GEOLOGIC CHARACTERIZATION OF THE DEEP GNEISSIC BEDROCK AT CHALK RIVER LABORATORIES (ONTARIO) USING ORIENTED DRILL CORE AND INTEGRATED BOREHOLE SURVEYS

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ABSTRACT

As part of an overall feasibility study, multidisciplinary surface and borehole investigations are being conducted on the Chalk River Laboratories (CRL) property in order to characterize the rock mass and to assess the technical viability of siting a deep Geologic Waste Management Facility (GWMF) for permanently managing CRL's low- and intermediate-level radioactive waste at a reference depth of 500-1000 m. The current borehole program has included the drilling of seven cored boreholes to lengths of up to 1200 m and vertical depths of one kilometre. This paper presents some of the borehole techniques used to obtain the data required for bedrock characterization and the results of geologic interpretations.

Detailed logging of oriented core provides the most direct information on fracture and lithologic characteristics and is supplemented by data from borehole geophysical surveys that include

1. electrical logs (normal and single-point resistivity, and magnetic susceptibility),
2. natural gamma logs,
3. fluid temperature and resistivity logs,
4. 3-arm caliper logs,
5. image (optical and acoustic televiewer) logs, and
6. flow-meter logs.

The electrical logs and natural gamma logs corroborate the visual generalization of rock types and fracturing into lithostructural domains and assemblages. Some fracture filling minerals are preferentially distributed in the broader rock units. Pyrite fracture filling occurs preferentially in a garnetiferous quartz-monzonitic assemblage, which has a low magnetic signature, whereas hematite filling occurs predominantly in a magnetite-rich and garnet-poor granitic assemblage. Graphite-bearing rocks are reflected by a markedly low resistivity. Diabase dykes, represented by positive magnetic anomalies at surface, have similar signatures in borehole intersections.

Fracture orientation patterns determined from borehole image logs are similar to those from core measurements, but are more tightly clustered. There is a predisposition for a brittle fracture set to develop along pre-existing low-dip ductile fabrics although other fracture sets also occur. The identification of open fracture locations, used to select intervals for hydraulic tests, is more confidently established using caliper and image logs as compared to drill core logging, although the core is required to determine the mineralogical character of these features. Heat-pulse flow-meter logging can confirm the hydraulic significance of fractures. Borehole fluid properties are also used to locate open fractures in the boreholes. The core logs and geophysical survey logs supplement each other and provide independent verification of rock mass conditions.

Keywords: borehole, core, geology, geophysics, fracture, filling, fabric, fold

1. INTRODUCTION

As part of an overall feasibility study, multidisciplinary surface and borehole investigations are being conducted on the Chalk River Laboratories (CRL) property in order to characterize the rock mass and to assess the technical viability of siting a deep Geologic Waste Management Facility (GWMF) for permanently managing CRL's low- and intermediate-level radioactive waste at a reference depth of 500-1000 m. The current borehole program has included the drilling of seven cored boreholes to lengths of up to 1200 m and vertical depths of one kilometre. This paper presents some of the borehole techniques used to obtain the data required for bedrock characterization and the results of geologic interpretations.

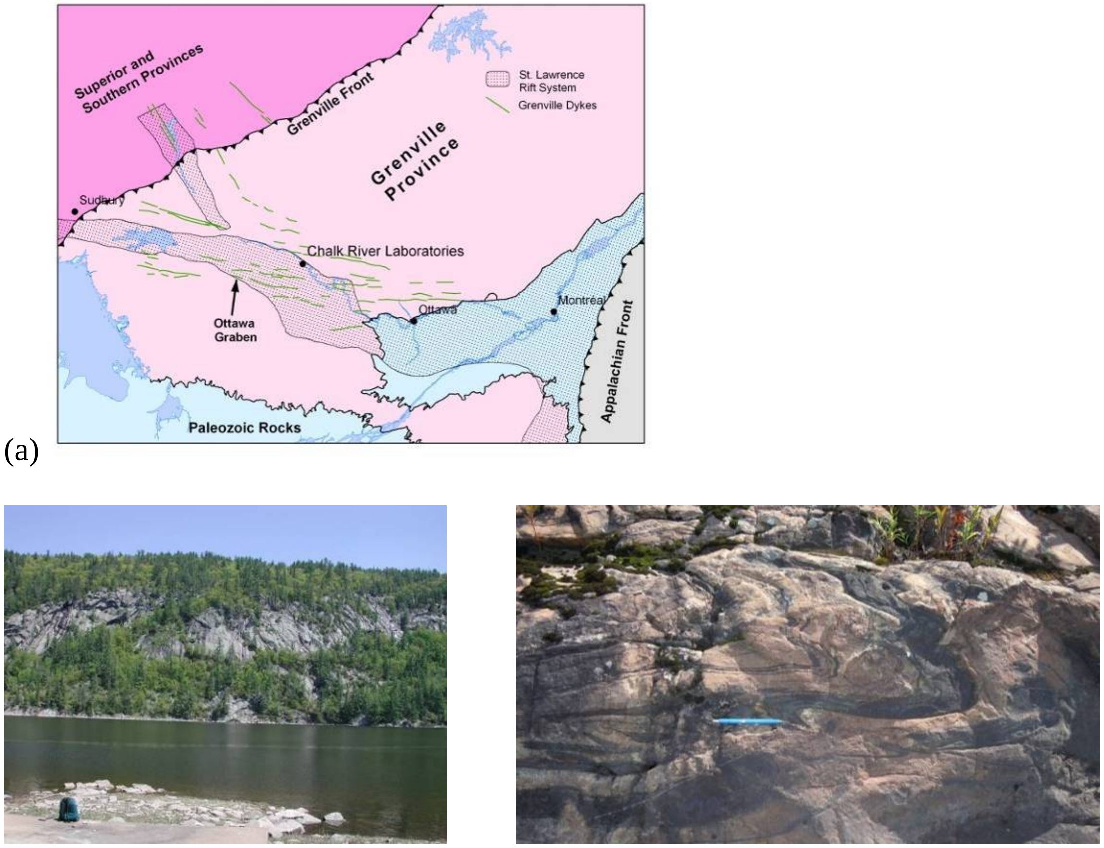
The CRL property has been the site of a number of previous characterization studies, which included surface studies, shallow borehole investigations, and investigation in a single deeper cored borehole (CR-9) drilled to a vertical depth of 560 m. The current multidisciplinary borehole investigation program provides information on bedrock and groundwater conditions at, and below, potential depths for a GWMF. The geologic characterization of the property is intended to provide information on fracture and lithologic conditions that will be integrated into comprehensive multidisciplinary descriptions of the geosphere, along with stress and hydrogeologic/hydrogeochemical conditions. Elements of the geosphere models are ultimately used in the performance assessments of the GWMF. This paper presents some of the borehole techniques used to obtain the required data and the results of geologic interpretations. This paper includes results from hydraulic tests in the CRG boreholes [1], but focuses on the geological and geophysical surveys that are a precursor to or an interpretive aid for these definitive tests on hydraulic conditions, and the hydraulic test results are not addressed in any detail but are included for comparative purposes.

