Application of Borehole Geophysics in Characterizing the Hydraulic and Geomechanical Properties of Fractured Crystalline Rocks

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ABSTRACT

Conventional logs such as the calliper, natural gamma, electric resistivity, acoustic transit-time, and bulk density logs can be interpreted to indicate the location of fractures and lithology contacts in crystalline rocks, and can be used to infer the extent of geochemical alteration or weathering associated with fractures and faults. The importance of fracture characterization and in situ measurement of geomechanical properties prompted the U.S. Geological Survey to modify existing borehole measurement and analysis techniques, and to develop new equipment for these applications. These include acoustic borehole televiewer modifications and new analysis methods for fracture characterization and in situ stress interpretation, acoustic waveform logging for fracture interpretation, and high-resolution borehole flowmetering. These measurements were used in conjunction with conventional geophysical logs and various surface geophysical soundings to investigate the hydrology of fractured granitic rocks at research sites near Lac Du Bonnet, Manitoba, Canada, and Mirror Lake, New Hampshire. Geophysical log analysis in both studies indicates that ground water circulates to substantial depths through intensely weathered fracture zones associated with ancient faults, intrusions, and lithologic contacts. Only a few of the many fractures which appear open and permeable in the vicinity of boreholes are shown to produce or accept flow under ambient hydraulic-head conditions, or during pumping tests, supporting theoretical predictions that fracture interconnections are as important as fracture aperture in the determination of flow path transmissivity. Results from these studies indicate that the flow of water through fracture zones and faults is best modeled as flow through a series of interconnected, heterogeneous conduits composed of short, discontinuous fracture segments.

INTRODUCTION

Many important applications in hydrogeology, including development of water resources in bedrock terrains, radioactive waste disposal, contaminant dispersal, and the relationship between pore pressure and mechanical stability of foundations are concerned with the flow of ground water in fractured crystalline rocks. However, the heterogeneity of fracture flow systems and the complex scale problem involved in characterizing such flows make the prediction of flow in fractured rock terrains one of the most complicated and difficult problems in hydrogeology. The U.S. Geological Survey has undertaken a long-term program in the application of borehole geophysics to the characterization of ground-water flow in fractured rocks. This paper describes the results obtained after nearly a decade of research at two sites in eastern North America where geophysical well log data have been synthesized with surface geophysical soundings, core analysis, and geological data to provide a description of flow in fractured granitic rocks at depths ranging from less than 20 to more than 1000 meters.

GENERAL CONSIDERATIONS IN THE APPLICATION OF BOREHOLE GEOPHYSICS FRACTURE CHARACTERIZATION

Geophysical measurements in boreholes provide important information on the in situ properties of fractured rocks. Conventional geophysical soundings cannot resolve individual fractures because relatively large wavelengths are required to achieve the depth of penetration needed to propagate seismic or electromagnetic waves into the interior of a rock mass. Well logs provide access to rock mass interior by means of boreholes, while measurements are made on a scale ranging from a few centimeters to a meter immediately adjacent to the borehole wall. Ideally, these measurements are made under natural conditions, where rocks are subject to in situ stresses, and where they are saturated with natural formation waters. In practice, the borehole wall rocks are subjected to a stress concentration caused by the borehole, and fractures have been damaged by drilling and possibly invaded by borehole fluids. An important aspect of geophysical log interpretation in fractured rocks is the elimination of these effects in the numerical analysis. In some situations, the response of borehole wall rocks to drilling-induced effects (invasion, hydraulic fracturing, and formation of borehole wall breakouts) may provide a useful and possibly quantitative indication of rock properties.

EQUIPMENT AND INTERPRETATION METHODS

Conventional geophysical measurements, including calliper, gamma, neutron, temperature, and acoustic logs, can be useful in providing a qualitative indication of the distribution of fractures along boreholes[7,10]. In many situations, these logs provide an indirect indication of fractures, because borehole response is controlled by the combined effects of borehole enlargement in fracture zones, clay alteration products in rocks adjacent to the fractures, and infilling minerals within fracture openings. In general, the permeable openings associated with fractures fill a much smaller amount of the volume sampled in the geophysical measurement than that filled by the borehole enlargements or altered rock[9,12].

In addition to the conventional geophysical logs used in most geotechnical applications, several recently developed techniques have important applications in characterizing fractured crystalline rocks. These include the acoustic borehole televiewer (BHTV), acoustic full waveform log (AFW), and heat-pulse flowmeter (HPFM). The BHTV provides a photograph-like image of the borehole wall, indicating fracture strike and dip, and providing a qualitative estimate of fracture aperture[23,13]. Probably the single most important problem encountered in applying BHTV logs to the interpretation of fractures in crystalline rocks is accounting for the effect of drilling damage and mechanical enlargement of fractures on the BHTV image. The AFW log provides a means of sounding fractured rocks extending away from the borehole, with an effective sampling depth ranging from 20 cm to more than a meter. This approach is especially effective when used as a means of investigating the properties of fractures previously identified using the BHTV[10]. Recent analysis indicates that AFW logs can be used to interpret fracture permeability in situ, if the effects of high-frequency oscillations associated with acoustic waves are included in the interpretation model[14,12,10]. The HPFM provides high-resolution velocity profiles in boreholes, and can be used to identify those fractures producing or accepting flow during pumping or recharge[4,5]. Various techniques have been developed where these measurements are analyzed individually or in combination to provide useful insight into the nature of ground water flow in fractured crystalline rocks.

