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Application of statistical approaches to analyze geological, geotechnical and hydrogeological data at a fractured-rock mine site in Northern Canada

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Abstract Mine site characterization often results in the acquisition of geological, geotechnical and hydrogeological data sets that are used in the mine design process but are rarely co-evaluated. For a study site in northern Canada, bivariate and multivariate (hierarchical) statistical techniques are used to evaluate empirical hydraulic conductivity estimation methods based on traditional rock mass characterisation schemes, as well as to assess the regional hydrogeological conceptual model. Bivariate techniques demonstrate that standard geotechnical measures of fracturing are poor indicators of the hydraulic potential of a rock mass at the study site. Additionally, rock-mass-permeability schemes which rely on these measures are shown to be poor predictors of hydraulic conductivity in untested areas. Multivariate techniques employing hierarchical cluster analysis of both geotechnical and geological data sets are able to identify general trends in the data. Specifically, the geological cluster analysis demonstrated spatial relationship between intrusive contacts and increased hydraulic conductivity. This suggests promise in the use of clustering methods in identifying new trends during the early stages of hydrogeological characterization.

Keywords Fractured rocks · Hydraulic testing · Geotechnical data · Statistical modeling · Canada

Introduction

Groundwater can have a detrimental effect on slope/tunnel stability, increasing operating costs of both open pit and underground mining operations (Wyllie and Mah 2004; Beale 2009). Its presence can affect the design of excavations in two important ways. First, fluid pressure within discontinuities and pore spaces reduces the effective stress leading to a reduction in shear strength (Piteau 1970). Second, depending on the groundwater conditions, inflows can occur that may lead to specific water-management requirements within excavations. Excessive inflow or high water tables may result in a loss of access to part or all of the mine, increased costs associated with blasting, wear and tear on equipment, inefficient hauling, and unsafe working conditions. Fluid pressure and saturation state may, however, be controlled by an effective dewatering/depressurization plan (Sperling 1990; Sperling et al. 1992; White et al. 2004; Rodriguez et al. 2008). If these plans are designed effectively, they may also allow for steeper pit walls leading to long-term cost savings. However, these plans can have relatively high initial capital costs, require operator commitment to be implemented effectively, and can require significant lead time to allow for proper drainage. As a result, early characterization of the hydrogeological system and identification of characteristics that may influence stability are important for proper slope design and the design of effective dewatering and depressurization systems.

Characterization of the hydrogeological regime at most hard-rock (metamorphic and igneous) mine sites is commonly characterized by fracture-controlled groundwater flow, with complex flow dynamics owing to the presence of discrete fractures, fracture and fault zones, and a low permeability rock matrix (Fetter 1994; Caine et al. 1996; Singhal and Gupta 2010). Hydraulic properties of the rock mass are found to vary in relation to the complex interplay between in-situ stress, rock matrix properties and fracture characteristics, including aperture, density, persistence, orientation, interconnectivity, fill, and roughness (Snow 1970; Witherspoon et al. 1980; Lee and Farmer 1993; Zimmerman and Bodvarsson 1996). Targeted evaluation of hydraulic properties through traditional hydraulic testing methods (e.g. pumping, injection and/or slug testing) are cost prohibitive during the early stages of mine site characterization (Bellin et al. 2011). Thus, the use of empirical methods, which can

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estimate hydraulic properties from qualitative rock-mass-characterization schemes remain enticing, due to lower costs compared to traditional methods (Gates 1997; Hsu et al. 2011).

The use of empirical methods is a common practice in the geotechnical community, with borehole logging typically conducted to characterize the block shape and size, as well as the fracture surface conditions. This is done through the use of a series of categorical descriptors using systems such as the geological strength index (GSI) or rock mass rating (RMR) (Bieniawski 1973; Hoek et al. 2002). The end result is an estimation of the rock mass strength characteristics based on degree and type of fracturing. Since, hydrogeological studies are typically piggy-backed on geotechnical investigations to reduce exploration costs, cross correlation between data sets can provide additional insights into the role of fracturing on fluid flow (Bellin et al. 2011).

The purpose of this study is twofold: First, an evaluation of empirical hydraulic conductivity estimation methods based on traditional rock-mass-characterization schemes is explored through bivariate and multivariate (hierarchical) statistical techniques. Second, the study attempts to integrate the geological, geotechnical and hydrogeological data to assess the regional hydrogeological conceptual model for a northern mine site. To the authors' knowledge, this is a novel approach to hydrogeological characterization at a mine site. Finally, recommendations are provided to improve current rock-mass-characterization schemes.

Study site

Data for this study were collected at an undisclosed mine site located in Canada (Fig. 1). The geology of the site is characterized as a greenstone-hosted, quartz-carbonate vein, lode-gold deposit. Mineralization trends are hosted within regional antiformal and synformal folds, formed during syn- to post-peak metamorphism. Gold mineralization is considered coeval with quartz vein emplacement within the hinge zones of the regional folds. The site is cross-cut by a series of post-peak metamorphic diabase dykes with contact metamorphic haloes extending up to 20 m into the country rock. Late stage localized brittle faulting and regional shearing are observed throughout the region, with faults generally displaying dips of greater than 70°.

The general groundwater conceptual model for the site is considered unique to northern regions due to the presence of permafrost in the near surface. Frozen ground acts as an impermeable layer which restricts recharge, discharge and movement of groundwater, limiting the volume of unconsolidated material and bedrock in which groundwater may be stored (Williams 1970). Permafrost varies locally in thickness, areal extent and temperature as a result of variations in the thermal properties of the host material, climate, topography, geothermal gradient, vegetation, geology and hydrogeology. Research conducted in unconsolidated units of the Arctic Coastal Plain and its surrounding areas has shown that the permafrost extends to depths as great as 610 m, preventing the downward percolation of groundwater from snowmelt (Williams and van Everdingen 1973). However, even in the most northern climates, permafrost is not spatially continuous. Instead, zones of unfrozen ground, referred to as taliks, may exist that have small areal extent and persist from year to year (Yershov 1996). Taliks are typically located beneath lakes and may be either open, in that they penetrate the whole permafrost stratum, or closed and isolated from the lower groundwater system. The hydrogeology of the site is generally controlled by the presence of these taliks and is considered a low flux, lake-dominated flow system, with the highest hydraulic conductivities found within the taliks (Fig. 2).

The level of the water table is found to be controlled regionally by the locations of various lakes, which are frozen over for approximately half the year. Low hydraulic conductivity and low gradients throughout the region indicate that the overall groundwater flux is minimal. Groundwater recharge is also considered minimal and assumed not to fluctuate significantly throughout the year. This is due to the taliks providing the only direct recharge routes for groundwater flow and minimal fluctuations in annual lake levels.

Methodology

Hydrogeological data collection

Hydraulic conductivity data were collected using a packer-isolation, injection testing methodology. Tests were conducted synchronously with active drilling and guided by onsite hydrogeologists specifying test zone intervals during the drilling process. Intervals were selected to facilitate a random sampling of various geological features including, stratigraphic units, lithologic contacts and faults. While an attempt was made to test as many zones as possible, the limited number of samples means that some features were likely missed during the characterization. Although this is not ideal, it is common during such characterization studies, given the limited budget. Testing was conducted by first pulling back drill rods and exposing desired intervals. Next, a single hydraulic packer was used to seal the desired test interval below the drill rods.

Test zones varied between 6.0 and 108.0 m, with an average length of 48.6 m. Depths varied between 12.5 m below ground surface (mbgs) and 489.0 mbgs with an average depth of 175.5 mbgs. Boreholes were inclined between approx. 60 and 80°; however, presented depths have been converted to mbgs. Boreholes were HQ-sized diamond drill rods (hole size = 96 mm). Borehole geophysics was not conducted on any of the tested boreholes. Tests were conducted both in summer and winter, with summer testing near lake boundaries and winter testing underneath the lakes since winter drilling could be carried out from atop the ice.