The benefits of augmenting detailed core logging with data from a range of down hole surveys and tests are presented.

1.1 Geologic setting

The CRL property, shown in Figure 1a with regional geological features that affect the site's characteristics, is underlain by the Precambrian metamorphic rocks of the Grenville Province and is located near the northern margin of the Ottawa-Bonnechère graben (Figure 1b). The Grenville Province is regarded as a deeply eroded tectonic equivalent of the modern Himalaya Mountains and consists of various Precambrian rocks that were largely affected by a major mountain-building episode ('Ottawan orogeny', about 1095-1040 million years ago) associated with widespread high grade metamorphism, ductile NW-directed over thrusting and folding (Figure 1c), and tectonic juxtaposition [2], [3], [4].

Following a period of erosion and uplift, the region experienced the protracted evolution of the Ottawa-Bonnechère graben between the late Precambrian and at least the Mesozoic era. The initial development of the graben, as a failed arm of the St. Lawrence rift system [5] during the opening of the Early Paleozoic Iapetus ocean, is marked by the fracturing and intrusion of the W- and NW-trending Grenville diabase dyke swarm (Figure 1a) 590 million years ago [6]. Later crustal instability along the graben involved fault-controlled subsidence during early Paleozoic sedimentation [7] and further periods of faulting during the later Paleozoic and more importantly the Mesozoic, associated with the opening of the current Atlantic Ocean [8], [9]. The region currently experiences relatively low- to moderate-magnitude seismic activity along the graben, and activity related to the Western Québec Seismic Zone [10] whose overall distribution is oblique to and partly overlaps the graben, but which is distinct from the latter [11].



(a)

(b) (c)

Figure 1. (a) Location of the CRL property within the Grenville Province in relation to the Ottawa-Bonnechère graben and the Grenville mafic dyke swarm; (b) A bounding fault-scarp of the graben that is adjacent to the CRL property; (c) Local mesoscopic folding resulting from Ottawan orogeny. An example of local Grenville diabase dykes is presented in Section 1.3.

1.2 Property scale geologic investigations and characteristics

The CRL property has been the site of a number of geoscientific investigations related to nuclear waste management, which included research on the applications of various multidisciplinary borehole and surface techniques [12], as well as research specifically integrating borehole geological, geophysical and hydrogeological techniques [13], [14], [15], which are similar to those described in this paper. The property was also investigated for siting a shallow geological low-level waste disposal facility by integrating these techniques in three exploratory 200 m boreholes [16]. These geological and geophysical investigations enable site-specific evaluation of borehole characterization tools and techniques. They additionally also provide significant geological information on the lithology and fracture characteristics used in the GWMF feasibility study, such as the information for the CRL property bedrock geology map shown in Figure 2, which was modified after Raven Beck Environmental Ltd. [17], to integrate new information from the current CRG-series drilling program.

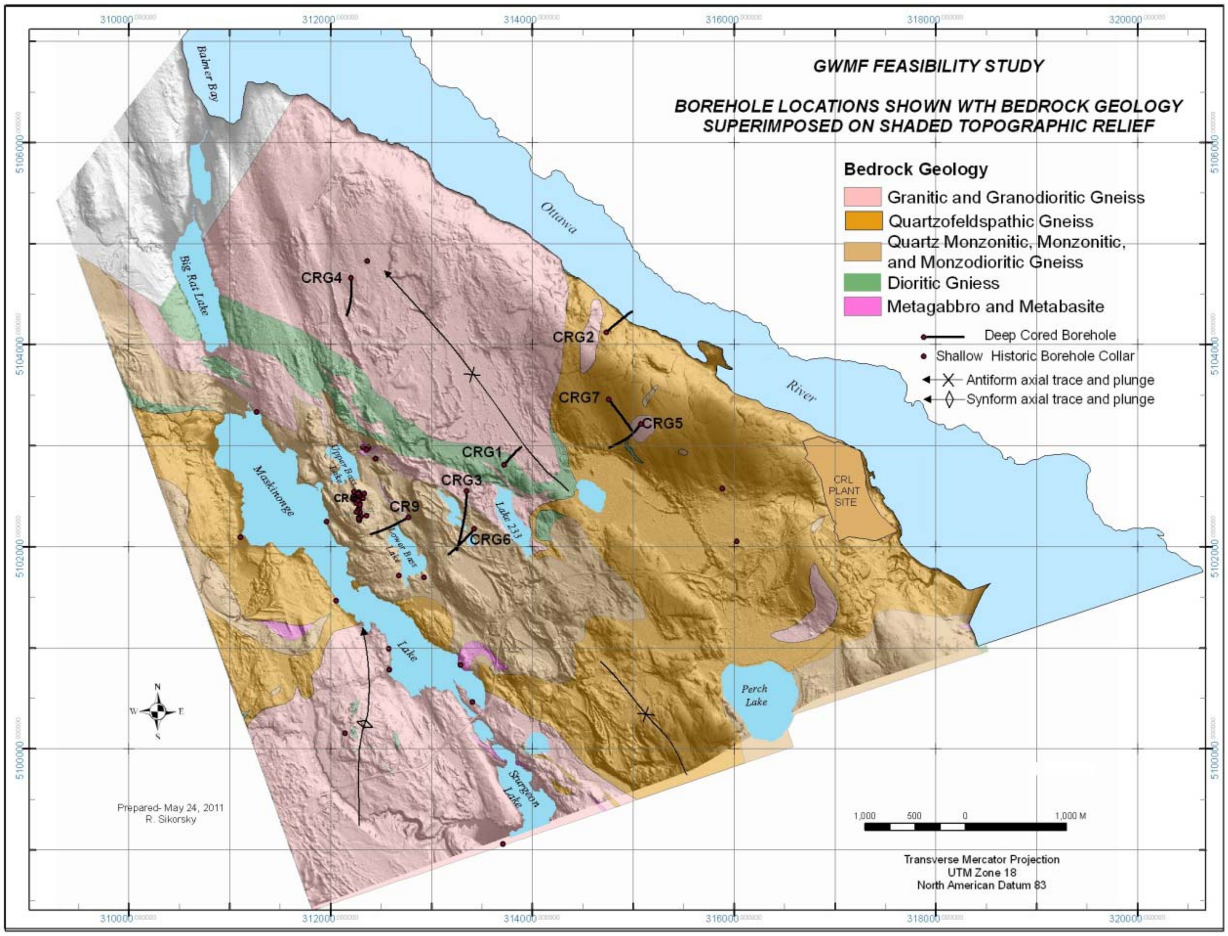


Figure 2. Borehole locations on the Chalk River Laboratories property shown with the bedrock geology superimposed on the shaded topographic relief.

