# Scale implications for estimating fractured bedrock permeability



Hendrik Voeckler Department of Earth Sciences – SFU & UBC, Forest Resource Management Diana Allen Department of Earth Sciences – Simon Fraser University, Burnaby, BC, Canada

# ABSTRACT

Characterizing flow in fractured bedrock aquifers requires estimates of fracture permeability at an appropriate scale. This requires an understanding of the fracture distribution and their fracture property data (i.e. orientation, persistence, aperture) as well as defining an appropriate scaling relation. To investigate scale implications for estimating fractured bedrock permeability, a field and modeling study was undertaken in crystalline rocks in mountainous terrain of the Okanagan Valley in central British Columbia. The study area is located in the footwall of the N-S striking Okanagan Valley fault zone (OVFZ). Fracture data were collected over a range of scales; from LANDSAT satellite image analysis, aerial (ortho) photo analysis and scanline outcrop mapping. Fracture distribution modeling focused on the fracture density, trace length, and appearance relation of strike direction. To investigate whether spatial distributions of fracture attributes are random or have a spatial correlation, semivariogram analysis was used. Permeability tensors of the bedrock aquifer are estimated at different scales using a discrete fracture network (DFN) approach using FRED® software by Golder Associates. The results are interpreted to infer possible scale effects on permeability.

## RÉSUMÉ

Caractériser l'écoulement en aquifères type rocs fracturés nécessite des évaluations de la perméabilité des fractures à une échelle appropriée. Cela exige de comprendre la distribution des fractures et d'avoir des données sur leurs propriétés, de même que de définir une relation d'échelle appropriée. Pour étudier les effets d'échelle pour estimer la perméabilité des aquifères fracturés, une étude de terrain et de modélisation a été entreprise pour des roches cristallines perméables dans les terrains montagneux de la vallée de l'Okanagan en Colombie Britannique centrale. Le secteur d'étude est situé près de la faille de la vallée de l'Okanagan. Des données de fracture ont été collectées à différents échelles à partir de l'analyse d'images satellites de LANDSAT, de l'analyse de photos aériennes, ainsi qu'à partir de lignes de scan. La modélisation de la distribution des fractures s'est concentrée sur la densité des fractures, la longueur de leur trace, et leur direction. Pour étudier si les distributions spatiales des attributs de fracture sont aléatoires ou ont une corrélation spatiale, l'analyse par semi-variogramme a été considérée. Des tenseurs de perméabilité de l'aquifère ont été établis pour différentes échelles en considérant une approche discrète du réseau de fracture (DFN) en utilisant le logiciel de FRED® de Golder Associates. Les résultats sont interprétés pour mettre en évidence de possibles effets d'échelle sur la perméabilité.

## 1 INTRODUCTION

In mountainous watersheds, fractured rock often comprises the upland areas, while valley bottom fill consists of unconsolidated sediment overlying bedrock. In general, there is a paucity of groundwater data in alpine environments worldwide. This is largely due to a lack of wells in alpine settings, which typically have sparse human population and terrain that poses significant challenges for access and drilling. However, there is growing recognition that mountains play a critical role in the hydrologic cycle, capturing precipitation by orographic effects, storing water in snowpack and in mountain aquifers, initiating transport of water from the surface to local and regional aguifers, and possibly even deeper to the upper crust of the Earth. In many cases, understanding regional aquifer systems requires an understanding of groundwater flow in adjacent mountains where most of the recharge occurs. Because mountains potentially serve as recharge zones and provide a gravitational driving force for deeply circulating waters, processes controlling groundwater movement into and

through all levels of mountain masses deserve further study (Caine et al., 2006).

Preliminary simulations by Wilson and Guan (2004) suggest that bedrock with sufficiently high bulk permeability (fracture and matrix) has the potential to allow for significant deep percolation (threshold of 10<sup>16</sup> m<sup>2</sup>). Various studies have provided estimates in excess of this threshold value (e.g., Caine et al., 2003; Surrette and Allen, 2008). Once the water has infiltrated, the capacity of a mountain block to transmit subsurface water to the basin depends on the hydrogeological architecture of the mountain block, particularly the properties controlled by regional geologic structural elements like lineaments/faults as well as small scale fractures (Caine et al., 1996; Olhmacher, 1999; Flint et al., 2001; Mayo et al., 2003; Haneburg, 1995; Mailloux et al., 1999)