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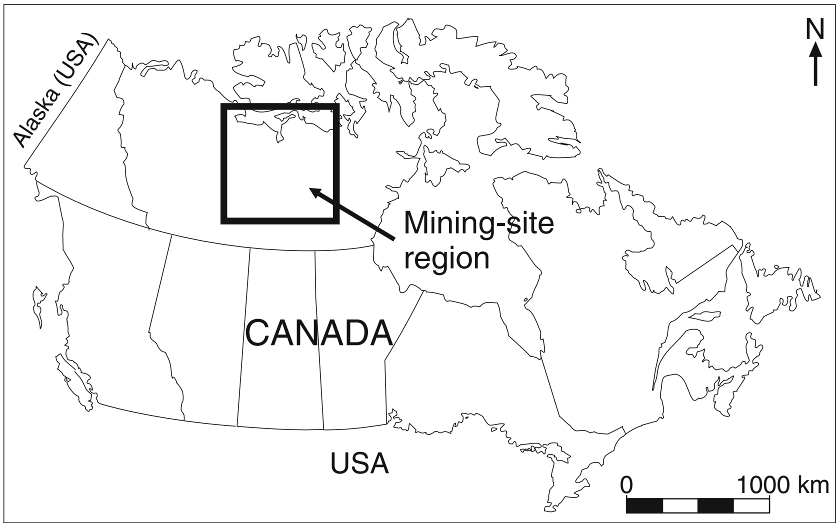

Fig. 1 General location of mining region understudy

Injection testing was conducted using the five-step Lugeon testing methodology, which is analogous to a step test (Lugeon 1933). The method involves injecting water in a series of fixed “steps” into a test zone at a specific pressures and recording the resulting flow rates once steady-state conditions have been achieved. The data collected from the Lugeon test were analyzed using the Thiem method (Singhal and Gupta 2010). A total of 43 hydraulic tests were analyzed using this method. The number of tests within each borehole varied between 1 and 5, with a total of 16 holes tested.

Rock mass parameters

Rock-mass-classification systems have gained widespread use in geotechnical design studies, providing a powerful aid in estimating rock mass strength values (Terzaghi 1946; Lauffer 1958; Deere et al. 1967; Wickham et al. 1972; Bieniawski 1973; Barton et al. 1974). At the study site, the modified rock mass rating (MRMR) system was used for rock mass classification (Laubscher 1975; Laubscher and Taylor 1978; Laubscher 1990; Laubscher and Jakubec 2001; Jakubec and Esterhuizen 2007). The system involves first estimating in-situ rock mass rating (RMR) values, based on current subsurface conditions, then modifying results to MRMR values based on projected future mining conditions. The current study focused on unmodified RMR values for statistical analysis, as they best reflect the current in-situ conditions under which hydraulic testing was conducted.

Unmodified RMR values range between 0 and 100 and are composed of three components: intact rock strength, fracture spacing and joint condition. Logging is conducted on a domain basis, with core visually subdivided into a series of zones with similar geomechanical characteristics. The intact rock strength (IRS) component is a measure of the uniaxial compressive strength. This parameter was largely ignored because intact rock strength is assumed to

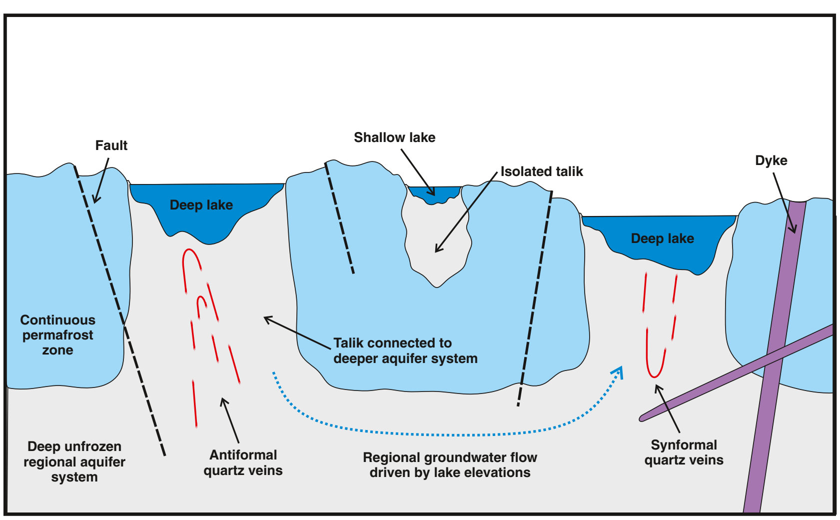

Fig. 2 Generic, schematic regional hydrogeological conceptual model for groundwater flow at the northern Canadian mine sites

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have little effect on the overall groundwater flow when compared to parameters describing the fracture state.

The fracture spacing component is a measure of the distance between all non-cemented, natural discontinuities within the rock mass. Laubscher (1990) presented two techniques to assess the effects of fracture spacing. In the first approach, fracture spacing is assessed using the rock quality designation (RQD) and fracture spacing separately. The alternative technique is to assess the relative fracture frequencies per meter of each individual fracture set. Data at the mine site were collected using the former of these two approaches.

RQD is a core recovery technique commonly employed within the mining industry, which assesses the percentage of core recovered that is bounded by discontinuities and greater than 100 mm in length compared to the total length of recovered core. The index has been in use since the mid-1960s as a measure of the rock quality (Deere and Deere 1988). The parameter is typically used in combination with either the number of joint sets (Q system) or the joint spacing (MRMR system) to estimate block size. The usefulness of block size estimation techniques in the geotechnical literature cannot be understated, as most rock-mass-classification schemes and/or failure criterion either directly or indirectly rely on block size in the determination of rock mass strength (Deere et al. 1967; Bieniawski 1973; Barton et al. 1974; Laubscher and Taylor 1978; Laubscher and Jakubec 2001; Hoek et al. 2002; Palmstrom 2005).

Fracture spacing ratings are assigned by taking into consideration the distance between all non-cemented discontinuities and the number of discontinuity sets. Fractures are considered to be any discontinuity which fully cross-cuts the borehole and may include joints, fissures, fractures, cracks, or natural breaks. The separation of mechanical and natural breaks is an important part of the overall assessment procedure as the extensive disturbance from the drilling process and core handling procedures can easily double the number of breaks within a length of drill core. If this is not taken into consideration, fracture frequencies could grossly overestimate the in-situ conditions. Bedded and/or foliated rocks are particularly prone to this, with core breaking at the surface during the inspection of the core. A hard cap of one fracture per 2.5 cm or 40 fractures per meter is typically used, as this represents the highest fracture frequency allowed in the Laubscher MRMR method. In addition, a maximum of three discontinuity sets are considered, as the method assumes that any other minor sets merely modify the shape of the block, but do not change its overall size (Laubscher 1990).

In addition to block size considerations, the Laubscher MRMR system also takes into account fracture fractional properties, through the characterization of large- and small-scale waviness, wall alteration, fill and in some cases the presence and/or absence of water along discontinuity surfaces (Laubscher 1990). The common integration of hydrogeological models or pore pressure distributions into geomechanical models has limited the usefulness of water content parameters in most rock classification systems. In addition, water content observations can be difficult to collect or subjective when using diamond drill sampling techniques. As such, the water content parameter is typically not recorded at most mine sites, including the one used in this study. Instead, the study focused on the effects of fracture roughness and fill on rock mass permeability. For a full description of the fracture conditions parameters used in this study refer to Laubscher (1990) or Laubscher and Jakubec (2001).

In addition to the standard parameters collected for calculation of the Laubscher RMR values, additional data were collected including micro-defect intensity and presence or absence of major structures. The micro-defect intensity is defined as the intensity of alteration of the rock masses, which results in a reduction of the overall rock mass strength. Values are assigned between 0 and 3, with a value of 0 indicating un-altered rock and 3 indicating heavily altered rock. Major structures are defined as any significant feature in the core that the geotechnician determines would cause a considerable decrease in the strength of the rock mass. Major structures are further broken down into four categories, namely: broken, gouge, fractured and sheared zones.

The geotechnical logging procedure described above was carried out for all hydraulic test intervals used in this study. Data were collected using 3-m long split-tube coring techniques (triple tubes), with the exception of two boreholes, where double-tube core barrels were used. Data collection was conducted by on-site geotechnicians at the drill rigs while core was still in split tubes. The data later underwent quality assurance and quality-control checks though a visual assessment of borehole photographs to ensure that collected data matched drill core. Geotechnical parameters presented herein are averaged results across the packer test intervals. Table 1 shows a summary of the various rock mass characteristics measured in this study.

