limited information about the rock mass through depth. On the contrary, the borehole televiewer logging method applied to all the four boreholes can provide detailed information on the rock mass characteristics. Moreover we investigate if the study of the thermal behaviour of borehole heat exchangers can provide additional information useful for the hydro-thermo-mechanical behaviour of the bedrock, by applying the Distributed Temperature Sensing technique.

METHODS

Borehole Televiewer Logging Method

This method consists in lowering an ultrasonic borehole imager (borehole televiewer; Zemanek et al., 1970) into the boreholes. This instrument is composed of a transducer which is rotated 360° while lowered down inside the borehole. An in-line centralizer allows the tool to be centered during the measurement procedure. The transducer transmits ultrasonic pulses, which travel through the drilling mud and undergo partial reflection at the borehole wall. The reflected pulses are received by the transducer and the travel time and amplitude data are recorded. The travel time depends on the borehole radius. The acoustic amplitude depends on the soil/rock impedance.

Thanks to a magnetometer/inclinometer, azimuth and deviation data are constantly measured (Monier-Williams, Davis, Paillet, Turpening, Sol, & Schneider, 2009). The inclination of the borehole at each point is calculated based on the moving average of these data over an interval of 10cm. The travel time and amplitude data are oriented with respect to the Magnetic North and are converted into colorized, continuous images with 360° coverage of the borehole wall.

Natural gamma radiation along the borehole is measured to characterise the clay content of the rock formation. It is based on the principle that different types of rocks typically have different gamma ray levels (Keys,1990). Moreover cuttings were collected for around every 5 m during the borehole drilling. The gamma-ray data and observation of the drill cuttings result in rock identification through depth. The data measurements (gamma-ray, deviation, acoustic travel time, acoustic amplitude) were conducted by the LIM company.

Distributed Temperature Sensing Technique

The four BHEs were equipped with fiber optics. Fiber optic cables were attached along the pipe loops while they were lowered down inside the borehole. Temperature is measured along the fibers by applying the Distributed Temperature Sensing technique (Soto et al., 2007). This technique is based on Raman optical time domain reflectometry (Dakin & Pratt, 1985). A laser pulse is injected into the optical fiber and the light is scattered and reemitted from the observed point. The Raman backscatter signal is temperature sensitive. The temperature along the fiber is determined by the intensity of Raman stokes and anti-stokes signals. The position of the temperature reading is determined by the arrival time of the reemitted light pulse. Temperature evolution is measured during hardening of the grouting material. The measurement is repeated several days after injecting the grouting material in order to determine the undisturbed ground temperature profile.

RESULTS

Fracture Characterisation

A detailed fracture characterisation (position, opening, orientation, dip angle) is obtained based on the acoustic signal travel time and amplitude. Figure 1 shows high-resolution images of the acoustic signal travel time and amplitude for an extended and a slightly fractured zone. Black zones in the travel time column correspond to low travel time values and white zones to high travel time values. Yellow zones in the amplitude column correspond to high amplitude values and indicate the existence of compacted soil or rock. Blue zones correspond to low amplitude values and indicate fractures, altered rock or soft soil. Random blue spots indicate locally broken rock due to the drilling.