The potential for percolation (recharge) into bedrock requires estimates of bedrock permeability (or hydraulic conductivity, K). While pumping test data can provide such estimates, typically only a bulk estimate is obtained. This is because the analysis of pumping test data rarely yields information on anisotropy (Kx  $\neq$  Ky  $\neq$  Kz) that can be related to fracture characteristics. To do so requires both a pumping well and several observation wells in a suitable test configuration. Thus, alternative approaches for estimating bedrock permeability have recently been tested. For example, Caine and Tomusiak (2003) characterized bedrock permeability at a local scale, where geometric characteristics were simulated through a discrete fracture network (DFN) approach on the basis of outcrop fracture data. Surrette et al. (2008) used a DFN approach to derive estimates of potential permeability based on outcrop measurements of fractures in different hydrostructural domains observed throughout their study region, and related the range of estimates to hydraulic properties derived from pumping tests. They related regional trends in permeability to structural elements.

Few studies have examined the permeability distribution over a range of different scales. Koike et al. (2006) investigated scale dependency on permeability using fracture data from LANDSAT satellite images, boreholes, and thin sections. However, the analysis was only carried out for two dimensions (x-y direction).

The objectives of this study are to estimate and compare bedrock permeability from outcrop-, ortho photoand LANDSAT data through DFN modeling. The bedrock permeability, along with an appropriate scaling relation is needed to allow for outcrop-based estimates to be upscaled and used for regional scale groundwater flow modeling. The study area is the Naramata and Penticton Creek Watersheds situated in the central Okanagan of British Columbia (Figure 1). The complexity of fracturing observed over a range of scales (outcrop to lineaments) is largely attributed to the Okanagan Valley Fault Zone. How the fracture characteristics vary in relation to the fault as well as how anisotropy varies over the range of scales are addressed in this study.

The approach used consists of DFN modeling using outcrop and lineament data. DFN modeling (Derschowitz, 1995) uses a stochastic approach to generate fracture distributions and compares these to observed data. The generated fracture data are then input into a flow model to derive estimates of the bedrock permeability. In this study, both outcrop scale fracture data and lineament scale data are used. The study comprises the first step of a more comprehensive project in which groundwater recharge and deep flow in a fractured bedrock aquifer will be modelled. Specifically, bedrock permeability data derived from DFN modeling will be used to characterize the lower layer of a coupled surface water-groundwater model in an alpine catchment at high elevation (Upper Penticton Creek UPC 241 as illustrated in Figure 1). Deep bedrock loss (i.e., recharge) will be simulated. The deep bedrock percolation then will be used to simulate recharge to valley bottom aquifers via the mountain block recharge mechanism.



Figure 1. Location map, including the lineament distribution analysed through aerial (ortho) photo analysis. The location of the Okanagan Valley Fault Zone (OVFZ) is shown. The Upper Penticton Creek catchment (UPC 241) is also shown

## 2 SITE DESCRIPTION

#### 2.1 Geographic Setting

The study site is the Naramata- and Penticton watersheds including the UPC241 alpine headwater catchment. These two first order watersheds are located east of Okanagan Lake and northeast of the City of Penticton in the Okanagan Valley of central British Columbia (BC) (Figure 1). The area of the Penticton watershed is about 184 km<sup>2</sup> and the area of the Naramata watershed is about 141km<sup>2</sup>. The Upper Penticton Creek catchment (UPC 241) is a headwater tributary to Penticton Creek, and drains an area of 4.74 km<sup>2</sup>. It is located in the north-eastern corner of the Penticton watershed, about 26 km away from the City of Penticton (Figure 1).

## 2.2 Geotectonic and Geologic Setting

The Okanagan Valley follows a gently west dipping crustal shear zone (Okanagan Valley Fault Zone - OVFZ), across which the upper plate moved westwards above the lower plate during the middle Eocene. Matching the lower- and upper plate rocks indicates about 90 km of offset (Tempelman-Kluit and Parkinson, 1986). The study area is located directly in the shear zone east of its main trace (in the footwall), which is located under the Okanagan Lake (Figure 1).

Bedrock is mostly exposed at lower elevations of the watersheds close to the lake as well as in higher parts above the tree line. Bedrock exposure at low elevation coincides with an area that receives little precipitation and, therefore, has less vegetation cover. Most of the rocks in the study area are mylonitic gneisses. Eastwards, at higher elevations further away from the main trace, the bedrock is comprised of granites and granodiorites (Johnson, 2006).

## 3 METHODS

## 3.1 Lineament / Fracture Data collection

Fracture data were collected at two scales. First, regional scale lineament analysis was carried out through aerial (ortho) photo interpretation using a stereoscope as well as through satellite (LANDSAT TM) images from the near-infrared band 4 (the latter dataset was provided by Natural Resources Canada).