GEOPHYSICAL STUDIES AT THE MIRROR LAKE, NEW HAMPSHIRE SITE

The Mirror Lake site is located in the White Mountains of central New Hampshire, where fractured granitic bedrock is overlain by 10-30 meters of glacial drift. Previous studies indicate a significant interaction between flow in the unconsolidated surface deposits and the underling fractured bedrock[21]. The bedrock is described as a moderately foliated metamorphic schist, extensively intruded by granite, and containing a few thin basaltic dikes[11]. The U.S. Geological Survey fractured rock study site consists of the approximately 2 square kilometer watershed of Mirror Lake, where an intensive study of ground-water flow in the unconsolidated surficial sediments has been conducted since before 1980. Extensive fresh outcrop exposure is available for the study of fracture population statistics where a recently constructed highway crosses the eastern edge of the watershed.

The initial approach to characterizing flow in the fractured basement rocks at Mirror Lake consisted of intensive study of fractures in a 100 square meter area where closely spaced boreholes would provide a large amount of information about the fracture distribution in a representative volume of rock. Five 70- to 220-meter deep boreholes encountered numerous fractures, most of which were dipping at 40 to 60 degrees to the east or west. BHTV log data were analyzed to give estimates of fracture permeability in the form of fracture density, and aperture-weighted fracture density, and are compared to similar measures of alteration constructed from nuclear and electric logs in figure 1[17]. These results seem to indicate a network of interconnected fractures, with fracture density decreasing irregularly with depth. However, surface to borehole seismic surveys performed to provide a larger-scale indication of fracture permeability disclose a single, nearly horizontal zone of hydraulic conductivity at about 50 meters in depth[3].

The apparent contradiction between the results of the geophysical log analysis and the larger scale seismic analysis was resolved by measuring the flow induced in observation boreholes during pumping with the HPFM (fig. 2). These results show that flow across the array occurs by means of nearly horizontal connections between short, discontinuous fracture segments. For example, the flow across the borehole array during the pumping was concentrated near the 50 meter depth indicated by the surface-to-borehole seismic study, although entrance and exit of flow in each borehole occurred via steeply dipping fractures. The consistency of these results is indicated in figure 3, where various geophysical measurements of fracture permeability are compared. The comparison is arranged so that the scale of investigation increases from less than a centimeter on the left (BHTV data) to more than 50 meters (surface-to-borehole seismic data) on the right. The interpretation of each of these data sets individually ranges from an irregular distribution of fracture permeability with depth on the left, to a single conductive zone on the right. Intermediate-scale measurements such as conventional straddle packer and injections tests indicate how the distribution of fractures shown on the BHTV logs is integrated into a larger-scale zone of hydraulic conductivity as the scale of the investigation is systematically increased. The quantitative estimates of effective hydraulic aperture in figure 3 are also consistent, with the exception of the large-scale seismic study, where questions about the mechanical compliance of fracture asperities are believed to affect the data inversion(15,3).