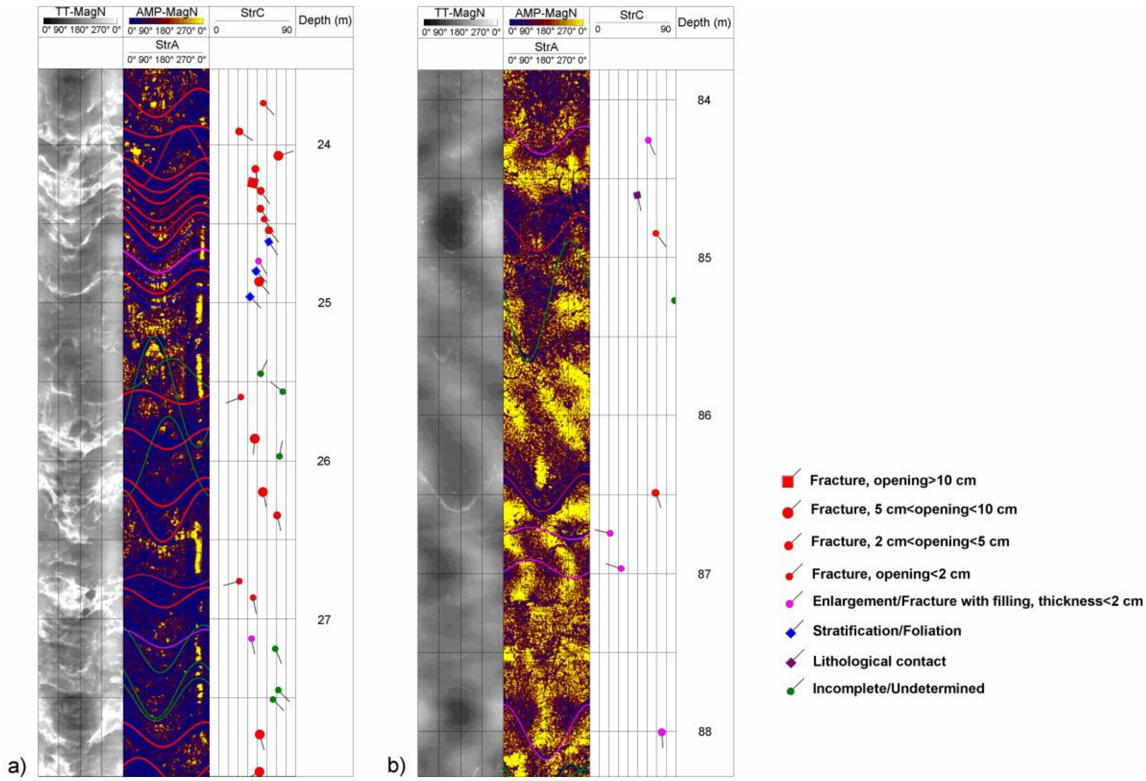

Figure 1 - High-resolution images of a) extended fractured zone in B4 and b) slightly fractured zone in B2, from left to right: acoustic travel time column, acoustic amplitude column, structural interpretation of each fracture (opening, orientation, dip angle) and corresponding depth values (supplied by the LIM company)

The distribution of fractures more than 5 cm wide for the four boreholes is shown in Figure 2. Based on these data fractures significantly vary in number and location in the four boreholes. B4 is more fractured than the other three boreholes consisting of 12 fractures more than 10 cm wide and 31 fractures of an opening between 5 and 10 cm, while B3 seems the less fractured consisting of one fracture more than 10 cm wide and 10 fractures of an opening between 5 and 10 cm. Moreover, extended zones of more than one meter thick consisting of large fractures (opening>than 10 cm) are observed in B1 and B4, between 25.6 and 27.1 m and 29.4 and 31.3 m depth respectively. B2 is characterised by a smaller fractured zone of 70 cm between 29.2 and 29.9 m depth. The depth position where the borehole diameter is larger than 150 mm is also shown in Figure 2. These measurements could indicate the gathering of open fractures between approximately 24 and 27 m for B1, between 20 and 31 m depth for B2 and B3 and between 13 and 33 m for B4.

Figure 3 shows the stereographic projection of the pole of each discontinuity for the four boreholes (Wulff net; Haff, 1940). The dip angle of most fractures varies between 40° and 70°/horizontal and the orientation between N40° and N80° for all the boreholes.