The map shows that the site is underlain predominantly by generalized granitic and quartz-monzonitic/quartzofeldspathic lithologic assemblages that at the map scale are gently folded along predominantly NNW shallow-dipping axis. Detailed assessment of folding in the recent studies has confirmed up to three additional phases of smaller scale folding [18]. The current CRG-series boreholes provide substantial new critical geological information for the site [19], [20], [21], [22], [23] and have intersected fracture densities that indicate the rock is generally of good to excellent quality based on RQD values, with significant faults spaced 100's of meters apart. The fracture orientations in the CRG-series boreholes comprise up to three common steep to vertical sets, and a shallow- to intermediate-dip gneissossity/foliation-parallel set that varies in orientation with the folding. Fracture fillings, in decreasing order of abundance, include chlorite, calcite, hematite, clay, sulphides, graphite, prehnite, and rare epidote.

1.3 CRG-series borehole description

Seven boreholes, ranging in plunge between 64˚ and 75˚ and between 760 m and 1200 m in length, were drilled as part of the GWMF feasibility study. The boreholes were drilled at NQ diameter (76 mm) using triple-tube drilling techniques, except for boreholes CRG1 and CRG5 which were drilled at HQ (96 mm) diameter to enable over-core stress tests. The boreholes are collared and directed to explore the central to NE part of the CRL property, and to investigate structures intersected in boreholes from previous programs, as well as structures that potentially underlie surface lineaments. The borehole locations and surface traces are shown on the bedrock geology map for the site in Figure 2, which includes a high resolution LiDAR digital elevation model that is an example of a data source for lineaments considered in planning the boreholes. The collar locations and orientations for boreholes CRG1 to CRG5 were selected as part of an initial multidisciplinary plan [24], and were followed up by boreholes CRG6 and CRG7, which were collared to enable interpolation of features intersected in previous drilling.

Salient examples of results from boreholes CRG1, CRG2, and CRG3, are presented in this paper. Two noteworthy specific targets for the boreholes include the E-W trending diabase dykes, because their contrasting high magnetic susceptibility at surface (Figure 3) was equally

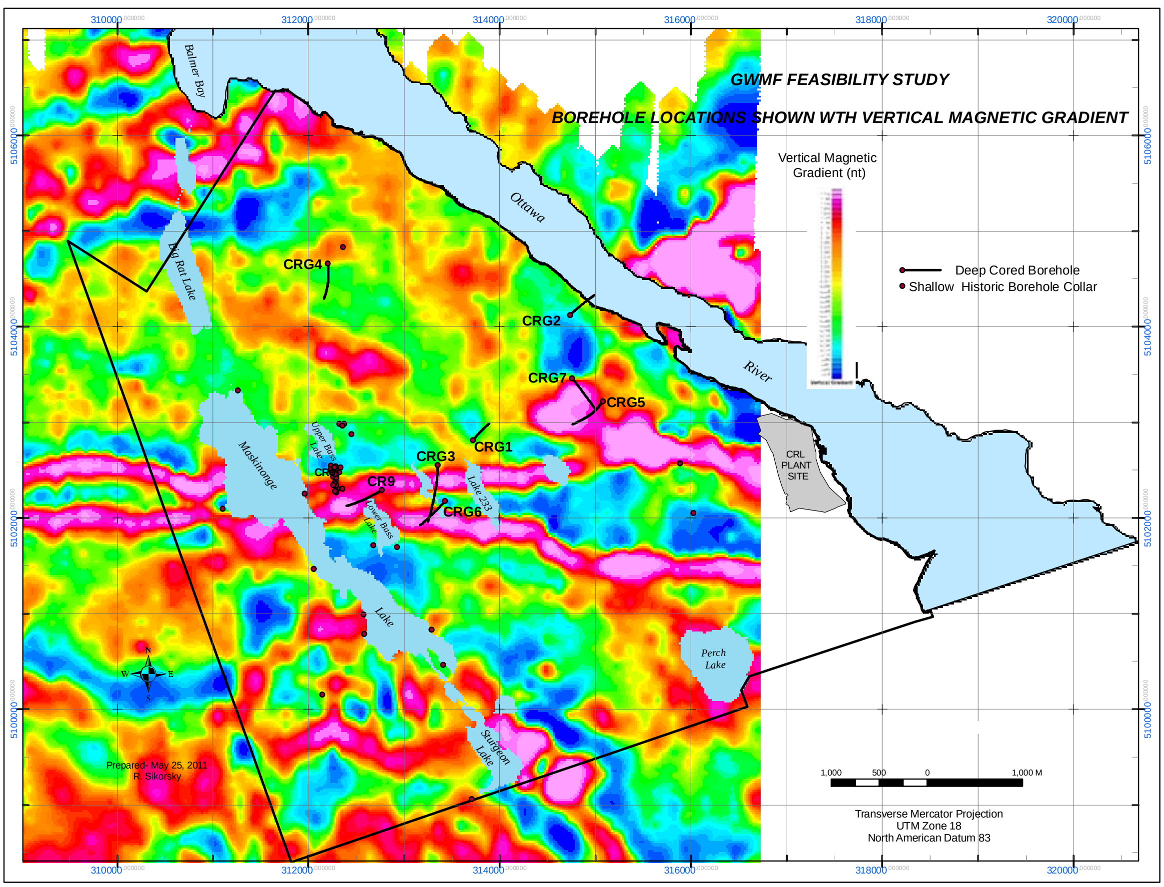


Figure 3. Borehole locations on the Chalk River Laboratories property shown on a vertical magnetic gradient map. E-W trending magnetic anomalies underlain by diabase dykes were investigated by boreholes CRG3 and CRG6.

prominent in the example of data presented for borehole CRG3, and the graben-bounding Mattawa fault zone which underlies the Ottawa River, because its intersection past 300 m in CRG2 consisted of a significantly higher density of fractures and a lower quality rock than was intersected in other boreholes.

2. CORE LOGGING AND BOREHOLE SURVEY DESCRIPTIONS

Detailed logging of oriented drill core provides the most direct information on fracture and lithologic characteristics. The geologic data captured from the CRG-series core were collected in two core logs that separately describe the fractures and lithology, and which provide a basis for establishing borehole-scale litho-structural domains that can be extrapolated and interpreted into broader property-scale descriptive and geometric geologic models. The fracture log, which records the data on brittle structures, includes information on fracture morphology, fracture fillings, related alteration, and the true orientations of the fractures. Fracture categories include intact fractures that are healed or sealed, broken fractures that have lost cohesion, and open fractures that are judged to be hydraulically significant on the basis of criteria such as asperity, poor fit of fracture surfaces, and the presence of soft filling. The lithology log, in addition to recording the mineralogical and textural characteristics of the rocks, includes classification and orientations of various ductile structures (mineral fabrics, gneissosity, fold components) that can help interpret the complex folding in the rock that has developed from deformational events such as the Ottawan Orogeny.

The core log information is supplemented by data from a variety of borehole geophysical surveys that include

1. electrical logs (normal and Single Point Resistivity (SPR), and magnetic susceptibility),
2. natural gamma logs,
3. fluid temperature and resistivity,
4. 3-arm caliper,
5. image logs (acoustic and optical televiewer (ATV and OTV)),
6. Full Waveform Sonic Logs (FWS), and
7. heat-pulse flow-meter measurements.

The fracturing of the Mattawa Fault, intersected by CRG2, posed a risk of lodging and losing tools in the borehole because of caving of the borehole wall. The borehole itself was therefore not surveyed and instead the magnetic susceptibility of the drill core was measured.