Fracture data were also collected at the outcrop scale. Before going to the field, geologic / hydrogeologic maps were utilized in selecting natural outcrop locations that were representative of lithologically and structurally distinctive rock groups found in the study area.

Fracture mapping was undertaken at 39 outcrop locations using traditional scanline mapping techniques (Figure 2) (Caine and Tomusiak 2003). Measuring tapes were laid out on at least two near-orthogonal outcrop faces trying to capture all possible fracture set orientations. Position, orientation (measured with a geologic compass), trace length, termination style, aperture, roughness (primary /secondary) and fillings were recorded for each fracture intersecting each scanline.



Figure 2. Scanlines laid out on a vertical outcrop face (top image) and on the upper orthogonal surface of the outcrop (lower image)

## 3.2 Lineament Density Mapping

Based on the extracted lineaments, a map was produced in ArcGIS identifying different zones of lineament densities throughout the study area. The densities of the two-dimensional features were defined by the added lengths of all lineaments intersecting a 1 km unit mesh and dividing them by the area of each grid cell.

Densities, of course, depend on the mesh size, which affects the correlation distance and variance of the density distributions: a large unit mesh size generates long correlation distances with small variance, but opposite relations are observed with a small size. The change of variance is considered significant in determining the unit mesh size (Koike et al 2006).

Following density mapping, an experimental semivariogram was developed for the lineament density identifying possible autocorrelation of the density distribution. The semivariogram was approximated by a model, and the parameters of the fitted model (range, sill and nugget) and the lag size were used for producing a contour map of the lineament density with the spatial analysis tool in ArcGIS. The kriging interpolation method, a common technique in geostatistics for the prediction of spatial processes at unsampled locations, was used (Al Mokredi et al., 2007).

3.3 Statistical Methods for Characterizing Fracture Sets

Using the results of the lineament density mapping three zones of different densities were identified: high, medium and low. The area of interest for this study is the UPC 241 headwater catchment, which is located in the low density zone (see lineament data in Figure 1) and, thus, is the focus for this paper.

Four outcrop fracture scanline measurement locations are located within this low density zone. The poles of all the fractures from the four outcrop locations are displayed in a lower hemisphere stereonet (Figure 3) and a density distribution was performed using a Gaussian counting model for the contouring. The statistical fracture data analyses were performed using the software SpheriStat for Windows.

Four sets can clearly be identified in Figure 3, and a cluster analysis was performed to separate each set and to obtain for each set individual statistical parameters (mean trend/plunge and dispersion factor k) that are needed for the discrete fracture network model generation. The fracture sets are described by a Fisher distribution where the dispersion factor k is a measure of the clustering of each set. The higher this factor, the more clustered are the data (Fisher et al., 1987).



Figure 3. All poles to the fractures (contoured) from outcrop locations within the low fracture density zone.

- 3.4 Discrete Fracture Network (DFN) Modeling for the Local (outcrop) and Regional (Lineament) Scale
- 3.4.1 Basic Concept of the DFN-Modeling Approach

A DFN (discrete fracture network) approach was used to determine fractured bedrock permeability at different scales. The following gives a short overview on the fundamentals of DFN generation.

DFN models belong to the so-called discontinuum model family. They represent a body of rock as an assembly of rock blocks separated by discontinuities. As discontinuities occur at a variety of scales (e.g., outcrop scale fractures regional scale lineaments). or discontinuum models must account for these complexities. The basic principle of stochastic discrete fracture models is that spatial statistics associated with a fracture network can be measured and used to generate fracture networks with the same spatial properties. Application of the DFN concept requires the measurement of fracture geometry in order to construct models that reproduce the observed statistics of the fracture network (Starzec and Andersson, 2002; Derschowitz, 1995)

#### 3.4.2 DFN Generation - Permeability Measurement

In a stochastic fracture network, most characteristic variables are represented as probability distribution functions. Based on the field data (e.g., fracture mapping on rock exposures), fracture network properties are approximated by the best-fit theoretical statistical distributions. Each generated fracture is a product of one Monte Carlo sampling from a number of statistical distributions, each representing a certain fracture property. The combination of all fractures generated in such a manner results in a three-dimensional discrete fracture field (Starzec and Andersson 2002). Figure 4 shows the DFN construction flow chart.