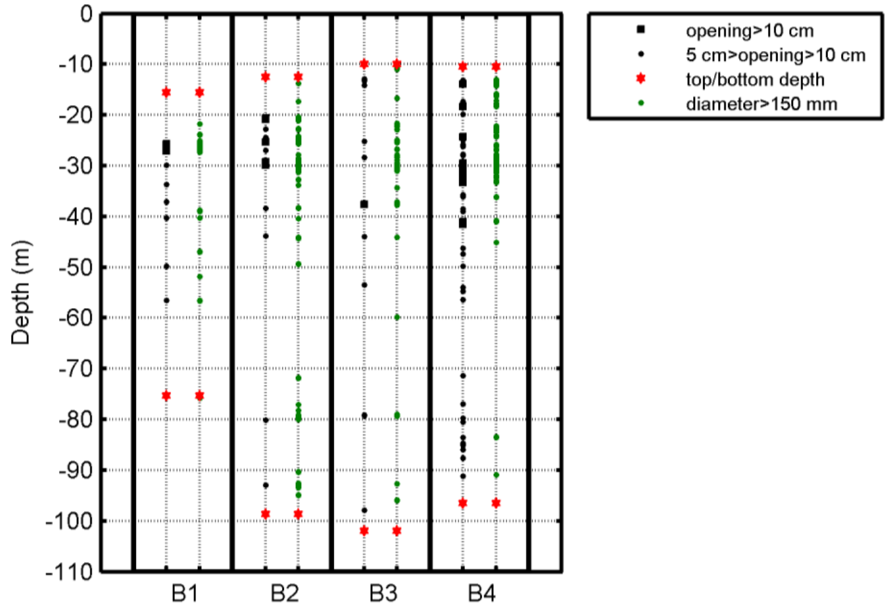

Figure 2 - Distribution of open fractures and borehole diameter larger than 150 mm for the four boreholes

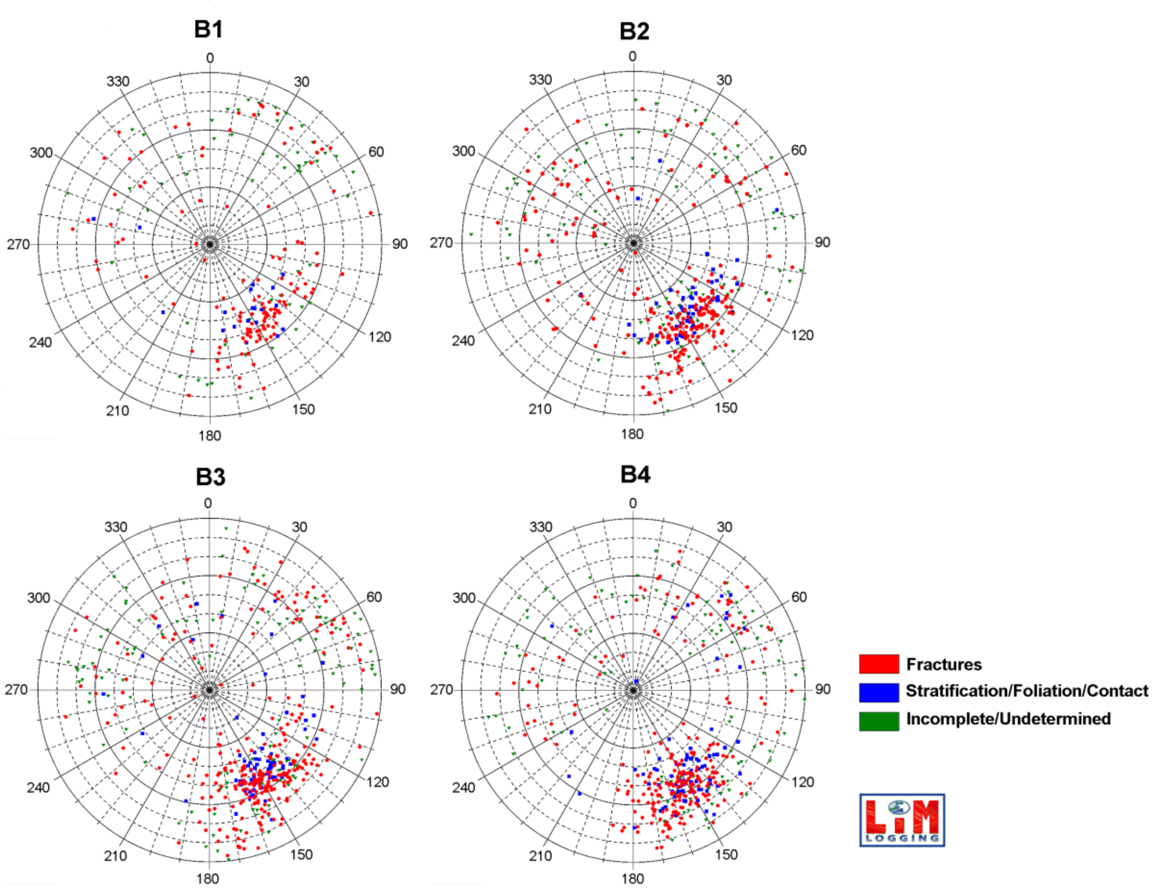

Figure 3 - Structural data projection of the pole of each discontinuity on the upper hemisphere for the four boreholes (supplied by the LIM company)

Thanks to fiber optics the temperature in the boreholes was measured during hardening of the grouting material and at the undisturbed state. Heat is generated during the first hours of hardening of the grouting material, and as a result temperature increase is observed. The following days temperature recovers back to the undisturbed state.