The electrical logs and gamma logs are used to assist and corroborate visual identification of rock types and their generalization into lithostructural domains. The resistivity logs can also be used to determine fracture characteristics and rock quality, along with the other five log types provide. The OTV logs additionally provide considerable information on lithology and rock fabrics, subject to suitable water clarity that can be impeded if fine drilling cuttings are not purged from the borehole. The use of these types of borehole based techniques for geoscientific bedrock characterization applications has been reviewed recently by Monier-Williams et al. [25] and Sikorsky et al. [26].

Borehole directional surveys included single-shot magnetic/inclinometer surveys carried out during the course of drilling to immediately detect and deal with potential deviation problems. Following the completion of drilling, a gyroscopic/accelerometer survey of the borehole was conducted. In addition, a continuous magnetic/inclinometer is included with the ATV survey. The magnetic surveys can be affected by magnetite in the rock, but any affected measurements provide erratic values that can be readily recognized and not used. The borehole orientation measurements from the magnetic systems provide independent verification of the gyroscopic/accelerometer survey data which are used to determine the borehole trajectory, to develop geometric site models, and to calculate the true orientation of planar features intersected in the borehole.

Reference borehole depths are determined by measuring the length of the drill string during drilling because this technique has the least stretch, and these depths are marked on drill core along a painted orientation reference line denoting the top of oriented core. Because of the inherent cable stretch in geophysical surveys, their depths are adjusted to match the reference depth marked on the core.

3. RESULTS

3.1 Boreholes CRG1 and CRG2

The data that are included in the graphic logs for boreholes CRG1 and CRG2 (Figure 4 and Figure 5) show some of the predominant geologic characteristics found on the CRL property, and are mainly derived from core logging, but some are substantiated by geophysical logs. The frequency distribution of all fractures and broken fractures along the boreholes is seen to differ between the boreholes, and particularly can be seen to be greater below 300 m in borehole CRG2 where the Mattawa fault zone is intersected. A range of rock types are intersected in both boreholes but comprise two broad assemblages that are correlatable at the property scale, and include an assemblage that consists of garnet-bearing quartz-monzonitic rocks and an assemblage that consists of magnetite- rich granitic rock types. In addition, the graphic logs show the distribution of fracture fillings. Chlorite, calcite, and clay are largely ubiquitous along the boreholes whereas hematite and sulphides can be seen to have uneven distributions that are related to the broad assemblages. Sulphides occur associated with the garnet-bearing monzonitic assemblage whereas hematite occurs predominately outside of the quartz-monzonitic assemblage.

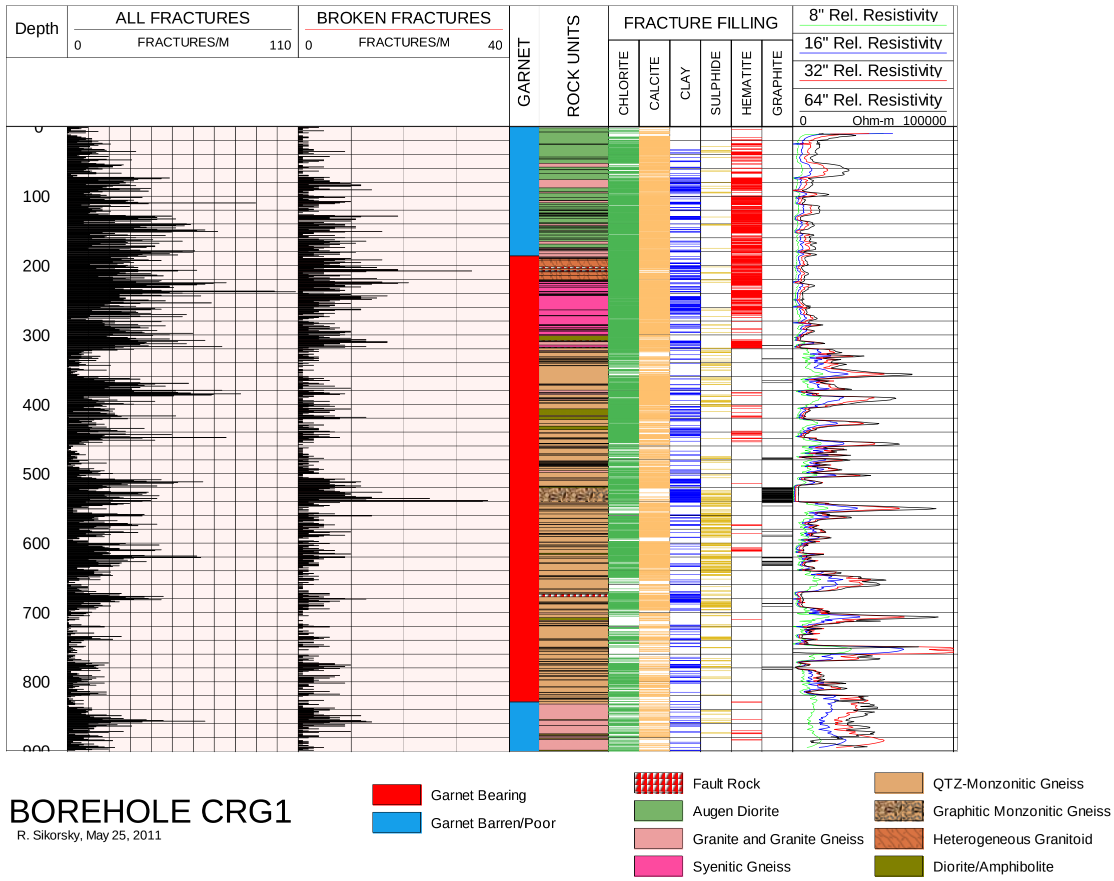


Figure 4. Graphic borehole log for CRG1 showing the fracture frequency distribution, fracture filling minerals, borehole rock units, the occurrence of garnet, and the normal resistivity measured in the borehole. Garnet aids definition of rock assemblages that are correlatable across the property. The distribution of hematite and sulphide fracture filling are seen to be related to the garnet barren/garnet bearing assemblages and rock units. The normal resistivity can be seen to be related to fracture frequency, clay filling, and graphite filling.