Figure 4. Flow chart showing how DFN parameters are simulated in the construction of a single best-fit DFN model (from Caine and Tomusiak 2003)

DFN parameters are simulated in the construction of a single best-fit DFN model. The software FRED (Golder Associates Ltd.) was used in this study. Raw-fracture orientation data from the outcrop measurements are plotted in a stereonet (see Fig. 3) where sets are determined. As mentioned, for each set, mean trend and plunge of the poles to the fracture planes and dispersion are calculated. Standard deviation, and a probability density function (PDF) of the trace-length distribution is simulated for each set (Caine and Tomusiak 2003). Fracture sets are generated in an example realization of a DFN model in a 20m x 20m x 20m cube for the outcrop scale and in a 6.8km x 13.6km x 6.8km for the lineament scale (see red squared area in Fig 9). The dimension of the regional cube size was selected in order to cover the whole variety of strike directions in the low density fracture zone, while the dimension of the outcrop cube size was selected based on the size of outcrops.

From the 2-dimensional trace maps of the lineaments it is impossible to separate sets and obtain mean trend/plunge values, which are necessary for the 3dimensional DFN generation. To do this, rose diagrams (Figure 5) of the outcrop fractures and lineament maps (from aerial photo analysis and LANDSAT TM4 analysis) for the low density zone were constructed and their appearance compared in order to identify possible similarities of the strike directions between the local scale outcrop and regional lineament scale features. Rose diagrams show the frequency distribution of the strike directions of fractures/lineaments.



Figure 5. Rose Diagrams: outcrops fractures (left); lineaments from aerial (ortho) photo analysis (middle); lineaments from LANDSAT TM4 analysis (right)

There are similarities between the three rose diagrams concerning the strike directions (however, frequencies differ), especially in respect of the strikes of the lineaments analysed through aerial photo interpretation (middle rose diagram in Figure 5) and the fractures of the four outcrop locations (left side rose diagram in Figure 5). The rose diagram of the lineaments analysed through LANDSAT TM4 interpretation on the right of Figure 5 seems to have only three of the four strike directions developed.

Figure 6 shows the four separated sets of the outcrop fractures determined through cluster analysis from the contoured stereonet (Figure 3) as described in Section 3.3. It appears that the N-S striking set (set 1) is absent in the analysis through LANDSAT interpretation. The implications of this are discussed later.



Figure 6. Separated outcrop scale fracture sets displayed in rose diagrams

Based on these four separated fracture sets and their defined strike ranges (Set1:  $20^{\circ}W - 20^{\circ}E$ ; Set2:  $20^{\circ} - 60^{\circ}$ ; Set3:  $60^{\circ}$ - $130^{\circ}$ ; Set4:  $130^{\circ}$ - $160^{\circ}$ ), all lineaments from aerial photo- and LANDSAT TM4 analysis were assigned to one of the four sets through a SQL query in ArcGIS. To generate the DFN models for the lineaments, however, additional data are needed, specifically trend/plunge and dispersion factors. Because these data are not available from 2-dimensional lineament maps, these parameters had to be approximated from outcrop measurements. This is a reasonable approximation because small scale fractures and regional scale lineaments from the same tectonic event should show similar strike directions and inclination angles. Figure 7 shows the four extracted

lineament sets from the aerial photo analysis (upper row) and the 3 sets from LANDSAT analysis using the approach just described. Their principle directions (shown through purple lines and ranges) show similar orientations to the sets from the outcrop locations seen in Figure 6.



Figure 7. Separated lineament sets from ortho photo analysis (upper row) and from LANDSAT analysis (lower)

Before the flow simulations can be performed to derive the estimates of permeability, it is necessary to upscale from the scanline P10 intensity (number of fractures per scanline length) to the P32 intensity (number of fractures per volume) (Caine and Tomusiak 2003: Oehman and Niemi 2003). During this upscaling process, simulated fracture intensities are fit to observed scanline intensities for each fracture set by using multiple realizations with simulated scanlines for determination of a best-fit, single DFN model. The relative error of the simulated P10 intensity should not be higher than 20%. Once a best single DFN model for each set is found, the P32 intensity for that model is noted. For archiving P10 intensities for the separated sets of the lineaments, imaginary scanlines intersecting each set are constructed in ArcGIS.

