REPORT ON:

Fractured Bedrock Field Methods and Analytical Tools

Volume II : Appendices

Submitted to:
The Ministry of Environment
April 2010

Submitted by:
Science Advisory Board
For Contaminated Sites in British Columbia

Prepared under contract by
Golder Associates Ltd.
Burnaby, British Columbia

Acknowledgements

The report herein on *Fractured Bedrock Field Methods and Analytical Tools* with a second volume of Appendices is presented for the information and benefit of the Contaminated Sites community in British Columbia. It is hoped that it will be of interest to practitioners in other jurisdictions as well.

The work was supervised by the SABCS through a Task Force chaired by Dr. Jean Cho. Golder Associates Ltd. were contracted to prepare the report and appendices. The Task Force was comprised of SABCS members Dr. J. Leslie Smith of the University of British Columbia, Steve Wilbur of Jacques Whitford, and chaired by Dr. Cho. Lavinia Zanini was the BC Ministry of Environment representative on the Task Force. Dr. Thomas Doe was the principal author, and the SABCS appreciates benefitting from his widely recognized expertise in the field. Special recognition is given to Dr. Ian Hers for his tireless efforts in bringing the work to completion.

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Science Advisory Board for Contaminated Sites in British Columbia
April 2010.

Disclaimer

Practitioners and others with interests in contaminated sites should be aware that this report including the appendices has not been adopted in whole or in part by the Ministry of Environment of British Columbia. While every effort has been made to incorporate the best available science, it should be used solely as scientific review and commentary by the reader and applied in practice solely at the readers discretion and responsibility. This disclaimer is consistent with SABCS Policy. See also the disclaimer included in the main report (which also applies to the appendices) that is endorsed by the SABCS

Use of this Material

Request for Comments

The Science Advisory Board for Contaminated Sites in British Columbia is soliciting comment on the documents, which together constitute a report to the BC Ministry of Environment on recommendations for the development of guidance on Fractured Bedrock for practitioners in British Columbia. Comments will be reviewed and compiled by the SABCS, and will be much appreciated.

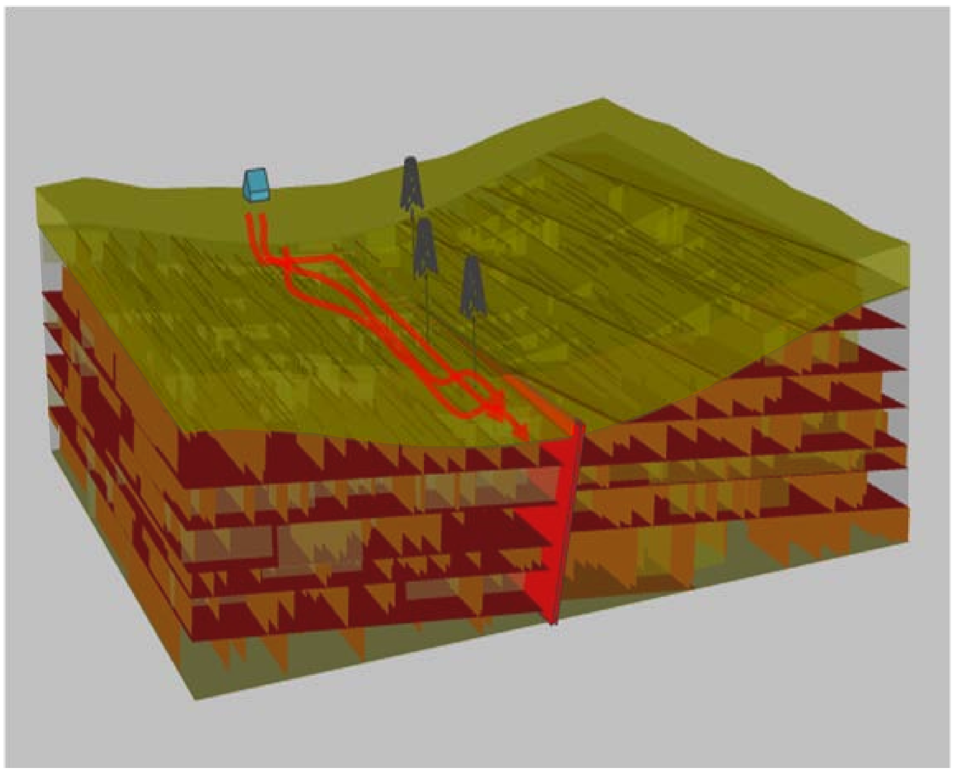
Please send your comments to the Science Advisory Board for contaminated Sites by email or email attachment to pwest@uvic.ca. Comments received by June 30, 2010 will be most useful in further refinement of this work. However, comments at any time on SABCS work are always appreciated.

Paul West, President
Science Advisory Board for Contaminated Sites in British Columbia

APPENDICES

FRACTURED BEDROCK FIELD METHODS AND ANALYTICAL TOOLS

Appendices



Submitted To: The Science Advisory Board for Contaminated Sites in British Columbia

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A- BASICS OF FRACTURE FLOW

This appendix discusses fundamental aspects of the flow and transport behaviour of fractures under six topic headings:

- Geologic origins of fractures and faults;
- Single fracture flow: the parallel plate analog;
- Transport in single fractures;
- Fracture-matrix interaction: dual porosity flow and matrix diffusion;
- Multiphase flow in a single fracture; and
- Fracture network geometric properties and their statistical description.

A.1 Geologic Origins of Fractures and Faults

Fractures are planar geologic features that form as a brittle material's response to strain or deformation. Deformations involve shortening, shear, and extension in directions that are reflected in the fracture orientations. Concentrations of deformation, such as the hinge of a fold, create local regions with elevated fracture intensity (Fisher and Wilkerson, 2000; Narr, 1991; Bazalgette and Petit, 2007). A brittle layer will require more fractures to accommodate the same strain as surrounding layers that are more ductile. Folded rock, in particular, may have different strains in different parts of the structure.

The deformations that create fractures are often the result of crustal-scale tectonic movements. Multiple deformation events may create overprint or reactivate older sets, from both tectonic and non-tectonic causes, as shown by Park et al. (1996) regarding glacially-reactivated fractures that affect stability in New Brunswick mine-pit slopes.

Deformation may exploit planes of weakness in the rock itself to open fractures along sedimentary bedding and metamorphic foliation.

Fractures appear not only in rock, but in any cohesive material like glacial till, where fracture pathways can carry contamination to glacial aquifers (Keller at al., 1986; Helmke et al., 2005; Harrar et al., 2007). Klint and Graveson (1999) relate glacial till fractures to a combination of glacial loading and interglacial freezing and drying.

Once created, fractures provide pathways for circulating groundwater. Geo-chemical and geo-biological processes then may modify the fractures by:

- Dissolving material from fracture walls, especially in carbonate and other soluble rocks;
- Concentrating and accelerating weathering of the host rock; and
- Precipitating mineral coatings and fillings that may seal the fractures, or prevent fluid interchange between the fracture and the host matrix rock.

As most groundwater contamination occurs through leakage from the surface, the fractures that matter most are often those at the surface of the bedrock. Consequently, processes that enhance or alter rock fracture properties in the near-surface environment deserve particular attention. These include the following (**Figure A-1**):

- Shallow fractures parallel to the ground surface that open from stress relief (exfoliation joints);
- Mechanical and chemical weathering that starts on the fracture surfaces and may proceed to affect the entire volume of rock between the fractures including effects of biologic activity like tree root invasion; and
- Fractures that open due to movements on rock slopes.

The removal of overburden by erosion unloads stress from bedrock, which can respond by the formation of unloading fractures. Unloading fractures, which include surface-parallel exfoliation joints, usually extend a few meters to tens of meters below the surface, hence the near surface zone should be a region of enhanced fracture flow unless weathering has altered the rock to low permeability materials like clays.

Structural geologists distinguish joints (Pollard and Aydin, 1988) from fractures that form in shear, such as shear zones and faults (Martel et al., 1988). Both laboratory experiments (Horii and Nemat-Nasser, 1982) and field studies (such as Martel et al., 1988) show that joints and shear features may be formed at different strain levels in the same progressive deformational field. Joints initiate at microcracks, often at mineral-grain boundaries. These extensile features are the most numerous fractures; they propagate with little energy, but they individually accommodate only small deformations. As a rock undergoes progressive strain, these cracks and joints coalesce into shear features that take more energy to create, but once formed can accommodate much larger strains (Figure A-2).

Joints, deformation zones, and faults display a range of internal structures, from simple to complex, which influence the fractures' hydrologic, and especially transport, behaviours.

Joints are simple parallel-walled features that most closely fit the classic parallel-plate analog paradigm, particularly if they are fresh and unaltered. Porosity enhancements in the rock may be present due to local, grain-scale crack development; but, unless there has been significant weathering or alteration, the hydrologic properties of the wall rock are unchanged. As addressed in the discussion on transport properties, simple joints will have relatively little in the way of retardation effects except by way of porosity in unaltered rock matrix.

Deformation zones, which may have thicknesses on the order of a few millimetres to several tens of centimetres (Andersson et al., 2004) have a considerably more complex internal structure. The geologic structure of small shear features has been studied at Sweden's Äspö underground laboratory (Andersson et al., 2004). Microscopic inspection of small-scale shear zones that are hydraulically active, reveal an internal structure made up of micro-breccias, clay gouge, and cataclasites, along with alteration halos in the fracture walls. These internal zonations within the shear zone have significant porosities that exceed 10% (Figure A-3).

Faults distinguish themselves from deformation zones by having thicknesses from tens of centimetres to tens of meters (or more) and lengths on the scale of kilometres. Caine (et al., 1996) have synthesized much of the hydrogeologic work on fault zones, creating a descriptive system that emphasizes the presence of different components of damage that vary in their hydraulic significance. Central to a fault is a core zone of intense deformation to the point of granulation (Figure A-3). For the portions of faults that form at shallow depth, this core zone may be a breccia of broken, angular rock fragments. Higher temperature and pressure conditions cause the formation of mylonites and cataclasites in the cores of fault zones (Braathen et al., 2004).

Shallow-formed faults core zones may be highly permeably and even solution-enhanced, or the core may contain finely ground rock that has altered to clay forming a barrier to flow. A damage-zone of intense fracturing and elevated permeability may surround the core. If the core is acting as a barrier, the fault as a whole evolves as a complex structure of high permeability parallel to the fault, and low permeability across it (Ganerød et al., 2008). The nature of the core damage zones vary depending on the depth where the fault has formed and whether the fault has been reactivated by later deformation. In addition to the fault zone itself, the “protolith” or wall rock of the fault zone may be altered and weathered by exposure to fluids circulating in the fault zone.

In summary, geologic processes are responsible for the creation of fractures. Fractures form through the deformation of brittle rock and soils. The formation of fractures is not limited to rock but can include highly cohesive sediments like glacial till. An understanding of rock deformation can aid in identifying regions where fractures are more likely to be more intense and more open. Such fractures may be the ones that dominate hydrologic behaviour. Faults and shear zones are often the most conductive fracture features. Much of the fracturing is the result of crustal strains due to tectonic forces; however, near the earth’s surface other sources become important including thermal strains due to heating and cooling of rock and slope-related deformations. Due to unloading and weathering, the bedrock surface is also a place to expect concentration of groundwater flow.

Figure A-1. Near Surface Fracture Enhancement.

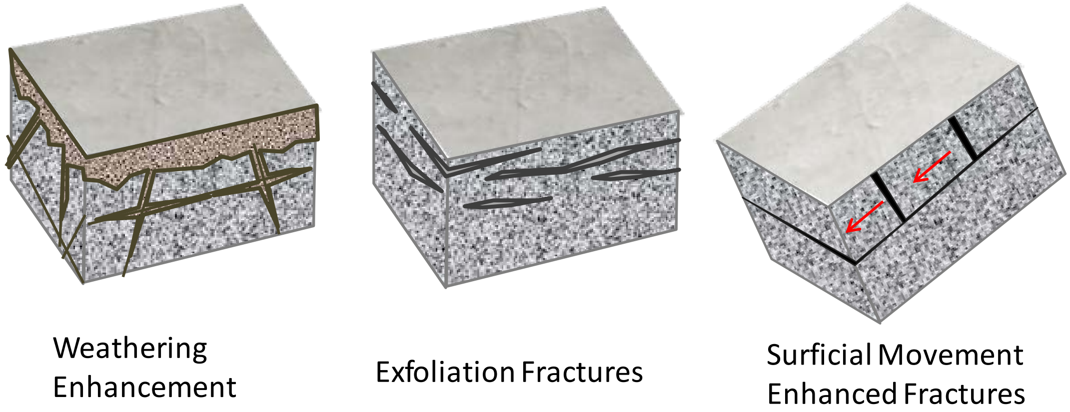


Figure A-2. Development of shear features from tension cracks (after Martel et al., 1988 citing Peng and Johnson, 1922).

Figure Note: Cracks form in extension parallel to the shortening and open in the direction of extension. With more strain, shearing develops creating fracture zones and small faults with complex internal structure.

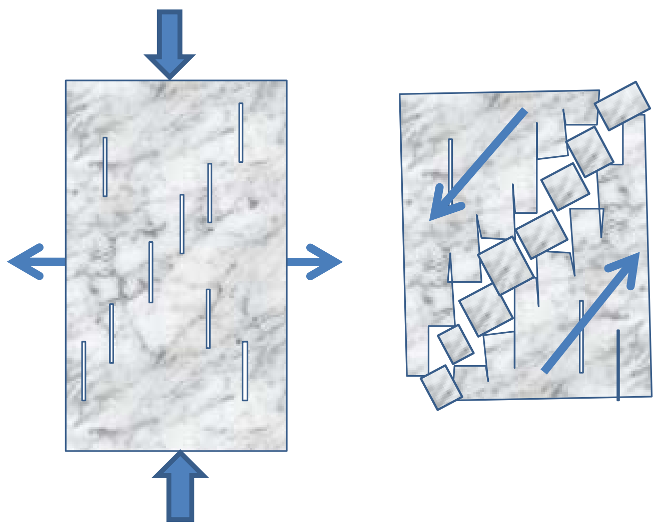
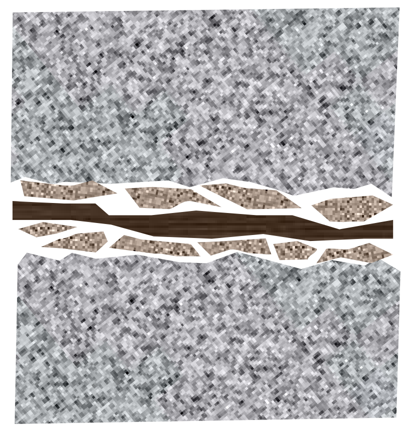


Figure A-3. Internal structures of joints, fracture zones, and faults.



A.2 Single Phase Flow and Transport in Single Fractures

A.2.1 Single Fracture Flow: The Parallel Plate Analog and the Cubic Law

The key hydraulic properties for a single fracture are (Figure A-4):

- Transmissivity (L^2/T);
- Storativity (-);
- Diffusivity, η (L^2/T);
- Hydraulic aperture, e_H (L);
- Storage aperture, e_S (L); and
- Transport aperture, e_T (L).

A single fracture is a planar feature, much like a confined aquifer, and its hydraulic properties are the same as those of an aquifer. Transmissivity is a measure of the capacity of a fracture to carry fluid, expressed as a flow rate or flux (L^3/T) through a conductor with a unit width (L) under a unit hydraulic gradient (-).

Storativity is the change in the pore volume of a fracture for a unit change in head. It may be related to the aperture, e, of the fracture, which is the distance between the fracture's two faces. Storage aperture, e_S, is volume of the fracture's opening over a unit area. The fracture porosity of a rock containing multiple fractures is the summation of the pore volume (or storage aperture times the area of each fracture) divided by the volume of the rock mass. Storativity, which is dimensionless, is primarily an effect of the compressibility of the fluid in the fracture, C, and the fracture's normal stiffness, k_n, which is the change in aperture for a change in effective normal stress, giving:

$$S = \rho g(1/k_n + e_S C)$$

where ρ is fluid density and g is gravitational acceleration.

Fluid flow under a head gradient is a diffusion process, like heat flow or solute diffusion, where the hydraulic diffusivity describes how fast pressure or head moves either through a fracture network or a porous groundwater flow system. It controls, for example, how quickly an observation well responds to a pumping well. Hydraulic diffusivity is the ratio of the flow conducting properties to the storage properties. For a single fracture or a single porous aquifer the diffusivity is equal to T / S.

Diffusivity ranges for fractures are generally much higher than those of porous rocks, as fractures are much more efficient fluid conductors for their pore volume. Typical diffusivity values for conductive fractures are 1 to 10 m^2/s and extremely open fractures have diffusivities greater than 100 m^2/s. Diffusivity, η, can be assessed approximately from a time lag, t, between a location of a pressure perturbation and an observation point r distance away using the radius of investigation equation (Streltsova, 1988), $t = r^2/4\eta$. As discussed later, diffusivity is very valuable for mapping fracture connectivity (Knudby and Carrera, 2006).

Transport aperture is the equivalent of porosity in porous media for assessing the velocity of groundwater transport. Groundwater velocity along a stream tube in a porous aquifer is the flux divided by the *flowing* cross-sectional area of the tube, which is the area of the tube times the porosity, as flow occurs only in the connected pores. The velocity of groundwater flow over a unit width of a single fracture will be the flux divided by the transport aperture, which is the flowing area of the fracture.

With respect to transport, a single fracture will also have a dispersivity. From fluid mechanics considerations, the velocity in a fracture has a parabolic profile even in an ideal smooth-walled fracture. Dispersion will be even more pronounced where the fracture walls are rough and the aperture is not uniform.

In principle all of these properties relate to the fracture aperture. The fundamental equation relating laminar flow in a single fracture to its aperture is the plate-plate analogue, also known as the cubic law, which states that velocity, v, and flow rate, Q, are proportional to the aperture by powers of 2 and 3 respectively (Figure A-4), or

$$Q = wi\rho g\, e^3/12\mu \text{ and}$$

$$v = i\rho g\, e^2/12\mu$$

where i is hydraulic gradient, w is fracture width, and μ is fluid viscosity.

The cubic law was introduced in the English-language literature by Snow (1965), and there has been considerable amount of experimental work (Witherspoon et al., 1980; Pyrak-Nolte and Cook, 1988; Konszuk and Kueper, 2003) and theoretical work (e.g., Sisavath et al., 2003) to investigate the validity and limitations of this expression. A natural fracture clearly deviates from a pair of smooth parallel surfaces in several ways, including roughness and partial filling from mineralisation. Nonetheless, the flow capacity of a fracture obeys a power law of aperture with exponents that, if anything, may be greater than three.

It is important to note that the constant relating the flow to hydraulic gradient cubic law, $\rho g\, e^3/12\mu$, has units of L^2/T, which are the units of transmissivity, not hydraulic conductivity. Recall that transmissivity is the property of an aquifer, while hydraulic conductivity (*L/T*) is the property of a material, like sandstone, within an aquifer. Hence, a single fracture is analogous to a porous, confined aquifer for which the transmissivity is the product of the hydraulic conductivity and thickness.

The concept of hydraulic conductivity therefore does not apply to flow within a single fracture. The hydraulic conductivity of an interval of a well will be the sum of the transmissivities of the fractures intersecting the interval divided by the interval's length, b, or

$$K = 1/b \sum_{i=1}^{n} T_n$$

Calculating hydraulic conductivity in a well can lead to ambiguities, when the fracture intensity is low. For example, a packer test in an interval of a well containing a single fracture, with a given transmissivity, T_f, will have a hydraulic conductivity that will depend on the interval length (Figure A-5), thus packer tests with different lengths around the single fracture will all have the same transmissivity, but will give different values of hydraulic conductivity.

In principle, the cubic law relates the flux, velocity, and storage properties to a single aperture value. In practice, flux values from flow tests, velocity values from tracer tests, and storage values from transient well tests all yield different aperture values. This has led some to argue that aperture needs to be viewed in different ways for each of these functions. This is not surprising considering the physical differences between ideal parallel plates and real fractures, which may have rough surfaces and heterogeneous aperture. Tsang (1992) notes that apertures based on tracer mass balances, tracer velocities, and simple applications of the cubic law can lead to a range of values. Furthermore, channelling within fracture planes can lead to further inconsistencies between parallel plates and actual fractures (Neretnieks, 2006).

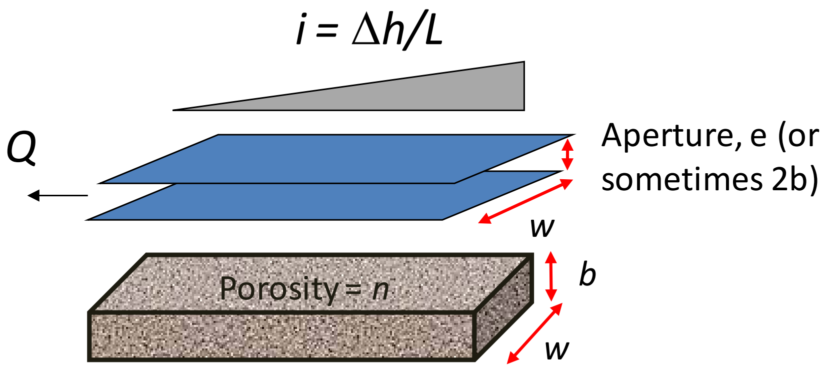
As discussed above, the transport aperture, e_T , relates the velocity to flux in a fracture. By a mass-balance definition (Tsang, 1992) this aperture would come from tracer tests where the aperture is simply flux divided by conducting area, or

$$e_T = Q / At_r$$

Unlike flux, the storage aperture sees all the interconnected pore volume within the fracture whether it is part of the active flow channels or lying in backwaters. By contrast, the transport aperture only sees the portions of fractures that are part of active flow channels (neglecting diffusive aspects). The hydraulic aperture, which is based on the cubic law and flux, will therefore be a lower bound expected value. The storage aperture should be an upper bound as it sees all connected volume, and the transport aperture will tend to lie in between the hydraulic and storage aperture values.

Underestimating the physical or effective opening of a fracture by using the cubic law idealization, may lead to overestimates of flow velocity, hence aperture values based on a cubic law calculation from transmissivity should be used with care. Tracer testing, though laborious, is the best means of estimating aperture for transport, especially if the key conducting features are known and can be tested directly (Sawada et al., 2000).

Figure A-4. Single fracture flow and aquifer equivalents.



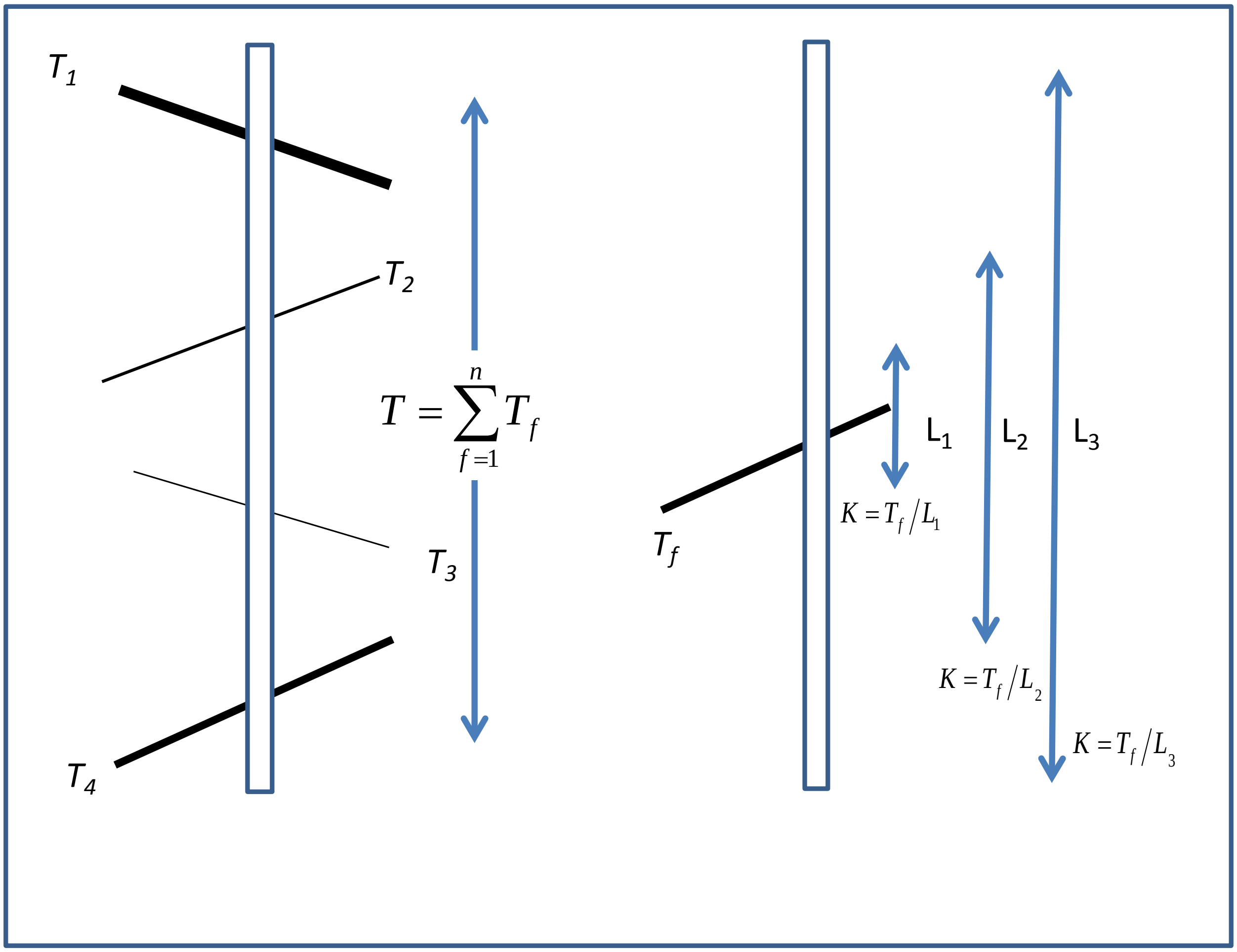
$$Q = wi\rho g\, e_H^{\ 3} / 12\mu = Tibw$$

$$T = \rho g\, e_H^{\ 3} / 12\mu = Kb$$

$$v = \frac{Q}{e_T w} = \frac{Q}{bwn}$$

$$S = \rho g \left(\frac{1}{k_n} + e_S C \right) = \rho g \left[(1-n) C_{solids} + n C_{liquids} \right]$$

Figure A-5. Transmissivity as a sum of fractures and ambiguities in definition of K.



A.2.2 Extensions to Fracture Networks

In three dimensions, single fractures intersect to form fracture networks. The network's properties are an aggregate of the properties of individual fractures and their geometric arrangements in three dimensions. If the fractures have a preferred orientation, such a network will "refract" flow from the direction of the large-scale hydraulic gradient into the planes of the fractures. Figure A-6 illustrates the effect of anisotropy using a simple fracture network model with dimensions of 1000 x 500 meters and a 100 meters thickness. A hydraulic head with a gradient of 0.2 acts across the 500 meter direction of the model, with constant-head boundaries on the sides, which also follow the gradient of 0.2 in the flow direction. The model has two sets of fractures, one with a constant transmissivity of $1x10^{-5}$ m^2/s and the other with $1x10^{-6}$ m^2/s, and constant transport apertures of 0.1 mm. The model has no dispersion, has diffusion but no dispersion. Water with particles representing a contaminant enters the network through a well near the upper, constant-head boundary.

The model results show the effects of anisotropy and dispersion. The particle tracks from the well do not exit the system directly downstream of the injection point, but are diverted by the more transmissive set to a point in that sets strike direction. Furthermore, the combination of non-uniform transmissivity and network anisotropy creates a dispersive effect at the exit of the model. A more realistic model with a higher degree of heterogeneity would show even stronger effects.

