HYDROGEOLOGIC DATA COLLECTION AND DEVELOPMENT OF CONCEPTUAL MODELS TO PREDICT MINE INFLOW QUANTITY AND QUALITY AT DIAVIK DIAMOND MINE, NWT

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ABSTRACT
Current mining of two kimberlite pipes at the Diavik Diamond Mine requires reasonably accurate estimates of groundwater inflow quality and quantity over the life of mine. Prior to mining, from 1995 to 1999, three conceptual hydrogeologic models were developed for the mine. The results of the numerical model, developed from each successive conceptual model, were used to develop field programs to address data gaps and/or to more accurately assess the most sensitive parameters.

RÉSUMÉ
Une estimation relativement précise de la qualité et quantité des écoulements souterrains est nécessaire pendant la période d’exploitation minière des deux cheminées de kimberlites à la mine de diamants Diavek. De 1995 à 1999, avant l’initiation de l’exploitation, trois modèles hydrogéologiques conceptuels furent développés pour la mine. Les résultats du modèle numérique, construit à partir des modèles conceptuels, ont servi à développer les programmes de terrain visant à combler le manque de données et/ou à évaluer de façon plus précise les paramètres les plus sensibles.

1. INTRODUCTION

The Diavik Diamond Mine is located on a 20-sq-km island in Lac de Gras, 300 kilometres northeast of Yellowknife, Northwest Territories of Canada (Figure 1). The mine is an unincorporated joint venture between Diavik Diamond Mines Inc. (DDMI; 60%) and Aber Diamond Limited Partnership (40%). Both companies are headquartered in Yellowknife. DDMI is a wholly owned subsidiary of Rio Tinto, which is headquartered in London, England, and Aber Diamond Limited Partnership is a wholly owned subsidiary of Aber Diamond Corporation of Toronto, Ontario. DDMI is the operator of the project.

Figure 1. Site Location

Presently DDMI is mining the A154 South and A154 North kimberlite pipes through the A154 open pit (Figure 2). To allow planning, engineering, and implementation of sufficient water handling infrastructure, reasonably accurate estimates of groundwater inflow quality and quantity over the life of mine are required. Infrastructure includes in-pit pumps and pipelines, a water storage facility and a water treatment plant. Because of the remote location of the mine and the need to transport large equipment and bulk materials on the winter ice road from Yellowknife, advanced planning is critical.

The mine is presently evaluating the feasibility of mining more ore underneath the open pit via an underground mining operation. In addition, construction of a second water retention dike is currently underway, which will allow open pit and underground mining of a third ore body called the A418 kimberlite pipe (Figure 2). These additional mine workings will increase the total mine inflows and further stress the existing mine water handling systems, which further emphasizes the need for reasonably accurate predictions of inflows and quality.

This paper presents a historical development of the conceptual and numerical hydrogeologic models used to predict mine inflow for the A154 area. In particular, it examines the changes in the models resulting from the discovery of a fractured rock zone (FRZ) associated with Dewey’s Fault, which extends through the two pipes and out beneath Lac de Gras and the influence of this highly permeable zone on groundwater inflow to the pit. The pit is developed in competent and relatively low permeable predominantly metamorphosed Archaean granitic country rocks, with some interspersed biotite schists. Lac de Gras provides a significant recharge boundary to the system as it borders the open pit.