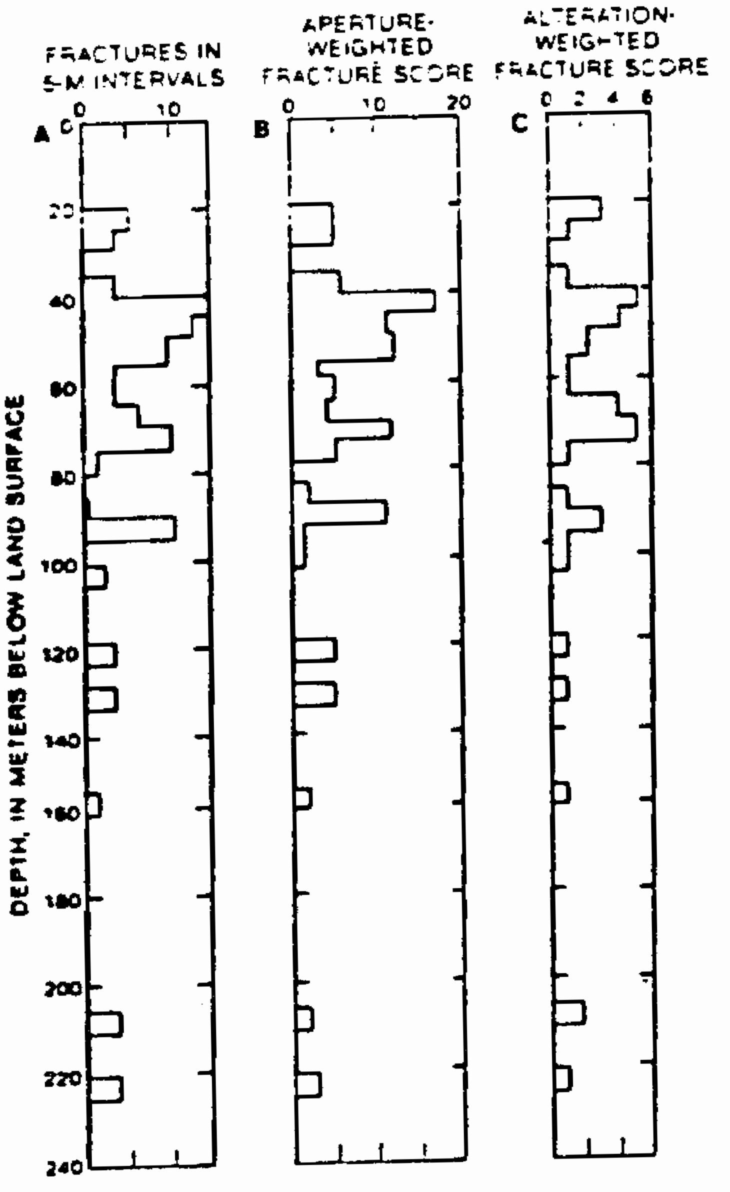

Figure 1: Fracture interpretation based on geophysical logs from borehole FSE4 at Mirror Lake, NH: A) fracture distribution indicated on BHTV log; B) fracture distribution from BHTV log weighted for relative size; and c) relative fracture alteration determined from nuclear, electric, and acoustic logs.

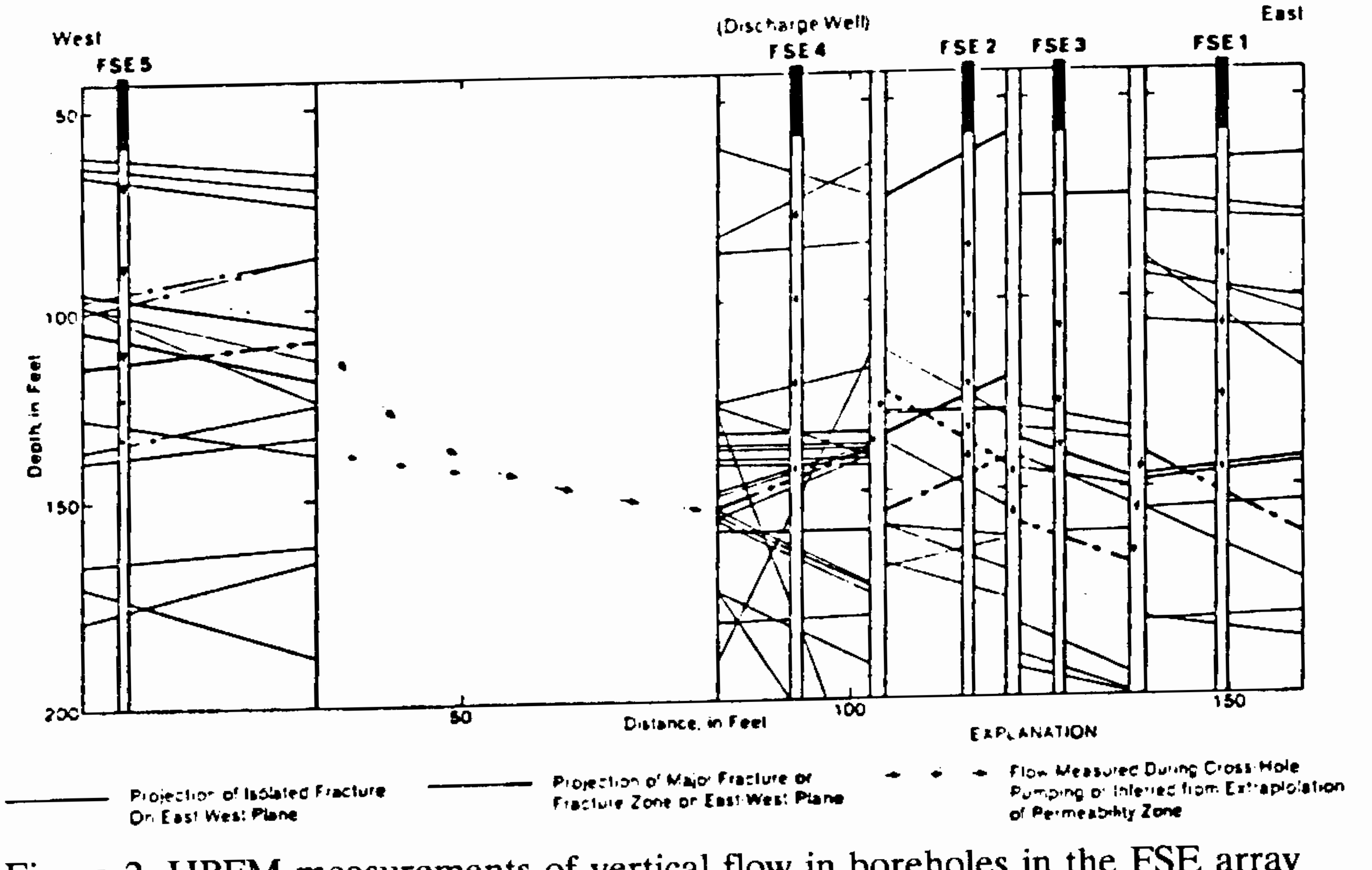

Figure 2: HPFM measurements of vertical flow in boreholes in the FSE array at Mirror Lake indicating horizontal flow along a horizontal path composed of discontinuous dipping fracture segments