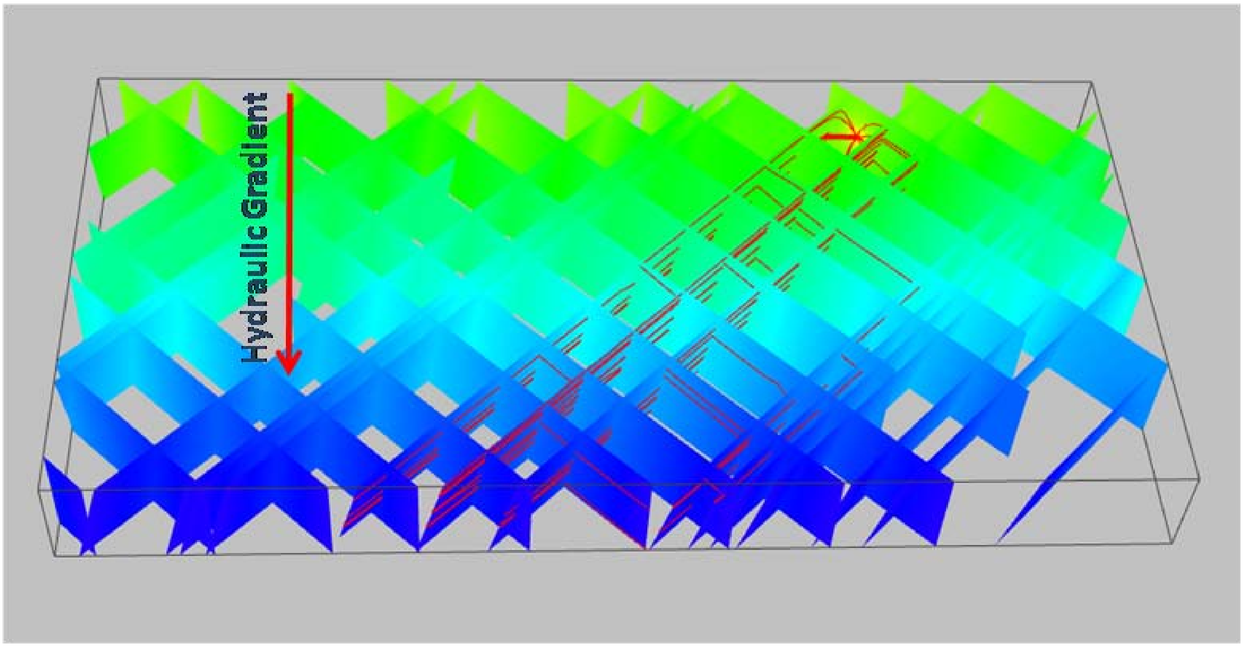
A.2.3 Single Fracture Summary

Despite some of its limitations and assumptions, the cubic law is still the fundamental concept for understanding flow in fractures. It essentially states that:

- The flow capacity and the velocity in a single fracture are power functions (cube and square respectively) of the fracture opening;
- Fractures are very efficient conductors for their volume in a rock;
- Small variations in fracture opening lead to large variations in flux and velocity; and
- A few fractures are likely to dominate flow, as a fracture that is even slightly more open than others can carry significantly more fluid.

Having dealt with single fractures, and having raised some issues of network behaviour, we move on to a more detailed discussion of the variability between fractures through the statistical description of fracture geometric and hydrologic properties.

Figure A-6. Effect of fracture orientation on flow direction.



A.3 Stochastic Description of Fracture Geometric and Hydraulic Properties

A.3.1 Background

Two major features that distinguish fractured groundwater flow systems from porous ones are:

- Complex geometries; and
- Heterogeneous properties.

Porous systems are usually sedimentary and the variability is distributed between layers that can be correlated laterally and relatively continuously. Although heterogeneities exist in some sedimentary systems, especially fluvial environments, they retain a relatively higher level of predictability due to stratigraphic continuity.

Fractured rocks have complex geometries where the conducting features occur in sets often with multiple, cross-cutting orientations. Fractures vary in size, or length in two dimensions; they have termination relationships that may reflect the timing of their origin, and they vary in intensity or frequency. The hydraulic properties of fractures, transmissivity, storativity, and effective porosity, all relate to aperture, albeit in ways that may be complex themselves.

The variability and unpredictability of fractures has encouraged the development of a technical discipline devoted to the stochastic description of fracture systems, focussing on geometric properties, mechanical properties, and hydraulic properties. The origins of this discipline go back to David Snow and the publications that came out of his dissertation at the University of California, Berkeley, in the mid-1960's (Snow, 1965). In particular Snow addressed a number of basic issues in fracture flow including:

- Frequency of conducting fractures (Snow, 1968);
- Statistics of aperture and transmissivity (Snow, 1970); and
- Anisotropy of flow in fracture networks (Bianchi and Snow, 1968; Snow, 1969).

The rock engineering community developed the stochastic geometry approach further in the 1970's and 1980's motivated by the need to account for the uncertainty introduced by rock fractures on rock slopes and underground opening behaviour (Baecher et al., 1977; Priest and

Hudson, 1976; LaPointe and Hudson, 1985; Priest, 1993). The design of block caving systems for mines continues to be an important topic for fracture statistical study.

Research programs for radioactive waste provided opportunities for making detailed surveys of rock fracture statistics (Rouleau and Gale, 1985). Computer programs that coupled synthetic fracture generation with flow codes led to Discrete Fracture Network models (Long et al., 1982; Dershowitz, 1984; Dverstorp and Andersson, 1989; Cacas et al., 1990). These models used Monte Carlo methods, which generate fractures by random sampling from probability distributions. Such tools, which are basic to risk assessment, build uncertainty and variability into predictive models.

A.3.2 Probability Density Functions and Properties

The first level geometric properties that are amenable to stochastic treatment are:

- Intensity and spatial distribution;
- Size; and
- Orientation.

Intensity and spatial distribution are somewhat different but closely related measures. A determination of intensity asks how much fracturing is present in a rock mass. The "how much" may be various measures including:

- Number per unit length in the core log or image log of a borehole;
- Number per unit length measures along a line sample of a rock exposure;
- Length of fractures per unit area in a fracture map; or
- Area of fractures in a volume of rock.

These measures have in common a unit of measure, which is inverse length. A classic problem in fracture modeling is inferring volumetric intensity (fracture area per volume), which is very difficult to measure directly, from its indirect measures of number of fractures per length of hole, or length of fracturing in the map of a rock exposure.

The spatial model asks the related question, how are these fractures distributed in space? The casual observation of an outcrop gives one the sense of a regular spacing to the fractures.

Although this spacing may appear constant, or perhaps normally distributed, actual measurements show that this is seldom the case.

The most commonly applied assumption in statistical descriptions is one where fractures occur randomly. The probability function that describes things that happen randomly in space (or time) is the negative exponential distribution. A system that produces random events is a called a Poisson process, and the probability density function that describes the interval, x, between these events that have an average frequency (or intensity), λ, is

$$P(x,\lambda) = \lambda\, e^{-\lambda x}$$

The λ is also called the Poisson parameter, describing event frequencies like accidents per work week, or fractures per meter. It happens to be both the mean and the standard deviation of the distribution. Figure A-7 shows the form of the exponential distribution. This distribution differs strongly from the normal distribution in being very asymmetric, with a strong skew towards smaller values. Fracture measurements in line samples commonly fit this distribution (Baecher et al., 1977), leading many who build fracture simulators to use a random, or Poisson process, as the basis for generating the fracture locations. The skewed distribution also implies that fractures cluster, because the distance between fractures is more likely to be a small value than a large value.

The Poisson process is not the only spatial distribution commonly used. The two most common alternatives are geostatistical distributions and fractal distributions. Geostatistics is a misleadingly-named field of probability studies that considers problems of spatial correlation. The “geo” part of its name comes from its original use for estimating ore reserves in the mining industry. The hypothesis that geostatistics addresses states that values of a parameter are spatially correlated, or simply stated, two samples of something like ore grade are more likely to be similar, if the sampling locations are closer together than if they are farther apart. Geostatistics tests this hypothesis using so-called variograms, which plot the difference between each value and all other values against functions of the distance between the sample locations. An ideal variogram defines three regions of correlation versus distance – a short-range which describes a non-spatially-correlated variability associated with very local values (called a “nugget”), a sloping “range”, which defines those distances over which values are spatially correlated, and a flat “sill” which are distances beyond which values have spatial correlation.

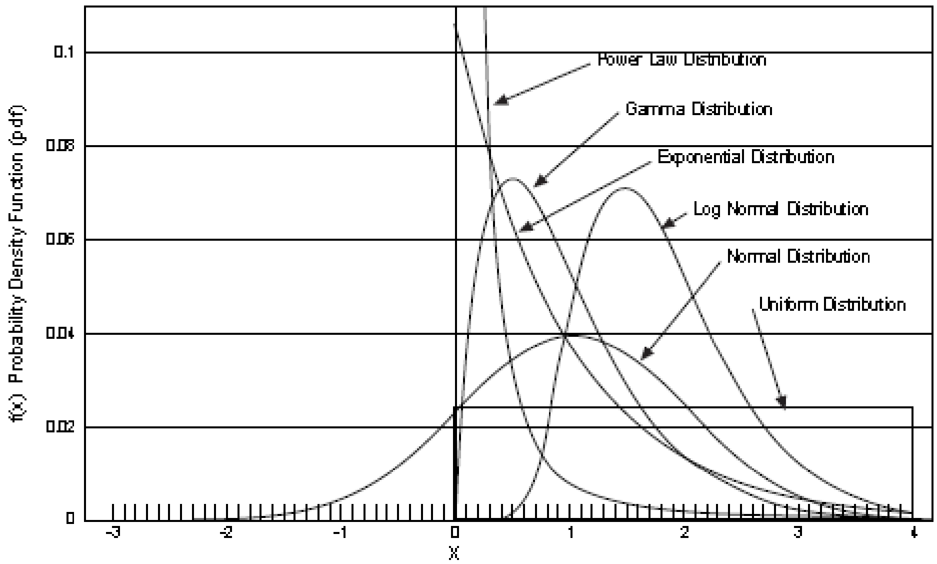
The other major alternative spatial distribution is based on fractal geometries (Barton and Larson, 1985; LaPointe, 1988). A recent review by Molz (2004) provides a useful survey of fractal description of porous and fractured systems, with a particularly good review of work on fracture networks, noting the ties between fractal geometries and power-law models, which are discussed further below in reference to fracture size distributions.

A complete review of fractal geometries is beyond the scope of this report, but there are two aspects of fractal concepts that have been applied to fractures – fractal dimension, which describes how patterns fill space, and self-affinity, which is the repetition of patterns at different scales.

Space-filling refers to how a pattern, such as fracture traces on a map or fracture planes in a volume, fills the available space, which is usually taken as an area or a volume. As an example, a pattern of regularly spaced lines in orthogonal directions on a map fills the two dimensional space of the plane of the map. If one were to start removing segments of those lines, the pattern would be filling less of the space, along with a decrease in connectivity (Figure A-8). Space-filling properties of fractures can affect well tests. A space-filling pattern of fractures in a two-dimensional space, like a fractured sedimentary layer, will produce a Theis-curve response, with its characteristic semi-log drawdown behaviour at extended time. Decreasing the fractal dimension and how the network fills the two-dimensional space produces other types of well test responses that can be related to the fractal dimension of the pattern (Barker, 1988; Chang and Yorsös, 1988; Doe and Geier, 1990). One method commonly used for assessing fractal dimension is box-counting, where a series of box-patterns with different scales is overlain a map, and the intensity of fracturing is determined from the intensity variations with box scale (Barton and Larson, 1985; LaPointe, 1988; Roy et al., 2007).

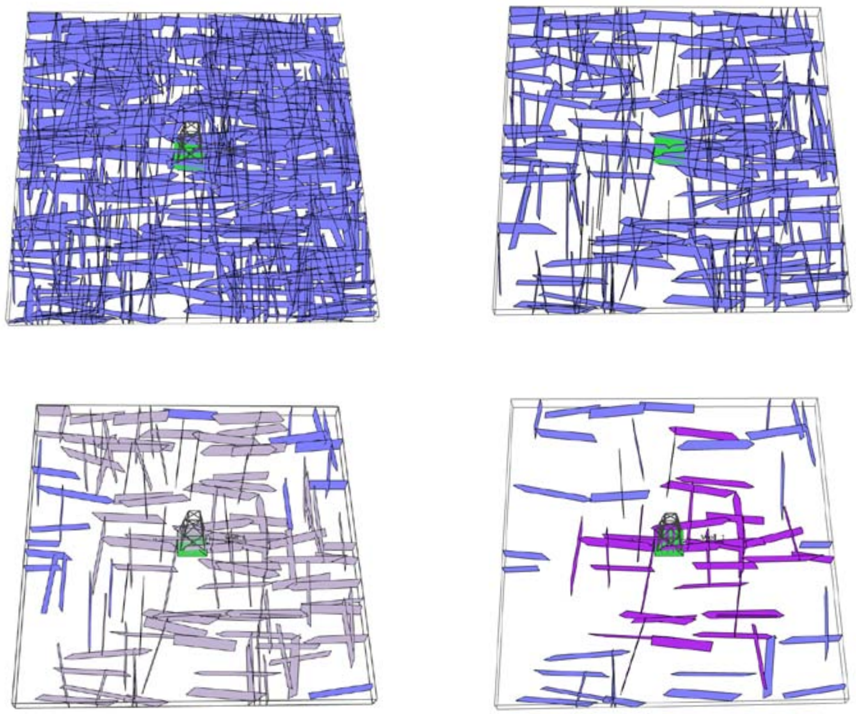
Self affinity means that patterns of fractures are repeated at different scales. The pattern and relative intensity of fracturing in self affine systems will appear the same regardless of the scale of view. Some studies have shown that patterns and fractal dimensions can persist with scale. Fracture network patterns and geometries often appear similar whether looking at hundreds of kilometres (lineaments), kilometres (faults), tens of meters (fractures in outcrop), (Oddling et al., 2004), or even millimetres or less (microfracturing in cores).

Figure A-7. Probability density functions for fracture geometry description.



	Normal	Exponential	Uniform	Log Normal	Gamma	Power Law
Mean	1	1	1	1	1	1
Std	1	1	1	1	1	1
Min	-∞	0	0	0	0	0
Max	∞	∞	∞	∞	∞	∞

Figure A-8. Decrease in fracture connectivity with lower intensity.



Contrasting colors show connectivity to well in center of simulation.

A.3.3 Fracture Size

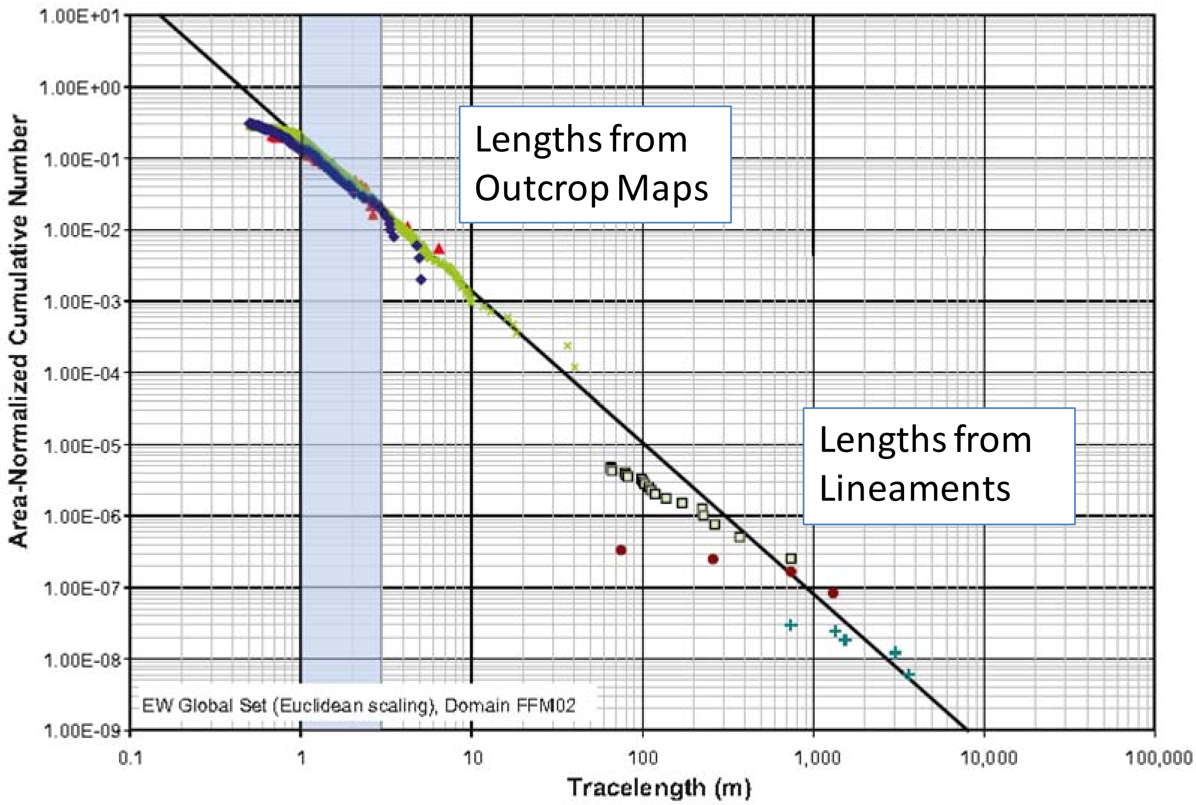
Fractal geometries are closely related to power-law distributions, which have seen increased application to fracture geometric and hydraulic properties in recent years. Power laws provide the basis for extrapolating properties, especially size, over large ranges of scales (Bonnet et al., 2001). Much of this work has come from earthquake studies to assess fault slip and risk from fault lengths and widths.

Fracture size requires some care as boreholes give no information on size, unless fractures are traced between wells. Mapped surfaces only give the fractures' length, which may or may not intersect a fracture across its largest span. Hence a distribution of fracture length data must be transformed to the fracture area, or equivalent radius, distribution. Furthermore, length data are usually censored, that is, there will be fractures that are larger than the mapped area. Hence the measurements will not have correct data for the largest fractures. In addition, field surveys employ a lower limit on measured size which reflects either a lower bound of perceived importance or the practicalities of completing a field survey in a finite amount of time.

Early investigations of fracture-geometry statistics (Baecher et al., 1977; Baecher, 1984; Priest and Hudson, 1985) generally matched field data for size to lognormal distributions, which are normal distributions of the log values of a parameter population. The lognormal distribution, like the exponential distribution, is asymmetric with a strong skewness to the smaller values. The skewness is highly significant because the largest fractures, which provide the greatest connectivity through a rock volume, are a relatively small part of the population.

Power laws have been widely applied to size data in recent years (Odling, 2004; Marrett, 1996; Marrett, et al., 1999). Power-law distributions have shapes that are very similar to lognormal distributions. The common method for assessing power-law behaviours plots the number of fractures having a certain size or greater, which is the cumulative number of fractures counting from largest to smallest, against the size. In a power law relationship, this plot is a straight line on double logarithmic axes. Often the data from any one scale will not be perfectly straight, perhaps due to the truncation effects of maps, but data from multiple scales will reveal a consistent power-law relationship (Figure A-9). Part of the appeal of power laws over lognormal, and other similarly-shaped distributions is the relationship between power-laws and other breakage processes, hence power laws may have a physical basis for application to fractures, while lognormal distributions are often chosen simply for their fit without any other rationale.

Figure A-9. Power law scaling of fracture size from lineament to outcrop scale.



From Fox, et al., 2007

A.3.4 Orientation

Fractures occur in sets that most often defined by having a common orientation. Within a set, orientation has a variability that can be described by a probability function. The spread of orientations is important because fractures that are parallel within a set do not intersect. The connectivity and anisotropy of a fracture network will depend on the number of sets and dispersion of orientations within each set.

There are a number of different orientation distributions (Fisher, 1993; Mardia and Jupp, 2000). These distributions apply to the consistency of orientation data, which for fractures, is usually expressed by the direction of the fracture pole, which is a vector normal to the fracture surface. The most commonly-used distribution is the Fisher distribution, which is also called the spherical normal because distribution resembles a bell-shaped, symmetric spread of orientations around a mean direction. The distribution is given by

$$f(\theta) = \frac{\kappa \sin(\theta) e^{\kappa \cos\theta}}{e^{\kappa} - e^{-\kappa}}$$

where $\kappa \approx \frac{N-1}{N-|R|}$, N being the number of poles in the set and the R magnitude of the vector sum of the poles. A continuing source of confusion regarding Fisher statistics is the fact that κ is inversely proportional to the spread of the data, hence a large κ indicates highly concentrated orientations and smaller κ's are more random (Dershowitz et al., 1998). For data that are non-symmetric about the mean, other distributions may be more appropriate, such as bivariate Bingham or bivariate Normal (Dershowitz et al., 1998).

A.3.5 Hydraulic Properties

Transmissivity and aperture also have been matched to lognormal distributions. Snow (1968) developed an approach for inferring the spacing of conductive fractures from packer tests. The common engineering approach to hydraulic testing is the use of fixed-interval lengths, where a set of packers is moved over consecutive intervals along the entire length of a hole. Unless the conductive fracture spacing is small compared to the packer interval, some of the tests yield no flow, or at least flow below the limit of measurement. Snow (1968) assumed that the spacing was random, or caused by a Poisson process, from which he could derive a relationship of conductive fracture spacing, l, from the fraction of no-flow tests, $P_{Q=0}$ that was a function of the packer spacing, b, to give

$$l = -\frac{\ln P_{Q=0}}{b}.$$

Having worked out the spacing of conductive fractures, Snow went on to develop estimators for the moments of a lognormal distribution of single-fracture transmissivities. He applied this approach to large databases of packer tests from US Army Corps of Engineers dam projects. This basic approach has been extended by Osnes (et al. 1988) and West (et al., 2006).

Perhaps the most extensive data sets of fracture transmissivities come from the Swedish radioactive waste research and siting programs. Fransson (2002) followed Snow's approach applying it to a large data base from Sweden's Äspö Hard Rock Laboratory using a non-parametric approach that was not tied to a specific type of probability function. The hydrogeologic characterisations have used both detailed packer testing and flow logging, which could resolve transmissivities of single fractures. The analyses treat fracture transmissivity as a lognormal variable, with mean values that are depth dependent (Rhén, 2007). Like fracture size, power-law distributions also can be fit to aperture and transmissivity data (Barton and Zoback, 1990).

A.3.6 Permeability Tensors and Stochastic Approaches to Equivalent Porous Media

One of the long-term goals of stochastic characterisation has been the development of up-scaled hydraulic properties from detailed descriptions of fracture geometric and hydraulic properties. Snow attempted to build permeability tensors for detailed aperture and orientation data (Bianchi and Snow, 1968). The development of permeability tensors using Snow's approach was an early goal of the Stripa Project in the late 1970's. The most widely applied method for using detailed data to build a permeability tensor is the Oda method (Oda, 1984), which weights the fracture's properties (such as orientation, aperture, and transmissivity) by the area of the fracture to determine its contribution to the tensor as a whole.

Fracture network models were developed partly to solve the same upscaling problem. Building a stochastic model involves several Monte Carlo steps, where a Monte Carlo model is one that assigns properties by randomly sampling the cumulative form of the property's probability density function. The specific steps Long et al. (1982) used were:

- select a number of random points in a two-dimensional area;
- at each point randomly create a line in a direction sampled from an orientation distribution for a specific fracture set;
- truncate the line to a length sampled from a length distribution;
- assign an aperture sampled from an aperture distribution; and
- repeat these steps for additional fracture sets.

Long then used this model to calculate equivalent permeabilities by turning the fractures into a network of one-dimensional finite-elements and determining the flow rate across the model for given head gradient. The anisotropic equivalent porous medium properties were determined by rotating the boundaries to force flow across the network in different directions.

Recognizing that this model is one possible "reality" that reproduces the statistics of the fracture network, one would create additional realisations to develop some statistical measures of the resulting permeability tensor values.

A.3.7 Lessons from Fracture Statistics

The discrete fracture network (DFN) model is the logical tool that comes from detailed studies of fracture geometry and property variability. In principle, DFN models, which are discussed further as simulation tools in the modeling section, could be the ultimate tool for simulating fracture networks; however, the approach has its critics.

Among the criticisms of the DFN approach is that its data requirements are too great for the approach to be practical (Neuman, 2005). The practical use of DFN models is discussed later in this report, but whether or not a DFN model should be used, fracture statistical studies provide important insights to the challenges of working in these media.

The most important lesson comes from the skewed probability density functions that describe the elements that are most critical to flow and transport. Whether the best choice of distribution is lognormal, gamma, exponential, or power law, the distribution will be one that is highly skewed towards fractures that are contributing the least to flow and transport. Length, aperture, and transmissivity, are properties where a small number of fractures – the longest, most transmissive, and most open – control the flow in a network. The rule of thumb that 10% of fractures control 90% of the flow is a direct consequence of these distributions.

This is not to say that the mass of fractures in the lower 90% of the population can be ignored. These fractures may serve as a diffusive volume, and they may be the major portion of the storage. This section has not discussed percolation theory, which looks at critical intensities of fractures needed to create continuous networks, but networks where the larger fracture are not connected will be controlled by the smaller fractures.

To summarize, the skewness of fracture distributions has several very important implications:

- Most fractures are relatively small.
- Most fractures are relatively non-conductive.
- The fractures that are usually responsible for most of the flow and transport are a small portion of the fracture population in the tail of a skewed probability distribution. Identifying this portion of the population is a key goal of site characterisation.
- If size and conductivity correlate, which is a reasonable assumption, a relatively small number of large and conductive fractures will likely dominate the hydraulic behaviour of a fracture network.

A.4 Transport Processes in Fractured Rock

Solute movement in a single fracture is a useful starting point for a discussion of contaminant transport in fractured rock. The basic conceptualisation (Tang et al., 1981; Sudicky and Frind, 1982) considers a set of fractures parallel with constant aperture and constant spacing (Figure A-10). Maloszewski and Zuber (1990, 1993), extends these concepts to tracer test analysis using what they call the SFDM, or Single Fracture Dispersion Model.

A hydraulic gradient acts along this fracture set, with equal fluxes moving in parallel through the network.

The coupled equation describing solute movement is:

$$\frac{\partial c}{\partial t}+\frac{v}{R}\frac{\partial c}{\partial x}-\frac{D_f}{R}\frac{\partial^2 c}{\partial x^2}+\lambda c-\frac{\phi_m D'}{\frac{1}{2}eR'}\frac{\partial c'}{\partial z}\Big|_{z=b}=0$$

Which can be simply stated as the change in solute concentration with time, $\frac{\partial c}{\partial t}$,is a sum of the following effects:

- $v\frac{\partial c}{\partial x}$ describes advection, which is simply solute being carried along with water flowing in the fracture. Water moves in the fracture with a velocity, v, consistent with the flow rate divided by the aperture and a unit width, w, or $v = q/ew$. Advection simply means solute flows with the water moving in the fracture at that fracture's average velocity. The retardation term , R, accounts for the solute's chemical interaction with materials on the fracture's surface.

- $D_f\frac{\partial^2 c}{\partial x^2}$ is the dispersive term, which accounts for variations in velocity due to the roughness and aperture variability of the fracture. With water moving at different velocities in different parts of the fracture, the solute spreads with distance along the flow path. The hydrodynamic dispersion coefficient, D_f lumps the effects of this velocity variability into a single term. The R term acknowledges that sorption on fracture surfaces also affects dispersion.

- λc represents radioactive decay with a half life of λ, but this term can represent any process that causes the composition of a solute to change with time, for example, by biologic activity.

- $\frac{\phi_m D'}{\frac{1}{2}e}\frac{\partial c'}{\partial z}\Big|_{z=b}$ reflects the exchange of tracer mass from the fracture into the porous matrix by matrix diffusion. D' is an effective diffusivity that describes the solute's depth and rate of penetration into a rock with a porosity, θ_m. D' is related to the free-water diffusivity (what one observes in the spreading of a drop of dye in a glass of water) by a tortuosity factor that accounts for the fact that a diffusing molecule does not travel in a straight line from the fracture into the matrix, but has to work its way around and through pores. The tortuosity factor is typically 0.1.

A.4.1.1 Retardation

Retardation refers to any property that slows or retards the velocity of the solute relative to the advective velocity. Retardation is a consequence of two separate effects; sorption and matrix diffusion. Sorption is a term that describes all the chemical interactions between a solute in the water and the solid surfaces in the rock. Some examples of chemical interactions are cation exchange in clays, where a one cation, like a metal, replaces another cation in the clay structure, or a biological reaction where an organic solute is consumed or transformed by bacteria. These reactions happen on the surfaces of the fractures as well on the surfaces of pores in the matrix. For transport calculations chemical interactions are often lumped into a single "distribution coefficient" that is a function of either area, K_A, for a fracture surface, or volume, K_D, for the matrix. Although both fracture surfaces and matrix pore surfaces may have similar reactivity with solutes, the matrix will generally have a much stronger potential for retardation because of its much larger surface area, provided there is a mechanism for moving solutes from the fractures into the matrix. This mechanism is matrix diffusion, which is discussed later.