Using the upscaled P32 intensities assigned for each fracture set for both the local scale outcrop fractures and the regional scale lineaments (the latter includes both the ortho photo and LANDSAT TM4 analysis), DFN models are generated at the respective cube sizes. These DFN models include all 4 fracture sets (however, only 3 fracture sets are available for the LANDSAT analysis). Flow through the cubes is simulated in each of East-West (x), North-South (y), and Top-Bottom (z) directions, and corresponding potential permeability values are computed for each of these directions. Water flow at standard temperature and pressure is simulated in the best-fit fracture models using the three-dimensional finiteelement code Mafic (Miller et al., 1995). Each element in the mesh is assigned a fracture transmissivity, T<sub>f</sub>, which can be directly related to fracture aperture correlated with transmissivity using the cubic law (Eq. 1) (e.g., Snow, 1968):

$$T_f = \frac{b^s}{12} \frac{\rho g}{\mu} \tag{1}$$

where T<sub>f</sub> is fracture transmissivity [L<sup>2</sup>/T], b is aperture defined later [L)] r is the fluid density [M/L<sup>3</sup>], g is the acceleration due to gravity [L/T<sup>2</sup>], and  $\mu$  is the dynamic

fluid viscosity [M/LT] (L = length, M = mass, T = time). Single values for transmissivity and aperture are assigned to each individual fracture in each DFN model.

The total volumetric flux computed between two opposing faces of each model is used to compute the one-dimensional, directional (i.e., north to south, east to west, and top to bottom) equivalent bulk potential permeability,  $K_p$ , for each full model domain face by using Darcy's law (Eq. 2):

$$K_p = \frac{\mu}{\rho g} \frac{Q}{IA}$$
 [2]

where Q is the simulated volumetric flow rate  $[L^3/T]$ , I [dimensionless] is the specified hydraulic gradient, A  $[L^2]$  is the specified cross-sectional area across which the discharge, Q, flows, K<sub>p</sub> is the calculated potential permeability  $[L^2]$ , r is the fluid density  $[M/L^3]$ , g is the acceleration due to gravity  $[L/T^2]$ , and  $\mu$  is the fluid dynamic viscosity [M/LT] (Caine and Tomusiak 2003). The term potential permeability is used because the orientation of the flow field is in the primary compass directions, and permeability estimates in these directions is estimated. These potential permeability estimates may not coincide with the true principal directions of anisotropy because this would require an infinite number of flow simulations in all possible geographic coordinate directions.

For each of the three permeability simulations, a total of five models were generated, and the statistical mean of the estimated permeabilities was noted. This is because a stochastic approach is used and the generated fractures/lineaments of each model generation are always a little different. Because of this, the calculated permeability values similarly vary over some narrow range. Table 1 gives an overview of the parameters used for generating the DFN models and estimating the permeabilities.

Table 1. Overview of DFN simulation parameters for the different scales

PARAMETERS	Scale	Set1	Set2	Set3	Set4
Orientation [º] (trend, plunge, dispersion)	Outcrop scale	85°/30°, k= 25	305°/58°, k= 45	349º/11º, k= 20	237°/53°, k= 55
	Aerial photo scale	85°/30°, k= 25	305°/58°, k= 45	349°/11°, k= 20	237°/53°, k= 55
	LANDSAT scale	set not detected	305°/58°, k= 45	349°/11°, k= 20	237°/53°, k= 55
Fracture/Lineament size [m] - Mean, Std. Dev.	Outcrop scale	2.35, 1.47	3.07, 189	1.65, 1.33	1.20, 0.44
	Aerial photo scale	1383, 625	2348, 1353	1837, 1486	2092, 1362
	LANDSAT scale	set not detected	3298, 1495	3028, 1035	4654, 3591
Fracture/Lineament Aperture [m]	Outcrop scale	const. / 1e-4	const. / 1e-4	const. / 1e-4	const. / 1e-4
	Aerial photo scale	const. / 0.5	const. / 0.5	const. / 0.5	const. / 0.5
	LANDSAT scale	set not detected	const. / 0.5	const. / 0.5	const. / 0.5
Fracture/Lineament Permeabilty [mD]	Outcrop scale	const. / 818	const. / 818	const. / 818	const. / 818
	Aerial photo scale	const. / 10000	const. / 10000	const. / 10000	const. / 10000
	LANDSAT scale	set not detected	const. / 10000	const. / 10000	const. / 10000
P32	Outcrop scale	1.92	3.10	3.29	2.00
	Aerial photo scale	2.10E-03	3.02E-03	2.16E-03	1.98E-03
	LANDSAT scale	set not detected	1.39E-03	8.15E-04	1.94E-03