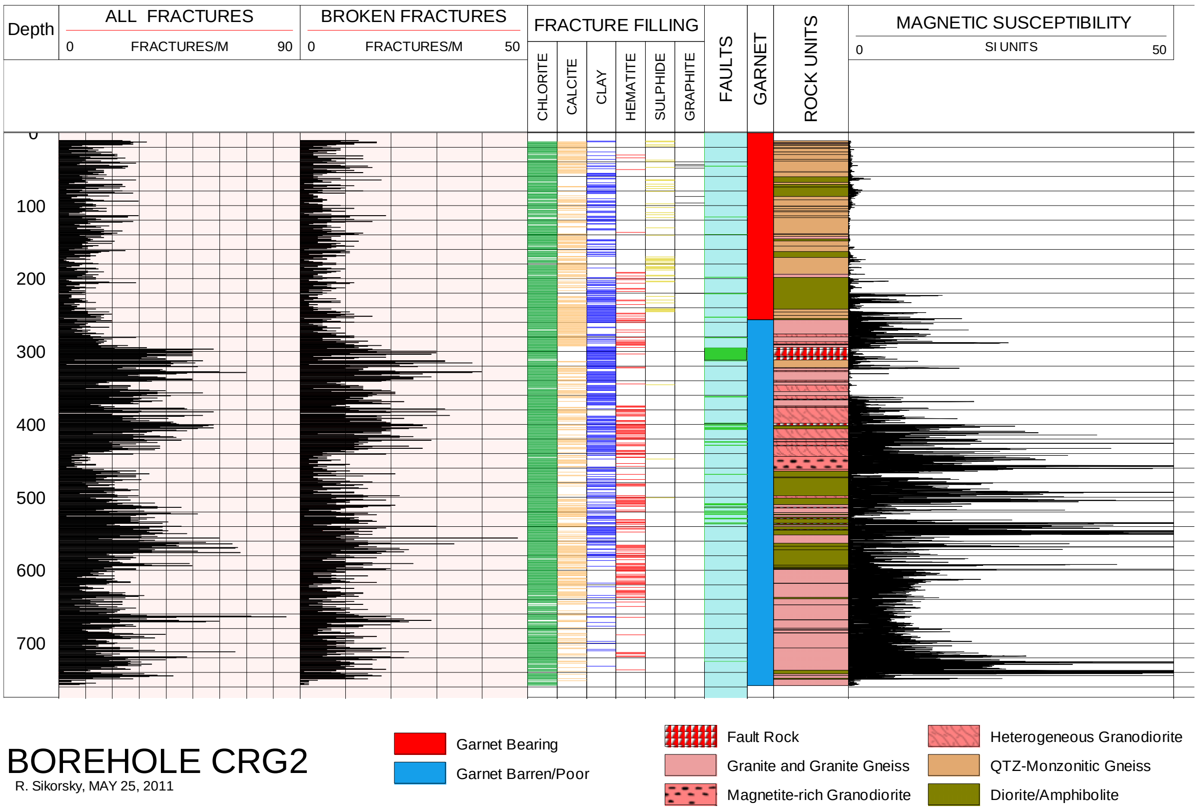


Figure 5. Graphic borehole log for CRG2 showing similar geologic relationships seen in Figure 4, but including the magnetic susceptibility measured on drill core. Magnetite-rich rocks comprise a granitic assemblage that is distinguished from the overlying garnet-bearing quartz-monzonitic assemblage.

The resistivity and magnetic susceptibility logs can be seen to correspond with these geologic features as well. In borehole CRG1, there is a lower resistivity associated with the higher frequency of fractures and the hematite filling in the upper part of the borehole above 320 m which includes distinct lithostructural domains, and a generally higher resistivity associated with the underlying monzonitic assemblage and the occurrence of sulphide filling. In the monzonitic assemblage there is also a good correspondence between the occurrence of fracture peaks with clay filling and a reduction of resistivity, and there is a marked reduction in resistivity associated with graphite because it is such a highly conductive mineral. The garnet-poor granitic assemblage near the bottom of the borehole corresponds with consistently higher resistivity. The magnetic susceptibility logs for borehole CRG2 show a marked increase in susceptibility associated with the transition from the quartz-monzonitic to granitic assemblage at about 260 m, except for an interval in the footwall of a large fault that may be due to alteration effects that have oxidized magnetite.

Fracture and lithologic fabric orientations are shown for borehole CRG1 in Figure 6. The lithologic fabric orientations including foliation and gneissosity were measured in drill core only, while fracture orientations were determined from drill core and from ATV logs. The fracture orientation sets for the borehole, from each of the two data sources are coincident (Figure 6a and 6b), despite the fact that the ATV survey was prematurely terminated at 600 m because of a temporary obstruction in the borehole. The ATV orientations are more tightly clustered than those from core, which has been noted for other CRG boreholes as well, because the latter data set includes smaller features, which are not resolved in the image logs, and which are secondary and more irregularly distributed than the larger primary fractures. The intermediate west-dipping lithologic fabric (Figure 6c) corresponds with a similar oriented fracture set and suggests that this rock anisotropy represents a plane of weakness. Similar relationships between the folded rock fabric and a parallel fracture set have been observed in other CRG-series boreholes.

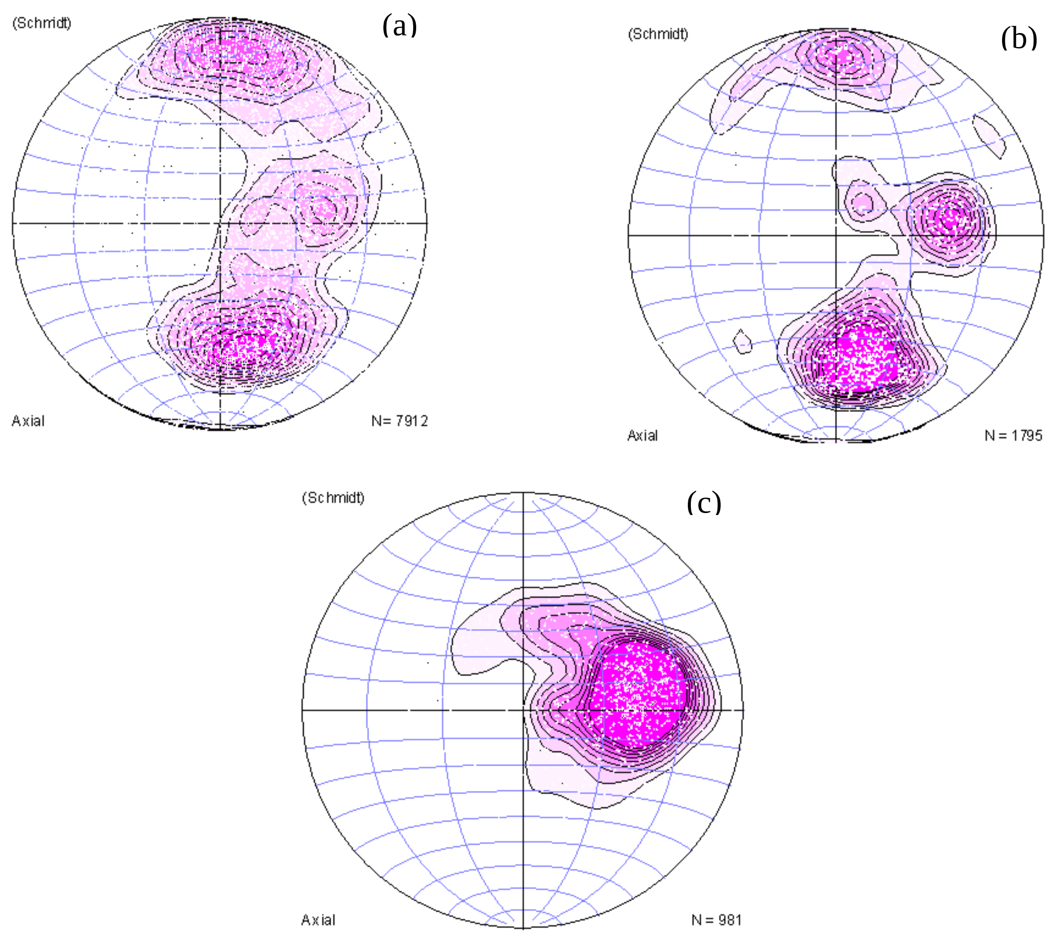


Figure 6. Equal-area plots contoured at 2% intervals of (a) fractures from drill core, (b) fractures from ATV logs, and (c) lithologic fabric measured in drill core.