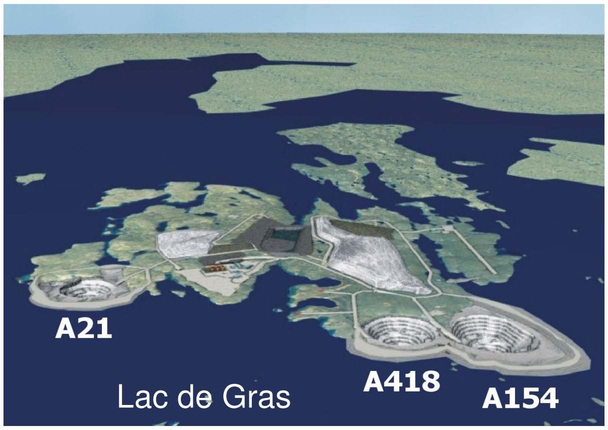

Figure 2. Conceptual Representation of the Mine Workings at the End of Mining

2. PRE-MINING CONCEPTUAL MODELS

2.1 1996 Field Data

The 1996 conceptual model for the site was based on air photo lineaments and bathymetry, structural data from geotechnical drilling investigations, packer testing at 15 to 60 m intervals along the length of eleven boreholes, measurements of discharge from flowing boreholes drilled along the exploratory decline, and data from four thermistors and pressure transducers installed at various depths along one borehole.

These data indicated that up to 4 potential shearing orientations are associated with brittle fault zones. The most prominent shear feature identified was a northwesterly trending feature between the A154 North and A154 South pipes.

During excavation of the exploratory decline, which was advanced from the permafrost under the East Island into the unfrozen A154S pipe under the lake, flow rates and shut-in pressures were measured in cover holes advanced ahead of the face. When high groundwater inflows were encountered each borehole was grouted immediately after it was completed. Over most of the portion of the decline advanced through country rock, total inflow was less than 80 L/min with the exception of a discrete feature located near to the A154S pipe. Flow from this structural feature varied from 150 L/min to 400 L/min. The feature was grouted where it was encountered in declines and drifts.

Air photo and bathymetry data were used to identify a number of trending lineaments. One borehole inclined at 45 degrees from the horizontal, GTH-23, was advanced from the decline into an interpreted fault zone located between the A154S and A154N pipes. Measurements of the shut-in pressure and the discharge rate for various intervals throughout the boreholes were used to determine hydraulic conductivity. The fault zone was encountered from a depth of 34 m to the end of the borehole at 137 m depth with inflows ranging from 10 L/min to 3000 L/min.

2.2 1996 Conceptual Model

Based on the field program described above, a conceptual model was developed that consisted of the following hydrostratigraphic units: lakebed sediments, near surface weathered rock, competent country rock, kimberlite, and fault zones in the country rock. The shallow competent country rock was inferred to be weakly fractured with a fairly uniform hydraulic conductivity of approximately 10^{-8} m/s to 10^{-7} m/s. A reduction in hydraulic conductivity of country rock was assumed to take place at depth due to an expected reduction in fracture aperture as a result of increased vertical loading. Such reductions in hydraulic conductivity with depth have been observed at other locations in the Canadian Shield (Stevenson et al., 1996 a & b, Ophori et al., 1996, Ophori and Chan, 1994). Based on results of packer testing, the hydraulic conductivity of the kimberlite was estimated to be between 5×10^{-8} m/s and 5×10^{-6} m/s.

Three steeply dipping fault zones were interpreted to be present based largely on lineaments in air photographs and bathymetry. These zones are as follows: a northeast trending feature to the east of the A154S pipe corresponding to a surface lineament up to 200 m wide, a northwest tending feature running through the A154 N and S pipes corresponding to a surface lineament up to 20 m wide, and a north-northwest trending feature to the south of the A418 Pipe also corresponding to a surface lineament up to 20 m wide.

Based on field investigations at the site and an adjacent property, permafrost conditions were inferred to be 240 m deep beneath the East Island. The depth of the permafrost was inferred to decrease towards the lakeshore and beneath the lake itself a thawed zone exists. Hydrogeologically, permafrost is considered to be virtually impermeable. Although a thin thawed zone referred to as the active layer occurs at the surface in the warmer months, this flow is negligible.

Hydraulic head data collected during packer testing and the pressure transducers installed in one borehole indicated that prior to mining the groundwater under Lac de Gras was near to hydrostatic. These conditions were likely the result of the presence of the lake acting as an extensive constant head boundary and the absence of recharge through permafrost on the islands and the mainland.