The aperture values (b in Eq. 1) for the outcrop scale fractures were taken from the literature. Folger (1995) used the cubic law to calculate apertures from transmissivity values obtained from single-well, short-term aquifer tests in Silver Plume in the vicinity of Conifer, Colorado. For ~20 tests, his calculated aperture estimates ranged between 60 and 570  $\mu$ m. Similar to studies by Caine and Tomusiak (2003) and Surrette and Allen (2008), a value of 100  $\mu$ m was used for fracture aperture for the outcrop simulations. Using this aperture value and applying the cubic law of transmissivity (Eq. 1), the potential permeability for the small scale fractures is estimated at 8.2x10<sup>-13</sup> m<sup>2</sup> (818 mD)

The lineament aperture estimate was more difficult to estimate because no similar studies have been undertaken. Lineaments can be expected to have a much larger effective aperture than individual fractures because they are comprised of numerous individual fractures. Thus, as a first estimate aperture was estimated using the results of a pumping test simulation. Pumping test data from a well in the study area was simulated using the FRED software by matching the simulated drawdown curve with the observed data. The parameters which need to be assigned in FRED are the aperture and fracture permeability. A good match was achieved for an aperture value of 0.5 m and a permeability value of 1x10 <sup>1</sup>m<sup>2</sup> (10000 mD). These results, of course, are nonunique, and certainly the values need to be verified more extensively by conducting further pumping test simulations; however, for the purposes of this study, they are used for defining lineament aperture and permeability.

In addition to the approach described above, one additional DFN model was generated. The original trace map from the ortho photo analysis was imported into FRED for the same cube size of the low density zone (6.8km x 13.6km x 6.8km) using the same aperture and lineament permeability values as used above. Lengths for each fracture set , however, were assigned such that they penetrate the whole length of the cube. When inserting a trace map into FRED, it is only possible to assign the same inclination value for all the lineaments of the same set and the depths of the lineaments of a set also has the same length. The estimated permeability values were compared with those achieved from the generated models.

#### 4 RESULTS

#### 4.1 Lineament Density Zone Estimation–Semivariogram Analysis

Figure 8 shows the semivariogram and the fitted spherical model for the lineament density data from the aerial (ortho) photo analysis. The semivariogram shows a strong autocorrelation between the data indicated by the up-sloping portion of the best-fit line (blue line). At a lag distance ~6000m, the curve becomes horizontal, indicating a threshold of autocorrelation for attribute values. In other words, grid cells which are separated by distances greater than 6000m no longer have density autocorrelation.



Figure 8. Experimental semivariogram of lineament density

Based on the semivariogram a spherical model was fit to the data. The parameter values (lag size, nugget and sill) were used to create a lineament density map from the ortho photo analysis for the entire study area (Figure 9). Lineament data from LANDSAT TM4 were not used because these were shown previously to be missing one fracture set.



Figure 9. Lineament density map

Three lineament densities zones were defined. The highest zones (white and tan zones in Figure 9) are situated close to Okanagan Lake and are in proximity to the trace of the Okanagan Valley Fault Zone. Moving east

away from the fault trace, the density decreases. This is not surprising because fracture intensity (or density) is often observed to decrease away from fracture zones and shear zones. (Mackie, 2002).

It also appears that the strike persistences of the lineaments are shorter in the high and medium density zones and longer in the low zone. However, it is suspected that this is merely an artifact of the mapping method, but it could also be related to different rock types. Gneisses mostly appear in the high density zone, while granites/granodiorites are mostly present in the low density zone. The areas on the edge of Okanagan Lake do not have any lineament data because they are covered with sediments, making it impossible to detect lineaments. Thus, the low density mapped along the lake edge is likely incorrect; being in close proximity to the fault would certainly result in much higher fracture densities.

Of particular interest to this study is the low density zone which encompasses the Upper Penticton Creek UPC241 headwater catchment (red rectangular outline in Figure 9). The red dots in Figure 9 show the three scan line outcrop locations also located within the low density zone. A comparison of the results at these two different scales within the low fracture density zone is given in the following section.

4.2 Hydraulic Conductivity (K) Estimation at the Different Scales

Fracture generation and permeability simulations for the outcrop scale fractures from the four outcrop locations in the low density zone, and for each of the lineament sets separated from the aerial (ortho) photo and LANDSAT TM4 analysis as well as for the imported trace map from the ortho photos resulted in estimates of potential hydraulic conductivity in each of the main flow directions (N-S, E-W, T-B). As noted earlier these do not necessarily coincide with the principal directions of anisotropy (Table 2).