Permafrost-related parameter–borehole distance from lakes

The general hydrogeological conceptual model proposes the existence of a thick permafrost zone with isolated unfrozen taliks beneath the regional lakes. Talik margins are here assumed to be near vertical, with frozen-unfrozen boundaries forming along the edges of regional lakes (Fig. 2). Based on this conceptual model, permafrost zones are assumed to be impermeable. Conceptually, isolated pockets of unfrozen ground can occur within permafrost due to brine concentration through freezing processes; however, this has not been found in tested areas of the study site (Gosink and Baker 1990).

While the conceptual model includes impermeable conditions within permafrost zones, thawing around active boreholes due to drilling processes are likely to cause a small permeable halo to form around test intervals, although the size of such a halo is uncertain, but likely of limited extent. As a result, hydraulic testing within permafrost zones is likely to show a low permeability, as opposed to impermeable conditions, when applying the Lugeon method.

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Table 1 Summary of rock mass parameters used in this study

Geotechnical parameter	Description
Rock quality designation (RQD)	The RQD was developed by Deere (1967) as a qualitative measure of the percentage of “good” quality rock within a borehole. The parameter is defined as “the percentage of intact core pieces longer than 100 mm in the total length of core”
Fracture frequency	The fracture frequency is defined as the number of discontinuities per meter which fully cross-cuts the borehole. Discontinuities included in this measurement include any joints, fissures, fractures, cracks, or natural breaks
Fracture sets	Fracture sets are defined as a group of fractures within a single borehole run which share a similar alpha angle. The alpha angle is the minimum angle between the maximum dip vector of the discontinuity and the core axis. As per the Laubscher MRMR system, a maximum of three fracture sets are recorded (Laubscher 1990)
Micro-deformational intensity	Micro-deformational intensity is a qualitative measure of the degree of alteration within the drill run that causes a reduction in the strength of the rock matrix. Values vary between 0 (unaltered) and 3 (heavily deformed)
Fracture roughness	Fracture roughness at the drill core scale is a measure of the unevenness of the fracture surfaces and tends to indicate the degree of movement that may have occurred along the fracture plane. Roughness data were collected using the International Society for Rock Mechanics scale, which varies roughness values between 1 and 9 (Barton 1978). The fracture roughness values were used in the statistical analysis by subdividing fractures into stepped, undulating and planar surfaces prior to comparisons with hydraulic conductivity estimates
Fracture fill	Fracture fill is an indication of the degree of alteration, buildup of precipitates, or gouge along fracture surfaces. Data were subdivided into four fill categories based on geotechnical logs, namely; unfilled fractures, non-softening filled fractures, softening fractures, and gouge filled fractures. ‘Softening’ filled fractures refer to soft deposits that can be chipped off of the fracture surfaces with a finger nail (e.g. clays, gypsum or fine micas), whereas, ‘non-softening’ deposits indicate harder material (e.g. calcite or quartz)

Based on the conceptual model, a spatial relationship should exist between hydraulic conductivity and borehole location relative to lake margins, with low hydraulic conductivity observed near lake boundaries. In order to test this hypothesis, the distances between test zones and lake boundaries were calculated using easting and northing locations for the midpoint of each packer test and 1:50,000 scale shapefiles of regional water bodies imported from the Natural Resources Canada online file directory (NRCAN 2011). Euclidean distance between packer tests and lake boundaries were then calculated within the software package ArcGIS (ESRI 2011).

Permeability classification schemes

Two permeability classification schemes are explored within this study, which have been proposed to empirically estimate rock mass permeability, namely, the hydropotential (HP) scheme of Gates (1997) and the “HC-system” of Hsu et al. (2011). These schemes attempt to rate the relative permeability of an interval of core using a simplified rock-mass-rating system. Both systems were designed for use in sedimentary rock environments, and have not been validated for other rock types. Nevertheless, given that there are few such methods, it was felt worthwhile to test the applicability of such systems in our case study.

HP scheme

The HP scheme proposed by Gates (1997) is based on the Q-system for geotechnical classification by Barton et al. (1974), with both systems using a similar empirical formulation. The system is based on six parameters, which are used to define the degree of fracturing, fracture surface conditions and saturation state of the fractures. Using these parameters an HP rating is calculated by:

$$\mathrm{HP_{rating}} = \frac{\mathrm{RQD}}{J_n} \times \frac{J_r}{J_k \times J_{af}} \times J_w \qquad (1)$$

where RQD is the rock quality designation, J_n is the fracture number, J_k is the fracture hydraulic conductivity, J_{af} is the fracture aperture and J_w is the joint water content. It should be noted that although J_k is referred to as the fracture hydraulic conductivity, the parameter is used to describe the joint infill material.

The HP scheme was originally designed to estimate rock mass hydraulic properties using outcrop data, with aperture (J_{af}) and fracture saturation (J_w) measured directly from the scanlines. However, for the purposes of this study, neither aperture nor fracture saturation data were available due to an inability to collect these parameters during drilling and recovery activities. As a result, a value of 1.0 was given to each of the parameters in final $\mathrm{HP_{rating}}$ calculations. The use of constant values should not have a significant effect on the final results, as the statistics are based on a rank-order analysis, and are therefore unaffected as the data ordering remains unchanged.

HC-system

An alternative to the HP scheme was devised by Hsu et al. (2011), which relies on the rock quality designation (RQD), depth, gouge content and lithology to estimate

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rock mass hydraulic conductivity. Ratings for the proposed system are calculated from:

$$HC_{rating} = (1-RQD) \times DI \times (1-GCD) \times LPI \quad (2)$$

where RQD is the rock quality designation, DI is the depth index, GCD is the gouge content designation and LPI is the lithology permeability index. Within this system, the depth index is calculated from:

$$DI = 1-\frac{L_c}{L_t} \quad (3)$$

where L_c is the depth to the midpoint of the hydraulic test, and L_t is the total length of the borehole. The gouge content designation is calculated from:

$$GCD = \frac{R_g}{R_t-R_s} \quad (4)$$

where R_g is the total length of gouge content, R_t is the total length of the drill run, and R_s is the total length of solid core. The lithology permeability index is a rock type specific constant used to describe the matrix permeability.

Statistical analysis

In contrast to conventional empirically based groundwater studies, this section outlines a methodology for a statistical approach to groundwater conceptual model development. Two main statistical approaches were employed, namely bivariate analysis and multivariate (hierarchical) cluster analysis. The methods were used to determine the relationships between the various rock mass properties and hydraulic conductivity. Table 1 lists the various parameters that were analyzed. A summary of the statistical techniques is provided in Table 2.

Bivariate analysis

Prior to bivariate analyses, normality tests were conducted on the geotechnical parameters in order to determine if parametric or non-parametric statistical methods should be used. Normality testing was conducted using the Shapiro-Wilk's Test (Shapiro and Wilk 1965). Based on the results of the analysis, the null hypothesis, that a sample originates from a normally distributed population, was rejected for all geotechnical parameters.

As a result, Spearman's rank order correlation was used to quantify the association between the various geotechnical parameters and hydraulic conductivity. It is a non-parametric technique for measuring the statistical dependence between two variables (Spearman 1904). The method assesses how well the relationship between two variables can be described using a monotonic function. The Spearman correlation coefficient or Spearman's rho (r_s) is calculated by:

$$r_s = 1-\frac{6\sum D^2}{n(n^2-1)} \quad (5)$$

where D is the difference between ranks of corresponding observations and n is the number of paired observations. Similar to the Pearson's product–moment correlation, Spearman correlation coefficients of +1 and −1 are obtained when each variable is a perfect function of the other (Pearson 1896). The advantages of the technique over the Person's product–moment correlation is that variables do not need to follow a normal distribution, the method is not very sensitive to outliers, and it is applicable to data collected on ordinal, interval or ratio scales. In addition to the correlation coefficient, standard hypothesis testing was conducted, which tested the null hypothesis that the ranks of one variable do not covary with ranks of the other variable (McDonald 2009). Hypothesis testing was conducted using the Hammer et al. (2001) software PAST. A significance level (p-value) of 0.05 was used throughout the study. Bivariate analyses were conducted within semi-log space with hydraulic conductivity on a logarithmic scale and rock mass parameters on an arithmetic scale.