During mining the open pits and underground mine workings act as sinks for groundwater flow (Figure 3).

Water is induced to flow through the lakebed sediments, dikes, and the bedrock into the open pits and underground workings. The hydraulic conductivity of the inferred fault zones would result in much of the groundwater inflow into the mine occurring through these zones.

Based on the 1996 conceptual model, a numerical hydrogeologic model of the site was constructed using MODFLOW (McDonald and Harbaugh, 1988). Because of the near hydrostatic conditions beneath Lac de Gras prior to mining, meaningful calibration of this model was not possible with the data available at that time.

Results of the numerical model indicated that model predictions of inflow to the proposed mine were most sensitive to the width and hydraulic conductivity of the fault zones included in the model. Model predictions were found to be significantly less sensitive to the hydraulic conductivity of the kimberlite and the relatively competent country rock, and to the depth and extent of permafrost.

Based on the results of the modelling, field investigations were recommended to determine if the surface lineaments corresponded to a significant hydrogeologic feature of high permeability and to determine the width of the zones if they were found to be present.

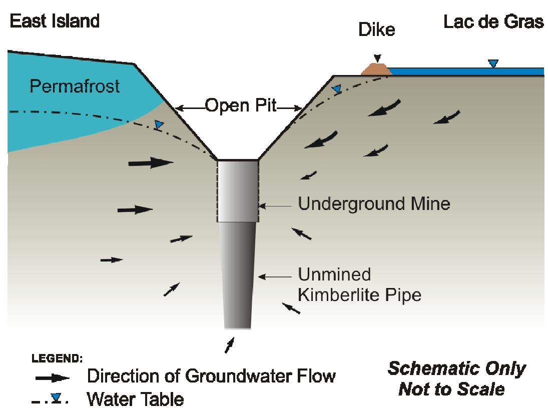

Figure 3. Conceptual Model of Groundwater Flow During Mining

2.3 1997 Field Data

The 1997 field investigations included geotechnical logging of 19 boreholes, six of which were drilled from the lowest level of the exploratory decline to the A154S pipe. In thirteen of these boreholes, packer testing was conducted at approximately 40 m intervals while thermistor strings were installed in four of the boreholes. In addition, a flow recession test was conducted in the exploratory decline using boreholes drilled from the decline.

The flow recession test was conducted on an apparent thin FRZ associated with a diabase dike running between the 154N and S pipes. The test consisted of allowing one borehole to flow and measuring the pressure drop in two adjacent boreholes. Time-drawdown and recovery measurements were used to calculate the hydraulic conductivity of the fractured zone. This analysis yielded a hydraulic conductivity value of approximately 3×10^{-5} m/s. These data used together with drilling conducted from the surface; however, suggested that this FRZ was associated with a diabase dike and limited to the area between the two pipes.

Surface drilling across all other surface lineaments indicated that these features were not likely highly permeable. In addition, a review of the air photo lineaments indicated that several of the features corresponded to “boulder trains” rather than structural discontinuities.

Following the drilling program undertaken in the 1997 field season, a general structural geology review was undertaken to identify FRZs based on Rock Quality Designation (RQD), core photographs, and fracture characteristics data in all boreholes that had been drilled at that time. Zones with enhanced fracture density relative to background were identified as FRZs. Three types of fractured systems were identified during this process: fractured rock with a significant fracture frequency, diabase dike contacts and kimberlite dike contacts. Data from all boreholes drilled at the site including delineation boreholes were then used to determine an average fractured rock zone spacing at the site. This analysis indicated that the average fractured rock zone spacing was 110 m and the average width was 4 m. Based on observations in the exploratory decline and the observed relationship with diabase dikes, the fractured rock zones were assumed to be steeply dipping.