Temperature was measured every 20 cm with a spatial resolution of 2 m. Figures 4 and 5 show the temperature profile for B1 and B4 respectively. The first approximately 18 m correspond to the thermally unstable zone where ground temperature is influenced by the outside temperature. The undisturbed temperature, measured 84 and 65 days after injecting the grouting material for B1 and B4 respectively, for a depth greater than 18 m decreases through depth at a mean rate of approximately 0.25°C/10 m in both boreholes.

The temperature profiles measured during hardening of the grouting material are characterised by local maxima of a significantly increased temperature value at 26 m for B1 and 29 m for B4. These local maxima of the temperature curves are probably due to a local larger quantity of grouting material and/or local lower thermal conductivity due to gathering of fractures. These locations correspond to extended fractured zones more than one meter based on the acoustic travel time and amplitude analysis. Though random large fractures more than 10 cm wide or smaller fractures of an opening between 5 and 10 cm cannot be identified by this procedure.

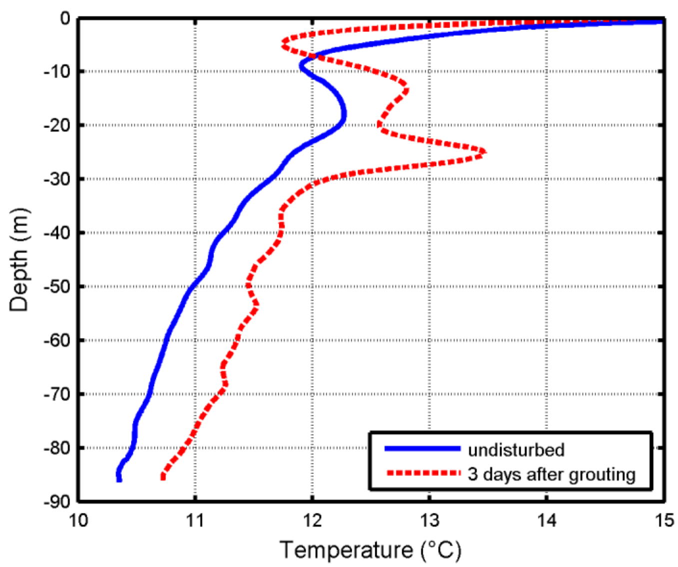

Figure 4 - Local maxima in temperature profile during hardening of the grouting material in B1

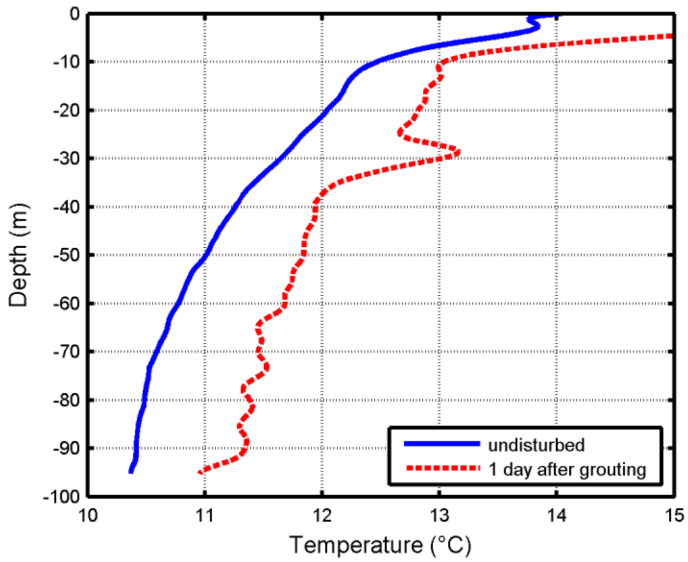

Figure 5 - Local maxima in temperature profile during hardening of the grouting material in B4

Rock Identification and Borehole Deviation

Figure 6 shows gamma-ray data measured every 5 cm for the four boreholes. High gamma-ray values indicate shale layers while low values indicate sandstone layers (Keys, 1990). Gamma-ray data and observation of the cuttings during drilling result in a detailed rock identification through depth for the four boreholes. The bedrock consists mainly of siltstone and shale interbedded with sandstone for the upper 65 m in B1, 72 m in B2, 75 m in B3 and 81 m in B4. The remaining parts of the boreholes are dominated by mainly sandstone/siltstone layers. Based on these data and the relative distance between the boreholes the mean layer dip angle is approximately 45° SE. The calculated layer dip angle value is included in the fractures dip angle range (40°-70°).