3.2 Borehole CRG3

The data presented for CRG3 are intended to illustrate geologic borehole survey data related to lithology, rock quality, and open fractures and their orientation. The data sets illustrate the use of multiple lines of evidence to interpret geologic characteristics and to increase confidence in borehole information and the resulting geosphere models.

In addition to showing the frequency of all the fractures and the broken fractures, the graphic log in Figure 7 includes the occurrence of open fractures interpreted from drill core, as well as other indicators of open locations in the borehole. The caliper log provides an objective indication of wider and possibly hydraulically open intervals in the borehole. A 3-arm physical caliper log along with a caliper log calculated from the ATV Travel Time (TT) are included in the graphic log, and these show a good correspondence of spikes. Open fractures, derived from the ATV data include orientations for the structures and are shown in the tadpole plot, which can assist in developing the hydraulic anisotropy for the rock mass. These features have been classified into two types, those with a continuous borehole aperture that are more likely to be hydraulically open, and those with a partial aperture that are less likely to be hydraulically open, for which examples are shown in Figure 8. Other classification schemes encompassing more data sets are currently being worked with however; straddle packer testing is ultimately required to definitively determine the hydraulic characteristics of the borehole and to identify open fractures. Comparison of the displayed indicators of open fracturing with the hydraulic conductivity shows a reasonable correspondence.

Two additional surveys in borehole CRG3 supplement the straddle packer hydraulic testing, and these include measurement of borehole fluid temperature/chemistry and heat-pulse flow-meter logging. Some small anomalies can be seen in the fluid temperature and resistivity at about 220 m, near a cluster of open fracture identified in the ATV log, and along a corresponding caliper spike and some open fractures identified in the borehole. A larger fluid resistivity anomaly also occurs at about 890 m and includes an association with similar logs, indicating that these borehole locations and their corresponding geologic features are hydraulically significant. The lack of a corresponding anomaly in temperature for the deeper feature suggests that the infiltrating fluids are in thermal equilibrium with the borehole fluids.

The deeper fluid resistivity anomaly is more specifically related to a feature in the image log and in the drill core, using a thermal flow-meter as illustrated in Figure 9. Under near-surface pumping conditions that reduced the hydraulic head and induced upward flow in the borehole, a flow was detected above a fracture at 885.4 m but not beneath this deep feature, indicating this chloritic and steeply N-dipping fracture is hydraulically significant. The difference in depths (Figure 9) between the flow-meter log, and the core and image logs, are due to cable stretch, which cannot be corrected for the flow-meter log and the fluid temperature/resistivity logs, because these surveys lack the discrete features that can be matched with the other logs.

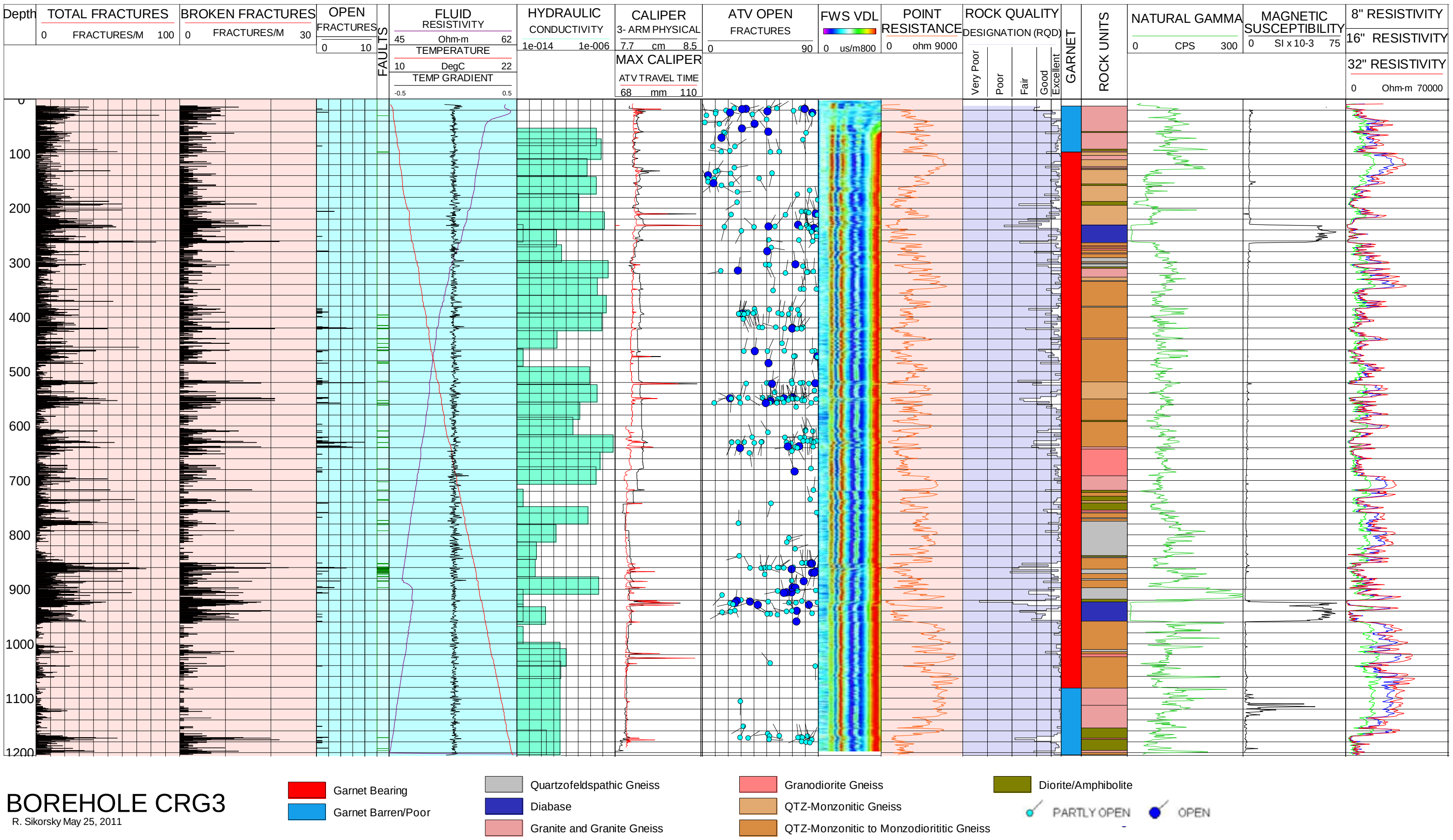
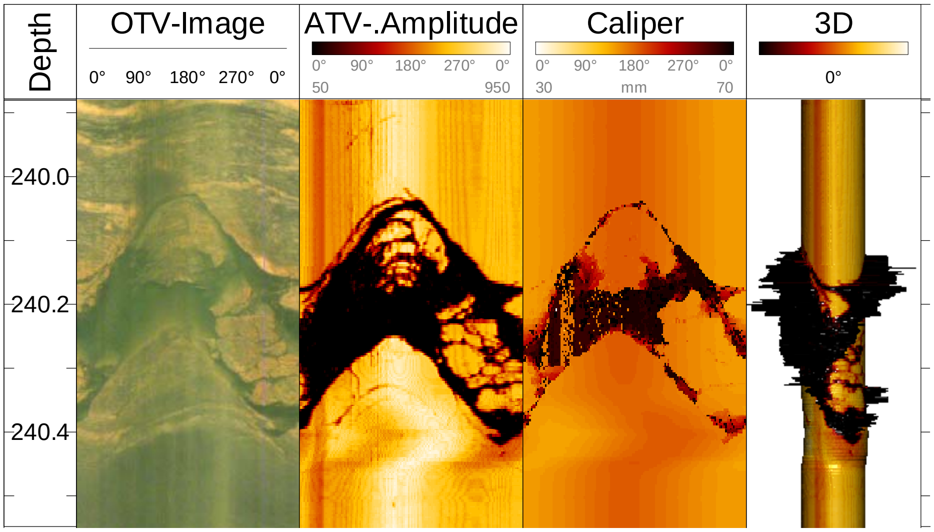
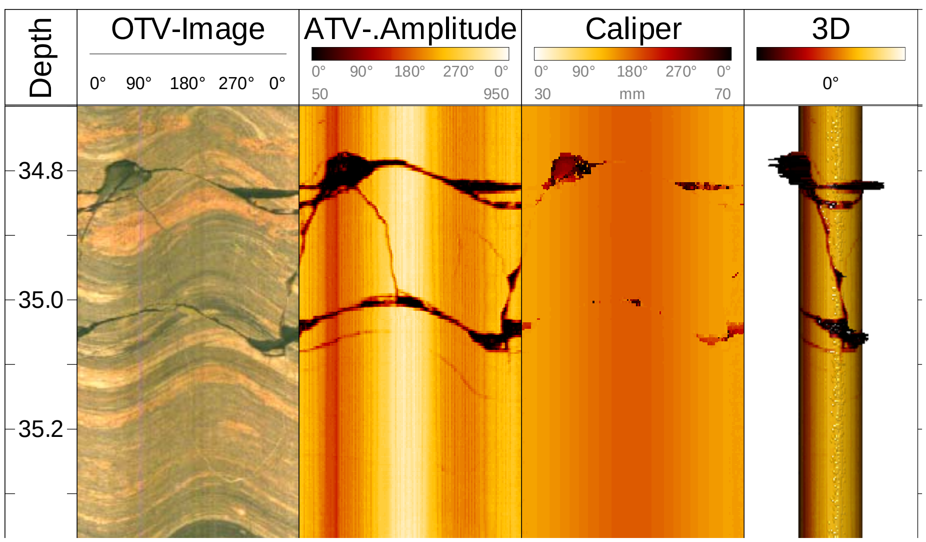