2.4 1998 Conceptual Model

The conceptual model of the site that was developed following the 1997 field season included four major hydrostratigraphic units: relatively competent country rock, fractured rock zones, kimberlite and thick diabase dikes. Lakebed sediments and weathered bedrock units were not included as major hydrostratigraphic units in this model as it was assumed that during construction of the dike, these sediments would be stripped and/or grouted. The geometric mean of the results of all packer testing conducted in each of these stratigraphic units was used to determine large-scale hydraulic conductivities.

Fractured rock zones were incorporated in the conceptual model as two steeply dipping near orthogonal sets at spacings indicated from the structural data (Figure 4). These sets were assumed to be oriented roughly parallel to the major diabase dikes identified at the site: one trending north-northeast and the other north-north-west. The fractured rock zones in the model intersected the A154N and S pipes and the A418 pipe. Because the lateral and vertical continuity of fractured rock zones could not be determined from field data, fractured rock zones were assumed to continuous across the model domain. This assumption would likely result in conservatively high inflows.

Diabase dikes that were less than 2 to 5 metres were found to be relatively highly fractured with a hydraulic conductivity similar to fractured rock zones. On the other hand, diabase dikes with widths greater than 5 to 10 metres were still found to be fractured, but the short fractures and blocky nature resulted in a lower hydraulic conductivity. The diabase dike to the east of the kimberlite pipes was assumed to behave as a low permeability barrier to groundwater flow through the competent rock.

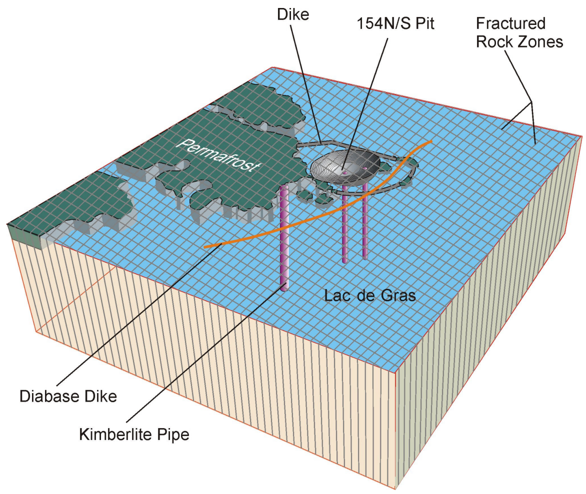

Figure 4. 1998 Conceptual Model

Packer tests conducted in the competent bedrock collected up to and including the 1997 field season were limited to less than 330 m depth. Although a reduction in the hydraulic conductivity of this unit was expected, these packer testing results did not show any trend in hydraulic conductivity with depth. Therefore, the hydraulic conductivity of bedrock was assumed to remain constant with depth in this conceptual model.

The results of a permafrost model for the site (Nixon, 1997a, Nixon 1997b) were used to revise the extent of permafrost in the 1998 conceptual model. Consequently, the depth of permafrost under the East Island was increased from 240 m to up to 390 m. Permafrost was also included in the model to a depth of 60 m underneath the small islands located to the east of the East Island.

2.5 Geochemical Data

In the Canadian Shield, the Total Dissolved Solids (TDS) in groundwater generally increases with increasing depth. Results of chemical analyses of deep saline water collected from several mines in the Canadian Shield were presented in Frape and Fritz (1997).

A review of geochemical data collected for the Diavik site was also conducted by Blowes and Logsdon (1997) and resulted in the determination of a Diavik TDS-depth profile similar to the profile presented in Frape and Fritz (1997). Both the site profile and the Frape and Fritz (1997) profiles are presented in Figure 5. The profile is based on Diavik site-specific data collected at depths up to 350 m and supplemented with data collected at the Echo Bay Lupin mine between 800 and 1300 m depth The Echo Bay Lupin mine is located approximately 100 km north of the site. Based on measurements of tritium concentrations, none of the site-specific samples showed evidence of dilution by modern groundwater such as drilling fluids or lake water.