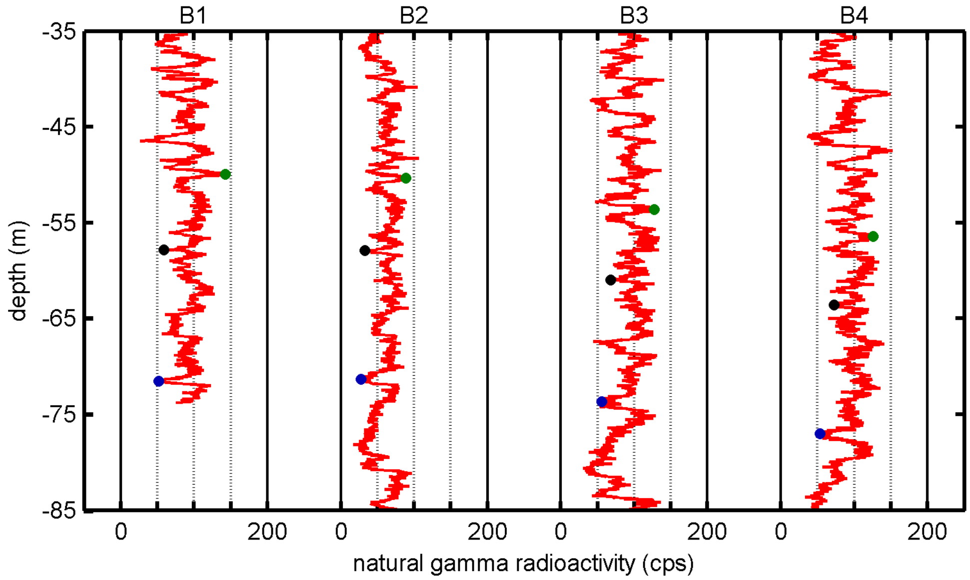

Figure 6 - Natural gamma radioactivity data for the four boreholes

The deviation of the four boreholes is shown in Figure 7. The inclination of the boreholes increases progressively through depth with a value of 6.82° in B1 at 75.8 m, 10.67° in B2 at 98.6 m, 13.69° for B3 at 102.1 m and 12.90° in B4 at 96.4 m. The inclination of the four boreholes tends to be perpendicular to the layer stratification.