Figure 7. Graphic borehole log for CRG3. The log shows independently determined data used to infer possible open borehole conditions, including frequency of fracture types in drill core, fault locations, fluid resistivity and temperature, open fractures extracted from the ATV data, a variable density plot for the full waveform sonic log, and single point resistivity. Hydraulic conductivity determined by straddle-packer tests provides a definitive assessment of the hydraulic conditions in the borehole and is included for comparison. The rock units for the borehole, displayed for comparison with gamma, magnetic susceptibility, and normal resistivity logs, show a prominent contrast in these physical properties for the diabase dykes compared to the rocks they intrude.



(a)



(b)

Figure 8. Example of a fracture with a continuous borehole aperture (a) and a partial borehole aperture (b).

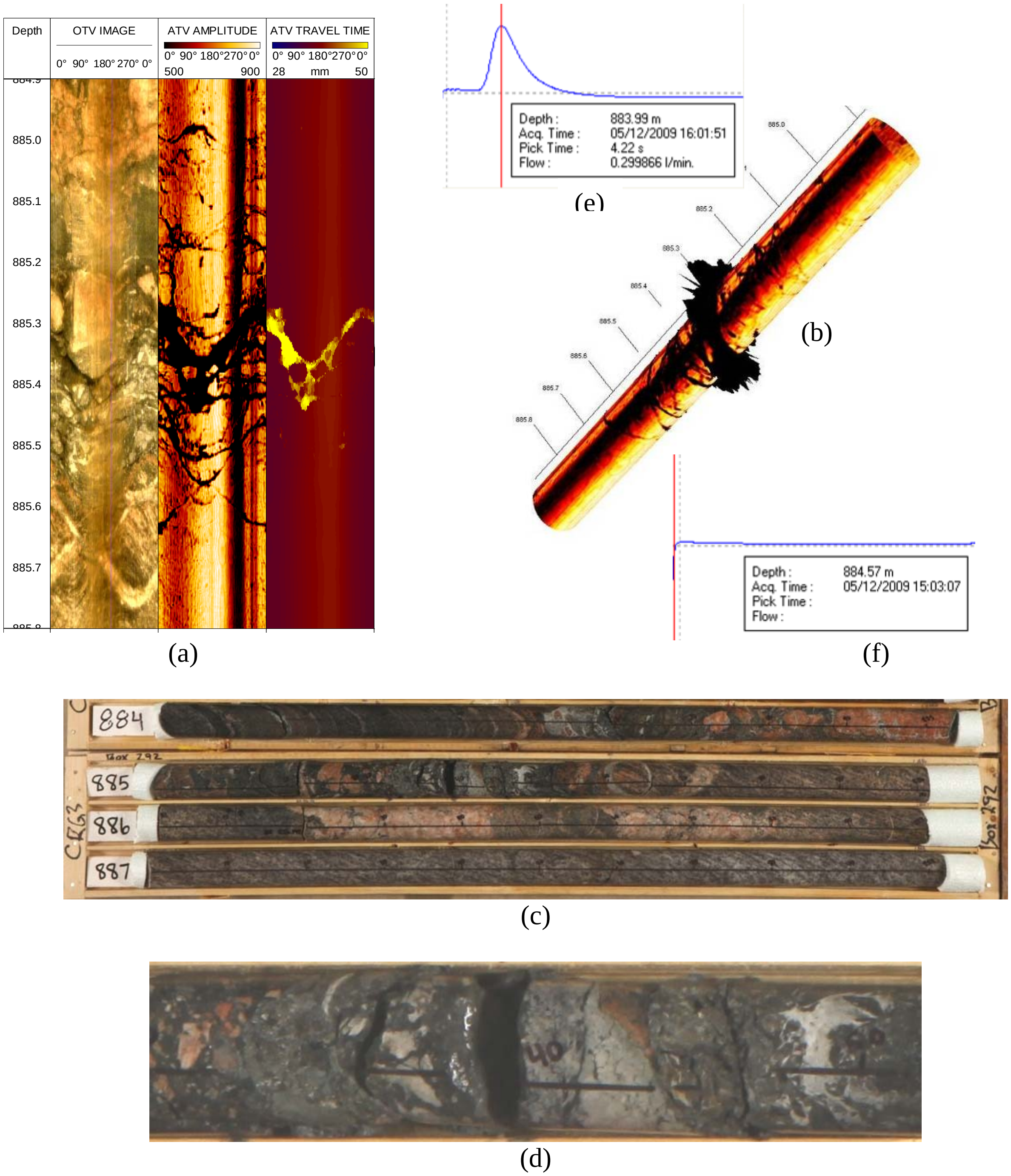


Figure 9. Synoptic illustration of the detection of an open fracture at 885.4 m in borehole CRG3. OTV and ATV amplitude and travel-time images (a) are shown along with a 3D rendition of the borehole diameter determined from the ATV travel time (b), and pictures of the open fracture in drill core (c and d). The 883.99 m graph (e, measured from above the fracture) of the heat-pulse flow-meter travel time indicates an upward flow, above this fracture in response to pumping at surface, whereas the flat graph for 884.57 (f, measured from below the fracture) shows no flow and suggests the water infiltration into the borehole is from this feature. The depth discrepancy for the flow-meter log compared to the ATV and core logs is due to cable stretch which is not compensated for in the flow-meter survey.

Borehole CRG3 was drilled to intersect the diabase dykes that underlie the major E-W trending lineaments which transect the CRL property. The intersection of these two highly magnetic features is especially obvious in the magnetic susceptibility logs, and these features also correspond with gamma and resistivity lows. Other less striking correlations between lithology and these three logs can also be seen.

CRG3 is the only CRG borehole on the CRL property that was found in the ATV logs to have borehole breakouts that are indicative of high differential stress, and these occur at 6 locations below 960 m. Four locations of poorly developed disking that also indicate high differential stress were intersected in core, and two of these occur below 961 m. Independently the core disking was initially considered a tenuous indicator because of the small size of the zones and the few disks. However, a direct correspondence was found between a zone of disking at 961 m and a borehole breakout (Figure 10). The core disking combined with the ATV borehole breakouts suggests that there is an increase in differential stress below 960 m. The orientation of the spalling indicates a SHmax orientation of WNW-ESE. Notably, a few of the caliper spikes at 961 m and below (Figure 7) are not related to fracturing, but are due to borehole spalling and are not expected to have any corresponding indictors of hydraulic activity.