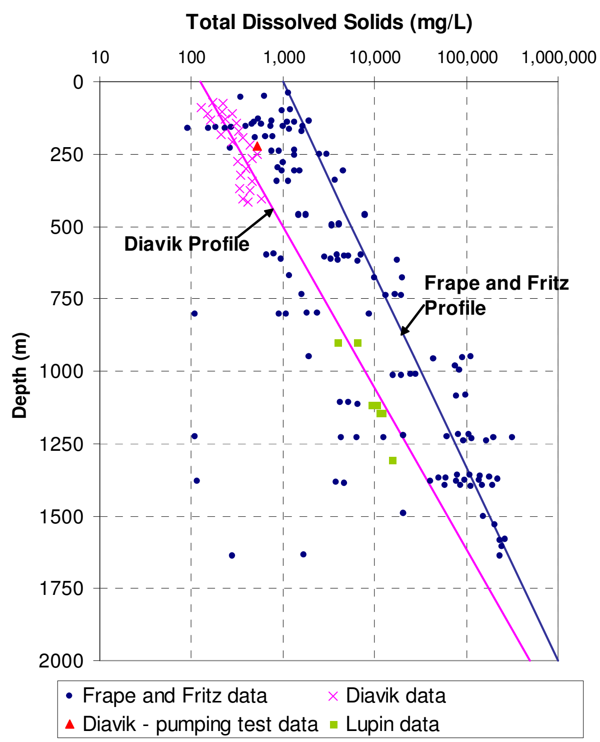

Figure 5. TDS-Depth Profile

2.6 1998 Numerical Model

Based on the 1998 conceptual model, a numerical hydrogeologic model of the site was constructed using MODFLOW. Initially a variable density model was used to assess the effects of density on the transport of deeper brackish water up into the mine. This modelling indicated that the density effects on transport were negligible compared to the hydraulic effects; therefore, a single density transport model, MT3D (Zheng, 1990), was used to simulate transport of higher TDS water from depth.

Fractured rock zones were simulated in the model as thin planar features of higher hydraulic conductivity at spacing similar to those determined from the review of the structural data.

The numerical model for the site was calibrated to inflows recorded during development of the exploratory decline. Results of the 1998 numerical model indicated that the model predictions of inflow to the proposed mine were most sensitive to the width and hydraulic conductivity of the fault zones included in the model. Model predictions were found to be significantly less sensitive to the hydraulic conductivity of the kimberlite and the relatively competent country rock, and to the depth and extent of permafrost.

Based on the results of the 1998 model, it was recommended that hydraulic conductivity testing and chemical analyses in boreholes at depths greater than 330 m be undertaken to constrain the TDS and hydraulic conductivity-depth profiles. In addition, it was recommended that flowmeter and fluid logging be undertaken to assess if the thin fractured rock zones identified in the review of the borehole logs were actually significant hydrogeologic features.

2.7 1999 Field Data

In the 1998 field season, twenty additional boreholes were drilled at the site. A total of 75 packer tests were conducted along the length of fifteen of these holes. A downhole camera survey was conducted in five boreholes. Temperature logging was conducted in four boreholes and flowmeter logging was conducted in one borehole. Results of all packer tests conducted from 1996 to 1998 were compiled into a database of over 800 tests.

Following the 1998 field season, the results of downhole camera, temperature, and flowmeter logging together with packer testing and visual inspection were used to investigate the hydrogeologic significance of fractured rock zones. Of the four boreholes in which fluid logging was undertaken (nearly 1300 m of logging) only two features of hydrogeologic significance were identified. A significant feature was one that was identified through the fluid and flowmeter logging as a flow anomaly and had a corresponding high hydraulic conductivity from the packer tests. Both features were found to be approximately 3 m wide. This result suggested that significant fractured rock zones at the site are much more widely spaced than previously assumed. Observations of flow made during the advancement of the exploratory decline reinforced this conclusion as only one major inflow was observed during development of the decline for the full 600 m of the decline completed in unfrozen ground.