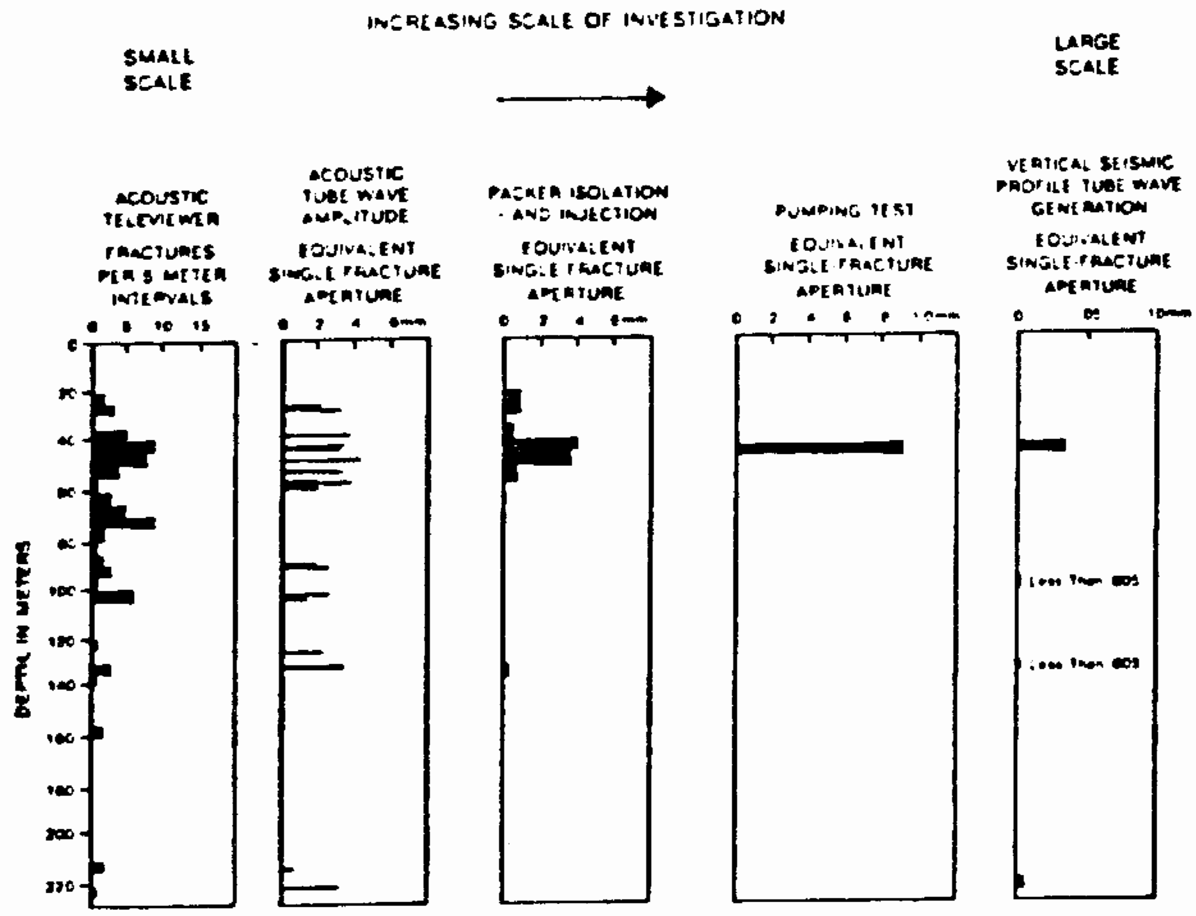

Figure 3: Comparison of fracture characterization methods applied to borehole FSE4 at Mirror Lake, with increasing scale of investigation towards the right[15].

Fracture flow studies at Mirror Lake were continued by constructing additional borehole arrays at other locations in the watershed, and by expanding watershed coverage so that these arrays are included in a profile of boreholes spaced at about 100 meters along an east-west transect[11]. These results demonstrate that the zone of large-scale hydraulic conductivity indicated in figures 2 and 3 is typical of many such zones encountered by other boreholes, but that none of these zones detected so far seem to extend over distances larger than 100 meters. At the same time, many boreholes intersect several such conductive zones, each characterized by different hydraulic heads. Long term measurement of the hydraulic heads in packed off intervals indicate that the heads in these isolated zones fluctuate in the same manner as heads in the overlying unconsolidated aquifer. All of these results indicate that flow in fractured bedrock in the Mirror Lake watershed can be modeled as a series of partially isolated flow systems within an extremely heterogeneous distribution of hydraulic conductivity. Therefore, large-scale flow paths are very difficult to define on the basis of fracture populations identified in individual boreholes. Systematic study of connections between fracture zones demonstrate the nature of the regional flow system, indicating how this irregular distribution of fractures is integrated into a large scale network associated with regional lithology and structure.

GEOPHYSICAL STUDIES AT THE LAC DU BONNET, MANITOBA SITE

The U.S. Geological Survey fracture study at the Lac Du Bonnet site in Manitoba, Canada was conducted as part of a larger joint study with Atomic Energy of Canada Limited (AECL). The AECL research is intended to develop techniques useful in characterizing the hydraulic and geomechanical properties of rocks suitable for siting radioactive waste repositories[12]. The Lac Du Bonnet site was developed to investigate ground water circulation repositories[12]. The Lac Du Bonnet site was developed to investigate ground water circulation in a granitic batholith. Intensive study of site hydrology by AECL scientists demonstrates that water circulates to depths greater than 1000 meters, with flow paths controlled by a series of eastward dipping fracture zones[1]. Various geophysical soundings indicate that these large-scale zones can be detected with conventional seismic refraction and electromagnetic techniques[2,19,22].