A.4.1.2 Dispersion

Groundwater does not move at a single velocity in a flow system. Even in a perfect parallel-plate fracture, the velocity theoretically has a parabolic profile. The addition of aperture variations and channeling means that there is a spectrum of velocities in a single fracture. At a larger scale, the fractures of the network further vary in their transmissivity properties. A lump of solute introduced at a single source point will arrive dispersed over time to an extent that depends on the fluxes and velocities of all the connected pathways between the points of entry and exit. The consequence of this velocity variability is the spreading, or dispersion, of the solute both in the direction of flow, longitudinal dispersion, and perpendicular to the direction of flow, or lateral dispersion. Longitudinal dispersion values come from tracer tests and observation of contaminant plumes. Lateral dispersion is seldom measured except by back-calculation of observed plumes. Dispersion is not the measure of a material property, but rather the measure of a complex process that usually has significant scale effects on its value.

Dispersion occurs in both fractured and porous media, but in fractured media, dispersion will have some constraint due to the fact that advective flow is confined to the fracture pathways. Hence, the plume that dispersion creates in a fractured rock will track the fracture network in the same way that advection follows the network. A calculation or numerical simulator that could incorporate all the heterogeneous properties of the flow paths and know the velocity at all points in the rock would reproduce the spreading behaviours of solute transport. But this level of knowledge is never achieved, hence calculations and numerical models use a hydrodynamic dispersion coefficient that works like diffusion to create dispersive behaviour.

Figure A-10. Matrix diffusion in parallel fractures with uniform spacing and aperture.

A.4.2 Further Considerations on Matrix Diffusion

Matrix diffusion is perhaps the most important single retardation process for transport in fractured rocks. It is the result of the random, Brownian, motion of solute molecules that move mass into any water-filled pore space that is connected to the groundwater pathway.

A particle of solute that is moving in the advective stream of a fracture may move into any matrix pore that is in contact with the fracture. From there, the particle may move back into the fracture and continue its advective journey. Or, with equal probability, it may move further into the matrix, if there is more connected volume further away from the fracture surface. Thus there is a diffusive mass exchange continually occurring in both directions between the porosity of the flowing fracture and the porosity of the rock matrix.

The pore space that is available for diffusive storage includes any water that is moving slower than the main advective streams, or not flowing at all. Although most reference is to porous matrix, damage zones around fractures and faults in hard, crystalline rock can also have significant matrix diffusion potential (Neretnieks, 1980; Birgersson and Neretnieks, 1990). A significant component of the safety assessments for radioactive waste sites comes from matrix diffusion.

The direction and the rate of fracture-matrix exchange depend on the relative concentrations of the solute in the fracture and the matrix as well as the amount of surface area available for this interaction. Although the diffusion process can be modeled mathematically as though it were "driven" by a concentration gradient, particles still move randomly, and apparent direction and rate of diffusion is a consequence the uneven concentration of the particles.

The net movement of mass due to diffusion is controlled by the diffusivity property of the solute in the liquid, D. This is the "free-water" diffusivity, which is the spreading one sees when gently placing a drop of dye in a glass of still water. Although the same processes are working in the porous matrix, the distance that a solute will diffuse into rock will be less than the distance it will diffuse in a mass of water, because the diffusion pathway in the rock is tortuous due to the structure of the pores. In other words, the diffusion in the rock matrix does not follow a straight line. The apparent diffusivity, D', accounts for the tortuosity, having values that are typically an order of magnitude lower that the free-water diffusivities.

Once a solute has diffused into the matrix, it may adsorb onto pore surfaces based on a retardation parameter, R'. The surface areas of matrix pores are many times greater than the surface areas of fractures, hence the fracture surface terms are often neglected in the presence of matrix with diffusion potential.

Lipson (et al., 2005) point out four important implications of matrix diffusion:

- The majority of the solute may be in matrix and not in the fractures;
- The net rate of solute movement may be significantly less than that of the groundwater in the fractures;
- Removal of contaminants from a system where matrix diffusion is operating will be controlled by diffusion rates, and potentially will be very slow;
- Stationary, immiscible liquid (DNAPL) will disappear into the matrix at a rate controlled by its diffusion into matrix water and not fracture water (Parker, et al., 1994, 1997). This disappearance time depends on the dissolution rate of the

DNAPL, fracture aperture, matrix porosity, and fracture spacing (or matrix block size). Disappearance time may be as little as days for large aperture fractures with a high porosity matrix.

The effect of matrix diffusion on a contaminant's velocity in groundwater water appears as a velocity that is retarded compared with the advective velocity in the fracture. Sudicky and Frind (1988) relate the retarded velocity, v_A, to the advective velocity, v, by

$$v_A = \frac{v}{\beta}$$

β is a retardation factor taking into account the diffusion process along with a matrix block geometry term and a solute decay term with a half life, $t_{1/2}$, as the original motivation of the work involved radioactive solutes, hence:

Retardation factor:

$$\beta = \frac{\theta_m (R'D')^{1/2}}{\lambda^{1/2} \frac{e}{2} R} \tanh(\sigma \lambda^{1/2})$$

Matrix block geometry facture:

$$\sigma = \left(\frac{R'}{D'} \right)^{1/2} \left(B - \frac{e}{2} \right)$$, and

Solute decay factor:

$$\lambda = \frac{\ln 2}{t_{1/2}}$$.

This expression can be developed for various different geometries of fractures and matrix blocks, which petroleum engineers call the σ factor. This case assumes parallel fractures with a spacing of $2B$. The next fracture also is carrying the same solute, which is diffusing into the matrix from the other side of the block. Given this symmetry, the solution uses half of the fracture, $e/2$, and half the block thickness. The capacity of rock to store diffused solute is not infinite, but it might be very big. The block geometry factor relates to this capacity.

The retarded velocity of a solute is sufficiently important that its simplifications are worth consideration. An actual fracture network will not have uniformly open fractures with constant spacing. Rather, one may expect the major portion of a solute may be carried in a few larger aperture fractures, which will have a larger spacing than the average value of all fractures. The matrix diffusion of such a system would act as if it had much larger or infinite blocks, at least early in its exposure time to a solute. The other important conceptual model is one of a zone of porous rock around a fracture. This case appears in non-porous rock, such as plutonic or metamorphic rocks, where a shear fracture or fault may have a zone of enhanced porosity extending several millimetres to several centimetres or more. In near surface environments, weathering will also create porous zones around conducting fractures. For these cases, the B value is the thickness of one side of the fracture.

Like credit-card debt, matrix diffusion sometimes solves short-term problems to the detriment of long-term ones. Matrix porosity may act as a persistent reservoir that can slowly release contaminants long after a site has been otherwise cleaned up. Matrix diffusion can confound pump-and-treat efforts, where the water appears to be clean, only to be re-contaminated by diffusion back from the matrix.

The assessment of matrix diffusion can use general values of rock porosity if they are known. Observations of contaminants in cores of recovered rock are valuable especially if one can measure the penetration distance from fractures and the contamination history is known. Tracer tests in a rock where matrix diffusion is active will create characteristic diffusive tails (Haggerty et al., 2001). Employing multiple tracers with different free-water diffusivities helps to confirm matrix diffusion if the tracers are retarded in proportion to the difference of their diffusivity values. Meigs and Beauheim (2001) used this approach to assess matrix diffusion in a porous carbonate rock, as did Andersson (et al., 2004) on shear features in Swedish granite. The same tracer-test approach at the US Geological Survey's Mirror Lake site, produced diffusive-like tails to breakthrough results without a separation of the tracers according to their free-water diffusivities. This observation led Becker et al. (2000) to conclude that dispersive processes could produce diffusive-like tails, hence long tails on breakthrough curves are not, by themselves, proof of matrix diffusion.

An assessment of matrix diffusion in the laboratory may be less expensive than a field-scale tracer test. If the tests show matrix diffusion is not significant, one saves the cost of a tracer test. Even if one does a tracer test, the laboratory measurements are very helpful for both assessing tracer tests and for performing scoping calculations of diffusion potential.

Mineral coatings on fracture surfaces should be considered before assuming matrix diffusion is active. Such deposits act may enhance the retardation of the fracture surface (Wels et al., 1996) while limiting interactions between the fractures and the matrix (Thoma et al., 1992).

A.5 Multiphase flow

Multiphase flow is the most complex and least understood of all fracture flow phenomena. Yet it is central to many key societal concerns including vadose zone groundwater, DNAPL transport, oil and gas production, and carbon sequestration. The understanding of multiphase flow has advanced greatly over the past 20 years with research in theory, laboratory testing, and field experimentation. Nonetheless, basic concepts are still evolving.

Multiphase flow occurs when immiscible fluids or fluids and gases share the same porous medium. For contaminant groundwater studies, multiphase effects appear in the vadose zone, where the phases are air, water, and immiscible non-aqueous phase liquids (NAPLs), and in the saturated zone, where flow involves water and NAPLs.

While single phase groundwater flow is only concerned with viscous behaviours, multiphase flow involves additional gravitational forces through fluid density contrasts and capillary effects at the interfaces of the solid and liquid or gas phases. Viscous effects become more complicated as the flow of each phase has a relative permeability that depends on its share of the pore volume (saturation) and its own density and viscosity.

Two main variables govern multiphase behaviour:

- The driving and resisting forces, specifically buoyant gravity forces deriving from density contracts, capillary forces acting at solid surfaces where phases meet, and viscous forces, which vary with the saturation percentages of the phases.
- Fracture network geometry, especially fracture dip and continuity of flow paths in the direction of buoyant flow. Unlike porous media, where gravity works vertically, the effect of gravity on a single fracture depends on the fracture's dip angle.

The importance of the different forces is a function of fracture aperture and fracture dip. Capillary forces are the dominant concern in fractures with smaller apertures, while gravity dominates in larger aperture fractures, where capillary forces disappear. Viscous forces operate alongside capillary and gravity effects over intermediate aperture ranges. In a rock with variable fracture apertures, different portions of the fractures or even different portions of the same fracture may be dominated by different forces.

The bulk of multiphase flow theory concentrates Darcian flow with capillary effects, drawing on Richards adaptation of the equations of saturated water flow in terms of vertical elevation, z, and the replacement of total head based on pressure head, $h = \psi + z$, and conductive properties that are functions of saturation, θ (Jury et al., 1992)

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial \psi}{\partial z} + 1\right)\right].$$

This approach appears to work best for smaller aperture fractures where capillary and viscous forces control flow.

Laboratory experiments on multiphase flow in fractures over the past twenty years (Fourar et al., 1993; Persoff and Pruess, 1995; Tokunaga and Wan, 1997; Su et al., 1999; Glass and Yarrington, 2003) have produced results wide range of unexpected and often perplexing results that may not be compatible with Richards's equation or Darcy flow. These involve various forms and combinations of fingering flows, blob flows, drop flows, and film flows. Field experiments (Fabyshenko, 2000a) show intermittent flow and changing pathways that may be considered mathematically chaotic (Fabyshenko, 2000b).

The scientific community is still developing a flow theory, or set of theories to encompass these behaviours. They appear to occur mainly in larger aperture fractures where gravity is the dominant force or in systems that have mixed regions of capillary, viscous, and gravity effects (Ghezzahei, 2004). They are a significant concern for contaminant transport prediction, as these processes often result in exceptionally rapid flows and large fluxes.

This discussion of multiphase flow addresses separately capillary dominated systems and gravity dominated systems. The section concludes with a discussion of possible delineations between the capillary and gravity dominated regimes, as well as the influence of fracture-network geometry.

Or (2008) has made some initial efforts to define the conditions where different flow regimes may act as well as the conditions that define the limits of Richards equation.

A.5.1 Capillary Dominated Systems in Smaller Aperture Fractures

Capillary effects derive their energy from the chemical interactions of solid surfaces with fluids and gases. Solids, which overall have a neutral charge balance often have an imbalance on their surfaces. These surface charges will attract or repel liquids depending on their compatibility with the solid's surface. When two fluids form an interface at a solid surface, the surface will preferentially attract one fluid over the other, where the "wetting" fluid is the more attractive and the "non-wetting" fluid is less so.

Besides the classic capillary tube, another method of studying capillary forces is the Wilhelmy plate (Hiemetz and Rajagopalan, 1997, Ch. 6), which can be an analog for a fracture surface. The method uses a thin plate that hangs on a balance. A meniscus, which may be either oriented up or down, forms at the intersection of the plate and the liquid. The imbalance when the plate contacts the liquid is a measure of the surface tension, σ, which is measured in units of force per length. This tension acts on the plate with a contact angle, θ, that reflects the strength of the wetting behaviour. The net force acting on the plate is $\sigma \cos\theta$. The plate sees sum of the forces on the both sides, or $2\sigma \cos\theta L$ where L is the plate's length, assuming a negligible thickness (Figure A-11).

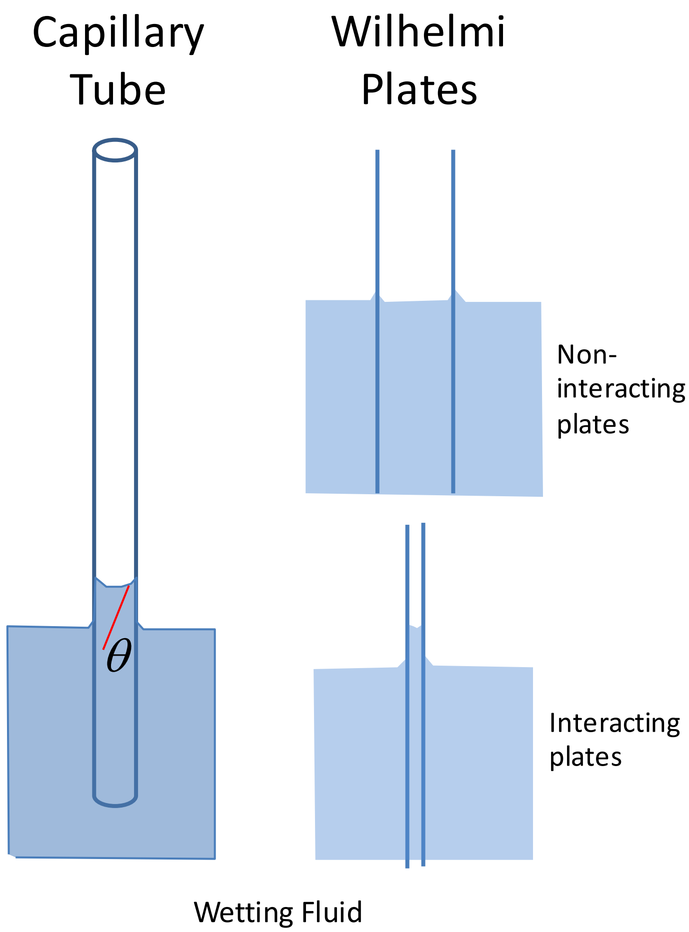
If we introduce a second plate into the same liquid at an appreciable distance from the first, the second plate will have a similar meniscus and the fluid surface between the plates will be flat. If we move the plates close together, the menisci of the two plates will interact drawing liquid into the space between the two plates, if the liquid is wetting.

The region between the plates is similar to a fracture with an aperture, e, where capillary forces will draw a wetting fluid (or repel a non-wetting fluid) between the plates. The height, h, that balances the weight of the liquid and the capillary force is

$$h = \frac{2\sigma \cos\theta}{\rho g e}.$$

This is identical to the equation for fluid rise in a capillary tube with the substitution of aperture for tube radius.

Figure A-11. Capillary tube and capillary pressure between parallel plates.



A.5.2 Capillary Entry Pressure

The capillary plate equations directly apply to the problem of DNAPL entry into a groundwater flow system. Kueper and McWhorter (1990) describe this problem, as one where DNAPL migrates through the vadose zone and water-saturated soil to the top of bedrock (Figure A-12). The pore throats of the soil are assumed to be large enough that the DNAPL will freely migrate to the top of the bedrock without capillary effects in the soil. On reaching the bedrock, the DNAPL will form a pool if it is unable to enter the fractures or pores of the rock.

At the intersections of fractures with the rock surface, the higher density of the DNAPL creates a gravitational force that acts on its contact with the water. As water is likely the wetting fluid, it resists the entry of the DNAPL with a capillary force at the interface given by:

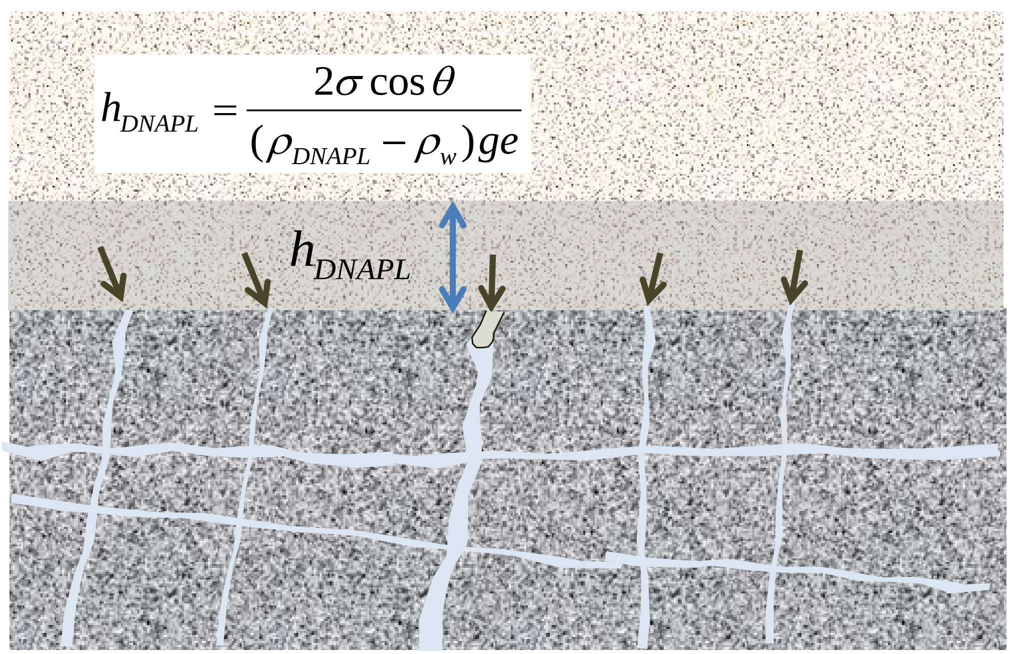
$$P_E = \frac{2\sigma\cos\theta}{e}.$$

The depth of a DNAPL pool or vertical height, h_{DNAPL}, to create this pressure is

$$h_{DNAPL} = \frac{2\sigma\cos\theta}{\cos(\rho_{DNPAL} - \rho_w)ge}.$$

The effect is fracture dip is very important in multiphase flow. As flow is largely confined to fractures, gravity will act with the sine of the dip angle, φ, from a maximum in vertical fractures to zero on horizontal fractures. Similarly the length of a DNAPL lens needed to create a sufficient pressure for entry will increase by $1/\cos\varphi$ as fracture dip angles become shallower.

Figure A-12. Capillary entry effects for ponded DNAPL.



Even after a DNAPL pond breaks through to bedrock fractures, its continued downward migration may be arrested by smaller aperture fractures or on fractures with decreasing dip. The relationships of dip and entry pressure were supported experimentally using laboratory tests on a pair of fractures in limestone by Longino and Kueper (1999). They also related the mobilisation and migration of a DNAPL to relationships of the capillary, viscous, and gravity forces (Bond number and capillary number) discussed further below.

Fracture dip also affects the gradients driving fluid flow in the unsaturated zone and saturated multiphase flow. The dip of the fracture constrains flow to move in the fracture plane in the direction of dip. Although the global hydraulic gradient is vertically downward, the gradient in the fracture plane will be $1/\sin\alpha$. Within horizontal fractures, gravity effects essentially disappear.

In fracture networks, gravity will drive flow in the dip directions of fractures. The vertical continuity of flow will depend on the existence of pathways that are continuous along fractures with sufficient dip to allow gravity to work. A preferred dip angle direction will move fluid preferably in that dip direction (Doe, 2001). A network may have vertical dead ends, or regions of horizontal dip where density-driven flows may stagnate creating local pools much like perched water systems in the unsaturated zone. This may remain stagnant (1) until they fill to a “tipping” point in the network where a vertical pathway continues or (2) until the height of the non-wetting phase column to create pressure gradients along shallow dipping fractures (Figure A-14).

The role of capillary pressure varies with the levels of non-wetting phase and wetting phase fluids. Capillary forces drive wetting fluids to occupy the smaller aperture fractures and the smaller aperture portions of heterogeneous fractures. Conversely, non-wetting fluids will be confined to the larger aperture spaces. The flow behaviours of fractures depend on the saturations of the wetting and non-wetting phases as well as the variability of fracture aperture the range of the variability, and the structure or pattern of the variability. As the saturation of the non-wetting phase increases, the regions it occupies will expand from the largest apertures into smaller apertures. The flow capacity for the non-wetting phase will increase as the continuity of phase occupancy increases. The wetting phase, being confined to the regions of aperture regions, may become immobilized if the regions it occupies lose continuity.

As the wetting phase increases its saturation, non-wetting liquids may similarly become isolated; however, they will occupy the largest aperture regions, thus diverting the wetting phase from the parts of the fracture with the highest intrinsic permeability. These behaviours depend, of course, what the largest and smallest apertures are in individual fractures or within fractures and whether or not the larger apertures form channels. A large aperture channel may be particularly conductive to a non-wetting fluid, if the channel's aperture is large enough that capillary forces are negligible.

Aperture is a critical issue for multiphase flow and predicting DNAPL invasion. The wall separation of a fracture and heterogeneity of aperture with the fracture controls the capillary pressures. Currently, other than back calculating aperture, such as from the observed depth of a DNAPL pool, the main means of getting aperture data from the field is from transmissivity data using the cubic law. The capillary issue of aperture mirrors the discussion of transport aperture, except that underestimating aperture for advective velocity is a conservative error that overestimates velocity, while underestimating aperture for capillary pressure will predict a capillary immobilisation that may be in error.

The focus of this discussion has mainly been DNAPL; however, it should be noted that similar capillary issues exist with LNAPLs, especially where changes in groundwater level may trap LNAPL's and prevent them from rising (Hardisty et al., 2003).

A.5.3 Viscous Effects

Viscous effects also play a role for apertures ranges that lie between the gravity and capillary regimes. Where two phases are present, the flux of each phase will depend on its saturation, or the portion of fracture volume occupied by that phase. The relationships of permeability to saturation are expressed in relative permeability curves, which are plots of each phase's permeability versus its saturation. Note that multiphase flow usually requires the use of intrinsic permeability rather than hydraulic conductivity as the phases usually have different viscosities and densities.

The simplest relative permeability curves are so-called “straight-line” curves, where each phase has a permeability that is linear function of saturation from 0 to 100 percent. The straight-line relationship implies that the two phases do not interfere with one another, which will usually be the case in larger aperture fractures. As apertures become smaller, and as capillary effects begin to have a role, the relative permeability relationships take on curvatures that reflect increasing interference between the two phases, as well as curves that may go to zero permeability at phase saturations above zero, where a phase becomes immobile.

A.5.4 Flow in Larger Aperture Fractures: Gravity versus Capillarity and Viscosity

At very large fracture apertures, capillary forces across fracture walls are reduced, and even viscous effects may become weak. Using a simple salad dressing as an example, the vinegar one pours into the oil flows directly to the bottom of the cruet. While such aperture conditions may seem extreme, they are most likely to occur near the surface where exfoliation jointing, slope deformations, or dissolution and weathering have enhanced the apertures of fractures. While an exact aperture number is difficult to specify it may on the order of 100’s of microns to a few millimetres.

Ghezzehei (2004) notes that the multiphase flows in very large fractures have distinct modes that depend on the flux that is available to sustain them. Unlike lower permeability materials, large aperture fractures may have flow capacities that exceed infiltration rates. The most important regimes of flow are in increasing order of flux rate:

- Flow of adsorbed films (Or and Tuller, 2000);
- Flow of sliding drops (Su et al., 1999; Doe, 2001);
- Rivulet flow;
- Stable film flow (Tokunaga and Wan, 2001; Dragila and Wheatcraft, 2001); and
- Unstable (turbulent) film flow.

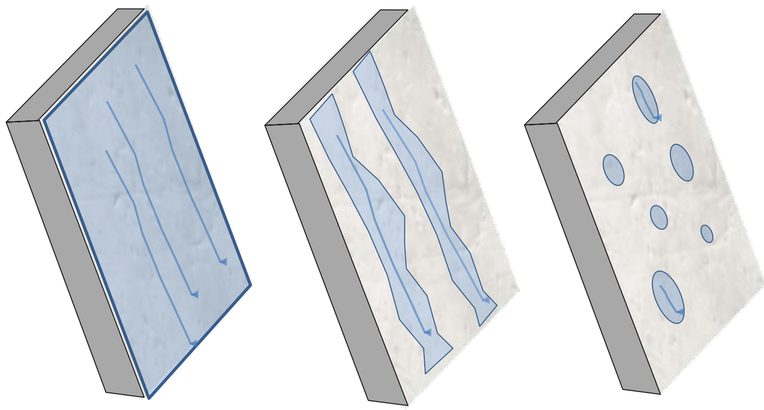
Figure A-13 illustrates films, rivulets and drops. Film flow, and especially unstable film flows can support fluxes that exceed even the cubic law, which is sensible given that there is only one wall of resistance instead of two. Sustaining film flows requires a large fluid source that may not exist except in intermittent events, like large storms. At lower fluxes, the film becomes discontinuous, breaking up in to rivulets, and at lower rates than that, the flow moves as discontinuous drops, much like those on a car windshield. Capillary forces hold the drop to the surface in an immobile state until the mass of the drop becomes large enough move the drop by gravity, at which point it may move very quickly. Such drops will typically lose mass on their trailing edges, and eventually coming under the control of capillary forces until they see a new charge of mass. Ghezzehei (2004) proposes a relationship between flux and contact angle as a control on the flow regime.

Another view of flow regimes relates intermittency and front stability to the relative strengths of gravity, viscous and capillary forces (Or, 2008). Intermittency is the observation of flow that occurs in pulses, sometimes on pathways that move with each event (Faybishenko, 2000b). Stability refers to whether displacement fronts of the invading phase are uniform or break into fingers, of either a capillary or viscous sort. The onset of some of these non-Darcian behaviours may indicate the limits of applicability for Richards's equation and its underlying concepts.

Or (2008) relates these flow phenomena to two useful dimensionless numbers:

- The Bond number (Bo), which expresses the relative importance of gravitational to capillary forces or $B_o = \frac{\Delta \rho g e^2}{\sigma}$, and
- The Capillary Number, which is relative importance of viscous to capillary forces $Ca = \frac{\mu \bar{v}}{\rho \sigma}$ where g is dynamic viscosity, and $\bar{v}$ is mean fluid velocity. In terms of aperture, this can also be given as $Ca = \frac{\mu Q i}{e w \rho \sigma}$ where Q is a flux, i is hydraulic gradient and w is a unit width of a fracture flow path. e should be transport aperture, the value equivalent to effective porosity that relates flux to velocity.
- A generalized Bond Number, $Bo^* = Bo - Ca$, Or suggests, may define the limits of Richards equation's applicability, specifically a critical value of 0.05, which is roughly equivalent to pore sizes or apertures on the order of 600 microns.

Figure A-13. Flow processes in larger aperture fractures (one fracture wall shown).



A.5.5 Multiphase Effects in Local Groundwater Flow Systems

This discussion so far has mainly considered either DNAPL or air-water systems.