Table 2. Overview of the mean permeability values simulated for the different scales and directions

DFN Modeling – Permeability Estimation at diff. Scales	K [m/s] E-W (x)	K [m/s] N-S (y)	K [m/s] T-B (z)
Local Outcrop Scale Fractures	6.2 e-6	5.6 e-6	5.1 e-6
Regional Scale Lineam. from Ortho Photos	3.3 e-4	3.4 e-4	2.6 e-4
Regional Scale Lineam. from LANDSAT TM4	1.7 e-4	1.6 e-4	9.8 e-5
Regional Scale Lineam. – Import. Trace Map	3.2 e-5	2.5 e-5	3.1 e-5

In general, when comparing the K results in each of the principal flow directions, the lowest values are simulated in z-direction, which coincides with the T-B (Top-Bottom) direction. The values for the x- and y directions (E-W, N-S) are similar at each scale (although the K value in x-direction for the outcrop scale is a little higher than in y-

direction). These values correspond very well with the P32 values for each set (Table 1); the P32 values are responsible for the number of fractures/lineaments generated in each model. For example, set 3 from the outcrop scale fractures, which is the E-W striking set (E-W direction is x direction in the DFN models), has the highest P32 intensity. Thus, the greatest number of fractures will be generated from this set) and will result in the highest K value for the x-direction. The correspondence between P32 values and K estimates indicates that care must be taken to obtain accurate fracture intensity data (P10) for each fracture set, observed in the field. Otherwise, the upscaling process (P10 to P32) will not accurately represent the fracture network. For outcrop based studies, this is important because it is not always possible to find orthogonal outcrop surfaces from which fracture measurements can be made.

One interesting result of the study is that the trace lengths values are the greatest for lineaments analysed through the LANDSAT image analysis (Table 1). Consequently, it might be expected that the LANDSAT data would yield the highest K values. However, this is not the case. The K values from the ortho photo lineament generation are higher. The reason for this somewhat unexpected result is the missing set 1 fracture data in the analysis of the lineaments through the LANDSAT TM4 image (see left rose diagram in Fig. 5). This result has important implications for using remotely sensed data for conducting DFN modeling in that it is important to capture all fracture sets in order to obtain representative estimates of K. If one set is not visible from a LANDSAT analysis, then the overall K of the fractured bedrock may be somewhat lower than if all sets were included.

The K results for the imported trace map from the ortho photo analysis appear to be about an order of magnitude smaller than the results for the generated lineaments. The imported trace map of the lineaments only takes into account those lineaments which appear on the surface. But, in reality, there are considerably more lineaments in the subsurface; these are simply not visible in two dimensions. As a result, the approach used to generate lineaments based on 3-dimensional data as described in this paper is a much better option for estimating K.

The K values simulated for the outcrop scale fractures differ by two orders of magnitude (lower) from the simulations for the lineaments. This is not surprising because the apertures and fracture permeabilities for the lineaments were assigned much higher values than those of the outcrop scale fractures. A sensitivity simulation was done to compare the results for lineament K if the same aperture and permeability values from the outcrop scale fractures are used to simulate the permeabilities rather than the higher values used to represent fractures at this scale. Results are in the range of 10<sup>-9</sup> m/s, or 3 orders of magnitude lower than the values estimated for the outcrop scale fractures. These results have important implications for conducting regional scale permeability simulations in that it is important that scale-appropriate apertures and permeabilities be assigned to the lineaments, and that apertures based on outcrop measurements not be used. While the estimates used in this study are uncertain, it is clear that aperture scaling must be taken into consideration. Additional simulations of pumping tests, and perhaps regional scale flow modeling are needed to better constrain these values.

#### ACKNOWLEDGEMENTS

Support for this research was from a Canadian Water Network grant as well as from a Natural Sciences and Engineering Research Council (NSERC) Discovery grant to D. Allen. The authors wish to thank Murray Journeay from the Geological Survey of Canada for providing access to the lineament data. We also thank M.A. Berg and J. Liggett for their assistance with fracture measurements in the field as well as Dr. Craig Forster from the University of Utah for his help using FRED software.