Geophysical logging of boreholes encountering one or more of these fracture zones indicates that each is composed of a heterogeneous distribution of fractures surrounded by altered rock. The width (vertical thickness) of the altered fracture zone can be defined using conventional nuclear, electric, and acoustic logs, but the extent of alteration and fracturing within the zones can only be related to logs in a qualitative way[12]. However, AFW logs can be used to provide quantitative estimates of fracture permeability. When AFW log data are dominated by the guided tube wave (Fig. 4), characteristics of this propagation can be related to fracture permeability. Both the reflection[6] and attenuation[20,12] of these waves can be calibrated in terms of fracture permeability. However, the fracture permeability measured by these waves needs to be related to steady state permeability using a dynamic permeability factor[20].

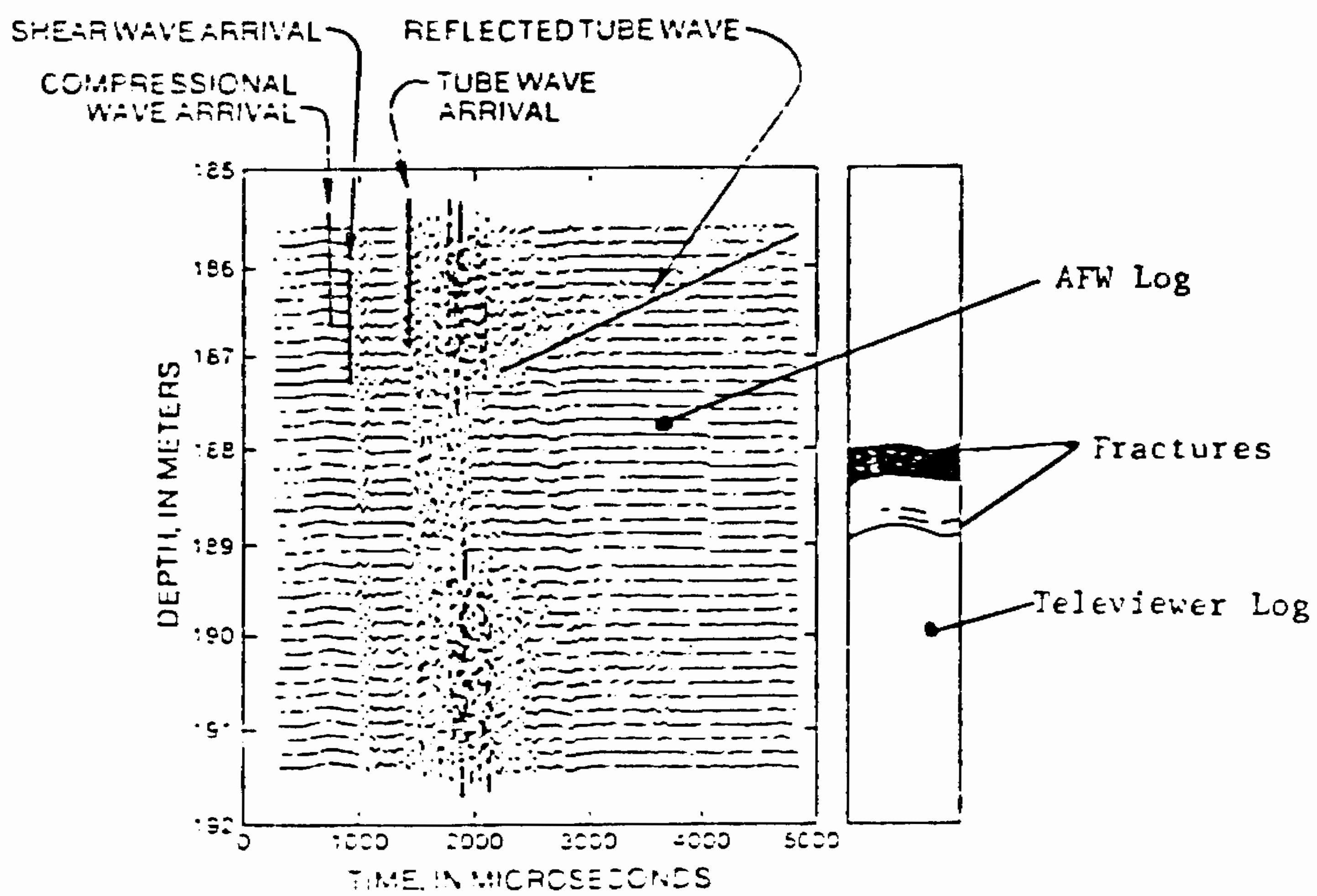

Figure 4: AFW data from borehole URL-M11 at the Lac Du Bonnet site indicating attenuation and reflection of tube-wave associated with a permeable fracture.