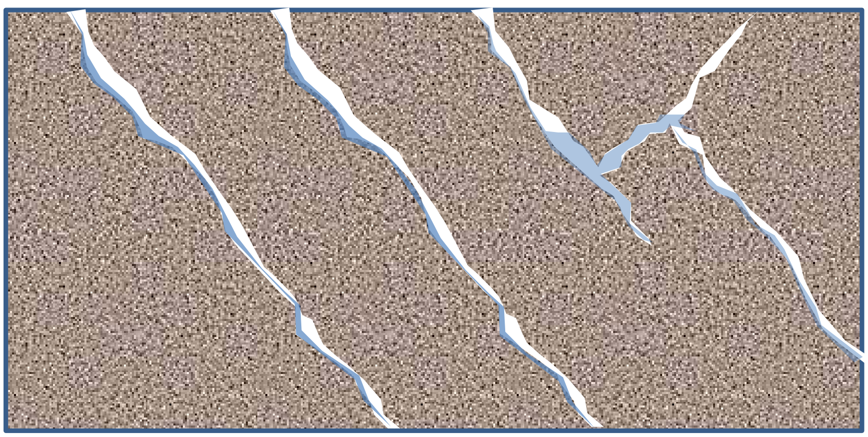
Hydraulic gradients with strong upward or downward gradients may also enhance or impede the movements of immiscible fluids that are gravity-driven (Chown et al., 1997). A vertical hydraulic gradient will arrest NAPL movement when it runs counter to the direction of density-driven flow and exceeds in magnitude (Chown et al., 1997):

$$\frac{\Delta h}{l} = \frac{P_c(0) - P_c}{\rho_w g l} + \frac{\Delta \rho}{\rho_w} \sin\varphi$$

Moving from a single fracture to a fracture network introduces complications of connectivity and dip-variability along a flow path. For density driven flow to travel vertically a pathway must be continuously vertical, either going down for DNAPL or up for LNAPL. If the pathway does not have this continuity, the gravity-driven fluid will be trapped, and accumulate in a pool until the pool reaches a length where it will find another vertically continuous path (Figure A-14).

The selection of aperture values for evaluating NAPL mobility must be done with great care to avoid overestimating immobilisation effects. The earlier discussion of aperture types made the case that aperture can vary greatly depending on whether it is based on flow, transport, or storage. The cubic law presupposes ideal, smooth fracture surfaces, when it calculates aperture from transmissivity values, which are flow-based. Actual fractures are rough-surfaced with wall separations that are likely to be larger the cubic law values, possibly considerably so. The capillary pressure increases inversely with aperture, hence an underestimate of the aperture will likely lead to an over-prediction of capillary forces and an overestimate of the fracture's potential for NAPL immobilization.

Figure A-14. Effect of fracture dip and continuity on gravity flow.



A.5.6 NAPL Disappearance Time

The previous section described how capillary forces at the interface of a solid and two liquids prevents non-wetting liquids from entering smaller-sized pore spaces, whether fracture or matrix. Liquids that are moving under gravitational density effects can also be trapped by the geometry of the fracture network, wherever a fracture path is not continuously moving up or down with the direction density effects want to move it. Once immobilized these liquids form single-liquid pools.

Thus immobilized, NAPL's begin to dissolve into the water and move into the matrix pores by diffusion, as discussed above. This may occur in any porous rock, even crystalline rocks like granite. Once in the pores space, the solutes may be further retarded in their motions by chemical interactions in materials, especially organics, in the pores and on the more surfaces. The dissolved materials then may diffuse into the matrix pore space.

As shown in Figure A-15 this process proceeds in three stages – an early stage when NAPL pool forms, an intermediate stage when dissolution has reduced the NAPL mass and broken it into discontinuous segments, and a third stage when the NAPL has entirely dissolved and diffused into the matrix.

Parker (et al., 1994 and et al., 1997) developed the mathematics to describe these simultaneous dissolution and diffusion processes. Her approach couples a one-dimensional solute-diffusion equation with the NAPL dissolution rate to obtain the total mass, M_t, that has dissolved and diffused into the matrix over a the two surfaces of unit area of fracture at an elapsed time, t, is:

$$M_t = \varphi_m S_w \frac{4}{\sqrt{\pi}} \left(R D_m t \right)^{1/2}$$

where S_w is the solubility of the NAPL in water. The mass of a fluid contained in this unit area, A, of fracture is the fluid's density, ρ_{NAPL}, divided by the aperture, hence the NAPL pool is gone when M_t reaches the total fluid mass of inside the fracture, or $M_t = \rho_{NAPL} / e_S A$. In a small departure from Parker, we specify this aperture as the storage aperture, e_S. A sight rearrangement produces the time when the NAPL will be gone, or,

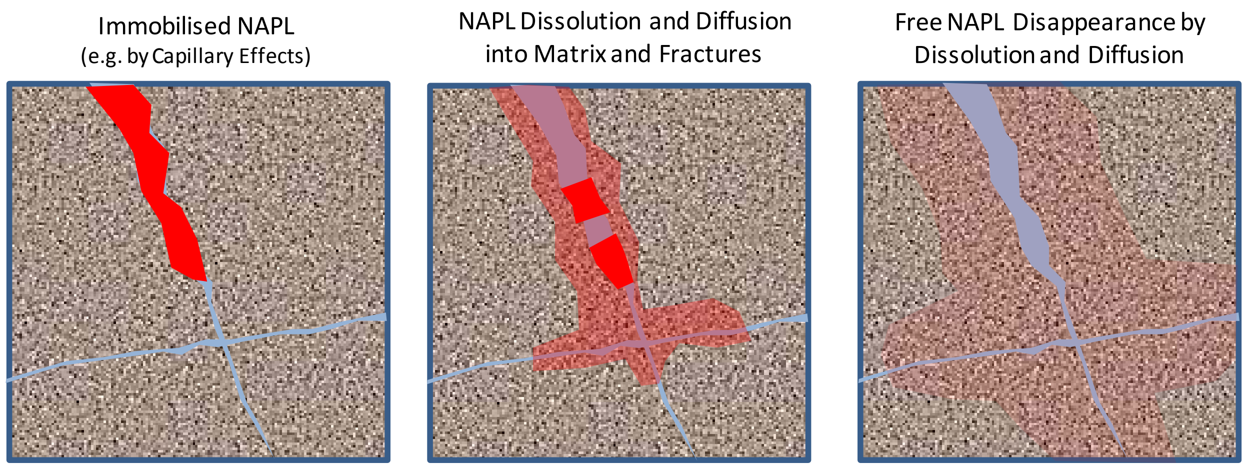
$$t_{NAPLgone} = \frac{\pi}{R D_m} \left(\frac{\rho_{NAPL} e_S A}{4 \varphi_m S_w} \right)^2 .$$

Recalling the earlier discussion of aperture types, which made the case for distinguishing the aperture values for flow (hydraulic aperture), velocity (transport aperture), and fracture volume (storage aperture). These values may differ from one another by more than an order of magnitude, where storage aperture tends to have the largest value, and hydraulic aperture, when based on ideal parallel plates, tends to have the smallest. Thus, using the hydraulic aperture, calculated from the cubic law, may underestimate the storage volume in the fracture and lead to a calculated disappearance time that is biased towards faster depletion.

Parker's (et al., 1997) second paper on this topic extended the analysis to consider matrix blocks, which are surrounded by fracture rather than a single fracture surrounded by infinite matrix. Finite-sized matrix block put a limit on the accessible matrix storage. Multiple releases of NAPL to a fractured bedrock may exceed the matrix's storage capacity, and with the excess going to reforming NAPL pools.

The conceptual model for finite blocks follows that of classic dual porosity flow by assuming block-bounding fractures are regularly-spaced with constant fracture properties. Cubic blocks are a special case where the fracture spacing is the same in three, orthogonal directions. The model accommodates unequal fracture spacings using a shape factor to account for different spacing cases. Petroleum engineers use this same approach for dual porosity flow rather than solute diffusion; however, as both are based on one-dimensional diffusion equations.

Figure A-15. Disappearance of immobile DNAPL by dissolution.



B- FRACTURED BEDROCK CHARACTERIZATION METHODS

B.1 Geological Characterization

Not all fractures are important for groundwater, and many aspects of the geology are not relevant to the groundwater conditions. Nonetheless, the conducting features in bedrock are the product of geologic processes, and discovering the geologic controls on groundwater-significant fractures is essential to a successful site assessment.

The geologic settings of fracture flow systems are highly variable. A pronounced plane of weakness in a rock, such as bedding in a shale or foliation in a schist, may be the main fracture control. At another site, for example in a massive granite, exfoliation or sheet joints within a few meters of the surface may be a dominant control. The dominate fractures in carbonate rocks, like limestones and marbles, are commonly solution-enhanced. The depositional and cooling processes of volcanic rocks create distinctive fracture systems that must be taken into account in the conceptual model development. In a rock that has been subjected to intense deformation from tectonic events, faults and fracture zones may be the dominating geologic features of a site.

Once a geologically-based conceptual model is established, a range of geologic tools come into play including:

- Desk Studies;
- Remote sensing and lineament studies;
- Geologic mapping of bedrock exposures; and
- Geologic investigations in boreholes.

B.1.1 Desk Studies

The initial stage of any investigation program involves desk studies that synthesize what is known from the specific site and similar sites. The study should draw on data from the same general region as the site and from analog geologic environments elsewhere. Published studies along with the experience of geologists and hydrogeologists (as well as drillers), who have worked in the area, are vital to forming the conceptual models that are the basis for all further work.

B.1.2 Lineament Studies

Fractures may express their geometric patterns on the earth's surface, even when the bedrock has some thickness of cover. Linear patterns in topography and vegetation are often detectable in air photos, satellite images, and other forms of remote sensing. Until these linear features are ground-checked for their origin, they are called lineaments, but the existence of some relationship between lineaments and water-bearing features has been well established (Lattman and Parizek, 1964; Mabee et al., 1994; Sander, 2007).

More recently, LIDAR, or laser-based topographic mapping has seen extensive applications at many scales from kilometres, using aircraft, to outcrop scales, using ground-based equipment (Nyborg et al., 2007). The basis of LIDAR is the imaging of a surface by multiple reflections from a large number of points. In forested areas, LIDAR has been particularly valuable as computer-based processing can sort the reflections and determine which are coming from the ground and which are coming from forest canopy.

Lineament studies are particularly useful in glacially stripped terrains such as the Canadian Shield, where the topography is controlled by contrast of competent rock and weaker, linear fracture zones and faults (Gleeson and Novakowski, 2009). Radioactive waste programs in Sweden have used such methods extensively (Nyborg et al., 2007; Rhén et al., 2007). Complementary aeromagnetic surveys have proven useful in siting studies for identifying conductive fractures based on the oxidation of magnetite. The interaction of circulating groundwater with the walls of fracture zones transforms magnetic oxides of iron to non-magnetic forms, creating linear anomalies with low magnetic responses.

Vegetation patterns also may follow fracture zones (Muldoon and Bradbury, 2003, 2005). Fracture-controlled lineaments may be wetter than surrounding rocks due to a higher underlying hydraulic conductivity and a lower elevation which concentrates groundwater discharge. Mineralisation in fracture zones along with preferential weathering also creates contrasting chemical conditions which may encourage one form of vegetation over another.

The presence of a feature in a lineament map does not assure its significance to a site's hydraulic behaviour as demonstrated by correlation studies of underground flows to tunnels where there are projections of surface lineaments. Mabee et al. (2002) compared projections of 38 lineaments to an underlying, 28-km water supply tunnel in basement rock. Of the nineteen flowing zones in the tunnel, thirteen coincided with surface lineaments while six had no feature expressing itself at the surface. Both Mabee's study and a similar one in Norway (Banks et al., 1992) found may of the mapped features were faults but were not hydraulically significant due to clay fault gouge. Not all fracture zones will have surface expressions, as some linear features may have non-geologic origins or not be hydraulically active. Suspected features need to be checked by ground investigations. Nonetheless, lineament studies are an important part of an initial characterization of a potentially fractured site.

B.1.3 Fracture and Fault Mapping

Although is it is difficult to estimate hydraulic properties without a direct measure of flow, the direct observation of fractures is an essential component of fractured bedrock investigations. We address first the use of rock exposures, which may be natural outcrops, excavations for construction purposes, or the exposure of bedrock by stripping of the shallow soil cover. Fracture mapping of rock exposures provides data that cannot be obtained in boreholes like fracture size and termination relationships as well providing a look at how other properties like aperture and fracture coatings vary along a fracture's length. Furthermore, the outcrop view provides a good sense of the architecture of the fracture network.

Fractures in surface exposures are often not representative of conditions at depth even a few tens of meters below the surface. They are likely to be enhanced and altered by mechanical and chemical weathering. Geomechanical effects can create very open fractures through slope movements that dilate fractures and exfoliation fractures that form by stress relief close to rock faces (Figure A-1). Nonetheless, near-surface fractures are often the most important for contaminant investigations for the following reasons:

- The surface is a common location for contaminant release, hence near surface fractures are often where contaminants enter the bedrock; and
- Near surface fractures may form their own hydro-geologic domain with distinct properties that derive from weathering.

Geologic mapping of fractures and fault zones is a well established component of fractured rock site investigations. Where rock exposures are present, fracture mapping provides information on the locations of specific features that may have hydraulic significance. Mapping also provides a basis for geometric descriptions of the fracture network geometry including orientation, set identification, fracture intensity, termination relationships, fracture size, roughness and planarity, and fillings and coatings.

A geologic reconnaissance of surface exposures can teach much about a fracture network. In particular, a survey of outcrops should note any features of fractures that suggest past of present groundwater activity such as:

- Observations of water recharge or discharge;
- Weathering or alteration halos and their depths;
- Visual assessment of matrix porosity, such as apparent porosity or friability versus high degrees of cementation; alteration haloes also provide evidence of past matrix diffusion;
- Thickness, alteration, and structure within faults or minor deformation zones;
- Open fractures and any fractures that appear to control opening;
- Relationships of fractures to other geologic features, such as bedding or foliation; and
- Any indicators of fractures that have particular hydraulic significance.

A more quantitative assessment of fractures may be warranted, particularly if data will be used in building fracture network models. Fracture scanline mapping lays out measurement lines along outcrops and records the properties of fractures that intersect the line, such as:

- Fracture orientation;
- Fracture location on the line (for intensity determination);
- Fracture length including how the fractures end (terminated in rock, terminated against other fractures, or indeterminate due to the extent of the exposure);
- Fracture opening (may be qualitative);
- Fracture coatings or fillings; and

- Other indicators of hydrologic activity.

Procedures for scan-line mapping appear in LaPointe and Hudson (1985) and Priest (1993). The International Society for Rock Mechanics (1978) has also published guidelines for fracture data collection. In particular, the mapping programme must take biases of orientation and censoring into account by seeking exposures in multiple orientations and correction intensity data for the angle of intersection between fracture sets and the scan line (Baecher, 1983; Terzaghi, 1964).

If there are bedrock pavements at a site or somewhere in similar rock, a fracture map of the surface will provide the same data as a scanline along with a better assessment of the spatial structure of the network. Modern methods using photogrammetry and LIDAR can greatly improve the mapping efficiency using computer processing (Kemeny and Post, 2003; Tonon and Kottestette, 2006). Computer-assisted fracture analysis has advanced greatly in recent years being driven by rock engineering needs for rapid assessments of rock slopes.

There are a growing number of published studies using surface mapping data to develop hydrological conceptual models. Mabee and Hardcastle (1997) integrated surface data with borehole fracture data, geophysical measurements, and hydrologic testing to show fracture filling controls that produced hydraulic barriers in a granitic research site. Research on fractured sedimentary sites in the Gulf Islands has produced excellent examples of scan-line surveys to support groundwater flow modeling (Chesnaux et al., 2009). Mapping work has shown that fractures vary according to hydrostructural domains with their own geometric and hydraulic properties (Surrette et al., 2007, 2008). Scan-line data also supported the development upscaled fracture hydraulic properties in a Triassic sandstone in the UK (Hitchmough et al., 2007).

Geologists who are new to fracture mapping concentrate on orientation data to the expense of other information. A fracture surface characterisation should include, even if qualitative, an estimate of spacing or intensity (corrected for orientation bias), apertures, fracture lengths, how fractures terminate, and notations any other geologic controls on the fracturing. Coatings, fillings, and alteration information can give insights to transport. For example, a rock that supports matrix diffusion will often display alteration haloes around fractures that have transported water. Of course, direct observation of flowing water is very important to record.

The removal of contaminated overburden may provide direct access to bedrock surfaces for mapping. In such cases, a key concern will be whether or not contaminants have entered the bedrock and close attention must be paid to open fractures and especially large aperture fractures. Measurements for volatiles have been successful locating fractures that contaminants through shallow overburden (Vroblesky et al., 1996), and could be applied to fracture exposures as well.

B.1.4 Borehole Studies

Boreholes provide a necessary third dimensional view of the fracture network. Geologic studies in boreholes give information on geometric factors such as intensity and orientation as well as showing how these characteristics change with depth. Boreholes often provide the best view of faults and fracture zones, which may be covered and have poor exposures at the surface.

The question of borehole orientation arises as vertical fractures or steeply dipping fractures are very important for movement of contaminants to groundwater. Vertical holes, while usually the easiest and least expensive to drill, clearly are likely to miss features, which may have hydraulic significance. Unless there is clear geologic evidence to show that horizontal features, like exfoliation or bedding fractures, dominate a site, strong consideration should be given to optimizing borehole orientations to intersect steeply dipping fractures. Data that are collected to determine fracture intensity information, must design the drilling program to minimise orientation biases, and correct data for the biases that cannot be avoided (Terzaghi, 1964).

Borehole drilling is an intrusive activity that may alter a groundwater flow system by injection of drilling fluids, water, or air, and by creating connections between fractures that may not have existed previously. Drilling into the core of a contaminated zone may have particularly detrimental effects in spreading contaminants, even when the hole is backfilled or completed later with a piezometer that isolates the conducting zones. Boreholes should therefore be completed for well-defined reasons, at carefully considered locations. The drill should never be a substitute for hydrogeologic forethought.

This section looks at geologic characterisation using boreholes, while later sections look at geophysical and hydrologic methods. The main use of boreholes for geologic characterisation is the identification of rock types and the characterization of fractures. For the latter purpose, core has traditionally been a requirement; however, the development of imaging tools has raised the possibility of replacing core drilling with less expensive methods without a significant loss of data quality.

B.1.5 Image Logging

Image logs are produced by geophysical logging tools that create an image of the borehole wall. These logs may be either direct optical images or they may map a geophysical property of the rock to the borehole surface to create an image of that property. There are three major tools for borehole imaging:

- Optical Televiewer, which produces computer-processed optical images;
- Acoustic Televiewer, which makes an image of borehole roughness and elastic properties; and the
- Formation Micro Imager, which uses a fine grid of sensors to make a very fine resistivity map of the borehole wall.

B.1.5.1 Optical Televiewer (OTV)

The optical televiewer (Williams and Johnson, 2004) is based on television technology and produces images that are close to an actual visual image of the rock. Although borehole television cameras have been in use for over forty years, the use of optical logging did not advance until the mid-1990's when tools were adapted to standard logging cables and computer-processing created undistorted, high-quality images in full color. Most televiewers start with an analog television image that is a reflection of the borehole wall taken from a conical mirror. The signal is either digitized either in the downhole tool or in the uphole electronics. The resulting image appears as either an unwrapped 360–degree cylinder or as a virtual core (Figure B-1). A built-in magnetometer records magnetic north for orientation. The resolution of optical televiewers is about 0.5 mm at its slowest logging rates, which are around 1 meter per minute. Fractures can be resolved to 0.2 mm.

As Figure B-1 shows, the quality of images, while not quite photographic, is sufficient for preparing logs of geology and fractures in boreholes. Optical televiewer surveys also can give qualitative information on hydrodynamics. Particulate movements can sometimes be captured in the log, and help to identify water flows in the borehole.

The software for analysing images is well developed (Figure B-2). The user matches sinusoidal traces to fracture traces on the image log. Typical "tadpole" plots show the orientations of the analysed features with depth along with color coding to show different fracture categories, such as open or closed.

B.1.5.2 Conventional Television Cameras

While not of the same quality as optical televiewers, conventional television cameras, which are mostly used for pipe inspections, can provide inexpensive alternatives to televiewer logging. The camera can be handled by hand. The image appears on a television monitor and it can be recorded on videotape with audio notations from the operator. The image is not oriented, and the image is a view down the well, nonetheless, the instruments may be purchased for under $1000 and work to several tens of feet of depth.

B.1.5.3 Acoustic Borehole Televiewer (ATV)

The acoustic televiewer produces images that rival the optical televiewer in resolution using acoustic pulses that reflect from the borehole wall back to the tool. The energy source rotates at a high frequency while the tool is being pulled up the hole. The measurement includes the travel time of the pulses as well as their amplitudes. From the travel time, the processing software can map the topography of the borehole wall in detail showing irregularities due to vugs, fractures, or other openings (orange-tinted view in Figure B-1). The amplitude signal shows how the rock is absorbing energy, and is influenced by the rock's elastic properties (gray images in Figure B-1). The acoustic televiewer, like the optical televiewer, produces a high-quality image that can be processed in similar ways as either an unwrapped map or a virtual core. Similar software also assists in analysing the fracture data.

The main distinction of the acoustic televiewer is its ability to work in fluids that are too cloudy to provide an optical image. On the other hand, an acoustic televiewer is more likely to miss some fractures and produce some "false" fractures than core or optical tools. As the image depends on elastic properties of the rock, heterogeneous zones of high or low energy absorption may appear as fracture-like features, though they may be part of the solid rock.

Figure B-1. Top: Optical televiewer image in granite. Bottom: acoustic televiewer image in meta-andesite.

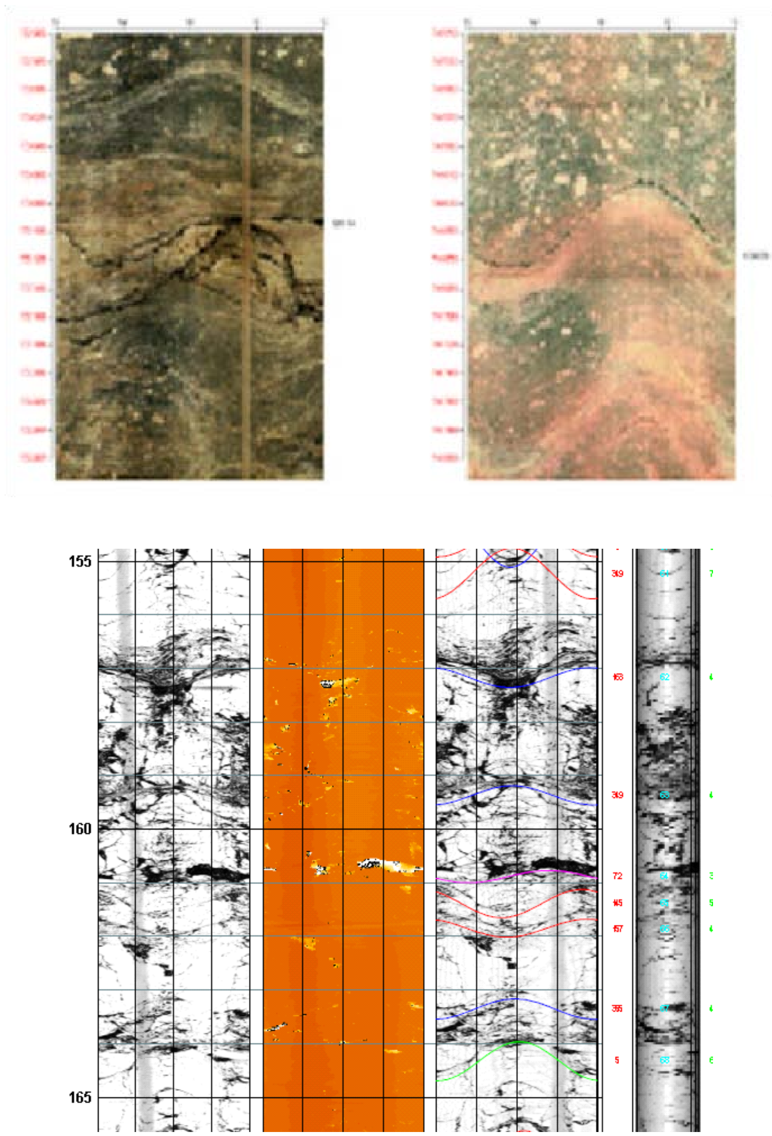
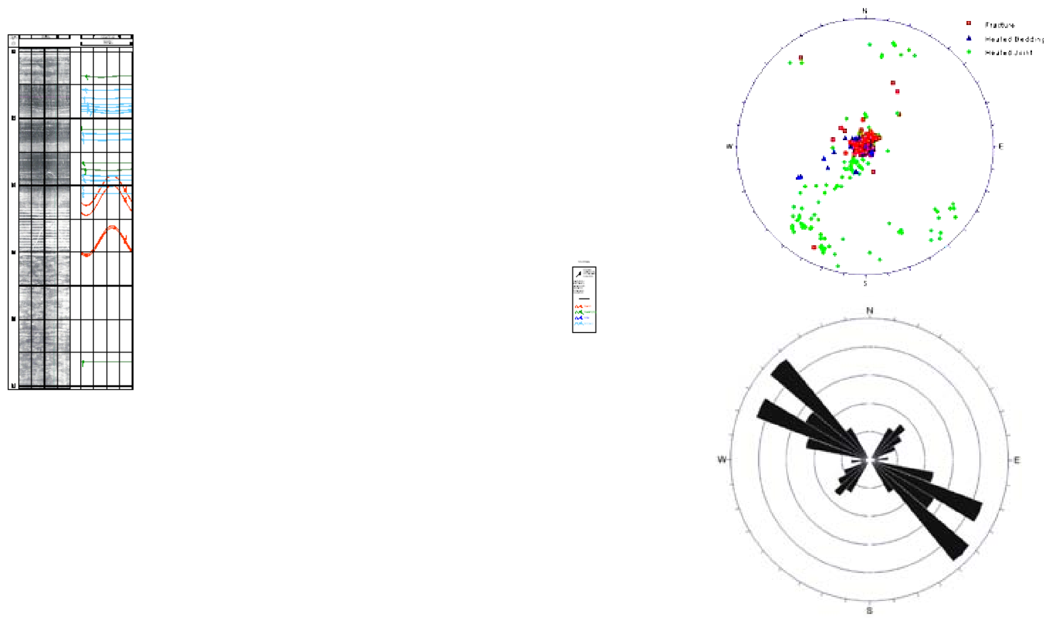


Figure B-2. Optical televiewer log with analysis and orientation plots.



B.1.5.4 Formation Micro Imager

The most common image logging tool in the oil industry is the Formation Micro-Imager, or FMI. It has not had as wide application in groundwater studies partly due to cost. The FMI tool uses multiple pads with a very fine array of resistivity sensors on their surfaces. The pads are pressed against the borehole wall and record a detailed image of resistivity variations as the tool is drawn up the borehole. The resulting image gives an oriented 360^{o} image of the hole, minus the gaps between the pads.

B.1.6 Core

Rock core analysis has long been the standard for subsurface investigations in bedrock. If possible, triple-tube or other methods that are less damaging to the cores should be used, and core should be handled carefully and stored immediately with reconstruction of core fragments into their original position to the extent possible. Precautions by wrapping or sealing core should be taken to preserve pore fluids, particularly in rock that deteriorates with air exposure or rocks where there may be contamination in porous matrix. Health and safety procedures for handling contaminated materials in the latter case are requirements. The removal or core should be noted by placing a block of wood or similar material with the same length as the removed material with annotation of the circumstances for the sampling.

Core logging should record the same properties as scanline mapping such as:

- Orientation (relative if the core is not oriented or if there are no geologic markers like bedding that can be used for orientation);
- Fracture fillings and coatings, which is important if they restrict communication between a fracture and a porous matrix;
- Crush zones, shear zones, alteration, and clay gouge;
- Roughness, slickensides, and other surface textures;
- Indicators of aperture such as crystals or other indicators of opening; and
- Evidence of contaminants in the rock or on fracture surfaces.

The need for core has been diminishing over the past two decades with the development of imaging and geophysical logging tools. Core drilling has been viewed as a significant expense compared, hence an important question for fractured rock characterisation is whether or not core is necessary. One function, where core may be irreplaceable by image logs, is the direct sampling of contaminants.

Table 1 summarises some of the relative advantages of image logs and core. Ideally one would want both; however, cost can be a factor and most core is drilled with water circulation, which may be a concern for some sites.

For the purposes of fracture geometric characterisation, borehole image logs provide nearly comparable quality and detail. Furthermore, image logs are superior for the most damaged zones, where core recovery is poor. Core orientation is not common and adds significantly to the time and expense of drilling, while image logs obtain orientation routinely.

Neither core nor image logs define which features are conducting and how much. Flow logs or packer tests are necessary for that task; however, once the conducting fractures are known, core and image logs are vital to describe the conducting feature geologically.