2.8 1999 Conceptual Model

In the third conceptual model for the site, country rock was characterized as a single hydrostratigraphic unit with a bulk hydraulic conductivity value. Given the apparent size and spacing of the fractured rock zones determined from the 1999 field program, and considering the scale of the proposed mine, it was concluded that these zones were effectively included in the bulk hydraulic conductivity of the country rock. Consequently, these zones were not explicitly included in the model. The 1999 conceptual model, therefore, consists of three main hydrostratigraphic units: country rock, kimberlite, and diabase dike. However, it was also concluded that fractured rock zones that are significant hydrogeologic features may be present at the site but have not been intersected in drilling; therefore, as a sensitivity, a number of such features at various orientations were simulated in the model to assess their affect on mine inflow.

Based on analysis of the entire packer testing results for the country rock up to 570 m depth and observed hydraulic conductivity reductions with depth at other sites in the Canadian Shield (Stevenson et al., 1996 a & b, Ophori et al., 1996, Ophori and Chan, 1994) the hydraulic conductivity of country rock was assumed to decrease with depth. Sufficient packer testing data to establish the hydraulic conductivity-depth profiles for the diabase dike and kimberlite units were not available for the site; therefore, conservatively low reductions in hydraulic conductivity with depth were assumed.

The numerical hydrogeologic model that was developed based on the 1999 conceptual model was constructed using MODFLOW and MT3DMS (Zheng and Wang, 1998) codes. As with the 1998 model, the 1999 numerical model was calibrated to inflows to the exploratory decline. The 1999 numerical model was used to predict inflows to the open pit and underground mines at the site during the feasibility stage of mine planning.

Based on the model results and available field data, it was recommended that mine inflow quality and quality, as well as hydraulic head and groundwater quality in monitoring wells to be installed near the mines, be monitored and reviewed on a continuous basis during mining. These data were to be used as a basis for comparison with the model predicted values and the model recalibrated, if necessary. The model would then be used for long-range planning of water management.

3. OBSERVATIONS DURING MINING

Open pit mining of the A154 N and S kimberlite pipes was initiated in 2002. After approximately one and a half years of mining, groundwater inflows to the A154N/S pit were approximately two times greater than predicted by the base case model. This discrepancy was within the range of the expected uncertainty in predicted pit inflow due to the uncertainty in model parameters; however, model simulations were conducted to determine the source of the observed discrepancy. Multiple explanations for the difference between observed and predicted inflows were proposed at that time, including uncertainty in the hydraulic conductivity of shallow competent bedrock, flow through shallow sediments, a high conductivity pathway created by the flooded exploration decline, and a highly permeable fractured rock zone.

Preliminary model simulations were conducted to assess the most likely source of the large inflows. Results of these simulations indicated that the most likely source of the greater than predicted inflows was a highly permeable FRZ associated with a fault zone, referred to as Dewey's Fault (Figure 6). This fault zone was uncovered during mining and a survey of seepage in the A154 N/S conducted in late 2003 suggested that at least 50% of groundwater inflow to the pit originated from this feature.

Figure 6. The FRZ associated with Dewey's Fault in the wall of the A154N/S Pit

4. CONCEPTUAL MODEL 2004

In mid-2004, a fourth revision to the conceptual model and corresponding numerical model for the site was undertaken. This included the incorporation of shallow sediments, weathered bedrock, a permeable FRZ associated with Dewey's Fault, and the as-built configuration of the dike around A154N/S pit into the numerical model for the site (Figure 7).