The BHTV, AFW, and HPFM measurements were applied in numerous boreholes at the Lac Du Bonnet site. These results indicate that although there are many apparently permeable fractures within the large scale fracture zones, only a few of the fractures intersected by the borehole produce water during pumping. Furthermore, these results indicate that the local permeability of the fracture zones is highly heterogeneous. Figure 5 indicates a pair of boreholes intersecting one of the large-scale fracture zones at the site (the lower fracture zone in the figure). Borehole-to-borehole seismic topography indicates a single large-scale fracture zone connecting the two boreholes and surrounded by unfractured and unaltered rock. BHTV and AFW logs run in boreholes URL14 and URL15 indicate where the boreholes encounter this fracture zone, and show that there are a few minor, relatively unaltered fractures located above and below the main fracture zone (Fig. 6). These relatively minor fractures were not indicated by the tomography.

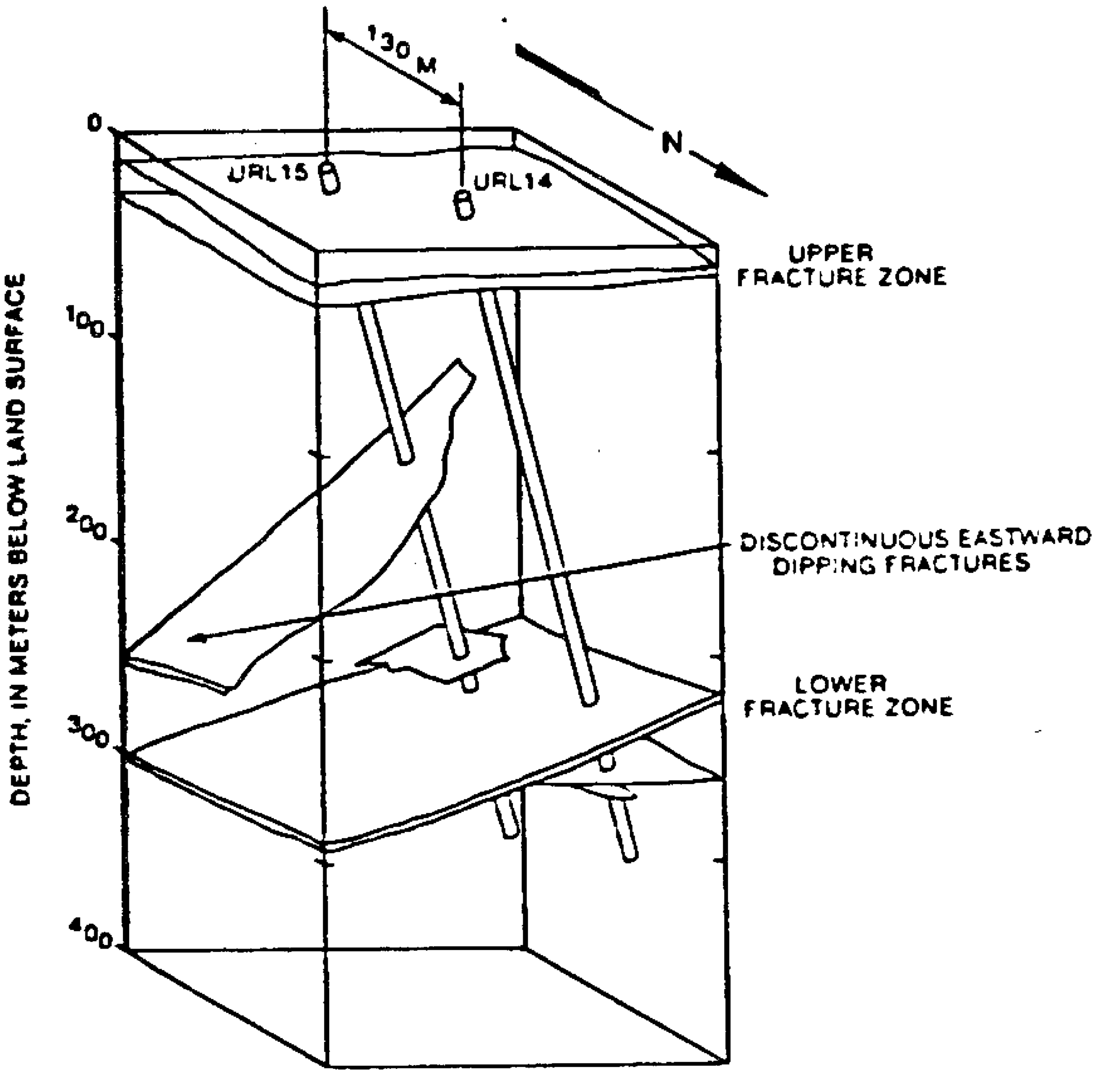

Figure 5: Schematic illustration of boreholes URL14 and URL15 at the Lac Du Bonnet site, indicating location of lower fracture zone and other discontinuous fractures intersected by the boreholes.

Pumping tests conducted in each of the boreholes in figure 5 indicate that the fracture zone is very conductive where intersected by borehole URL15, but much less conductive where intersected by borehole URL14. Cross-borehole pumping and HPFM measurements were conducted during steady pumping at 0.25 litres per minute from borehole URL14. The flowmeter measurements indicate that no flow is transmitted through the fracture zone between boreholes, while all of the flow produced by the pumping came from a single fracture set about 40 meters below the fracture zone in borehole URL14 (Fig. 7). The flow induced in borehole URL15 by this pumping consisted of the inflow at the main fracture zone, and outflow at an isolated set of fractures below. The lack of measurable flow along the fracture zone between boreholes is interpreted as the result of the heterogeneity of hydraulic conductivity within such large scale features. At the same time, the permeability of relatively fresh fractures below the primary fracture zone may be related to local distortions of the regional stress field. Such distortions and local reorientations have been discovered during overcoring, hydraulic fracture experiments, and excavation at the Lac Du Bonnet site(8), and are indicated by borehole wall breakouts in borehole URL14. Breakouts are stress inducted features known to be related to the presence of nonisotropic horizontal stresses(24). Breakouts are present for a short interval just below the main fracture zone in borehole URL14 (Fig. 8), and are closely associated with core discing, which is also known to be associated with nonisotropic stress conditions(18).