Although some geophysical logs can provide indicators of the presence of contamination, the recovery of core containing contaminants is more reliable, and it provides a means of recovering a sample and knowing where the contaminations comes from. In that regard, core may be most valuable in bedrock settings where matrix diffusion effects are suspected, such as fractured sedimentary rocks. Having core for laboratory measurements of diffusion is highly valuable for assessing the retardation of the matrix, even in non-sedimentary rocks, where alteration zones around conducting fractures can have significant matrix diffusion effects.

The question of whether to core or not to core must be decided on a site specific basis weighing the costs against the potential uses of the data. For fracture mapping, image logs provide similar if not superior results. If the cost is not a factor, it is better to have core as an additional check on information from other data sources, and core-drilling tends to produce boreholes with better wall conditions for setting packers and installing monitoring system. Also, if multiple holes are planned for a site, core drilling might be considered for one of initial boreholes to determine the value of the core, and provide a set of samples for later calibration of logging results if coring is not used further.

The main disadvantages of optical televiewers are the cost and need for clear water to produce an image. The image quality is poor or non-existent in drilling mud or water with suspended sediment that resists clean up.

Table 1. Comparison of Core and Image Logs.

	Core	OTV	ATV
Fracture Aperture	Difficult unless there is a partial filling that bridges the aperture	Best	Possible but can produce false "open" readings
Fracture Orientation	Uncommon add on	Good	Good
Fracture coatings	Good	Possible	Unlikely
Resolution	Best	Good	Good
Poor quality rock	Poor	Better look at structure of damaged zones	
Drill-induced fractures	Problem	Not a problem	Good for bore breakouts under high stress conditions (not likely at shallow depth)
Matrix Properties	Yes	No	No
Contaminants in Matrix	Yes	No	No
Works in cloudy water?	Not an issue	No	Yes
Works in air?	Not an issue	Yes	No

B.1.7 Limitations of Geologic Studies

Geologic investigations are an essential part of any site investigation programme. The association of water movement with specific geologic features allows the use of geologic insight to determine their likely distribution through a site.

While geologic mapping is a valuable tool for fracture characterization, it does have limitations for use in groundwater studies. What geology is not likely to do by itself is identify flowing features. West (et al., 2005) found that a skilled geologist could identify conducting features from core; however, most investigators find that measures like fracture intensity correlate poorly with transmissivity, and often the features that dominate flow in a well appear relatively insignificant in the core or image logs.

B.2 Geophysics

The ultimate dream of geophysics is a method that will return an image of the hydraulically significant fractures with the detail that medical imaging tools produce inside of a human body. The availability of such a method remains unrealized, although experiments in underground radioactive laboratories have made considerable progress towards this goal. A good overview of geophysical methods and fracture detection appears in Chapter 5 of the US National Academy of Sciences (NRC, 1996) study on fractures and fluid flow.

An ideal geophysical tool would measure directly or image the open space in fractures that provides pathways for fluid flow. Furthermore, the geophysical measure would need to be sensitive to a power law, like the cubic law, of fracture opening to detect the fractures that are carrying the major portion of the flow. Unfortunately, that tool does not exist either.

Nonetheless, geophysical measurements are a well-established component of site investigations. Although there are few methods that directly measure fracture opening, alteration zones around conducting rock fractures often have geophysically detectable signatures. Fracture zones and faults, have alteration haloes that have acoustic or electrical properties that contrast with unaltered, unfractured rock. These properties can be detected in surface, borehole, and cross-borehole measurements.

The two properties that most stand out when considering fracture zones and faults are electrical conductivity and seismic velocity. Electrical conductivity is most affected by water and its dissolved components, pure water having a very low conductivity that rises rapidly with its content of dissolved constituents. The apertures of single fractures are not generally large enough to have a clear signature in surface measurements, but altered zones with appreciable thicknesses (decimetres to meters more) can create detectable effects (Johnson et al., 2001). Furthermore, contaminants can also affect water conductivity and sometimes are detectable using geophysical methods if the contaminant's electrical properties contrast with those of the groundwater (Day-Lewis et al., 2003, 2006). Water content also includes adsorbed water in clay minerals, so clay content may also show up strongly in fracture alteration zones.

Acoustic velocity decreases in altered zones and faults. Large fractures, such as exfoliation joints near the surface can serve as surfaces for reflection of acoustic signals (Cosma et al., 2001; Schmeltzbach, 2007).

The discussion of geophysical measurements below focuses on four modes of measurement, airborne, surface, cross-borehole, and single borehole or borehole logging.

B.2.1 Airborne Geophysics

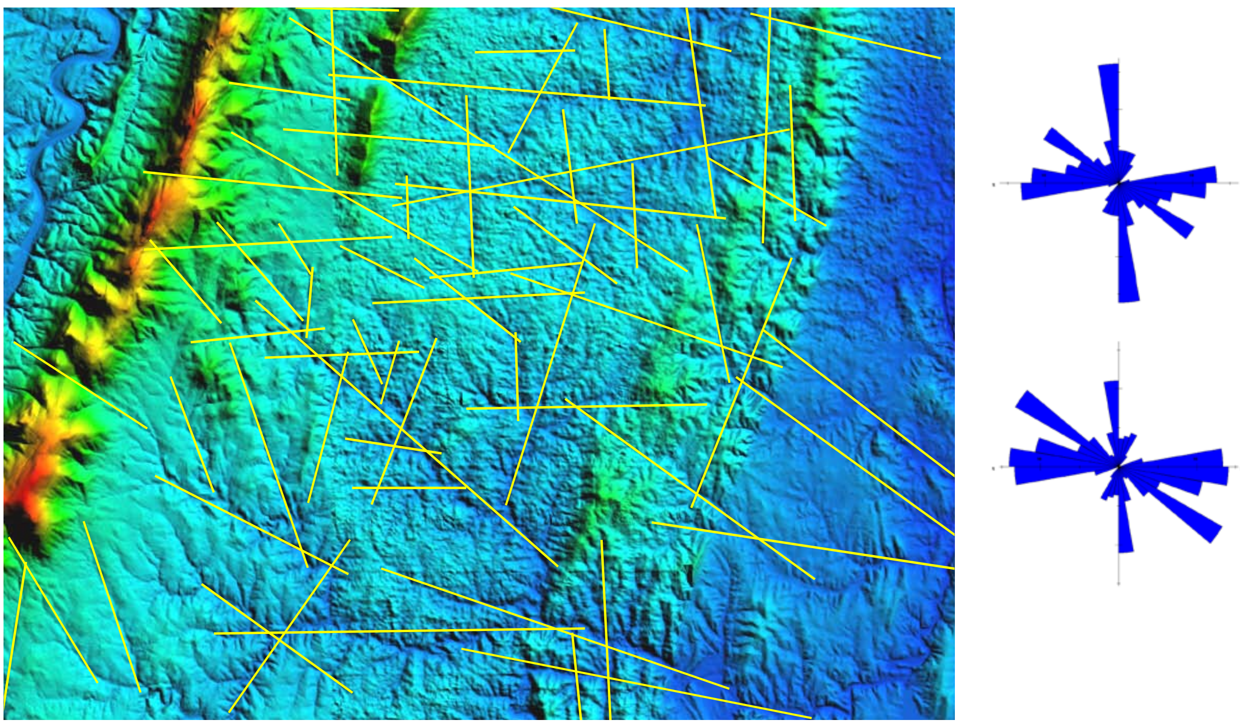
Airborne geophysical measurements mainly are for finding lineaments. Among the useful tools for airborne measurement are LIDAR, aero magnetic, and VLF electromagnetic (Bronley et al., 1994; Pedersen et al., 2009).

Lineaments are linear features that appear in air photos, vegetation patterns, and topography. LIDAR (LIght Distance And Ranging, also known as Airborne Laser Swath Mapping or ALSM) is a relatively new technology that reflects laser light from surfaces from many different directions (Nyborg et al., 2007). Computer processing of the returned signals can determine which signals reflect from the ground surface and which reflect from vegetation or tree canopy. The processed output is a shaded image of the ground surface that provides a high level of details for lineament identification, particularly in forested areas (Figure B-3).

Aeromagnetic measurements have been useful in the Swedish radioactive waste program, where conducting fracture zones and faults have alteration haloes that are depleted in magnetite by oxidising reactions with groundwater (Figure B-3, Nyborg et al., 2007).

Very low frequency electromagnetic signals, which are used for submarine communication, induce currents in electrically conductive ground (Pedersen et al., 2007). The resulting magnetic fields of these currents are detectable by airborne means, and serve as another lineament indicator.

Figure B-3. Electromagnetic lineaments and analysis (Golder Associates).



B.2.2 Surface Geophysics

The main methods of detecting faults and fracture zones from surface measurements are either electromagnetic or seismic.

B.2.2.1 Electrical Methods

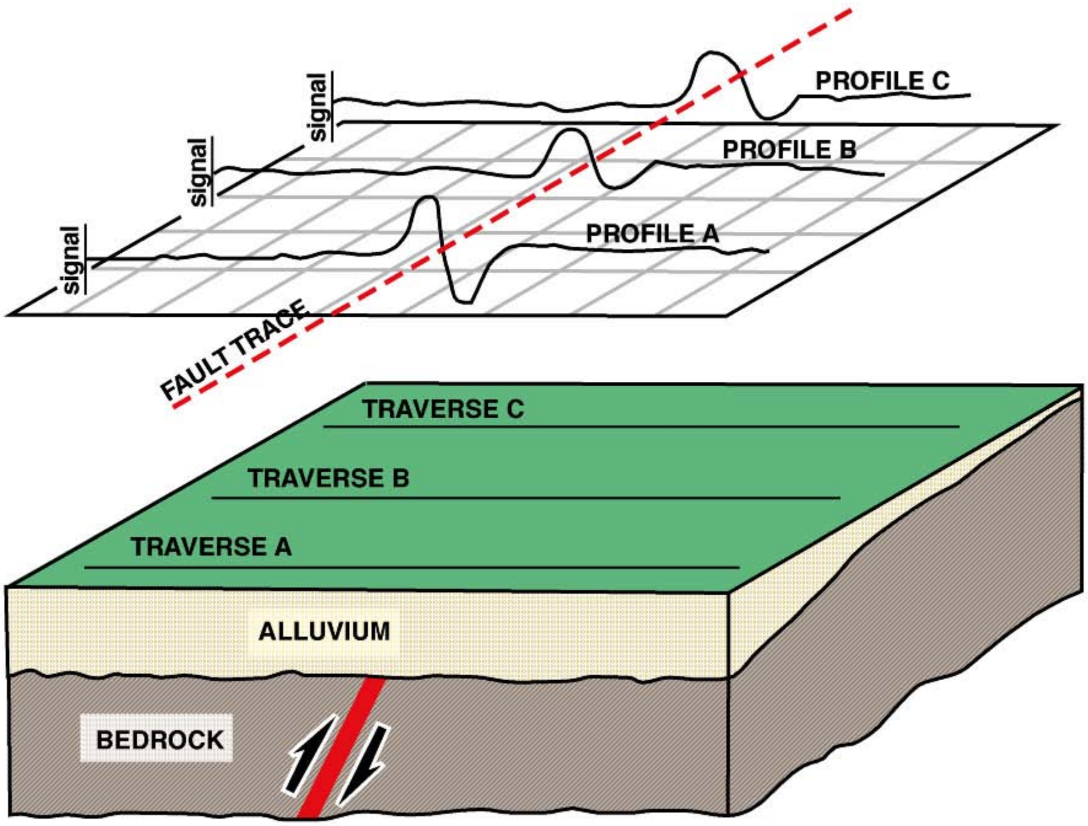
Electrical methods exploit variations in the electrical resistivity (or conductivity) to detect fractures. The main source of electrical variability, at least in consolidated or hard rocks, is water, which contributes strongly to electrical conductance. Water's contribution is pore water and especially adsorbed water on clay minerals. With respect to clays, electrical methods do not distinguish water sources; hence, electrical anomalies are not necessarily water-conducting features.

Electrical methods are employed as:

- Soundings, where electrical responses are measured in response to potentials applied to the surface;
- Passive measurements of currents induced by very low frequency signals (VLF); and
- Use of electromagnetic waves in ground penetrating radar (GPR).

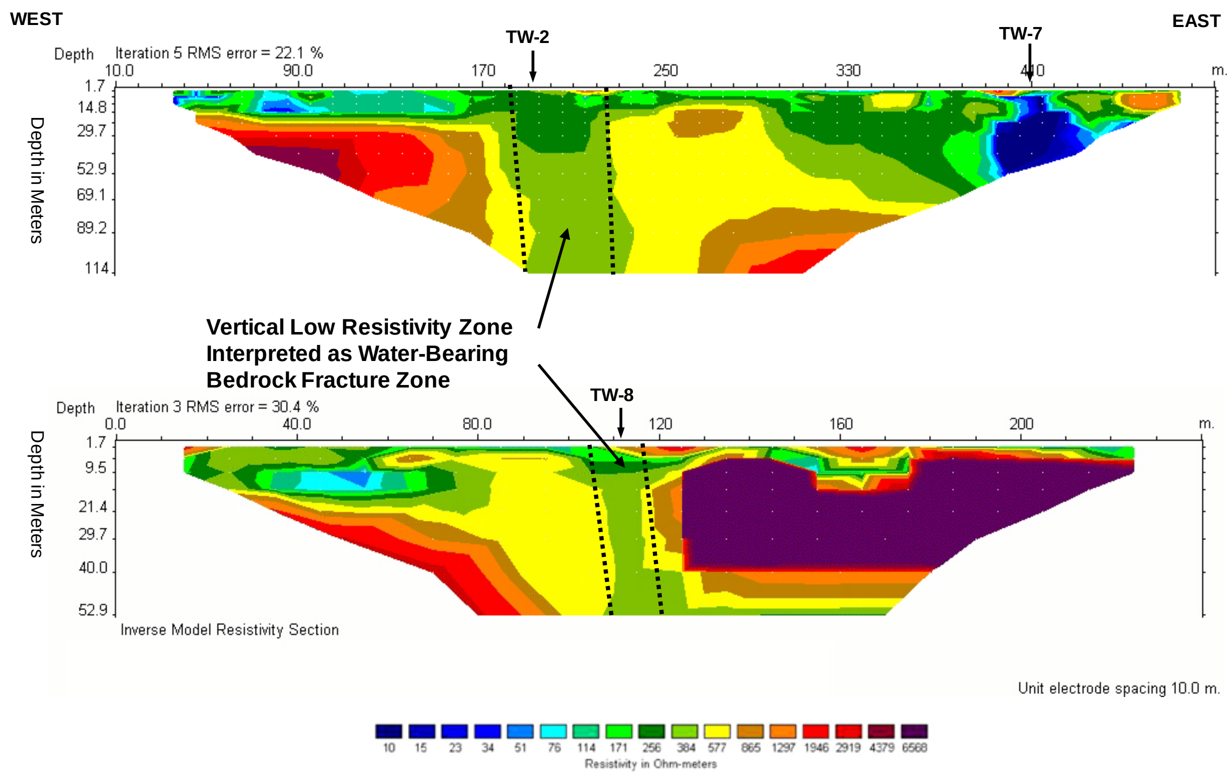
Sounding methods have been successful for finding faults and other features that produce large anomalies, at sites such as the USGS research site at Storrs, Connecticut (Johnson et al., 2001, Figure B-5). That said, electrical properties over larger scales can have properties of direction and persistence that are controlled in part by the preferred direction and connectivity of fractures with water or with conductive alteration zones (al-Hagrey, 1994; Skinner et al., 2004; Yavav and Singh, 2007). Such azimuthal surveys are reported to have success delineating water-bearing fractures (Boadu et al., 2005; Dutta et al., 2006; Bahtayneh et al., 1999). Surface-based electrical surveying uses sounding methods, which are measuring electrical properties between points on the surface or using electromagnetic waves to reflect off subsurface features, as in ground penetrating radar. Surveys using VLF-induced currents can be conducted as surface surveys as well as from airborne detectors. Adepulmi (et al., 2006) delineated major features that are likely small faults or shear zones. The strength of the response of these features to sounding owes to the development of alteration zones, which may reflect either weathering or older hydrothermal interactions.

Figure B-4. VLF detection of fractures.



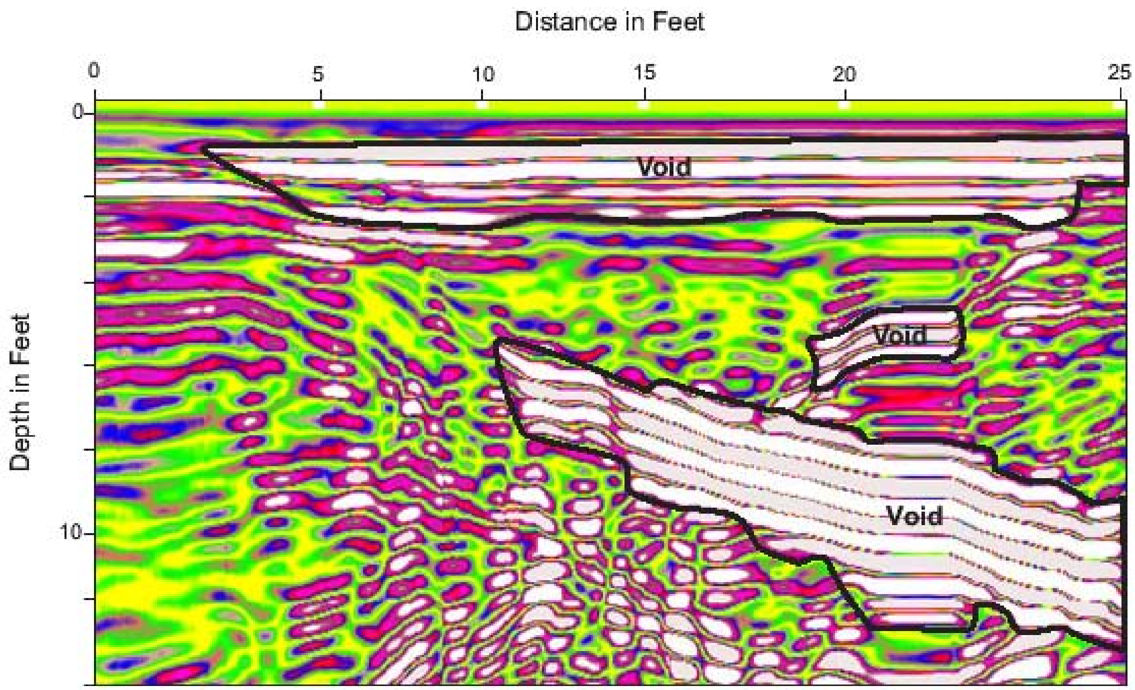
VLF Profiles
Indicating Location of buried fault

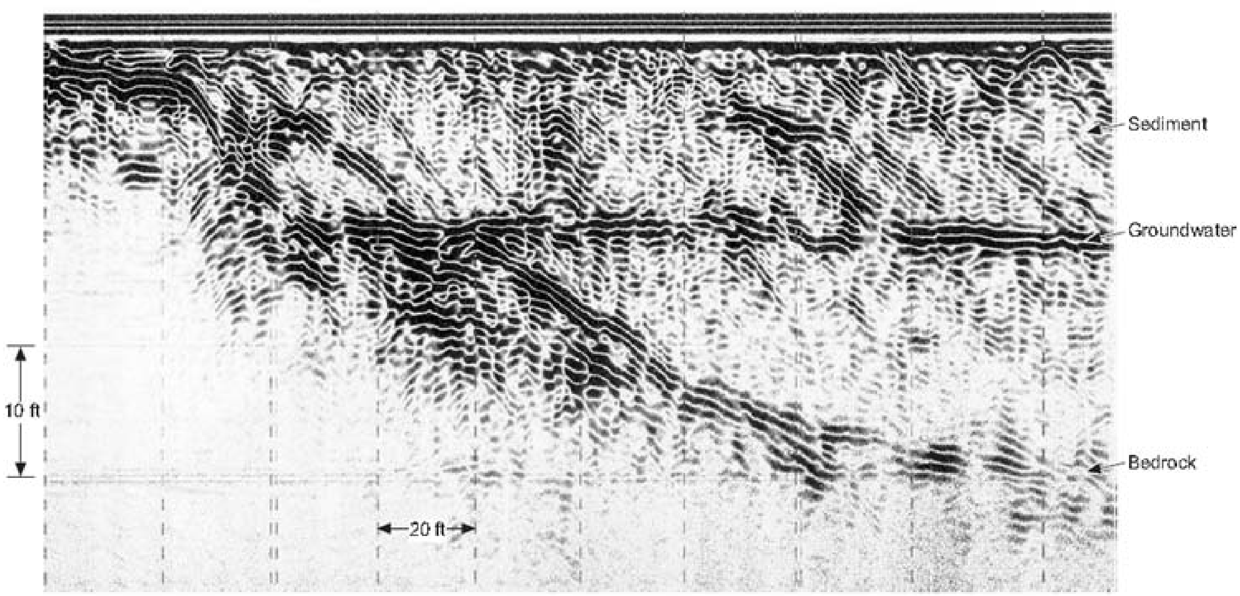
Figure B-5. Resistivity sounding to locate faults and fracture zones (Golder Associates).



Ground penetrating radar (GPR) operates in many ways like reflection seismic surveying using high-frequency electromagnetic waves which reflect back from features in the rock. The method mainly sees reflectors that have higher electrical conductivity than the surrounding material. It has been successful in defining fractures in the shallow subsurface (Figure B-6, Grasmuek, 1996; Travassos and Menezes, 2004; Porsani et al., 2006). The USGS also used GPR with confirmatory flow logging in boreholes to identify sheet-like fractures at the Storrs site (Johnson et. al., 2001, 2002).

Figure B-6. a. Ground Penetrating Radar (GPR) detection of voids. b. location of water table and bedrock surface (Golder Associates).





Theoretical and laboratory work has indicated that GPR may not work well for fractures with apertures in the 2-4 mm range, but the detection can be enhanced by introducing water with higher electrical conductivity into the rock (Lane et al., 2000). Field experiments have confirmed this effect (Day-Lewis, et al., 2003; Grégoire et al., 2006).

Like other electrical methods, the penetration of GPR decreases strongly with increasing electrical conductivity at the frequency ranges required for fracture detection, hence these methods do not work well when there is a conductive overburden cover or in rocks that are relatively conductive, like shales (NRC, 1996).

B.2.2.2 Seismic Methods

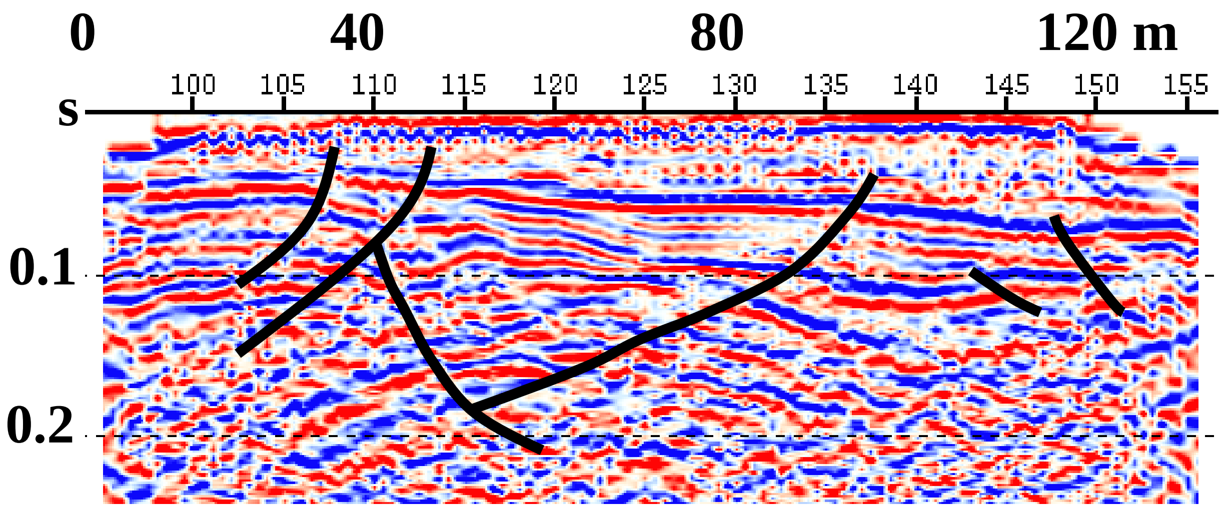
The main focus of seismic development has been the interpretation of seismic reflection data, mainly in the oil and gas industry, while refraction methods are much more common in engineering geology and hydrogeology. Refraction methods do not detect fractures, except possibly for mapping buried bedrock surfaces to define unexposed topographic lineaments.

Seismic reflection has become highly sophisticated, being the indispensible exploration tool for oil and gas. Usually seismic methods are focussed on layer sedimentary rock; however, seismic data are increasingly being used to detect variations in elastic properties of rock including anisotropic responses that may relate to fracture intensity (Perez et al. 1999; Sayers, 2009, Pugin et al., 2009). Figure B-7 shows the detection of bedrock surfaces as well discontinuities associated with likely faults and fractures.

Nonetheless, seismic surveys have been applied in radioactive waste studies. Kim (et al., 1994) was successful in obtaining good seismic reflections from open, exfoliation fractures to over 100 meters depth (Kim et al., 1994). Juhlin (1995; Juhlin and Stevens, 2006) used seismic reflection to delineate a major, sub-horizontal fracture zone at a granitic study area in Sweden.

Surface geophysical methods are useful primarily for identifying larger features prior to drilling. These include faults and fracture zones that have some thickness, or fractures that are surrounded by an alteration zone. The presence of conductive fluids, appearing naturally or by human introduction can enhance electrical results. GPR can be very effective in resistive rocks that are not buried under a conductive overburden.

Figure B-7. Fracture and fault identification by seismic reflection (Golder Associates).



B.2.3 Borehole Geophysics

In recent years geophysical tools that once were privileged to the oil industry have seen increased application to hydrogeologic and engineering applications with the adaptation of tools for shallower depths and smaller borehole diameters. This discussion on borehole geophysics refers to methods that are measuring geophysical properties, like electrical, sonic, or radiation effects. Image logs like optical and acoustic televiewers are discussed as geologic characterization tools, while borehole flow meters, which measure flow velocities in a borehole, appear along with hydrogeologic characterisation methods.

The main goals of a borehole geophysics program are the following:

- Locate conductive fractures;
- Evaluate flow directions and identifying water from different sources, either chemical or thermal;
- Identify zones of contamination; and
- Assess rock matrix properties for porosity to assess matrix diffusion potential.

Borehole logging infers fracture locations by several means including:

- Temperature logs that show entry or exit points of water flow with distinctive temperature values;
- Caliper logs that show washouts or enlarged zones where weak rock around faults or fracture zones is preferentially eroded by drilling;
- Gamma radiation logs which show clay content, where clays have adsorbed radionuclides or where radon bearing water is entering a hole;
- Resistivity and acoustic logs, which can indicate altered zones, but may or may not indicate conductive fractures; and
- Stoneley wave logs, which show the tube wave reflections (tube waves being acoustic surface waves that travel on the borehole wall and reflect at voids like fractures).

B.2.3.1 Identifying Conductive Fractures

Identifying the conductive fractures in boreholes is an essential characterisation step to understand fracture flow systems. Conductive fractures often correlate to damage, which can be mechanical or chemical. This damage appears as lower resistivity and slower acoustic velocities, hence velocity logs and resistivity logs have some relationship to conductive fractures. Fractures are more likely to wash out to create zones of borehole enlargement that appear in caliper logs. Gamma logs reflect the adsorption of naturally radioactive materials to clays, and show conductive fracture locations, as well as fractures that may be clay-filled and non-conductive. While conductive fractures may create a response in wireline logs – acoustic velocity, resistivity, gamma-ray, or calliper – the presence of an anomaly in these logs does not assure that a conductive fracture is present, so despite considerable effort on the part of the logging industry to create a logging suite for fracture identification, the use of wireline logs by themselves is not adequate to characterise conductive fractures reliably.

Fortunately, modern flow logs locate conductive fractures directly, and image logs provide a visual means of describing the conducting fracture geologically. The traditional wireline logs neither supplant flow logs and image logs, nor do they provide additional value, hence their use is limited with respect to conductive fracture location.

Although wireline logs may not detect specific fractures, fracture properties may be correlated to specific strata in sedimentary or other layered rocks. Morin (et al., 2000) used geophysical logs in fractured sandstones and shales, specifically gamma and resistivity to identify specific stratigraphic units, as well as two layers that formed different fracture domains due to contrasts in mechanical properties.