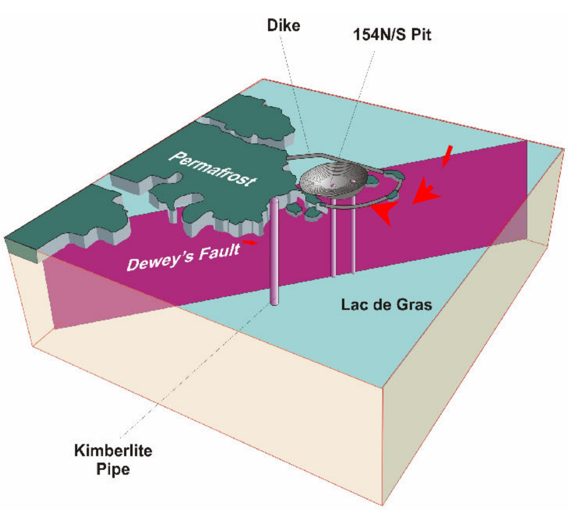

Figure 7. Conceptual Model 2004

The initial hydraulic properties for the weathered bedrock and shallow sediments were based on the results of hydrogeologic testing. The contribution of these components to pit inflow was found to be significant only in the very early stages of mining.

In preliminary simulations, the FRZ associated with Dewey's Fault was assumed to be 30 m wide with a hydraulic conductivity of 3×10^{-5} m/s from the ground surface to 500 m depth. Beyond 500 m depth, the hydraulic conductivity of the fault was assumed to be 1×10^{-5} m/s. Based on these modelling results in was recommended that additional testing be undertaken in the FRZ associated with Dewey's Fault to accurately assess its hydrogeologic properties and width.

5. DEWEY'S FAULT

The field program to investigate the hydrogeologic properties of Dewey's Fault included core logging and the collection of fluid temperature and electrical conductivity, caliper, optical and acoustic televiewer logs. In addition, both packer tests and a pumping test were performed in the fault zone.

The results of the field investigations indicated that the FRZ associated with Dewey's Fault is about 100 m wide and the inclination is approximately vertical. The FRZ does not consist of a uniform highly permeable zone, but is composed of sparsely spaced highly permeable discontinuities within a lower permeability pseudo-matrix. The fracture spacing in Dewey's Fault was found to be virtually identical to that of the relatively competent bedrock. Depending on the orientation of a borehole drilled within the FRZ, none or many of these highly permeable fractures would be intersected. In addition, as shown on Figure 8, the probability distributions for the hydraulic conductivities measured from packer testing in the FRZ and the country rock overlap to a large degree. Because of the nature and distribution of fractures within Dewey's Fault it was found that all the logging data (televiewer, core logging, and fluid logging) needed be used together in order to identify the FRZ. Figure 9 shows an example of a data synthesis plot that includes all these data for one of the boreholes and the identification of the FRZ associated with Dewey's Fault as a zone of enhanced hydraulic conductivity.

The late 2004 re-calibration of the numerical hydrogeologic model involved revisions to the original numerical model of the site so that the model predicted water quality and quantity matched the measured values in the groundwater inflow to the A154 Pit. During calibration, the progress of mining was simulated using as-build pit shells provided by DDMI for October 2003, March 2004, and July 2004. The model was also calibrated to the response observed during hydrogeologic testing of Dewey's Fault that was undertaken in 2004, water level drawdowns measured in piezometers along the dike perimeter since the initiation of mining in the A154N/S pit and to observations made during seepage surveys conducted in October 2003 and July 2004.

During model calibration, the model was run repeatedly and the model parameters were adjusted until model predictions were in reasonably good agreement with field observations and measurements. During calibration, the hydraulic conductivity of the competent bedrock at the site was virtually unchanged from the value used in the 1999 model.