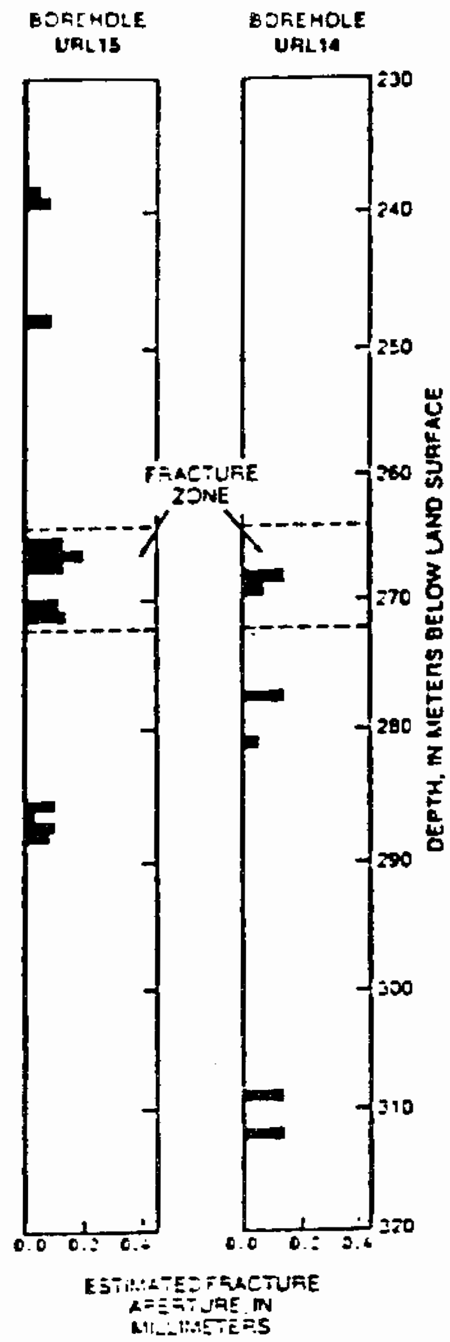

Figure 6: Distribution of fracture permeability in boreholes URL14 and URL15 in vicinity of the lower fracture zone, with effective hydraulic aperture of fractures estimated using AFW tube-wave attenuation analysis.

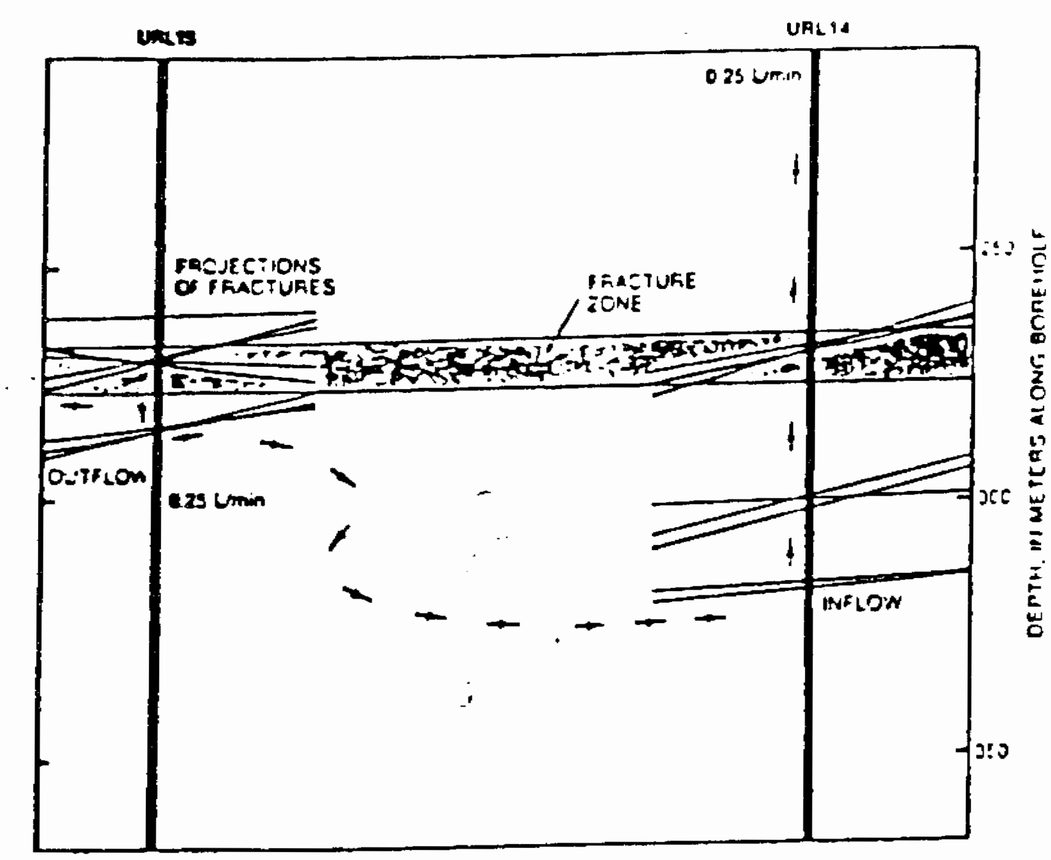

Figure 7: Distribution of flow in the vicinity of the lower fracture zone as indicated by HPFM measurements made during pumping of borehole URL14 at 0.25 liters per minute