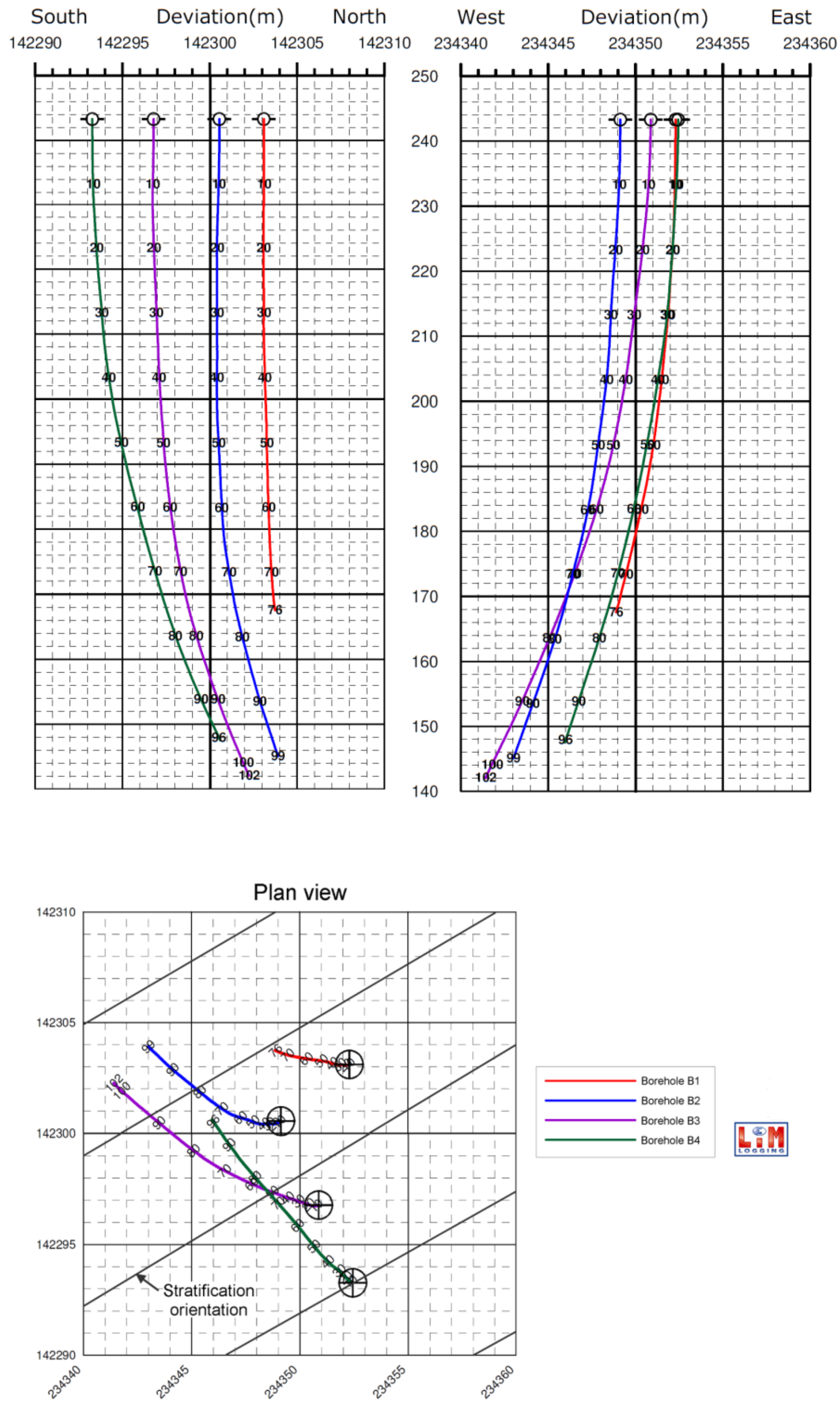

Figure 7 - Deviation of the boreholes (data supplied by the LIM company)

DISCUSSION

The borehole televiewer logging results provide a detailed fracture characterisation including information about the opening, orientation and dip angle. The temperature measurements during hardening of the grouting material indicate extended fractured zones, probably filled with grouting material. The filled with grouting material fractures would locally affect the fracture transmissivity and hence the rock mass permeability. Moreover the grouting could locally reinforce the rock mass and modify its mechanical characteristics. Grouting materials display different thermal properties than air or water, that fill the open fractures, and hence influence the locally effective thermal properties of the rock mass. These parameters are important for the hydro-thermo-mechanical behaviour of the bedrock.

CONCLUSIONS

A detailed bedrock investigation is presented based on two geophysical methods, the borehole televiewer logging method and the Distributed Temperature Sensing technique. The fracture characterisation (position, opening, orientation, dip angle) is obtained based on the acoustic signal travel time and amplitude. The fractures are characterised by the same dipping and orientation but significantly vary in number and location in the four boreholes, despite the close distance between them. Extended fractured zones of more than one meter, probably locally filled with grouting material, can be identified by the measured temperature profiles during hardening of the grouting material. Gamma-ray data and observation of the cuttings during drilling result in rock identification through depth as well as in determination of the layer dipping. The inclination of the four boreholes tends to be perpendicular to the layer stratification. The bedrock heterogeneity is indicated due to the uneven distribution of fractures in the four boreholes and with depth as well as due to the alternation of different rock types. The combination of the two geophysical methods as presented provides information useful for the hydro-thermo-mechanical behaviour of the bedrock. The contribution of the thermal behaviour of borehole heat exchangers to bedrock investigation will be further studied by conducting Distributed Thermal Response tests (Fujii et al., 2006). During the tests we will measure the temperature variation thanks to the installed fiber optics. These data will allow us to correlate any anisotropic thermal behaviour to the geological characteristics. It will also allow us to investigate any possible influence of the opening of random fractures to the thermal behaviour based on experimental data. Then the available information could be used for a detailed numerical model.

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