Another, albeit non-traditional, exception is the Stoneley wave log, which is a fracture-focussed log that appears frequently in petroleum logging. This log detects open fractures from the Stoneley wave, which is a surface wave that travels along the borehole wall, much like Raleigh waves travel the earth's surface in earthquake events. The Stoneley wave tends to reflect from open fractures rather than cross them producing reflections that can be detected and related to fracture opening (Hornby et al., 1989). This not a common log in groundwater use; however, it is small added value over a flow log.

B.2.3.2 Evaluating Vertical Gradients

Although flow and image logs largely replace wireline logs for conductive fracture identification, temperature and fluid conductivity logs are very useful for providing information on different water sources entering a well (Morin et al., 2000). Boreholes into fracture networks often short-circuit local networks that were otherwise poorly connected. The connectivity along the well produces flows between water-conducting intervals bringing in water from zones with different temperatures or different water chemistries, which have contrasting electrical conductivities. The movement of these waters over time also show the direction of vertical hydraulic gradient, as well as the locations of conductive fractures (Figure B-8).

B.2.3.3 Identifying Zones of Contamination

The conductance of pore fluids influences the geophysical responses of logging tools. Many contaminants, like petroleum derivatives, are likely to be much less electrically conductive than water. The detection of some contaminants may be amenable to methods developed in petroleum for assessing whether rock is oil, gas, or water saturated. Contaminants with electrical properties that contrast with water, may be detectable using fluid conductivity logs. Other logs, such as neutron logs, may provide information on contaminant presence (Endres and Greenhouse, 1996).

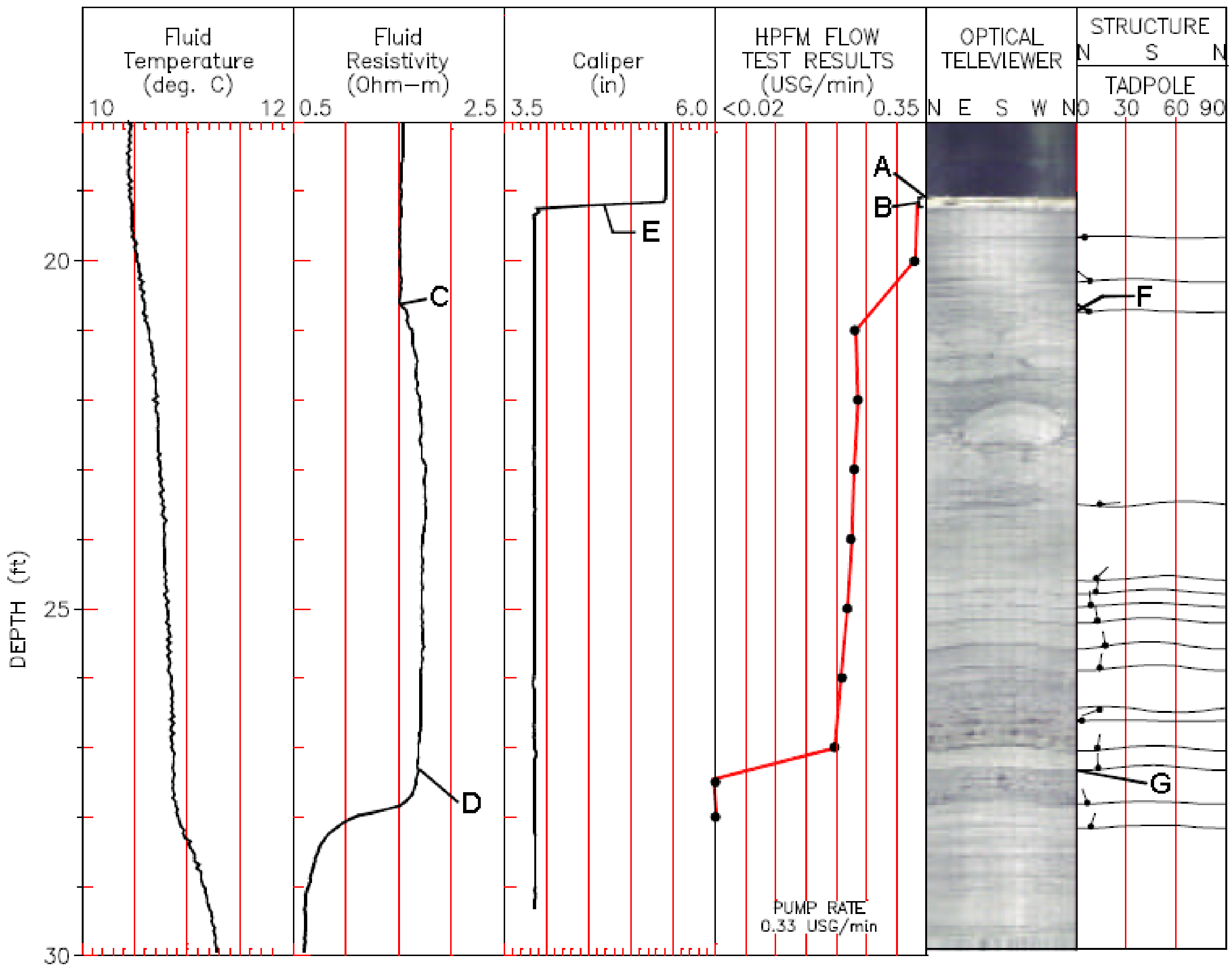
B.2.3.4 Assessing Rock Properties for Matrix Diffusion

Rock porosity is a key input for assessing matrix diffusion in porous, fractured rock. Geophysical logs are well adapted to recording variation in porosity using neutron and resistivity logs, among others. Formation factor, which is central to Archie's Law relating electrical resistivity to porosity, is closely related to the tortuosity parameter that connects free-water to effective diffusivity of solutes. While a of log porosities might not fully replace a laboratory measurement of diffusivity or porosity, wireline logs will give information on the variability of porosity, which would otherwise require a prohibitive number of tests to establish.

B.2.3.5 Borehole Logging Summary

While borehole logs can be very useful indicators of open or flowing fractures, the inclusion of image logs and flow logs, which are discussed in the geology and hydraulic characterization sections respectively, are greatly superior to any other borehole log. In other words, the direct measurement of flow is the most important indicator of a flowing fracture, and image logs are best indicators, with core, of the fracture orientation and other properties.

Figure B-8. Borehole logging suit, HPFM is the heat pulse flow meter (Golder Associates).



A – Bottom of casing

B – Exposed grout at base of casing

C and **D** – Inflections on the fluid resistivity log showing formation water entering and exiting the borehole

E – Caliper anomaly – HQ (4") cored hole to 5.4" casing

F and **G** – Bedding partings (fractures) contributing to flow in the borehole

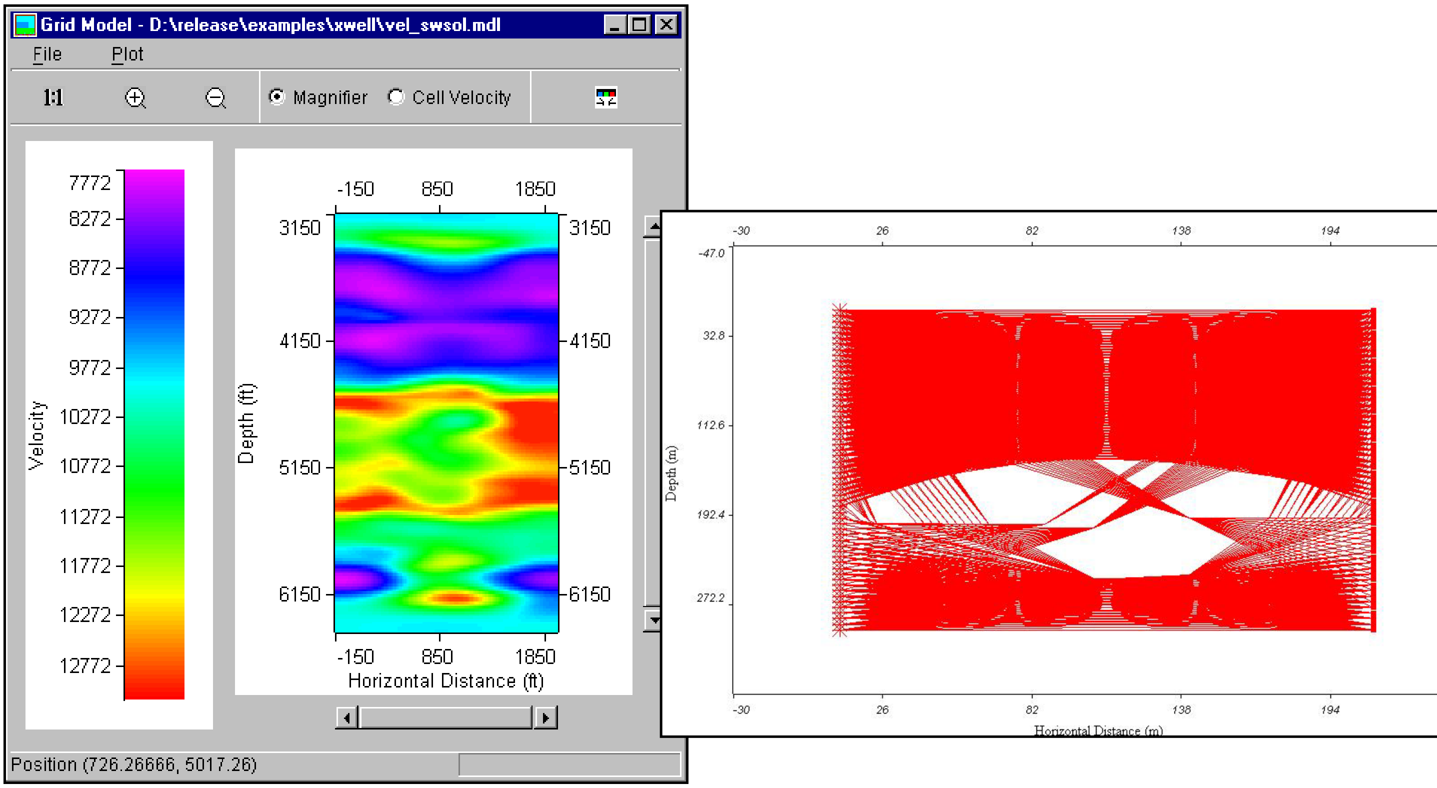
B.2.4 Cross Borehole Geophysics

Single-well, borehole logs provide information about rock properties close to the well. Even if one uses a flow log to find conducting features, geophysics can also extrapolate the fractures away from the hole, and locate other fractures near the well. A good overview of cross-hole and single-hole reflection methods appears in the NRC (1996, Chapter 4) fracture and fluid flow study.

The two main methods for gaining a view with distance from a well are radar and seismic. These can be applied in either a single well mode, where one is obtaining reflections, seismic or electromagnetic, or as a cross-hole mode using tomographic methods, which infer the properties of a volume or slice based on the velocity variations of a very large number of ray paths across the volume.

Borehole radar had one of its first major applications in radioactive research sites in Sweden in the 1980's (Olsson et al., 1992), and later at Canada's Underground research Laboratory (Serzu et al., 2004). For the types of resistivity contrast typical of granite and granite fractures, the wavelengths of the radar put limits on how thin a zone can be detectable, which is about 10-cm (NRC, 1996). Other examples of radar application include Wänsted (et al., 2000) and Soon (et al., 2004). Grégoire (et al., 2006) applied radar reflection to study the effects of remediation using steam. As with GPR, replacement of water in fractures with fluid having different electrical properties, usually saline water, effectively delineates the conductive fracture network (Day – Lewis, 2003, 2006). Corresponding cross-hole and single hole reflection methods use seismic waves (Cosma, 2001). Surface to single borehole seismic methods are known as vertical seismic profiling (VSP, Majer, et al., 1997).

Figure B-9. Crosshole acoustic tomographic section. Right: wave paths for inversion (Golder Associates).



B.2.5 Geophysics Summary

Geophysics has its major role in pre-drilling investigations to determine lineaments, faults, and major fracture zones using airborne or surface measurement data. Electromagnetic methods appear to be more commonly used, but seismic methods also have value particularly for depths to water table and bedrock.

Cross borehole measurements are also very promising, though the measurement of conductivity and acoustic anomalies will be second-order indicators of flowing fractures except for radar tomography with saline injections. The latter would most likely find a use when targeting a specific conductor, as injecting an entire site from boreholes with sufficient density for a full fracture-network characterisation would seem impractical.

For conducting fracture location, single borehole logging has been supplanted by flow and image logging; however, single hole logs of water conductivity and temperature are useful for understanding dynamics of groundwater flow system. Standard geophysical logs may have an important role in sedimentary systems for identifying fracture-controlling stratigraphy and determining rock porosity values that are important for matrix diffusion.

B.3 Hydraulic Characterization

B.3.1 Properties and Basics

Hydraulic testing in fractured rocks has the dual objectives of identifying the geometry of the conducting features, and providing their hydraulic properties. The key properties of single fractures or conductors for flow and transport are the following:

- Transmissivity (L^2/T);
- Storativity (-);
- Diffusivity (L^2/T); and
- Aperture (L).

Aperture is likely not a single value, but a number of different values depending on it use, such as, being the link between flux and velocity or determining capillary pressures.

This section covers four types of testing:

- Steady flow methods, which make the simplifying assumption that flow is in a steady (non-transient) state. Steady flow methods are mainly applied to packer tests that are used in civil and mining applications and to the interpretation of flow logs.
- Transient flow methods, which are more rigorously correct, where the time-varying head or flow can be interpreted for both hydraulic properties and flow geometry.

- Interference tests, which use the responses of monitoring points to pumping to determine storativity, diffusivity, and connectivity.
- Tracer tests, which are essential for identifying transport processes and properties.

B.3.2 Steady Flow Methods: Packer Testing and Flow Logging

B.3.2.1 Packer tests

The use of borehole tests to determine hydraulic properties has evolved largely independently in hydrogeology, civil engineering, and petroleum engineering. Hydrogeologists and petroleum engineers base most of their work on transient flow, where one measures changes in pressure or hydraulic head over time due to a prescribed rate or pressure change in the flow system. C.V. Theis' recognition that storage (and diffusion) impose time-varying conditions is still recognized as one of the seminal ideas in hydrogeology.

By contrast, steady flow assumes that pressure and flow reach a steady state where neither flow nor pressure change in time. This only occurs when the fluid that is being removed from the groundwater system as the well is being exactly replaced somewhere else, usually on a boundary with something with such a large permeability and storage that the pumping well cannot affect its pressure, which is also called a constant-pressure boundary. A well test will act in transient manner, until its pumping effects reach that boundary and the flow becomes truly steady.

To a test engineer on a well site, the pressures and flows can appear to be steady, while a logarithmic plot shows clear transient behaviour. Both hydrogeologists and reservoir engineers sometimes will use the simplifying assumption of steady flow for analysis, especially when a pumping event does not have transient data. A driller's measurement of specific capacity is such a case.

The simplest form of the steady flow solution is the Theim equation for flow to a well in the center of a single, planar aquifer or single planar fracture (Figure B-10):

$$Q = \frac{2\pi T \Delta h}{\ln R/r_w}$$

The aquifer (or fracture) has a constant-pressure boundary at a distance, *R,* from the well. This distance is called the *radius of influence*. This radius of influence is never known precisely, if it even exists at all, but its appearance in a logarithmic term provides forgiveness for imprecision. The driller's simple approximation of transmissivity by specific capacity, or $Q/\Delta h$, is a reasonable approximation under many circumstances. Petroleum engineers use a similar approximation called the production index, or PI.

Civil engineers use steady flow methods extensively, especially when the testing of fractured rock is involved, as in dam foundations or underground caverns (Figure B-11). The common test for such applications is the *packer test*, so named for usually using inflatable balloons, or packers, to seal a section of well for injection or withdrawal. Packer tests often use a fixed spacing of packers. If the spacing were three meters apart, the testing would be done every three meters over the entire length of the hole. Packer tests are usually run by the driller using the drill pump as an injection source. Typically a packer test uses a constant injection pressure controlled by the drill pump, which the driller runs in steps recording the flow rate for each step.

Figure B-10. Steady radial flow in a single fracture or an aquifer.

$$T = \frac{\ln(R/r_w)Q}{2\pi\Delta h} \cong \frac{Q}{\Delta h}$$

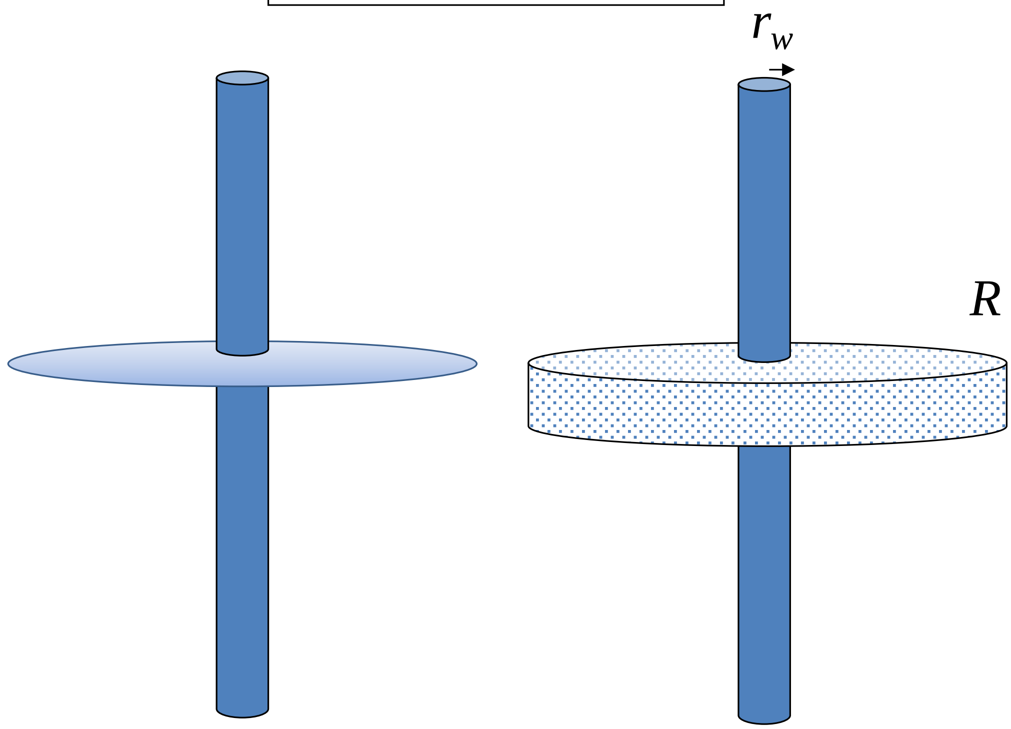
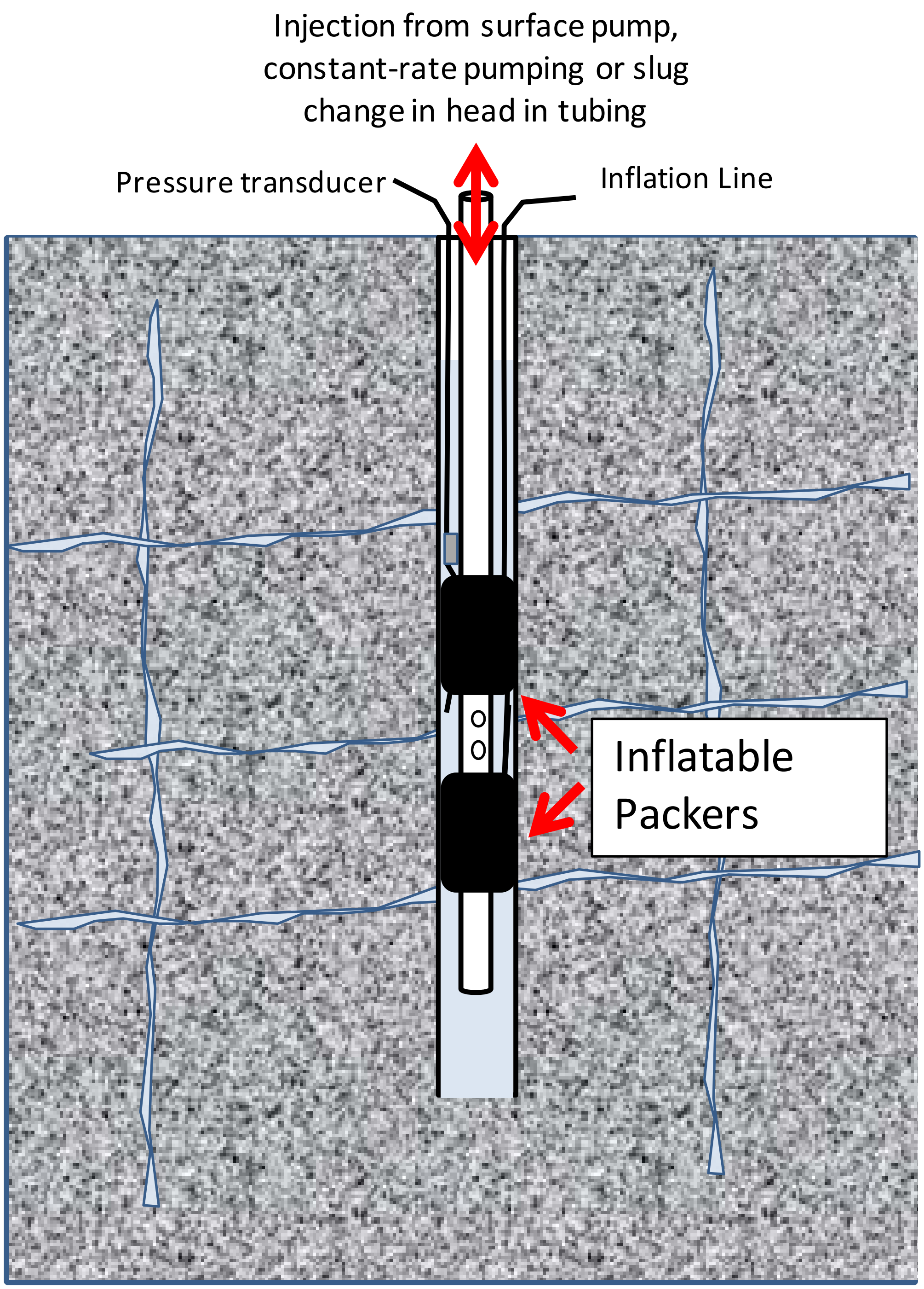


Figure B-11. Packer test layout.



A practical guide to steady flow methods as applied in civil engineering well testing is Hvorslev's (1951) classic work from the Corp's Waterways Experiment Station. A later 1975 report by

Ziegler compiled variations of the Theim equation for determining the hydraulic conductivity, K, of an interval with length, l, in the form of

$$K = C\frac{Q}{l\Delta h}$$

where C is a constant that varies with assumptions about the boundary conditions, of which Theim's equation is a special case. Mathias and Butler (2007) provide a more recent compilation of these factors.

The Lugeon test (Lugeon, 1933) is a variation of this approach that is commonly used for grouting rock foundations. Drillers run the test by applying a 10 bar overpressure to well and recording the flow rate. The results are given in Lugeon units, which is the flow rate in litres per minute per 10-bar overpressure and 10-m borehole length. Besides Lugeon, Hvorslev, and Ziegler, papers by Moye (1967), Braester and Thunvik (1984), Brassington and Walthall (1985) cover the same ideas and are more accessible.

For tighter rocks, engineers will also use the falling head test. This test is performed identically to the slug test (Cooper et al., 1968; Butler, 1997) where the level in the well, or the drill pipe connected to the packers, is quickly changed and the test consists of the well's recovery over time. Unlike the slug test, which uses a transient flow solution based on storage in the rock, the falling-head test solution derives the change in head with time by equating flow rate of the Theim equation to the flow produced by the falling head and solving by a separation of variables (Hvorslev, 1951; Bouwer and Rice, 1976) to produce:

$$K = \frac{r_w^2 \ln R/r_w}{2l}\frac{1}{t}\ln\frac{h_0}{h_t}$$

where r_c is the casing radius where the water level is varying. The falling head plot puts log of percent recovery against time. Although a time-honoured method, true transient methods using Cooper, et al. 1968 or the solutions in Butler's slug test book (Butler, 1997) are preferable to steady methods.

B.3.2.2 Flow Logging with Spinner and Heat-pulse Logs

A more direct method of scanning boreholes for conductive fractures is flow logging, which has made detailed transmissivity scanning of fractures in a well practical and efficient. Flow logs are run in one of three modes:

- Ambient, or Static where there is no artificial pumping and the flow is caused by vertical head differences between conducting features;
- Pumping, which identifies the flowing fracture locations and rates; and
- Crosshole, which records changes in flow in an observation to pumping in another well to map connectivity (Williams and Paillet, 2002).

The transmissivity calculation for a single fracture or for a section of a well is simply the flow rate that can be attributed to the zone divided by the drawdown during the logging (Figure B-12). This method of calculating hydraulic properties uses either the Thiem equation, or one its alternative forms, such as specific capacity.

Flow logging uses downhole flow meters that are placed in the hole using tubing or a wireline. The common flow meter types are the spinner log, heat pulse flowmeter log, and electromagnetic flow meter log. Spinner logs (Molz et al., 1989) use an impeller that rotates at a speed proportional to the flow rate. Although these logs are common in the oil industry, where they are called production logs, in groundwater work these have been replaced by heat pulse or EM (electromagnetic) flow meter logs except in higher flow cases.

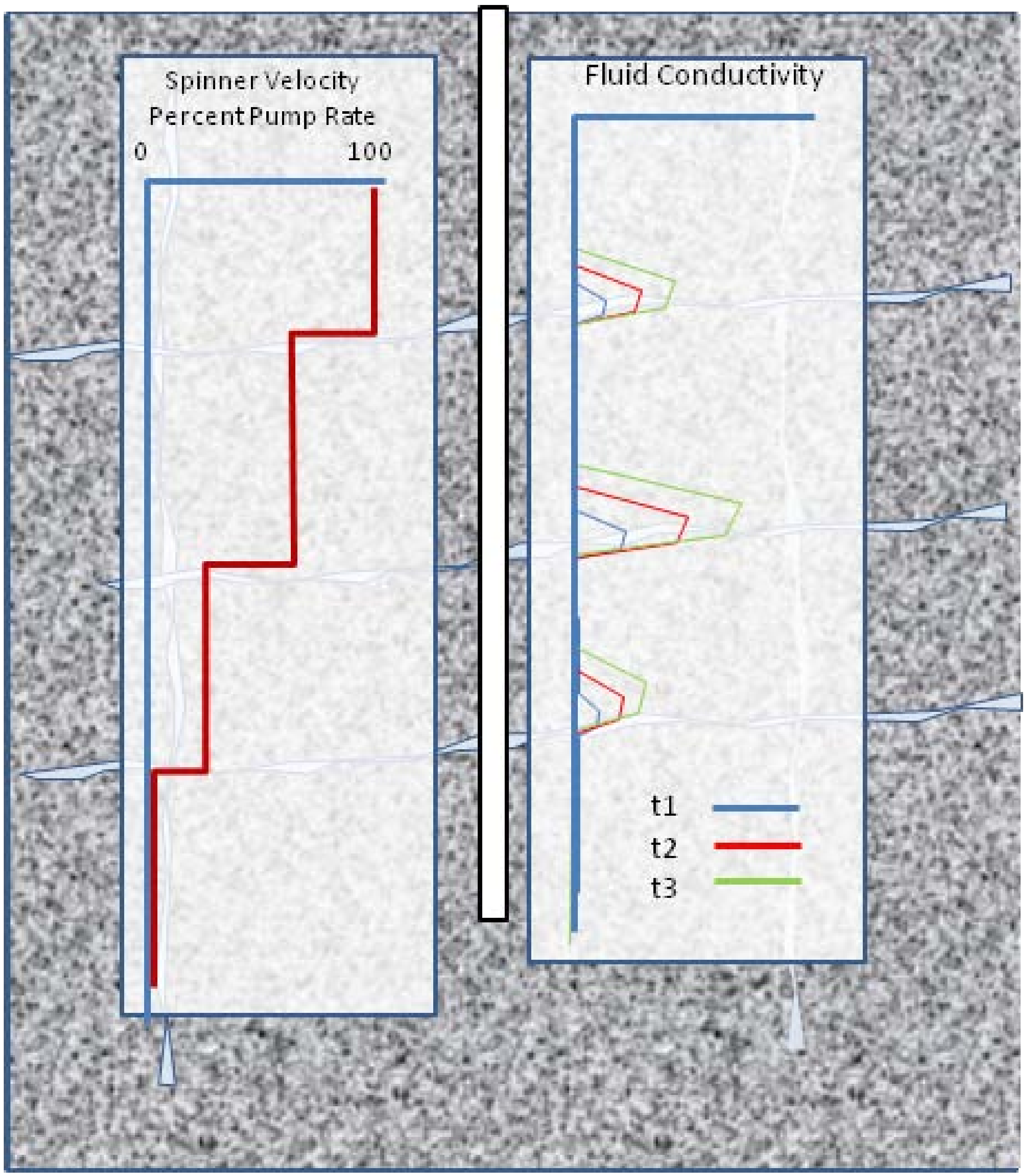
The heat-pulse flow log is currently the most widely applied logging method (Paillet and Pedler, 1996, 1987; Paillet, 1998; Hess and Paillet, 1990). The logging tool employs either a packer or flexible rubber cups to isolate a logging interval. Often only a single packer is used, so the tool is measuring flow from the entire hole below the meter. The tool diverts flow into a tube containing a heat source and two temperature sensors, one above and one below the heat source. For low flows, the tool measures the travel time, up or down, of a heat pulse. For rates that are too high to get an accurate travel time, the tool also can apply a sustained heat signal and measure the attenuation of temperature at the sensors, which will be proportional to the flow rate. The heat-pulse flow meter takes measurements at specific depths, hence the operator may scan a hole using coarse measurement spacings and then refine the measurement positioning to determine the locations of specific conductors.