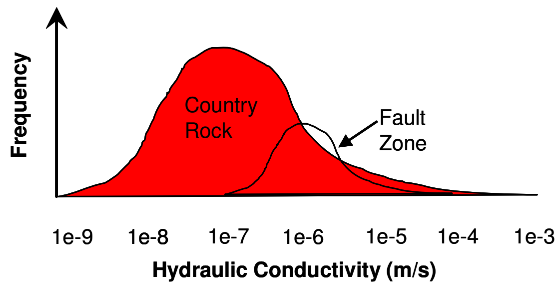

Figure 8. Conceptual Representation of the Results of Packer Testing

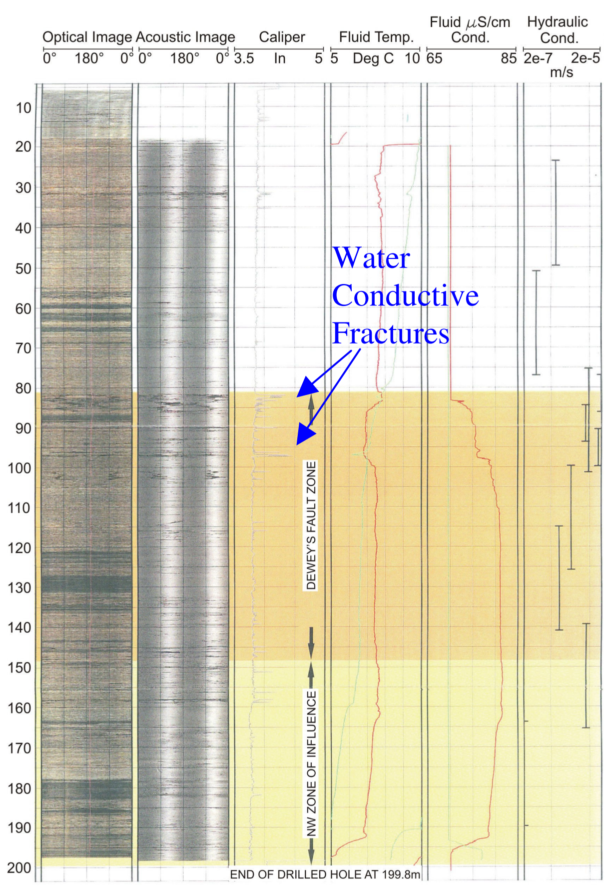

Figure 9. Borehole Data Synthesis Plot

An evaluation of the predictive capabilities of the site-scale model was performed in 2005. In this evaluation the numerical model that was calibrated in late 2004 was used to predict inflows to the 154N/S Pit and the hydraulic heads in the pit walls for 2005. These predictions were then compared to the observed values for 2005. If the predicted and observed values were similar then the model was considered to be verified and capable of providing reasonably accurate predictions of future mine inflows and hydraulic heads. These model simulations were done *without* any modification to hydrogeologic parameters that were used in the model calibration of late 2004.

A comparison of model predicted quantity and quality of inflow to the A154 N/S Pit to the observed values up to the end of 2005 indicated that the model provided an accurate predictive tool for inflow quantity and quality.

6. DISCUSSION

The development of the conceptual hydrogeologic models and their corresponding numerical models for the Diavik Project followed a logical and usually effective methodology. The results of each successive model were used to direct future field investigations. The aim of each of these investigations was to develop a more accurate hydrogeologic model.

Once mining began at Diavik, it was found that the final pre-mining model underestimated the quantity of groundwater inflow to the mine. Although the hydraulic conductivity of the relatively competent country rock was found to be reasonably accurate, a narrow FRZ (representing less than 10% of the open pit wall) of enhanced permeability resulted in nearly twice as much inflow as was predicted by the final pre-mining model.

Testing during mining indicated that the FRZ was not a zone of uniform high permeability but was comprised of highly permeable vertical fractures that were sparsely spaced within the zone. These characteristics made it difficult to detect this zone using only core logging and packer tests in individual boreholes. Rather several downhole investigative methods including core logging, packer testing, televiewer and fluid logging, were used together to identify a zone of enhanced permeability associated with Dewey's Fault.

7. ACKNOWLEDGEMENTS

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