Un-paired group analysis

The Mann–Whitney test was used to compare tests conducted in permafrost and talik zones. The method is a non-parametric test, which assesses a null hypothesis that two data sets originate from the same population (Hammer 2011). The test involves the calculation of the U statistic:

$$U = n_1 n_2 + \frac{n_1(n_1+1)}{2} - T_1 \quad (6)$$

where n_1 and n_2 are the number of data points in the first and second sample groups, and T_1 is sum of ranks of the first sample set. The U statistic varies between zero and the product of the sample size of the two data sets. Following calculation of the U statistic, results were used to test the null hypothesis against a significance level (p-value) of 0.05 within the software package PAST (Hammer et al. 2001)

Hierarchical cluster analysis

Cluster analysis groups similar observations within a data set (Jain et al. 1999; Jain 2010). The algorithms for conducting a cluster analysis are broadly classified into two primary groups: (1) hierarchical or agglomerative methods, and (2) partitioning methods (Kaufman and Rousseeuw 1990). For the purposes of this study,

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Table 2 Summary of statistical techniques

Statistical technique	Description
Shapiro-Wilk's test	Normality test, conducted to determine if a sample set originates from a population with a normal (Gaussian) distribution
Spearman's rank order correlation	Non-parametric measure of the correlation between two data sets, using a rank-order analysis. Values vary between −1 (strong negative correlation) and +1 (strong positive)
Mann–Whitney test	Test used to assess if two sample sets originate from the same population
Hierarchical cluster analysis	Subdivides a data set into a series of clusters based on the similarity between sample points. Used to identify board trends in the data sets

hierarchical methods were chosen as they do not require the user to pre-define a set number of clusters.

Hierarchical clustering methods work by first starting with n clusters, where n equals the number of observations (Jambu and Lebeaux 1983). Next, clusters are grouped by merging the two closest clusters based on the relative distances between them; these Euclidean distances can be thought of as the amount of separation between observations within a multi-parameter space (StatSoft 2007). The process is repeated, with each stage merging the next closest pair of clusters, until all the observations are grouped within a single cluster. Amalgamation of the clusters was done using Ward's (1963) method, which clusters observations to minimize within-group variance; this is done by minimizing the sum of squares of any two groups (Hammer 2011). The final product of the technique is a dendrogram, which is used to visually identify clusters and shows the progressive relationship among observations at increasing distances (Jain and Dubes 1988). Distances are normalized to values between 0 and 1 to give a percentage of similarity.

In this study, clusters were used to identify associations between the hydraulic conductivity and various parameters. Two cluster analyses were performed. The first (geotechnical cluster analysis) included hydraulic conductivity measurements and four key parameters assumed to influence these measurements: fracture frequency, number of major structures, depth of hydraulic test and distance from lakes.

The second cluster analysis (Geological Cluster Analysis) considered geological logs for the boreholes. The logs consisted of a simplified categorization scheme, with units categorized into broad geological categories. The first step in the cluster analysis involved converting the geological data from a nominal to binary scale needed for the cluster analysis. The conversion was done by creating a variable for each of the geologic units and assigning either a value of 1 or 0 depending on whether the particular geological unit is present (1) or not (0) within the packer test interval. Following data conversion, the cluster analysis was conducted using the geological and hydrogeological data.

All cluster analyses were conducted using the TIBCO Spotfire S+ software package (TIBCO 2010). Prior to inputting the parameters, data were normalized using a z-score transformation, in order to reduce excessive weighting of variables due to differences in measurement scales (Jain and Dubes 1988). Interpretation of the cluster analysis results was aided by summary statistics for the various clusters and box plots in order to determine which parameters were controlling the clustering algorithm.

Results

This section provides a summary of the statistical techniques applied to the study site. Techniques were applied to a total of 43 packer tests conducted within 16 boreholes. Hydraulic conductivity estimates were found to vary between 4.8×10^{-11} and 2.4×10^{-7} m/s, with a geometric mean of 1.6×10^{-9} m/s. Analysis of test interval size indicates that it does not have a significant influence on the results (regression coefficient = −0.29). Depth of the test interval shows a similar trend with a correlation coefficient of −0.28. Bivariate analyses are conducted using spatially averaged data (e.g. hydraulic conductivity, RQD, etc.), as geotechnical data are commonly collected in this manner at mine sites.

Bivariate analysis

General geotechnical parameters

The results of the Spearman analysis indicate a weak to non-existent correlation between the hydraulic conductivity and commonly collected geotechnical parameters: RQD, fracture frequency, number of fracture sets and micro-deformational intensity (Fig. 3). The strongest relationship is observed with fracture frequency; however, the correlation is weak with a Spearman coefficient of 0.33. The results are consistent with other studies, suggesting that other parameters, e.g. aperture, may have more control on the hydraulic conductivity (Romm 1966; Hamm et al. 2007; Singhal and Gupta 2010).

The overall poor correlation between the fracture frequency and hydraulic conductivity may be the result of the inability to distinguish transmissive and non-transmissive fractures. Morin et al. (1997) showed only approximately 18 % of fractures within a fractured rock aquifer is associated with fluid flow. The implication for this study is that the frequency of transmissive fractures is likely only a small percentage of the total fracture frequency, with the ratio of transmissive to total fractures likely varying between test zones.

Fracture roughness

Regression analysis of fracture roughness data indicates that no statistically significant correlation exists with either the stepped or undulating fractures. However, a weak positive correlation is found between the planar fractures and hydraulic conductivity (Table 3). The higher

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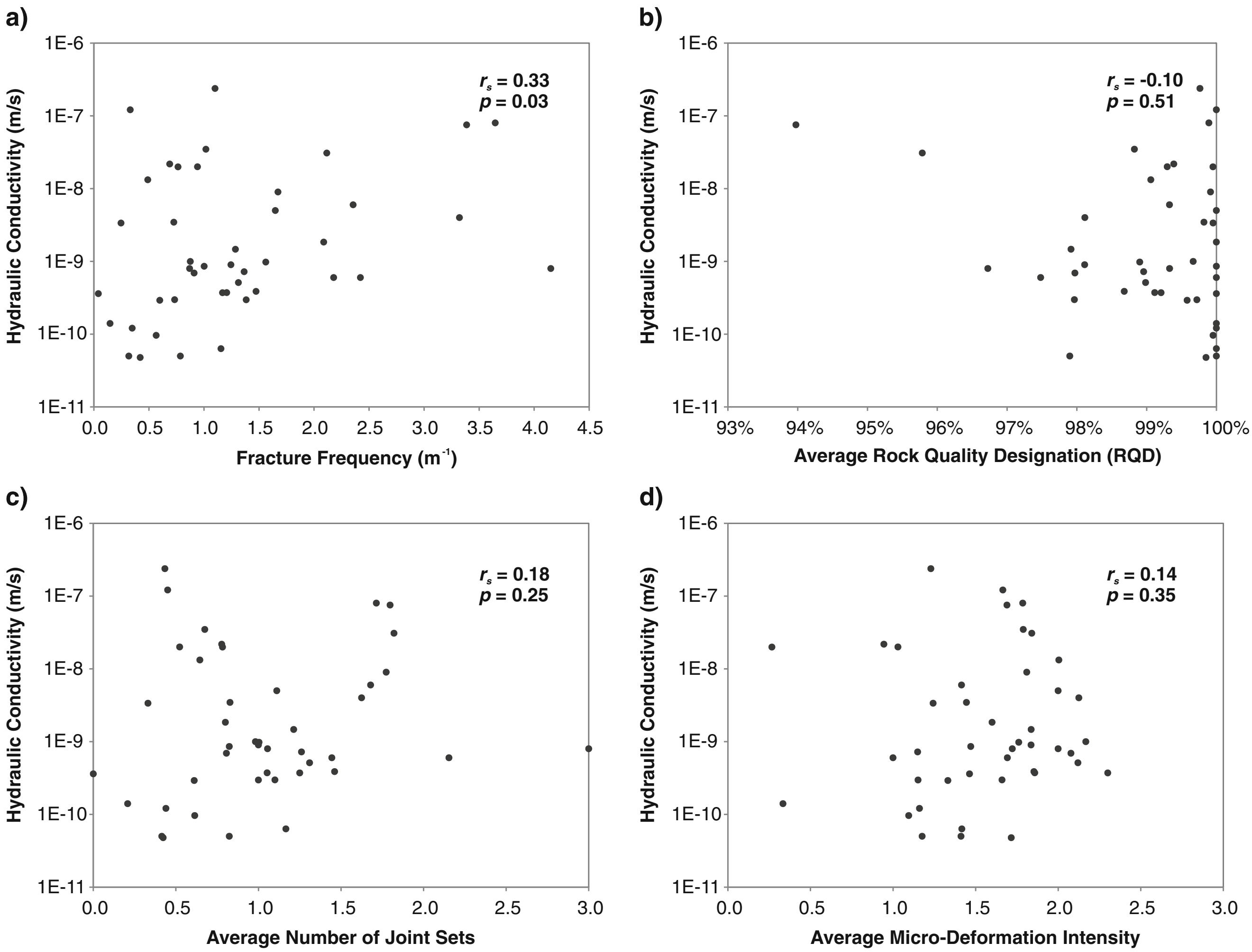