An adaptation of the heat pulse flowmeter, the Posiva log, has become one of the key tools for fracture characterization in the radioactive waste programs of Finland and Sweden (Rouhiainen, 2000; see Fransson, 2007 for use of data in statistical analysis). The flow meter derives its name from the Finnish radioactive waste disposal agency, which funded its development and remains, along with the Swedes, its main user. This log is considerably advanced over other flow meters logs both in its ease of use, and its quality of data. The computer system automates the measurements, controlling a winch to move the tool between successive test zones, and performing the tests without the need for an operator's intervention.

Except for the Posiva log, and other configurations that use a straddle isolation system, the log's flow rate is the cumulative flow from below the flow meter. The determination of transmissivity from such a flow log involves the following (Figure B-8, Figure B-12):

- Taking flow value between two measurements points;
- Correcting for ambient flow;
- Assuming a hydraulic head difference between the well and the static head in the fracture system; and
- Applying the Theim equation or one of its variants.

Figure B-12. Spinner and fluid replacement logging.

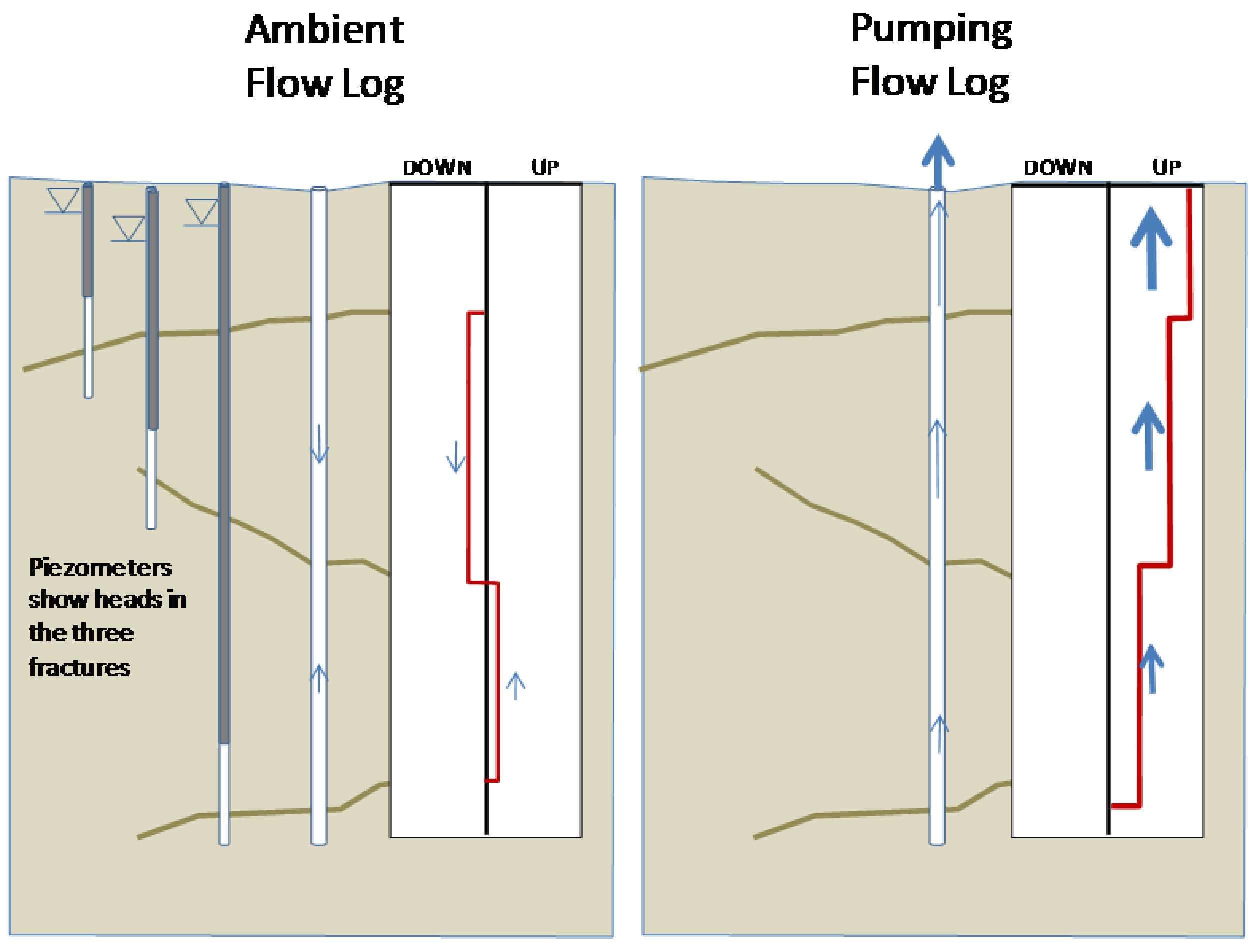


B.3.2.3 Ambient versus Flowing Logs and the Determination of Vertical Head Gradients

Flow meter logs should be run in both “ambient” and “pumping” modes. The ambient log is run with no pumping or injection of the borehole, and it measures the natural vertical flows between conductors that may have different head values. In this mode, one can identify the upward or downward flow associated with the major fractures, if they have different heads in the flow system. Such data are very valuable for understanding the hydrodynamics of the flow system, as upward flows indicate upward hydraulic gradients that would limit downward migration of contaminants, while downward flows would identify a condition where deeper movement of the contaminants would be more likely (Figure B-13).

A flow log’s primary determinations of hydraulic properties come from a log run under pumping conditions. However, the pumping-condition flow rate cannot be known without correction of the ambient flows, as the ambient flows may be in a similar or even higher range than the pumping flows.

Figure B-13. Ambient and pumping flow logs.



B.3.2.4 Fluid Replacement Logs

Another variant on flow logging is the fluid-replacement log (Paillet and Pedler, 1996; Tsang and Doughty, 2003; Doughty et al., 2005). This method was developed in the radioactive waste community to provide a simple, rapid borehole scanning system for flowing fractures. Fluid replacement logging removes the water in the well and replaces it with another fluid that has an electrical conductance that contrasts with that of the formation water. Once the fluid is replaced, the borehole undergoes repeated runs of a water conductivity probe while the hole is being slowly pumped. The resulting conductivity log shows the location of the major conducting features (Figure B-12). Software for analyzing the log data can invert the profiles to also give the flow rates from each major conductor.

Fluid replacement log is the electrical conductivity taken in “snapshots” over time (Figure B-12). Repeated logs while pumping show native water returning to hole around the flowing fractures. OTV image shows main conducting fracture.

B.3.2.5 Cross-hole logs and Horizontal Flow

In addition to flow meters that measure flow along a well, various efforts have been made to produce flow meters that measure flow across a borehole (Wilson et al., 2001; James et al. 2006). These flowmeters are designed for estimating natural fluxes or velocities including direction. While such data can be very valuable, an evaluation of velocity and direction needs to include enough measurements to account for local heterogeneity. Comparisons of flows before and during pump tests can indicate connectivity.

As a steady flow method, transmissivity values obtained from flow logs have the same limitations with respect to skin effects as those from packer tests. Due to skin, flow logs will generally underestimate transmissivity compared with a more rigorously-analysed transient test. Given this uncertainty, packer tests and flow log data should be viewed as a scanning tool to identify conducting features and provide a first estimate of their properties. Once identified, a more reliable set of hydraulic properties values can be obtained by running a transient hydraulic test on the zones that contain significant conducting features. Running a transient test on every conductor can be very time consuming, hence flow logging can be seen as a method for determining where in a hole one should focus one’s transient testing efforts.

As a summary of packer testing and flow logging, the identification of conducting fractures in borehole is perhaps the most important step in a facture flow characterisation, along with image logging to identify the geologic features that is flowing. Packer testing with many short-interval tests still can provide data on flowing fractures; however, flow logging accomplished the same goals more efficiently.

B.3.2.6 Reliability of Steady Flow Methods

The transmissivity values that come from steady flow tests may be reliable except in heterogeneous rocks, which unfortunately is most cases. If the well has a “skin” effect, that is a zone near the hole of reduced transmissivity, a steady flow test will only reflect that reduced condition. Skin effects can arise from the invasion of cuttings into the fracture during drilling, or simply the penetration of a borehole in a heterogeneously low-transmissivity portion of a fracture. In either case, the skin effect will lead to erroneously low transmissivity values.

B.3.3 Transient Methods

Transient tests determine hydraulic properties from the changes in pressure or flow with time. The most common mode of running a transient test is by constant-rate pumping. Tests may also use constant head conditions, which are useful if wells are flowing, or slug tests, where the test is the response to an instantaneous change in head in the well. Transient analyses usually use type curve matching or various forms of asymptotic solutions for late time. This section draws strongly on two sources that are outside mainstream hydrogeology, but are very appropriate for addressing well testing in fractured rock. One is the petroleum literature (Streltsova, 1988; Horne, 1996) and the other is the body of radioactive waste experimentation, which has taken many petroleum concepts and advanced them through focused research on test sites.

B.3.3.1 Is there a Well Test Response that is Unique to Fractures?

Contrary to widely-held beliefs, there is no well test solution that is distinctive to porous media or to fractures. The source of some confusion is the use of linear (one-dimensional flow) for well test interpretation of artificial hydraulic fractures (Gringarten and Ramey, 1974). This and similar solutions were developed for a fracture that is vertical with respect to the well (see Figure B-17). The linear flow response of this solution appears in many other situations, both fracture and sedimentary, and not all (one might say even most) fracture networks do not produce this response.

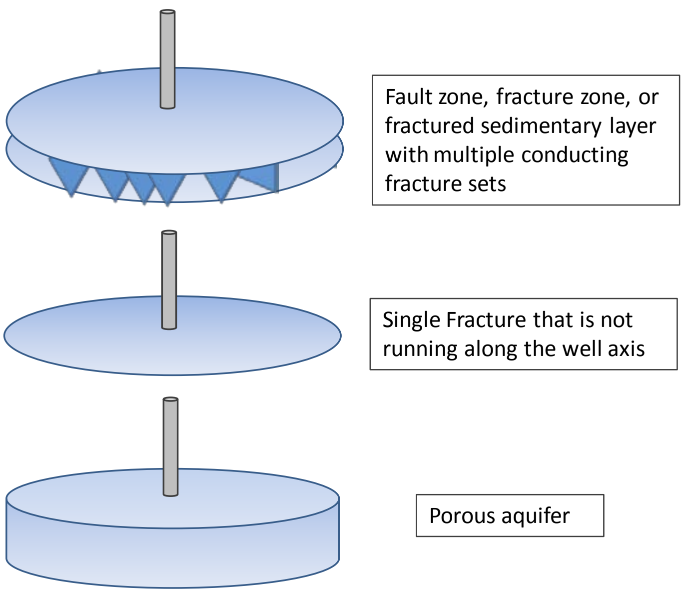
Just as the infinite conductivity fracture solution does not apply to all natural fractures, radial flow solutions are not unique to porous media. The most widely used well-test solution is the Theis curve, which is also know to petroleum engineers and mathematicians as the exponential integral, or Ei function. This equation is the solution for radial flow in an infinite planar feature to a well acting a point sink in the plane.

The planar geometry of the Theis curve applies equally well to any of the following (Figure B-14):

- A planar aquifer with a thickness that is small compared to the likely radial distance that pumping will affect;
- A single horizontal fracture or fracture in any orientation as long as the well is not coincident with the fracture plane;
- A single planar fault zone; and
- A sedimentary layer with sufficiently high fracture intensity that a flowing network is filling the two-dimensional space.

By symmetry, flow in any sector of a radial region about a well will produce Theis-type flow, even a sector as small as one degree. Indeed the only requirement that a region's geometry must have to produce a Theis curve is that it has a cross-sectional area that increases linearly with distance from the well.

Figure B-14. Radial cylindrical geometries that produce "Theis" curves.



The Theis curve has an asymptotic solution where the change in head with time, or the change in head with distance at particular time, varies with the log of time. Plots of head or pressure with time or distance produce straight lines on semi-log plots when the Theis assumptions are met.

Much of the confusion about fracture and well testing comes from misconceptions about solutions from petroleum engineering, which account for the effect of an artificial hydraulic fracture on flow in a planar reservoir. These solutions involve various linear flow geometries. Linear flow is a geometry where the flow lines are parallel, or linear. Any pipe-like conductor will produce linear flow. Flow from a surface into the matrix is also linear flow, as is the equation describing diffusion between fractures and matrix blocks. The asymptotic solution of head or pressure for linear flow is a square-root of time, which plots linearly against a square-root time, or with a half-slope on a double logarithmic plot.

The primary requirement of linear flow is that the flow area remains constant with distance. A wide range of both fracture and porous geometries will produce linear flow including:

- Flow from the face of an infinitely conductive hydraulic fractures to matrix;
- Flow in a sedimentary channel, such as a course sand or gravel channel in a fluvial environment;
- Flow in a fracture network that is confined to a layer, but with a single strong preferred orientation;
- Flow in any fracture or feature that the well intersects by running in the plane of the feature; and
- Porous media flow in wells that are deviated to run parallel to the bedding of a horizontal stratigraphic unit.

The flow of a finite-conductivity fracture may display two forms of linear flow - the linear flow of the vertical fracture from the well and linear flow over from the face of the fracture into the porous matrix.

To round out the picture of geometry and well testing, the third basic geometry is spherical flow, which is flow that is not confined to a planar aquifer or reservoir. A well that produces from a point in a three dimensional network may produce spherical flow. This geometry also appears in partial penetration of a thick sedimentary layer.

B.3.3.2 The Pressure Derivative

The introduction of the pressure derivative to petroleum engineering in the 1990's (Bourdet et al., 1983) revolutionized test interpretation. The pressure derivative is a misleading term because it is not the derivative of pressure with time, but rather the derivative of pressure with log time, hence it is really the semi log derivative. From this point on, note that the term "derivative" refers to this semi-log derivative (Figure B-15).

When Bourdet proposed this plotting method, most well test analysis was done using semi log plots looking for a semi log straight line, whose slope is proportional to transmissivity. In hydrogeology that is still the case. Bourdet was looking for a way to reduce the subjectivity of semi log line interpretation, recognizing that an analyst can often find straight lines that are not really there. He reasoned that when the semi log straight line condition is met, the semi-log slope is constant, and the slope of the derivative is zero. Thus, when the semi-log derivative is plotted on a log-log plot with data itself, the region of semi-log straight line validity is clear from the flat line portion of the semi-log derivative.

Derivative curves have fully penetrated well test practice in petroleum engineering, and one seldom sees an analysis without it. Spane and Wustner presented a computer code in Ground Water for calculating derivatives in 1993. Since then, derivatives are gradually appearing in hydrogeologic practice, and they are becoming an option in popular well test software for groundwater.

Part of the success of the derivative is that it proved to be good for much more than just the semi log slope, and it has distinctive characteristics for most well test geometries. In effect, the derivative curve for a well test is a "map" of properties and conditions starting at the well, in the early time data, and moving to progressively greater distances with time. This distance grows according to the radius of investigation, which can be expressed as (Streltsova, 1988) as $r = 2\sqrt{\eta t}$ where r is the radius of investigation. In fracture networks, this distance lies along the fracture pathways, hence the actual Euclidian distance may be less due to network tortuosity.

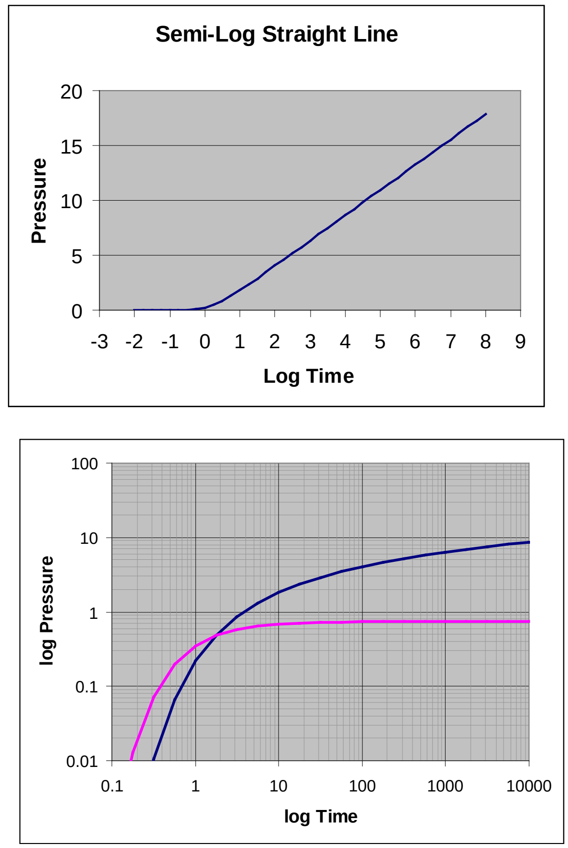
One way to read the derivative as a map involves recalling that the semi log slope is inversely proportional to transmissivity. A deviation of the derivative from a flat slope indicates changing conditions with distance. A deviation upward shows that the test is "seeing" less permeable or mobile material, while a deviation downwards indicates more permeable conditions.

Figure B-15. Theis or Ei curve plotted as log and semilog and the semilog derivative.

- Plots $\Delta P/\Delta \log(t)$
- Intent to make semi-line clear
- Effect is a very powerful tool to interpret geometry from tests

$$\frac{dP}{d\log(t)} = \frac{dP}{dt}t$$

- Derivative is a map of transmissivity versus distance from the well
- Shape of derivative constrains network geometry



The regions of the test curve are (Figure B-16):

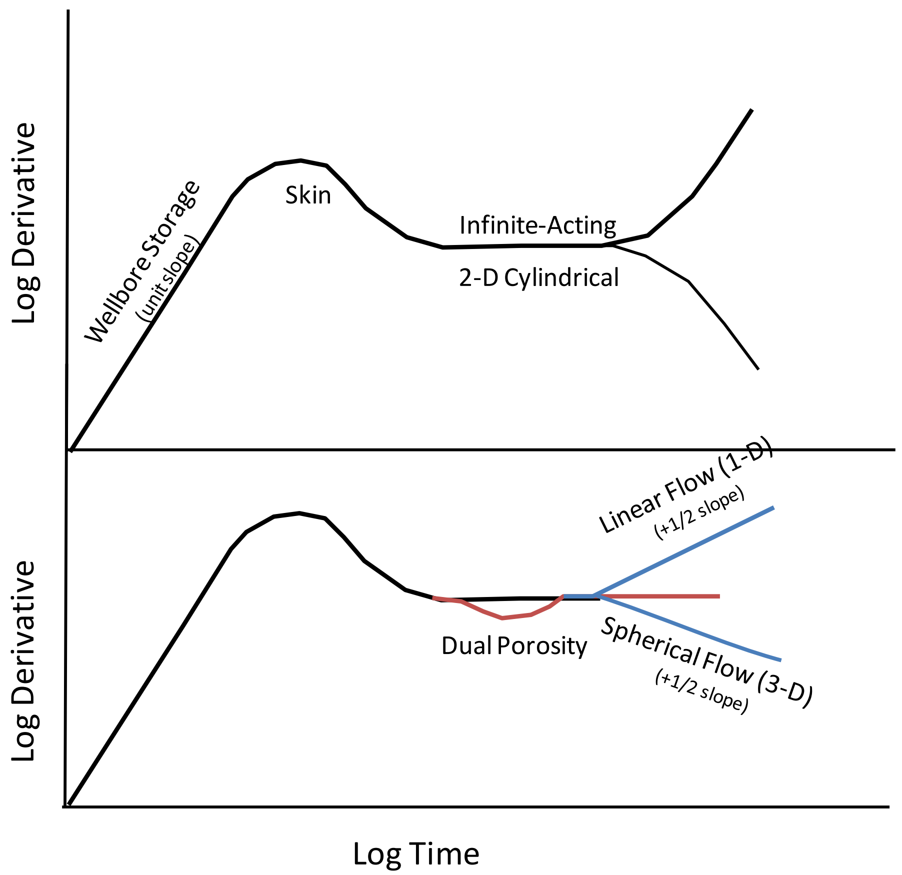
- *Wellbore storage and skin*: These are the near well effects. Wellbore storage is the period of time at the beginning of the test before drawdown has mobilized flow from the rock, and the fluid is mainly coming from storage in the well itself.

This drawdown is linear with time and has a slope that equals the flow rate divided by the cross-sectional area of the well. Skin is the heterogeneity in the immediate vicinity of the well. Usually skin is considered mud invasion or damage from drilling. This can be the case, but it also can appear from any heterogeneity of the fractures or aquifer at the location of the well. More often than not, the skin is a restriction, so the skin appears at the end of wellbore storage as a downward drop in the derivative curve.

- *Infinite acting behaviour*: This is a term used by petroleum engineers for the validity of the semi log log line. For radial, cylindrical flow, assumed for Theis conditions, the derivative becomes flat. For linear flow it has a positive half slope, and for spherical flow, a negative half slope. These slopes are very distinctive in the derivative.
- *Dual porosity*: The dual porosity behaviour may appear within the infinite acting period. Dual porosity flow is a temporary charge of fluid from a system that is overall acting in a Theis manner. As additional permeability or storage moves the derivative downward, the dual porosity effect appears as a downward trough beginning with the mobilization of fluid from the rock and returning to the original flat derivative when the matrix block contribution is exhausted.
- *Boundary effects*: A flow system that ultimately has no-flow boundaries ultimately will be depleted by pumping. When that limit is reached, the system is pumping from a closed volume where each increment of fluid removed causes a drop in pressure or head by a constant factor related to the volume and total compressibility of the flow system, thus creating a straight line drawdown in the data and a unit slope in the derivative. Constant pressure boundaries cause the derivative to take a strong drop, which is also distinctive. Closed or no flow boundary effects appear when a fracture system is highly compartmentalized.

Dual porosity flow is another form of well test response that is associated with fractures. Dual porosity flow produces two parallel semi-log lines with an offset in the middle. The offset represents an additional charge of fluid mass from the porous matrix, which is diffusing much like solutes in matrix diffusion. The well test produces an initial semi-log line produced by fractures in the unit, until sufficient mass from the matrix causes a deviation from the semi-log line (Figure B-16). Later in time, when the matrix is depleted, the well test continues on a semi-log slope representing flow in the fractures (Streltsova, 1988). While dual porosity flow might appear to be distinctive to fracture-matrix systems, Streltsova points out that dual porosity flow shares its mathematics with leaky flow between an aquifer and a thick aquitard.

Figure B-16. Basic elements of well test derivative plots.



B.3.3.3 Flow Dimension and Composite Dimension

If there is a change in properties or geometry, short of a flow boundary, the derivative may have multiple infinite acting periods. For example, if a planar, Theis-type feature changes transmissivity to a higher value at a particular radius, the semi-log plot will show two different straight-line slopes separated by a transition that might last about a half to a full log cycle of time. The derivative will show the composite behaviour by moving from one flat slope line, through a downward transition, and moving to a second flat slope.

Flow dimension (Figure B-17, Figure B-18) is an advanced concept developed in the groundwater literature and the petroleum literature at about the same time (Barker, 1988; Chang and Yortsös, 1988). Flow dimension was conceived as a way that fractal geometries might influence well test behaviour. Linear, radial cylindrical (Theis), and spherical flow each apply to geometries that have one, two and three dimensional forms. These are the integer dimensions. They produce a derivative with a straight line in logarithmic plots that relates to the dimension, n, by $1-n/2$. Thus linear, one dimensional flow has a slope of +1/2, radial cylindrical flow has a slope of zero, and spherical flow has a slope of -1/2. Doe and Geier (1990) noted that a further effect is the way that the area of flow, A, grows with distance or, $A \propto r^{n-1}$ (Figure B-17). The area in a linear conductor grows by $A \propto r^0$, radial cylindrical flow grows by, $A \propto r^1$, and spherical flow grows by $A \propto r^2$ (Doe and Geier, 1990).

Figure B-17. Geometries of flow dimension for fractures.

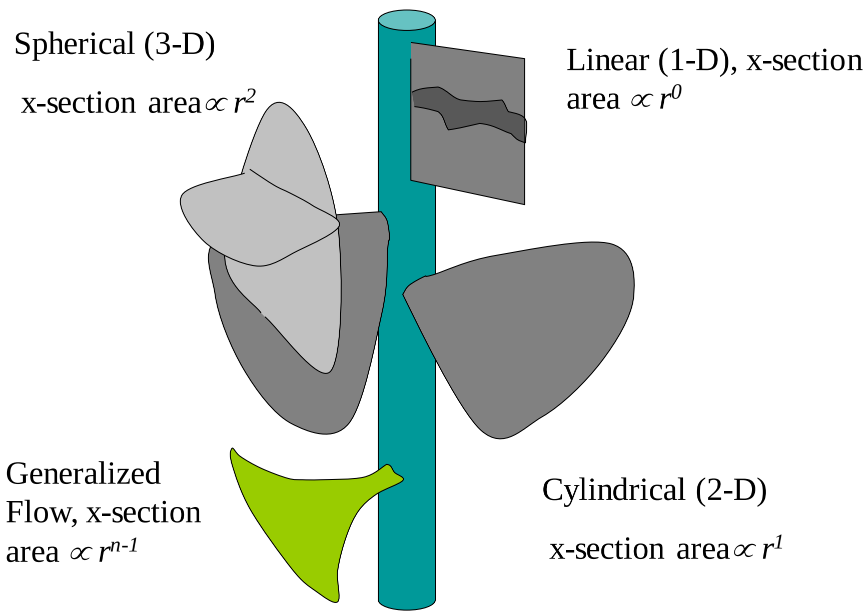
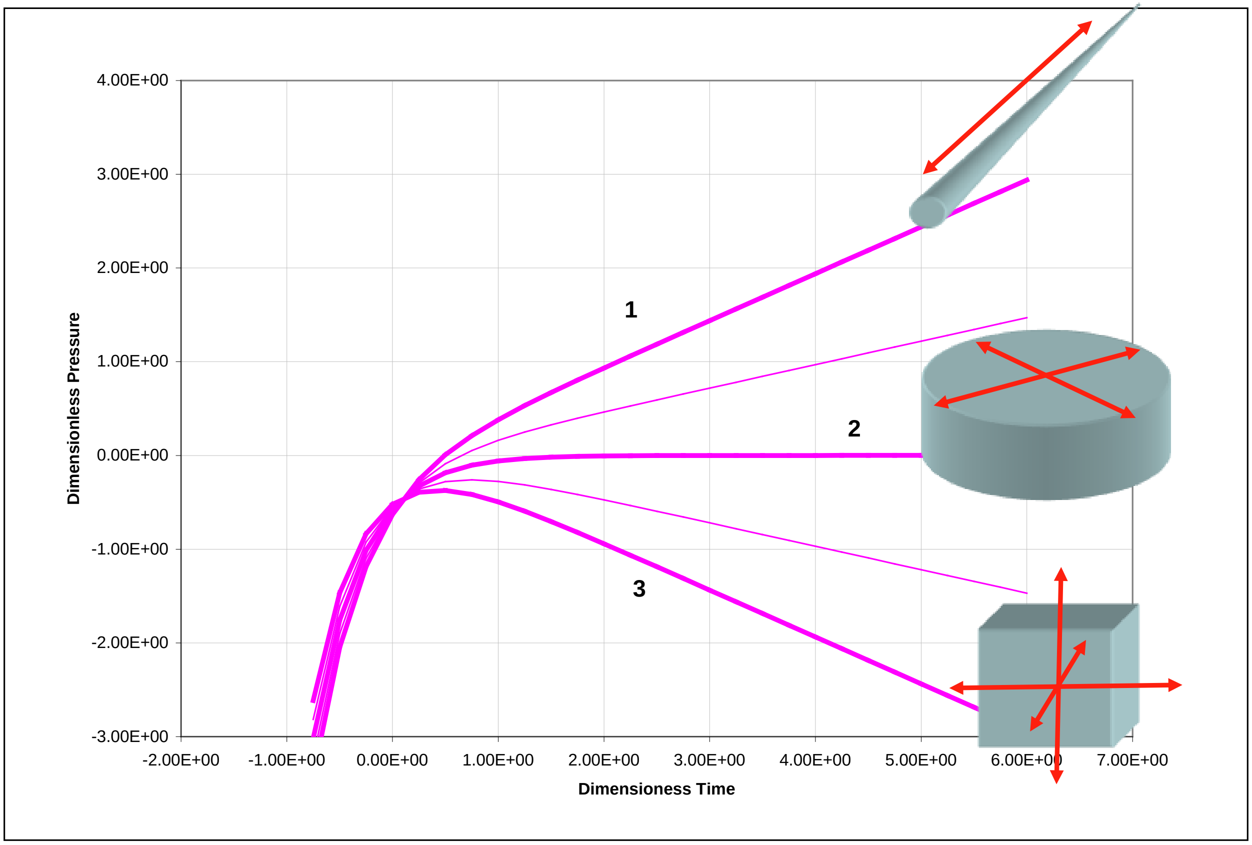


Figure B-18. Generalized Dimension Derivative Curves.