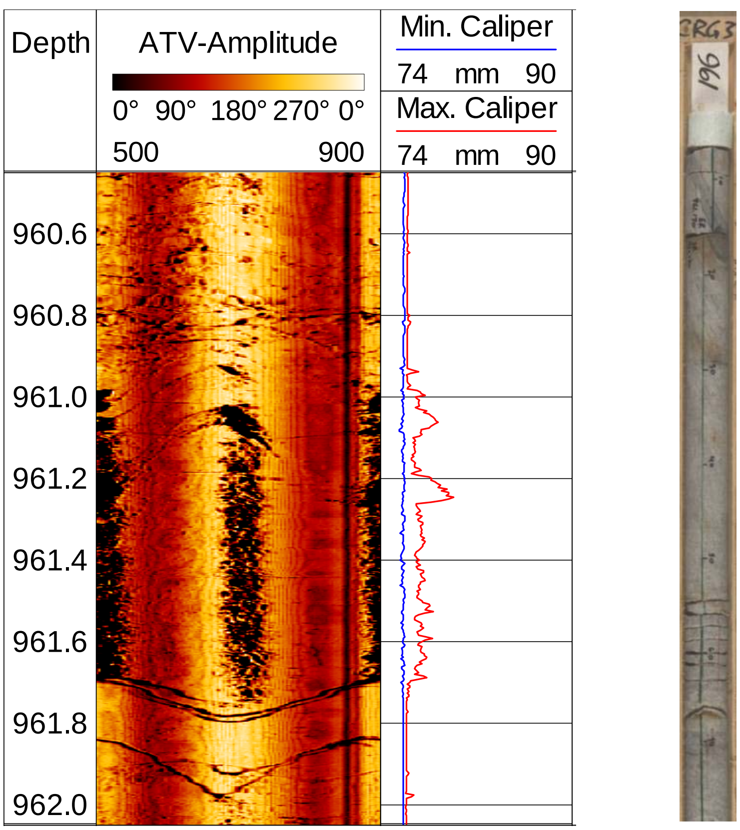


Figure 10. Stress-induced borehole breakout from 961 m in borehole CRG3 shown together with a corresponding zone of disking in core.

The rock quality can also be interpreted and substantiated by measurements from surveys that can infer its integrity. The Rock Quality Designation (RQD) provides a direct and quantitative measurement of the integrity of the rock that is established from counts of broken fractures in core. Most of the borehole can be seen in Figure 7 to comprise excellent quality rock, except for a few meter scale intervals that are good or fair. Comparison of these locations that have lower RQD, with the FWS and SPR logs shows a remarkable correlation, with most intervals of low RQD corresponding with lows in resistivity and with intervals of attenuation in the FWS logs. The correspondence even includes a similarity in shape of the RQD and SPR graphs such as those at 230 m and 920 m. The indirect indication of poorer rock quality in FWS and SPR logs results from an increased occurrence of attenuating fractures, which are also less resistive due to alteration or fillings as was shown for the normal resistivity near fracture peaks and clay filling in CRG1.

4. CONCLUSION

A variety of borehole techniques are available to geologically characterize the gneissic rock mass underlying the CRL property for the purpose of assessing its suitability to host a GWMF to permanently manage CRL's low- and intermediate-level waste. The examples that have been presented for boreholes CRG1 and CRG2 demonstrate that even though core logging can provide much of the fracture and lithological data that is used to establish lithostructural domains, the interpretation of the core log data can be supported by the addition of corroborating geophysical surveys. The examples provided for borehole CRG3 also show how the definition of lithologic and fracture characteristics derived from core can be corroborated with borehole geophysical surveys, but more importantly the examples for CRG3 particularly show that, for purposes of capturing data for developing discrete fracture networks used in groundwater flow modeling, the core log data can be significantly supplemented by *in situ* borehole surveys. These additional surveys are particularly important when they are made available for establishing locations for, and interpreting results of, straddle packer hydraulic tests that provide definitive and quantitative hydraulic characteristics of the rock mass intersected by the borehole. The development of stress models which primarily rely on over coring and hydrofracing techniques can also be supplemented by core log data combined with data from image logs. The acquisition of multiple data sets, which may appear to be redundant, are recommended for developing the required geologic models that can be extended into a robust hydrostructural architecture. The use of these multiple lines of evidence increases the confidence in descriptive and geometric geosphere models that underlie safety cases.

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