Fig. 3 Bivariate analysis of general geotechnical parameters

correlation coefficients calculated for the planar fracture surfaces compared to the stepped and undulating fracture surfaces indicate that fluid flow is likely restricted along fractures with rough surfaces and is more easily facilitated along smooth walled fractures. In concept, this is likely due to flow within fractures with rougher surfaces either being forced to flow in a more channelized manner, or exhibiting more turbulent behaviour (Romm 1966; Singhal and Gupta 2010).

Fracture fill

Regression analysis of fracture fill conditions indicates a weak to moderate, statistically significant correlation between unfilled fractures and hydraulic conductivity (Table 4). This is consistent with other studies which have observed a positive correlation between unfilled fractures and increased hydraulic conductivity (Banks et al. 1992, 1994). The same correlation is not observed between the other fill categories.

Distance from lakes

Mann-Whitney analysis of the data sets from talik and permafrost zones suggests that the two groups originate from independent populations (p-value=0.01). This is consistent with the conceptual model, which predicts lower hydraulic conductivities beyond lake boundaries. However, further exploration of the data indicates that tests performed within the assumed permafrost regions cluster in areas of low fracture frequencies (Fig. 4). Therefore, the observed low hydraulic conductivity values may actually reflect a lack of permeable fractures within the test zones. This trend of lower fracture frequencies

Table 3 Spearman rank-order results for fracture roughness

Parameter	r_s	p-value
Stepped fracture frequency (m^{-1})	0.26	0.09
Undulating fracture frequency (m^{-1})	0.14	0.93
Planar fracture frequency (m^{-1})	0.40	0.01

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Table 4 Spearman rank-order results for fracture fill

Parameter	r_s	p-value
Stained and unstained fracture frequency (m^{-1})	0.41	0.01
Non-softening fracture frequency (m^{-1})	−0.11	0.50
Softening fracture frequency (m^{-1})	−0.05	0.75
Gouge filled fracture frequency (m^{-1})	0.11	0.50

away from the regional lakes may reflect a regional trend of reduced fracture development away from emplaced ore bodies, as deposits are located beneath the regional lakes.

Rock-mass-permeability schemes

The HC-system and HP value rock-mass-categorization schemes were designed to estimate hydraulic conductivity values using in-situ rock properties (Gates 1997; Hsu et al. 2011). However, regression analysis from this study showed no statistically significant correlations between the HC-system and hydraulic conductivity, while the HP scheme only showed a minor statistically significant correlation (Fig. 5). These results are not altogether surprising given the poor correlation between RQD and hydraulic conductivity mentioned previously, which is used by both systems as an indicator of the degree of fracturing. Moreover, both systems assume that all fractures contribute equally to the overall hydraulic properties of the rock mass, and fail to explicitly distinguish between the frequencies of permeable and impermeable fractures. Finally, both systems assume average values for fracture properties, i.e. fill, roughness, etc., instead of exploring the influence of individual fractures.

Hierarchical cluster analysis

Geotechnical cluster analysis

Clusters were identified using hierarchical cluster analysis (Fig. 6a), based on a percent of similarity of 45 %.

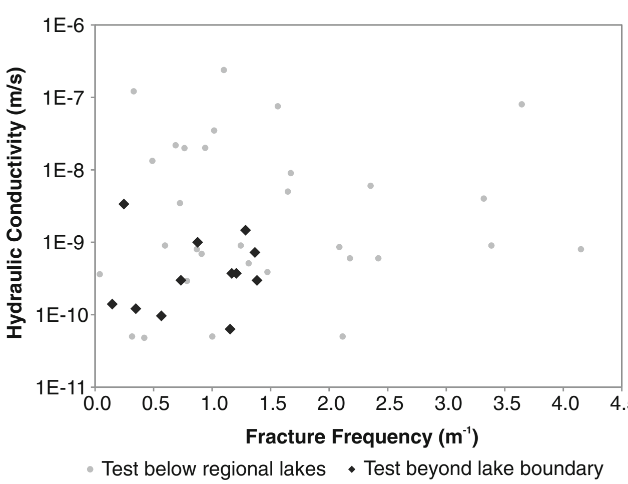

Fig. 4 Tests conducted below and beyond lake boundaries. Tests conducted beyond lake boundaries are found to coincide with low fracture frequencies

Summary statistics for the identified clusters are presented in Fig. 6b. Clusters A and B are both associated with tests conducted in the talik zones, with sub-clustering relating to the degree of fracturing and depth of testing. Differences between the clusters are due mainly to variability in the number of major structures, with low to moderate major structure frequencies observed in cluster B and none observed in cluster A. The large variability in hydraulic conductivity observed in clusters A and B make it difficult to associate particular studied parameters with higher permeabilities. However, the similarity between the clusters suggests that the presence or absence of major structures does not limit the possible range in hydraulic conductivity.

Cluster C remains an independent outlier and is associated with the highest number of major structures per meter, suggesting that the test was likely conducted within or near a fault zone. The presence of gouge within drill core and low hydraulic conductivity suggests that, if a fault is present, it may be acting as a barrier to groundwater flow. The final cluster (D) is associated with packer tests conducted within permafrost zones, and displays an overall lower average hydraulic conductivity than preceding clusters.

Although the geotechnical cluster analysis was able to identify a number of parameters that can together relate to hydraulic conductivity, no new significant associations were found in the data that were not already evident from the bivariate analysis. For example, although data points that are located a considerable distance from regional lakes are found to cluster with the lower hydraulic conductivities, this observation had been noted previously. Therefore, although the geotechnical cluster analysis helps to confirm the results of bivariate analysis, it does not appear to provide new information.

Geological cluster analysis

Figure 7a shows the results of the cluster analysis conducted using the geological logs for the boreholes. The first large cluster (A) is associated with the mafic volcanic (MV), deformation zone (DZ), and late mafic intrusion (MI) units. Hydraulic conductivities vary between 1×10^{-10} and 8×10^{-8} m/s, with a geometric mean of 8×10^{-10} m/s (Fig. 7b). The cluster can be further subdivided into three subsets. Hydraulic conductivities within clusters A_2 and A_3 generally display below average values, suggesting lower permeability within deformation zones and mafic intrusion units. In comparison, cluster A_1 displays the largest degree of variability, indicating that