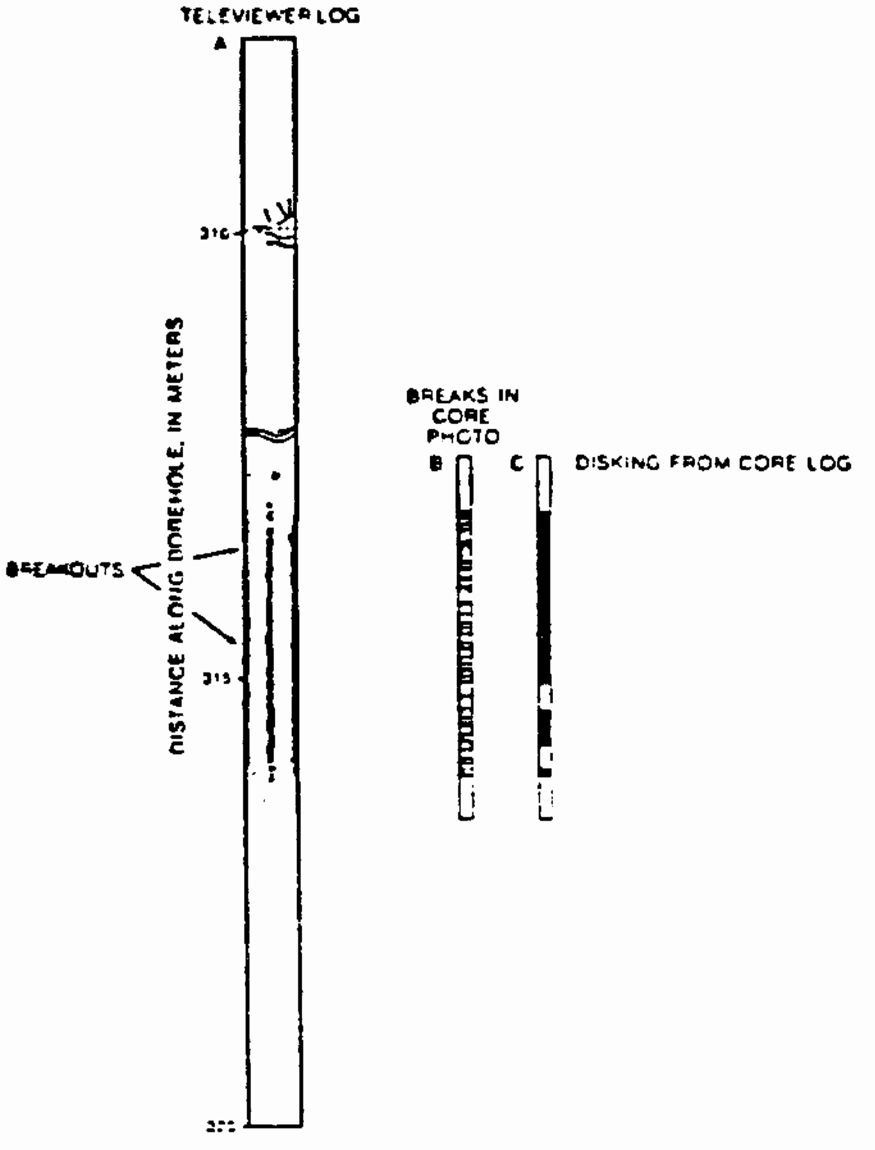

Figure 8: Distribution of borehole wall breakouts in borehole URL14 indicating the discontinuous nature of the breakouts, and correlation of breakouts with core discing.

CONCLUSIONS

The U.S. Geological Survey has conducted nearly ten years of intensive geophysical investigation of fractured crystalline rock at research sites at Mirror Lake, New Hampshire, and Lac Du Bonnet, Manitoba, Canada. These results indicate that various geophysical measurements can be used to characterize fractures in situ, but that the most effective characterization results when multiple measurements of different geophysical properties are used. Furthermore, the heterogeneity of fracture permeability on more than one scale makes these local assessments of fracture properties very difficult to relate to larger scale flow regimes that may control contaminant dispersal from radioactive waste repositories, or water influx into tunnels and galleries. Effective characterization of fracture hydrology and ground water circulation in crystalline rock terrains needs to address scales ranging from that associated with individual boreholes up to the scale of regional structural features. Results from the Mirror Lake and Lac Du Bonnet sites indicate that a useful model of such heterogeneous fracture flow systems can be obtained if the scale effects are addressed by integrating geophysical well logs, cross-borehole measurements, surface geophysical soundings, and other geological information available from cores and surface exposures.

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