## REFERENCES

- Al-Mokredi, M. S., H. Guangdao, and B. F. Al Bassam. 2007. Using Remote Sensing data to Delineate the Lineaments for Hydrothermal Mineral Prediction in Heqing Area, Northwest Yunnan Province, China. *Journal of China University of geosciences* 18: 142-147.
- Caine, J. S., A. H. Manning, P. L. Verplanck, D. J. Bove, K. G. Kahn, and S. Ge. 2006. Open-File Report 2006– 1189. USGS.
- Caine, J. S., and S. R. A. Tomusiak. 2003. Brittle structures and their role in controlling porosity and permeability in a complex Precambrian crystalline-rock aquifer system in the Colorado Rocky Mountain Front Range. *Bulletin of the Geological Society of America* 115: 1410.
- Caine, J. S., J. P. Evans, and C. B. Forster. 1996. Fault zone architecture and permeability structure. *Geology* 24: 1025-1028.
- Dershowitz, W., 1995, Interpretation and synthesis of discrete fracture orientation, size, shape, spatial structure and hydrologic data by forwards modeling, in Myer, L.R. et al., eds., Proceedings of the Conference on Fractured and Jointed Rock Masses, Lake Tahoe, California, June 3–5, 1992: Rotterdam, Balkema, p. 579–586.
- Fisher, N.I., Lewis, T., and Embleton, B.J.J., 1987, Statistical analysis of spherical data: Cambridge, Cambridge University Press, 329 p.
- Flint, A.L., Flint, L.E., Bodvarsson, G.S.W., Kwicklis, E.M. and Fabryka-Martin, J. 2001. Evolution of the conceptual model of unsaturated zone hydrology at Yucca Mountain, Nevada. *Journal of Hydrology*, 247: 1-30.
- Folger, P.F., 1995. A multidisciplinary study of the variability of dissolved 222Rn in groundwater in a fractured crystalline rock aquifer and its impact on indoor air [Ph.D. thesis]: Golden, Colorado School of Mines, 181 p.
- Haneberg, W.C. 1995. Steady state groundwater flow across idealized faults. *Water Resources Research*, 31: 1815-1820.

- Johnson, B. J. 2006. Extensional shear zones, granitic melts, and linkage of overstepping normal faults bounding the Shuswap metamorphic core complex, British Columbia. *Bulletin of the Geological Society of America* 118: 366.
- Koike, K., and Y. Ichikawa. 2006. Spatial correlation structures of fracture systems for deriving a scaling law and modeling fracture distributions. *Computers & Geosciences* 32: 1079-1095.
- Mackie, D.M., 2002. An integrated structural and hydrogeologic investigation of the fracture system in the Upper Cretaceous Nanaimo Group, southern Gulf Islands, British Columbia [M.S. thesis]: Burnaby, Simon Fraser University, 358 p.
- Mailloux, B.J., Person, M., Kelley, S., Dunbar, N., Cather, S., Strayer, L. and Hudleston, P. 1999. Tectonic controls on the hydrogeology of the Rio Grande Rift, New Mexico, *Water Resources Research*, 35: 2641-2659.
- Mayo, A.L., Morris, T.H., Peltier, S., Petersen, E.C., Payne, K., Holman, L.S, Tingey, D., Fogel, R., Black, B.J. and Gibbes, R.D. 2003. Active and inactive groundwater flow systems: Evidence from a stratified mountainous terrain, *GSA Bulletin* 115: 1456-1472.
- Miller, I., Lee, G., Dershowitz, W., and Sharp, G., 1995. Mafic<sup>™</sup>, Matrix/fracture interaction code with solute transport, version b1.5: Redmond, Washington, GolderAssociates, User Documentation.
- Oehman, J. and A. Niemi. 2003. Upscaling of Fracture Hydraulics by Means of an orientated Correlated Stochastic Continuum Model. *Water Resources Research* 39: 1277.
- Ohlmacher, G.C. 1999. Structural domains and their potential impact on recharge to intermontane-basin aquifers. *Environmental and Engineering Geoscience*, V(1): 61-71.
- Starzec, P., and J. Andersson. 2002. Probabilistic predictions regarding key blocks using stochastic discrete fracture networks-example from a rock cavern in south-east Sweden. *Bulletin of Engineering Geology and the Environment* 61: 363-378.
- Surrette, M. and Allen, D.M. 2008. Quantifying heterogeneity in fractured sedimenatary rock using a hydrostructural domain approach. *Geological Society of America Bulletin*, 120(1): 225–237.
- Surrette, M., Allen, D.M. and Journeay, M. 2008. Regional evaluation of hydraulic properties in variably fractured rock using a hydrostructural domain approach. *Hydrogeology Journal*, 16(1): 11-30.
- Tempelman-Kluit, D., and D. Parkinson. 1986. Extension across the Eocene Okanagan crustal shear in southern British Columbia. *Geology* 14: 318.
- Wilson, J. L., and H. Guan. 2004. Mountain block hydrology and mountain front recharge. Groundwater Recharge in a Desert Environment: The Southwestern United States, edited by JF Hogan, FM Phillips, and BR Scanlon, American Geophyscal Union, Washington, DC.