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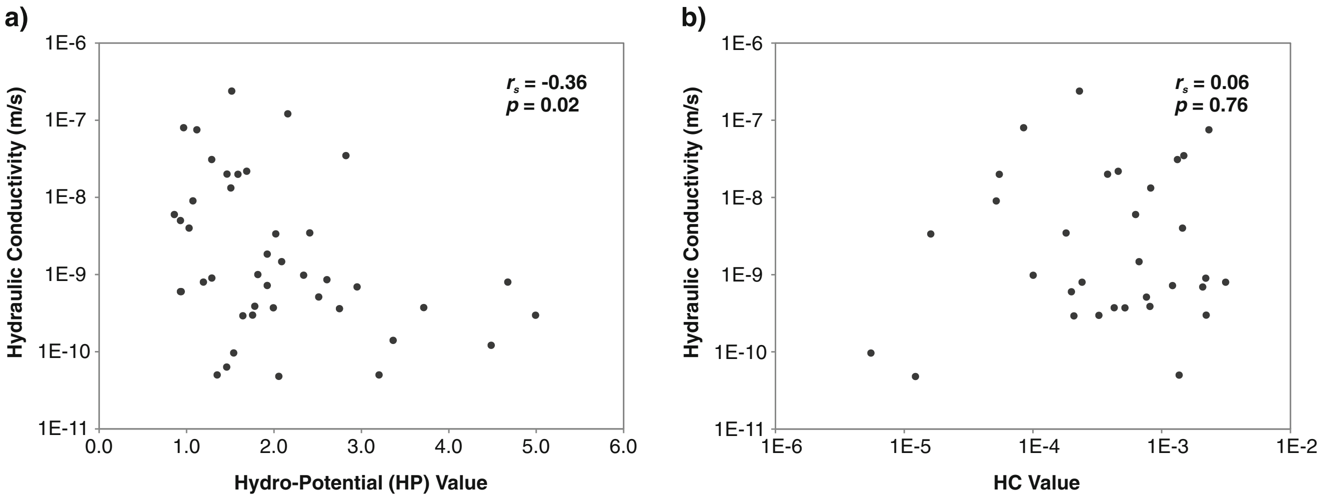

Fig. 5 Relationship between rock-mass-permeability-classification schemes and hydraulic conductivity data: **a** HP value and **b** HC value

the presence or absence of mafic volcanic is a poor indicator of overall permeability.

Cluster B is associated with tests conducted along the boundary of the diabase dykes (DD) and MV. The hydraulic conductivity within the cluster displays a bimodal distribution, with clusters B_1 and B_2 having geometric means of 4×10^{-8} and 3×10^{-10} m/s, respectively (Fig. 7b). The differences between the two clusters are the result of differences in the permafrost conditions, as all tests within B1 occurred beneath regional lakes.

Cluster (C) is associated primarily with the interbedded volcanic and sedimentary rock (VS) units. However, other lithologic units, including the epidote-bearing gabbro (EG), quartz vein (VN), intermediate volcanic (IV), and interbedded argillite and sandstone (WA), are also present. This cluster has the lowest geometric mean hydraulic conductivity at 5×10^{-10} m/s, and ranges between 5×10^{-11} to 3×10^{-9} m/s (Fig. 7b). Sub-clustering within C is based on the presence or absence of the interbedded wacke and argillite unit (WA).

The presence of both the MV and interbedded volcanic and sedimentary rock (VS) units defines cluster (D), although other units are also present. In general, hydraulic conductivities within this cluster are moderate for the site, with a geometric mean of 2×10^{-9} m/s and a range of 4×10^{-10} to 9×10^{-9} m/s (Fig. 7b). Subdivision of the unit into sub-units contributes little to the overall understanding of the site as each of the sub-sets display similar values.

Finally, cluster (E) is defined primarily by tests performed within the interbedded wacke and argillite (WA), argillite and siltstone (SAi), and wacke and sandstone (WS) units. Hydraulic conductivity values vary between 5×10^{-11} and 8×10^{-8} m/s, with geometric mean value of 2×10^{-9} m/s (Fig. 7b). The cluster can be further subdivided into two subsets based on the presence (E_1) or absence (E_2) of the quartz vein (VN) unit, with veined units displaying a higher hydraulic conductivity of 1×10^{-8} m/s compared to 4×10^{-10} m/s.

Based on the results of the geological cluster analysis, two main trends are identified. First, a large amount of variability exists within the MV unit, with hydraulic conductivity values ranging between 5×10^{-11} and 8×10^{-8} m/s (cluster A). Second, packer tests which straddle VN and DD boundaries are associated with higher hydraulic conductivities (sub-clusters B_1, B_2 and E_2).

Discussion

Usefulness of geotechnical data in hydrogeological characterization

The primary goal of the study was to assess the usefulness of cross-correlation between hydrogeological and geotechnical data sets. The initial assumption of the study was that groundwater is controlled by the fracture network, with high hydraulic conductivity features controlling the groundwater flow system within a low permeability matrix. However, the Spearman rank order correlation analysis showed only limited, statistically significant correlations between the fracture properties and hydraulic conductivity. The majority of fracture properties (i.e. fracture frequency, rock quality designation, etc.) were found to have no statistically significant correlations with hydraulic conductivity. This lack of statistical significance may be due to the small sample sizes; however, it raises the question that if groundwater flow is conceptualized as fracture-dominated in hard rock settings, why is there such a lack of evidence demonstrating this dependency? Traditional fracture network studies have generated discrete fracture networks (DFNs) which assume that most, if not all, fractures transmit fluid (Surrette and Allen 2008). However, if this were the case, a stronger statistical correlation between general fracture frequency and hydraulic conductivity would have been expected. Instead, statistically significant correlations were only observed when fractures were broken down into sub-categories. In one regard, these results are consistent with flow impeller studies which have shown that fracture flow into boreholes is limited to a small number of fractures (Morin et al. 1997). However, this raises a major question in the mine water industry, namely, given the limited number of transmissive fractures,

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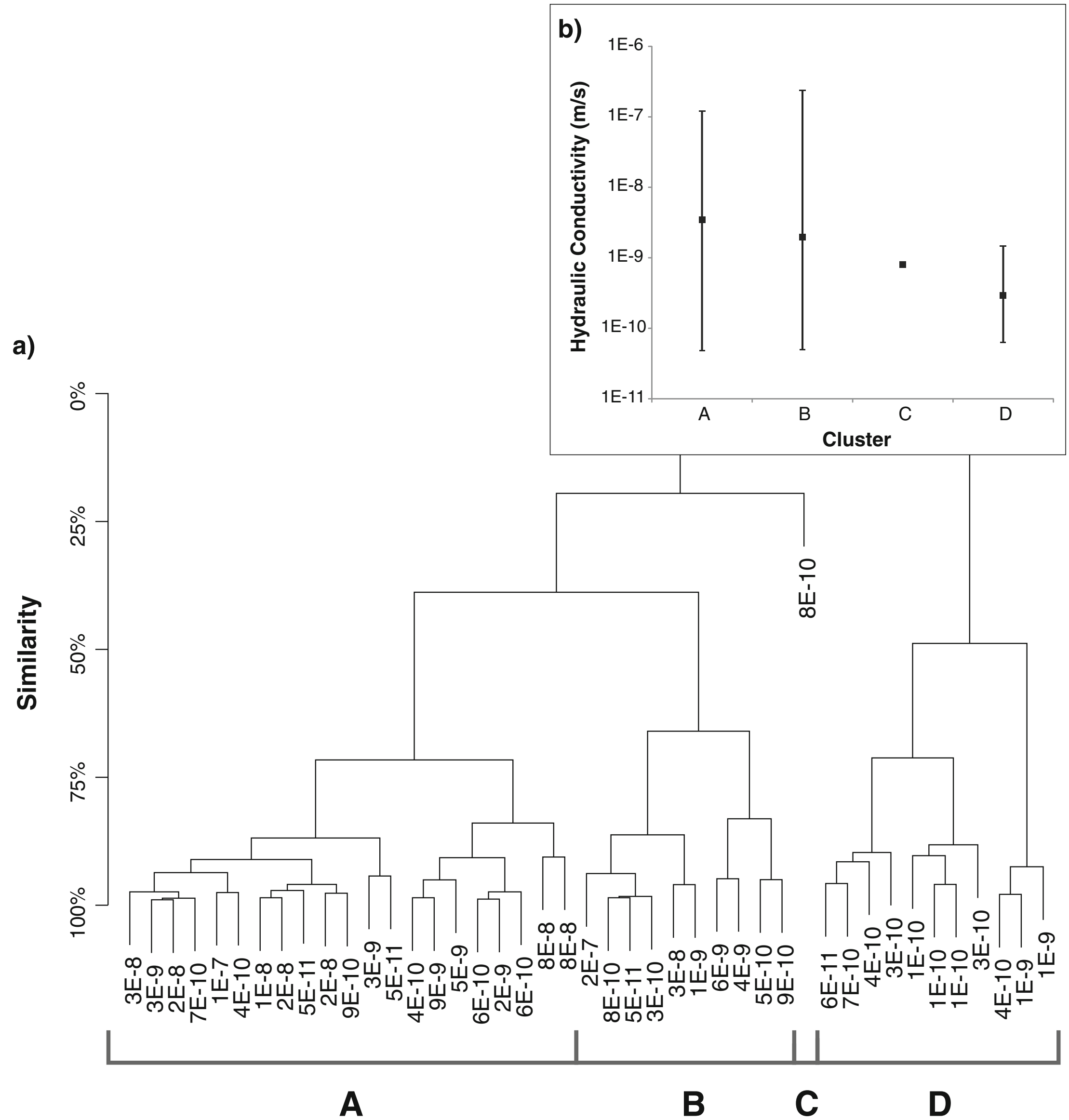

Fig. 6 **a** Hierarchical cluster analysis results for select geotechnical parameters (values are hydraulic conductivity results in m/s). **b** Hydraulic conductivity summary for sub-clusters, geometric mean (*squares*), minimum and maximum (*bars*)

how can borehole logging techniques be adjusted to better understand subsurface fluid flow?

Traditional geotechnical logging practices attempt to characterize the block shape and size through a series of categorical descriptors of the drill core. For example, the commonly employed Hoek-Brown failure criterion currently relies on the geological strength index (GSI; Hoek et al. 2002). This parameter is a quantitative representation of the block shape and fracture conditions that compose a rock mass. The problem with this representation from a hydrogeological perspective is that instead of collecting detailed data on individual fractures, rock mass data are collected with the idea of estimating average block shapes and internal friction coefficients. If future data are to be collected with hydrogeological needs in mind then a shift needs to occur in the way data are logged. A few rock mass permeability classification schemes have been proposed, including the HP and HC schemes (Gates 1997; Hsu et al. 2011). However, results from this research demonstrated that both systems are limited in their ability to predict hydraulic conductivity values from rock mass properties (Fig. 5). This limitation can be attributed to the selection of input parameters used in the formulation of both systems. This includes the over-reliance of RQD as an indication of the fracture state, despite its limitations in closely and widely spaced fracture systems (Palmstrom 2005). In addition, both systems assume that all fractures contribute equally to groundwater flow, despite this and other research indicating that flow is heterogeneously distributed within the fracture network (Banks et al. 1992, 1994).

The HP scheme is further limited by the fact that it was designed for use with outcrop data. As a result, the system relies on the use of fracture aperture and water content

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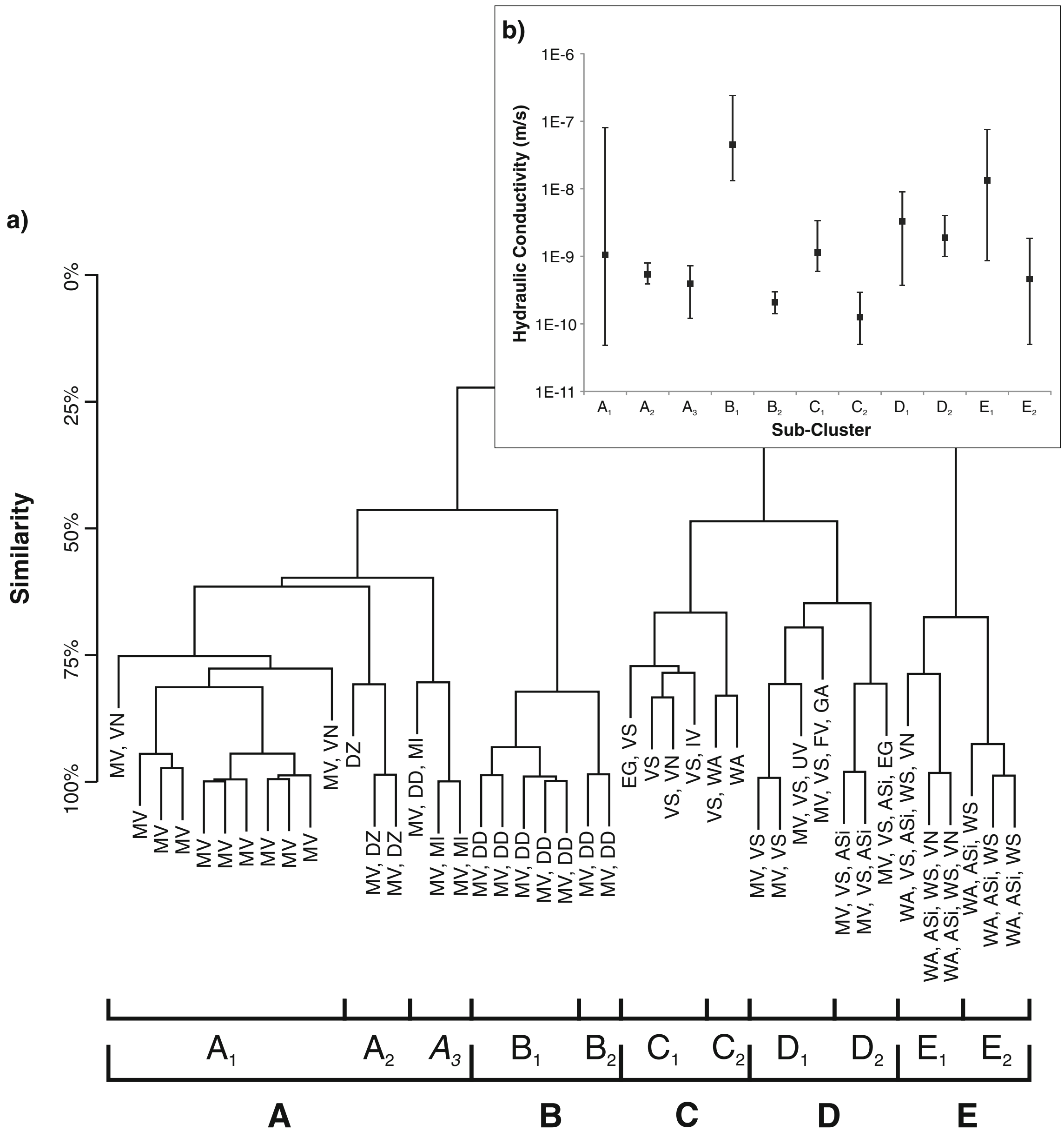

Geological Units:

MV - mafic volcanics	UV - ultramafic volcanics
VN - quartz vein	FV - fragmented volcanics
IV - intermediate volcanics	GA - graphitic argillite
DZ - deformation zone	ASi - argillite and siltstone
MI - late mafic intrusives	WA - interbedded wacke and argillite
DD - diabase dykes	WSa - wacke and sandstone
VS - interbedded volcanic and sedimentary units	EG - epidote-bearing gabbro

Fig. 7 **a** Hierarchical cluster analysis results for geological units. **b** Hydraulic conductivity summary for sub-clusters, geometric mean (*squares*), minimum and maximum (*bars*)

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parameters which are difficult to collect using traditional borehole techniques. In the case of the water content parameter, it was originally designed to indicate the amount of seepage observed at the outcrop from a given fracture set. However, due to active borehole flushing techniques during diamond drilling, it is nearly impossible to assess the degree of seepage using the original scheme devised by Gates (1997). This scheme could, however, be revised to consider factors such as the degree of staining and/or fluid alteration along joint surfaces, to give a similar indication of fluid flow, provided future projects wish to use the scheme for rock mass classification.

In the case of the fracture aperture parameter, used in the HP scheme, the variable is currently difficult to collect given modern diamond drilling techniques and collection methodologies. As a result, any use of the scheme requires a constant value to be used. However, with further development and increased use of televiewer technology it is likely that this parameter will be collected on a more regular basis at mine sites. Although televiewer aperture readings can be dubious due to in-situ rock mass disturbance around boreholes, the collected information is still likely better than the alternative of having no information. Incorporation of this parameter into the HP scheme should also be altered to better reflect the non-linear dependency between hydraulic conductivity and aperture, as described by the cubic law (Witherspoon et al. 1980).

Additional limitations also exists within the HC-system, as it fails to take into consideration variations in fracture conditions by only considering a total gouge content within a given test interval. While the gouge content is surely an important factor, other types of fracture fill can play an important role in fluid flow. This was outlined in the bivariate analysis by the increases in correlation coefficients with unfilled and planar fractures compared to total fracture frequencies. In addition, secondary fracture features such as persistence and aperture undoubtedly play an important role in the overall fluid flow characteristics and need to be taken into consideration in any rock mass permeability scheme.

Although both the HC and HP schemes present a formal methodology for the classification of rock mass properties and estimation of fluid flow characteristics, both methods are limited in their ability to empirically estimate hydraulic conductivity values. The bivariate analyses presented in this study have shown the limitations of the methodologies when applied to rock masses not originally considered when these techniques were first formulated. Instead, a new system needs to be developed which takes into consideration the shortcomings of these methods, and presents a formal methodology for rock mass classification within a hydrogeological framework. Although this is beyond the scope of this research, a number of propositions are put forth, upon which any new rock mass permeability classification scheme could be based.

First, on-site detailed descriptions of joint surface conditions should be conducted by personnel familiar with hydrogeological characterization, with the aim of identifying possible flow conduits. Data from this research has confirmed results from previous researchers (Banks et al. 1992, 1994; Morin et al. 1997; Sausse and Genter 2005) that fracture flow is not homogenously distributed throughout the fracture network, but instead occurs preferentially along a small number of discrete features. Therefore, it is important for any rock-mass-permeability scheme to have a way of classifying fractures based on their likelihood of fluid transmission. This should involve detailing the degree of staining/infill on any given fracture, as well as looking at the "freshness" of the fracture surface or how weathered the surface appears. This identification should be conducted by qualified personnel to ensure consistency across, as well as between sites.

Second, an indication of how continuous the core is across a fracture plane should be recorded; such an indicator would represent how well two pieces of core match-up across a given fracture plane (Fig. 8). Where the core continuity across the plane is high, it can be assumed that the in-situ fracture likely has a low aperture and, hence, poor ability to transmit fluid, whereas a poor core continuity would indicate a higher in-situ aperture. Although this is a qualitative approach and not a direct measure of aperture, it is likely to be the best method of estimation using traditional borehole collection methods. The advent of increased televiewer use in the mining industry may make this parameter obsolete; however, until such time, a core continuity factor should be implemented in rock characterization studies. As a result, it is proposed that any scheme should collect these data in a similar fashion to that shown in Fig. 8.

Finally, a far more detailed means of describing fault zone characteristics in relation to fluid flow properties is required. The presence of barrier and/or conduit type faults is often very important for mining activity, as faults either act as major inflow centers or compartmentalize and restrict dewatering efforts and can lead to high pore pressure gradients (Caine et al. 1996; Goodwin et al. 1999; Faulkner et al. 2010). Characterization efforts are further burdened by the difficulty in identifying faults during active drilling, landing packer testing equipment within the specified zone and orientation issues associated with explicitly testing either core and/or damage zones (Anderson 2006; Benedek et al. 2009). For these reasons, it is important to develop a characterization scheme which can be used by the hydrogeological, geotechnical and structural geology communities, which collects the necessary information for hydrogeologists to make educated approximations of fault zones characteristics so they can be categorized as either barrier and/or conduit type features. For this to happen, a synergy needs to evolve between these three communities, with all parties involved understanding the requirements and limitations of the other disciplines.

Assessment of the hydrogeological conceptual model

The second goal of the study was to advance the understanding of the hydrogeological conceptual model

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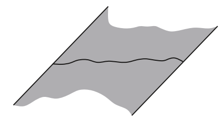
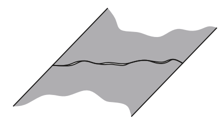
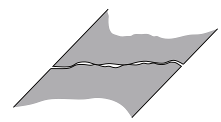
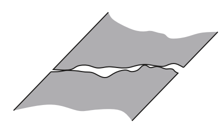
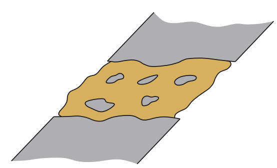
ID	Description	Figure
Fully Connected	Fracture is fully connected along borehole trace with no observable aperture / gap between fracture planes	
Minor Non-Continuity	Fracture displays minor non-continuity along borehole trace (<1 mm)	
Moderate Non-Continuity	Fracture displays moderate non-continuity along borehole trace (1 - 3 mm)	
Major Non-Continuity	Fracture displays major non-continuity along borehole trace (3 - 10 mm)	
Displaced	Fracture planes fully displaced with either rubble and/or gouge between surfaces (>10 mm)	

Fig. 8 Proposed categorization scheme for core continuity

at the study site using a statistical approach. Such an approach differs from traditional site characterization methods which are empirically based. While the approach did not change the general overarching conceptual model, it did refine it and provide additional evidence for a number of its characteristics. First, the approach demonstrated a relationship between hydraulic conductivity and distance from lake boundaries in both the bivariate and cluster analysis, suggesting that the presence or absence of permafrost is an important factor effecting groundwater flow. The bivariate analysis indicated that the association may be complicated by the additional observed relationship of low fracture frequencies away from ore bodies; however, later thermistor string installations have confirmed freezing conditions exist beyond lake boundaries confirming initial permafrost conceptual models. Given this association, future inflow predictions will need to take into consideration the presence of permafrost, as well as the possibility for higher than predicted hydraulic conductivities, due to sub-surface thaw near mine installations.

The second major advance in conceptual model understanding was achieved through the geological cluster analysis. Prior to the study, no direct relationship had been observed between hydraulic conductivity and lithology. However, results from the cluster analyses suggest an association between higher than average hydraulic conductivities and intrusive contacts. The first of these intrusive contacts, diabase dykes, were observed to be associated with a zone of increased vug development within bounding mafic units, suggesting increased porosity and likely increased permeability along contacts. These results suggest that dykes are functioning as a conduit-barrier type feature (Caine et al. 1996), which could limit dewatering/depressurization efforts due to compartmentalization effects (Beale 2009).

The second intrusive contact identified in the cluster analysis to be associated with high hydraulic conductivity was the quartz vein unit. Quartz veins at the site are known to be associated with central anticlinal/synclinal structures. Given the increased propensity of extensional features within the anticlinal/synclinal hinge zones and

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brittle nature of the quartz material itself, it is possible that increase flow rates are due to increased fracturing in, and around, quartz vein material. However, without further testing, the exact location of higher permeability structures is uncertain, and the association between higher hydraulic conductivity values and quartz veining is considered speculative.

Finally, the analysis technique was unable to attribute general flow characteristics to the regional faults; with the geotechnical cluster analysis unable to differentiate significant variations between tests conducted in the presence or absence of major structures. This inability in identifying trends is partially due to limitations in the data set, as most faults have only a single hydraulic conductivity estimate, which makes the extrapolation of results to overall fault behaviour questionable. In addition, the heterogeneous nature of faulting makes it difficult to determine if tests reflect either core and/or damage zone hydraulic conductivities.

Conclusions

This study employed a holistic approach to hydrogeological characterization which incorporated hydrogeological, geotechnical and geological data. The study tested both bivariate and multivariate statistical techniques to explore the cross-correlations between the data sets, and aimed to assess the conceptual groundwater flow model for a northern mine site. The results of the study demonstrate that:

- Standard geotechnical measures of the degree of fractures, such as the RQD, are poor indicators of the hydraulic conductivity potential of a rock mass at the study site. None of the standard geotechnical parameters tested were found to have a Spearman correlation coefficient greater than 0.33.
- Although correlations were weak, and unable to be used for prediction, a stronger correlation with hydraulic conductivity was observed between unfilled and smooth fractures compared to filled and rough factures. This suggests preferential fluid flow within the fracture network, which is consistent with other researchers (Morin et al. 1997; Banks et al. 1992, 1994).
- Evaluation of the HC-system and HP value rock-mass-permeability systems showed limited to no statistically significant correlations between either system and hydraulic conductivity at the study site. These results suggest that caution should be used when applying the designed systems at other sites, as estimated hydraulic conductivity values may not be representative of actual in-situ conditions.
- Comparisons between the geotechnical and hydrogeological data sets using hierarchical cluster analysis showed no new trends that had not already been previously noted in the bivariate analysis. This suggests that while cluster analysis may be useful during early stages of trend analysis, it is limited in identifying new trends after a site has been previously characterized.
- Hierarchical cluster analysis between the geological and hydrogeological data sets was able identify a number of general trends, including an association between quartz veining and diabase dyke contacts with higher than average hydraulic conductivities.

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