Barker (1988) and Chang and Yortsös (1988) showed that fractal geometry describes how patterns "fill" space. If a pattern fills a space, it has the same dimension as the space itself. For example, a pattern of lines that fills a two-dimensional space has a fractal dimension of 2. If that pattern does not completely fill the space, it will have a dimension between 1 and 2, depending on how completely the space-filling appears. Non-space filling fractal patterns produce non-integer dimensions in well tests. A pattern that has a dimension of 1.5, will have an area that grows with distance by $A \propto r^{0.5}$, and produces a straight line derivative with a slope of $1-1.5/2=0.25$.

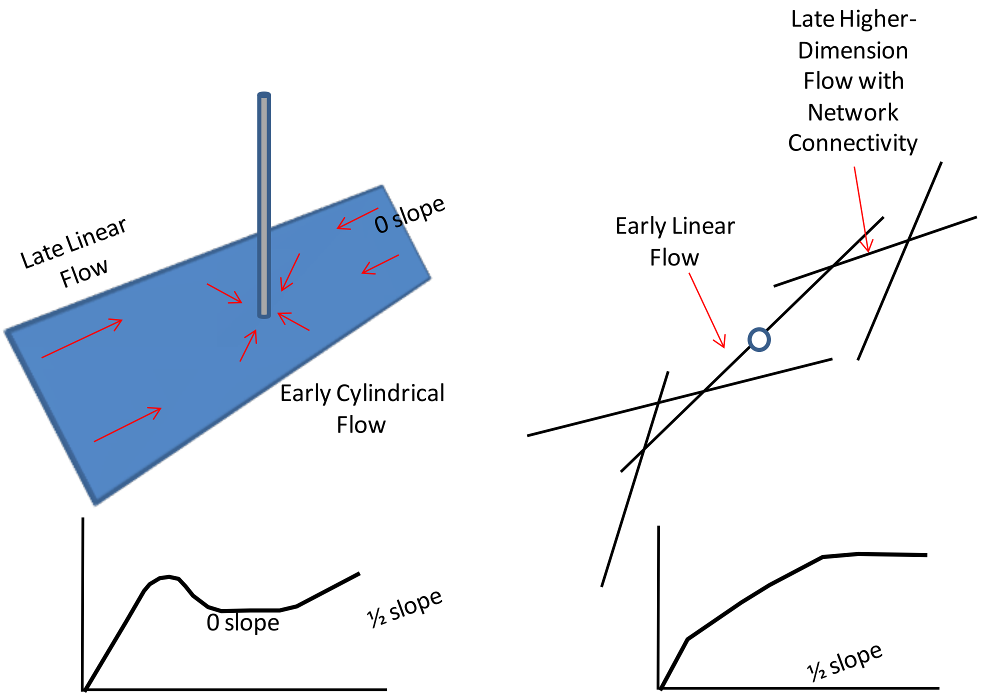
Barker's well test derivation is particularly elegant, as he showed that a single mathematical function, the incomplete gamma function, describes all well test dimensions, where the value of

$1-n/2$ is an argument in that function incorporating dimension. The Theis curve (Ei function), as well as the linear and spherical flow equations, incorporate the error function, which are special cases of the incomplete gamma function for integer dimension values.

The development of dimension is not a mathematical fantasy. Barker developed his theory to explain well tests at the Stripa Mine test facility that would not otherwise match existing curves. Doe further has shown that these dimensions can also be related to fracture intensities, where high fracture intensities fill space to produce the same dimension as the space they fill, or if less intense, to produce a dimension less than their space. Le Borgne (2004) has shown that the granite fault zones that supply a mid-sized town with water in Brittany have both pumping and interference responses that follow a dimension between 1 and 2.

Composite well test curves relate to systems where the properties change with distance. This can be a change in transmissivity of a fracture or aquifer at some distance from the well. The effect of the composite is to have two flat derivative portions, an early one for the closer region, and a second for the more distant region. The two flat derivatives are separated by a transition from about a half to a full log cycle. Not only hydraulic properties, but dimensions also can change at a boundary (Leveinen, 2000). Karasaki (et al., 2000) developed analytical solutions for a composite like the right side of Figure B-19, which shows some simple examples of dimension change. One is a case of an extensive fault or fracture zone (or aquifer) which is a rectangular feature of some extent. The early time portion of the test sees 2-D flow until the head effects reach the boundary of the feature, when the flow changes to linear (1-D).

Figure B-19. Examples of composite dimension behaviour.



B.3.3.4 Rate Normalized Plotting of Derivative Data: Using Derivative to Assess Network Geometry

A particularly powerful extension of the derivative is the rate-normalized plot (Cristian Enachescu, personal communication). This plot puts all the derivative curves from a site's well testing on a single plot, where the drawdowns are normalised by their rates to allow this comparison. Wells that are connected to the same volume have derivatives that merge in time, that is, they "see" the same volume, and thus have the same derivative.

Figure B-20 shows an example of a rate normalized plot for different source wells in an experiment that was conducted at the Äspö Hard Rock Laboratory in Sweden (Andersson et al., 2004). In the early time, the derivatives of each well are quite different as they are only detecting local variations close to the well. In later time, the derivatives merge into a single line that reflects the larger-scale properties of the conductor. In the last part the curve, the derivatives all drop and appear to reach a second stabilization. This drop indicates the connection with a feature with a transmissivity that is about one order of magnitude higher than the fracture zone these wells are pumping.

B.3.4 Other Single Hole Tests

The discussion on well testing has focussed on constant-rate testing and the derivative curve. Other test designs include slug tests and constant-head tests. Slug tests interpret hydraulic properties from the recovery after an instantaneous change in well head. Slug tests are simple to perform, and provide good test data. Butler (1997) provides a comprehensive review of slug test methods. Dimension effects were first considered based on slug tests in fractured rock (Barker and Black, 1983). Derivative interpretation methods exist for slug tests, as well, though the curves do not have the distinctive form of those of the constant-rate test, hence the geometric interpretations of the test are more difficult. It is possible to deconvolute any test, even ones with bad rate control, into equivalent constant-rate tests. This approach applies to slug tests as well (Chakrabarty and Enachescu, 1997), though it has not been widely applied.

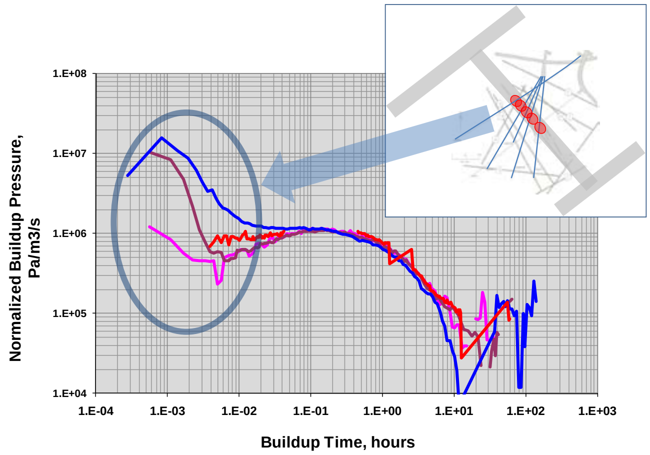
B.3.5 Interference Tests: Diffusivity and Storativity Determination

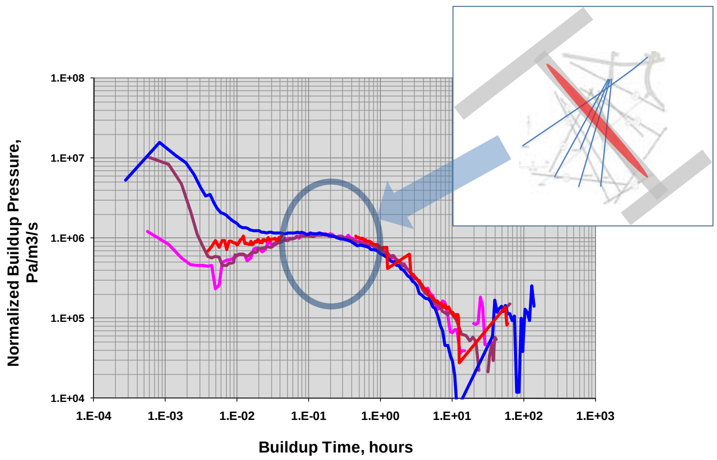
Interference tests are pumping tests that are performed while monitoring heads in observation wells. Interference tests are particularly useful for determining connectivity in fracture networks. Interference responses from either pumping or slug tests can be used, and pulse interference tests may be particularly efficient in fractured rock (Stephenson and Novakowski, 2006).

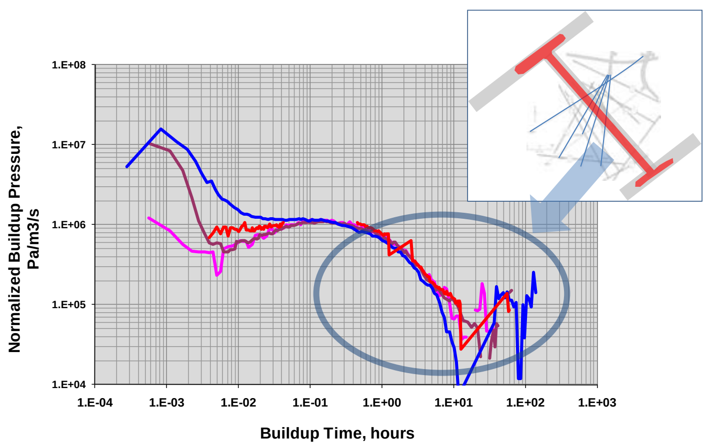
Interference tests have two major functions:

- Determine storativity and diffusivity; and
- Evaluate fracture connectivity.

Figure B-20. Äspö Laboratory block scale tracer test with normalized derivatives.







B.3.5.1 Storativity Calculation

In principle, the semi log plot of a source well test, for Theis or two-dimensional behaviour, gives both the transmissivity and storativity by:

$$T = \frac{2.3Q}{4\pi m} \qquad S = \frac{2.25Tt_0}{r^2}$$

$$t_0 = t \text{ intercept}, \; m = \text{semi log slope}$$

The storage calculation assumes that a well has no skin, that is, there is no drilling or natural variability affecting flow very close to the well. If there is a skin, the storativity calculation is not reliable. The use of skin in well testing is one area where petroleum and hydrogeology methods of well testing differ.

This leaves the calculation of storativity to interference tests. The basic parameter that comes from interference responses is the diffusivity, η, which is a measure of the speed of pressure propagation. The time match in a type curve analysis gives the lag time, and hence the storativity.

Conventional hydrogeologic practice then calculates storativity from the time match point,

$$t_{match} = \frac{4\eta t}{Sr^2} = \frac{4Tt}{r^2}$$

Note that this calculation requires knowing transmissivity, which in principle can be obtained from the type curve match of the observation well, but this assumes that the system is homogeneous.

A fundamental flaw in conventional hydrogeologic practice lies in the determination of transmissivity from observation wells. To determine a transmissivity one needs a flow rate, and the only flow rate one has is the rate at the pumping well, hence transmissivity values are strongly biased to the pumping well's rate. This bias is not an issue in a homogeneous system, but in heterogeneous fracture networks, this becomes a major source of error.

One can judge this error in two ways. The first is the frequent observation that transmissivity values from observation wells appear to be relatively homogenous, but storativity values are highly variable, which can be an artefact of not knowing how the pumping well's rate is being drawn through the fracture network. The second is the fact that in a homogenous system, the drawdown in an observation well is inverse to the transmissivity, hence small observed drawdowns produce large transmissivity calculations. If one considers a heterogeneous fracture network, one would expect poorly connected parts of the network to have smaller drawdowns than well-connected parts. Yet the assumption of homogeneity that is inherent in observation well test analysis assigns larger transmissivity to the points with small drawdowns.

In summary, transmissivity and storativity must be considered carefully when using interference well test data, that is, data from observation wells. What is relatively robust in the analysis of observation well data; however, is the diffusivity. Diffusivity can be affected by the tortuosity of the fracture flow path. LeBourgne (2004) in a study demonstrating fractional dimension flows in crystalline-rock wells for municipal water supply points out that diffusivity can have effects that vary with the flow dimension. The distance one uses to assess diffusivity is usually the straight-line distance between the source well and the observation point. However, actual fracture networks, even those that are very well-connected, will often conduct fluid on pathways that have some level of tortuosity. Hence fracture diffusivities based on straight-line paths may underestimate the true values.

B.3.5.2 Diffusivity for Mapping Connectivity

Nonetheless, diffusivity is perhaps the best indicator of connectivity in fractures. If tortuosity is not a major concern, the time to a response at an observation point is given by the radius of investigation equation, which can be expressed as $r = 2\sqrt{\eta t}$ or $t = r^2/4\eta$. This useful equation can be used to estimate diffusivity from any definable perturbation and not just designed well tests.

The speed of a well test response, which diffusivity measures, is perhaps the best indicator of fracture connectivity – even more so than drawdown (Knudby and Carrera, 2006; Beauheim, 2007). Diffusivity values are one means of distinguishing fractured from unfractured media. As fractures have very low storativity, they typically have high to very high diffusivities. Typical fracture diffusivities are of the order of 1-10 m^2/s, and very transmissive features can have diffusivities in the 100 m^2/s range or higher. Porous media, on the other hand, have much higher storage, hence they have much lower diffusivity values for a given transmissivity.

B.3.6 Tracer Tests

Tracer tests are much less often performed than pumping tests, which is not surprising given the fact that they require considerably more effort and time and, in fractured media, often produce no results as the tracer decides to go somewhere other than the pumping well. Nonetheless, tracer test are the definitive means of acquiring transport properties – not only transport aperture but also information on matrix diffusion and other retardation processes.

Tracer tests produce two types of data:

- The arrival time, which gives the porosity or transport aperture, and
- The breakthrough curve shape, which is influenced by hydrodynamic dispersion and retardation effects like matrix diffusion and chemical reactions between the tracer and the rock.

The aperture or transport porosity is an essential parameter to predict contaminant transport velocity. The travel time of a tracer from injection to recovery point will be a function of the flux or flow rate divided by the velocity, which gives a length value which is the transport aperture.

Tracer tests usually involve one well where tracer is introduced and another where it is recovered. The main variations involve the relative pumping or injection rates of the introduction and recovery wells. Some common tracer test configurations are the following (Figure B-21):

- Divergent – tracer introduction to an injection well with recovery in a passive or weakly pumped observation well;
- Convergent – tracer is introduced by very low injection in one well for recovery in another that is being pumped at low rates for sampling;
- Dipole – tracer is introduced into a well that is injected at a rate equal to or lower than the pumping well;
- Single well – tracer is injected from a single well and then recovered by pumping from the same well; and

- Point dilution – tracer is introduced as a slug into a well and monitored for dilution by passing groundwater as a means of estimating natural flux.

The radioactive waste research projects in several countries including Canada, Sweden, the US, Japan, and Switzerland have produced a considerable body of experience in tracer testing in fractured rock. One problem that plagues tracer tests is poor or no recovery when the pathway is not well known. Some tracer tests have had problems even when the pathway was thought to be well known. In general, one can recommend that tracer tests are a very inefficient way to map connectivity compared with pressure interference tests, as pressure travels much faster than a tracer. Furthermore, if there is a poor connection, pressure will provide a quicker answer.

A tracer test breakthrough curve has several periods (Figure B-22). The breakthrough curve is influenced by the test design, which itself can create greater or lesser dispersion. A dipole test purposely spreads the flow field to sample a larger area, and the relative strength of the dipole rates determines the spread, along with the fracture geometry, while a convergent test tends to sample a direct pathway along the fractures between the tracer source and pumping sink. The analytical or numerical model of the test will take these factors into account.

The breakthrough periods are:

- First arrivals which are fast paths that are relatively undispersed;
- The peak which reflects the main advective travel time;
- The tail which shows various effects;
- Log-symmetric form only if there is longitudinal dispersion on a simple pathway;
- Matrix diffusion from -3/2 slope;
- Dispersion from heterogeneous pathways; and
- Off set and retardation by sorption.

The theoretical effect of matrix diffusion is a -3/2 slope tail. This slope assumes a constant block geometry for the matrix; however, distributions of block size, as one would expect in variably fractured rock, will produce different slopes both theoretically and in actual observations of tests in porous, for example, fractured dolomite at the Waste Isolation Pilot Plant in New

Mexico (Haggerty et al., 2001; Meigs et al., 2001). This process may be related to fractal distributions of block sizes. Different processes – dispersion and diffusion – have the same basic mathematical form, hence a unique interpretation requires a good tracer test design. Using multiple tracers with different free-water diffusivities will confirm matrix diffusion by producing reduced peaks and offset tails with higher tracer diffusivity (Andersson et al., 2004; Meigs et al., 2001). The same forms of tails can also be produced by dispersion on complex fracture pathways. Tracer tests at the USGS's Mirror Lake site had diffusive-like tails, but the absence of an effect with variably diffusive tracers showed that this was a dispersion effect (Becker et al., 2000).

Tracer tests are best used to characterize transport properties once pathways have been affirmed. For this reason, convergent or dipole tests are preferable to divergent tests both because the pathway is focused to the recovery well and the concentrations at the recovery well will be greater. Dipole tests and convergent tests differ mainly in the strength of the tracer injection. A convergent flow test will produce a relatively narrow path that will spread only by lateral dispersion, hence, a dipole may be desirable if one wants to sample a broader pathway. The single well tracer test does not measure aperture or effective porosity.

The choice of a tracer depends on the parameters and processes one wishes to measure. A "conservative" tracer is one that does not react chemically with the rock. Reactive tracers may be chosen to determine whether or not the chemical interactions with the rock provide some level of chemical retardation. Using reactive tracers will slow or even prevent tracer recovery. Because there are multiple non-chemical reasons why tracer may not be recovered, it is important to use conservative tracers with reactive tracers so retardation or non-recovery can be property attributed.

Single well dilution tests are very useful for evaluating groundwater flow velocity. The tracer dilution test injects a fixed tracer mass into a test interval, and then passively observes the dilution of the tracer in the well as it moves off with the groundwater's flow. Although this is a tricky test to interpret for natural velocities, it is very interpretable when repeated under different pumping conditions. The strength of a dilution rate to pumping in different locations is a clear indicator of connectivity between the tracer observation point and the pumping well (Andersson et al., 2004; Pitrak et al., 2007).

Matrix diffusion can also be a motivation for tracer testing, though laboratory measurements might provide an equally useful demonstration. The free-water diffusivity of a tracer, which is rate of diffusion of a tracer in standing water, also influences the diffusivity of a tracer into the matrix. Thus a mix of tracers with different free-water diffusivity values, even though conservative, will have different breakthrough behaviours than can confirm the effects of matrix diffusion.

In addition to introduced tracers, the most valuable tracers of all can be the ones that were in the rock already. These can either be the contaminants themselves or non-contaminant tracers, such as stable isotopes or distinctive radionuclides from human activity. The form of a contaminant plume will provide valuable insight into pathways and velocities, which can be evaluated by numerical modeling.

Figure B-21. Tracer Testing Methods.

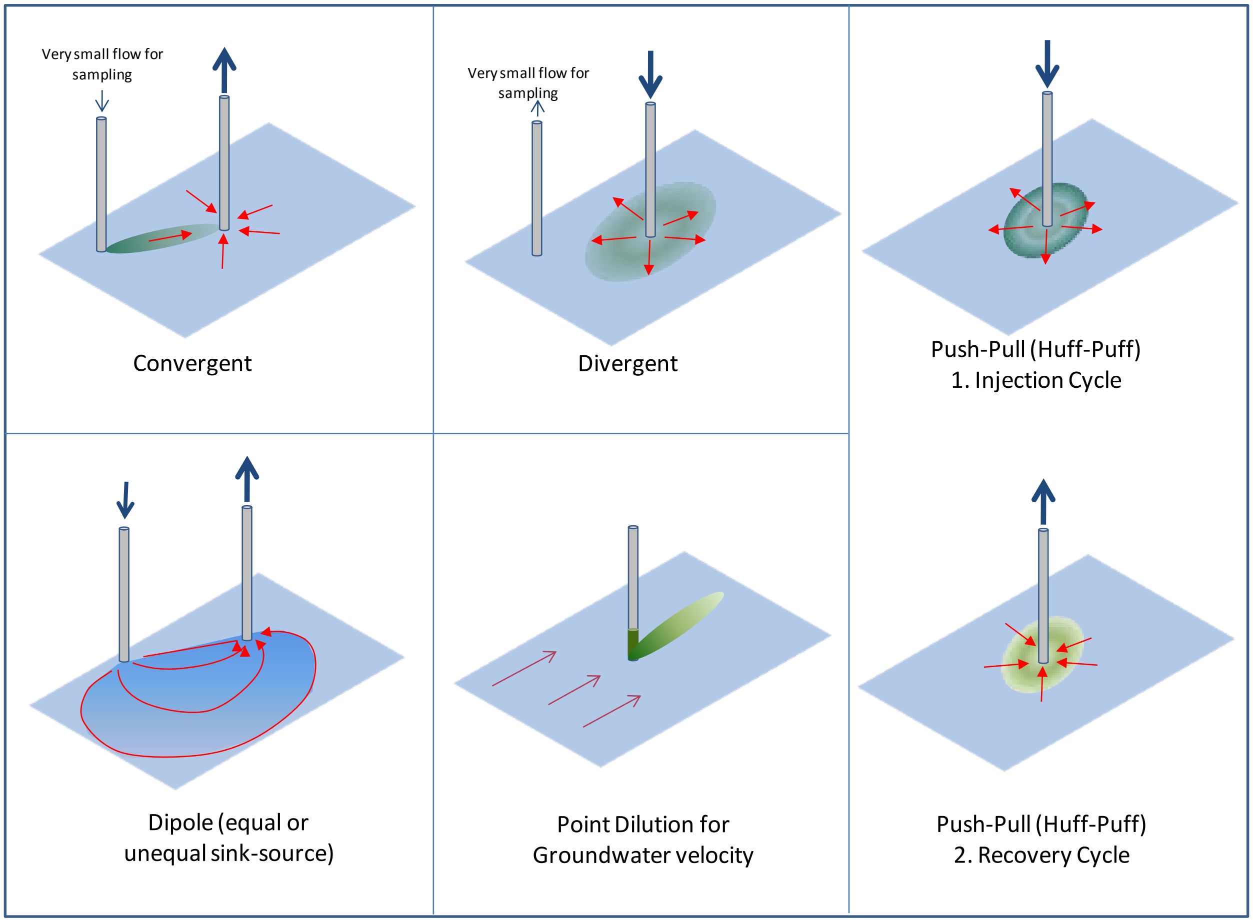
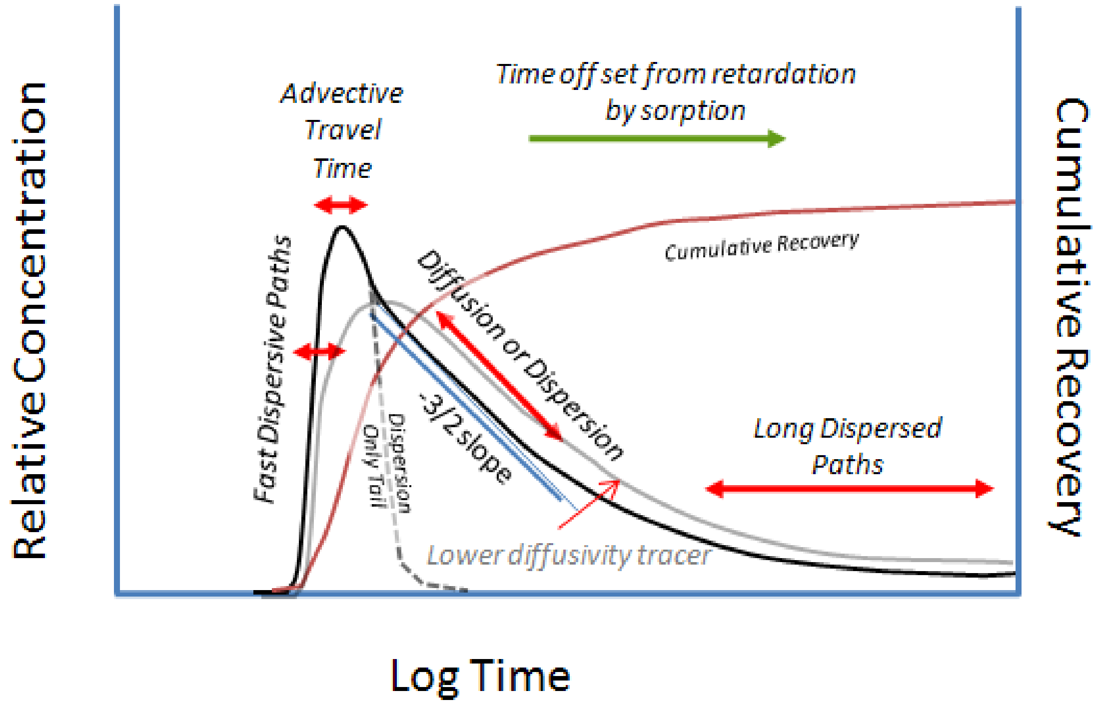


Figure B-22. Tracer test breakthrough curve interpretation.



B.4 Monitoring Systems and Borehole Completions

The proper completion of exploration and monitoring boreholes is extremely important in fractured, contaminated sites for the functions of:

- Monitoring hydraulic head;
- Allowing access for repeated water chemistry sampling; and most of all
- Preventing cross contamination of conductive fractures along the borehole.

Einarson (2006) presents a good overview of monitoring methods. An ideal monitoring system isolates each significant conducting fracture in the borehole, measures pressure or head, and, if needed, provides access for groundwater sampling. The design of a monitoring system requires information on the depths of the significant conducting fractures. While image logging, core analysis, and other geophysical logs are helpful for identifying these fractures, only hydraulic data, such as flow logging or packer testing data, can be considered definitive.

Fractures that might have potential cross flow along an open borehole are especially important for isolation, as the borehole may provide contaminant migration pathway, either upwards or downwards, between fractures that would otherwise have poor connections. The potential for cross flow between fractures along a borehole can be determined by measurements of static head taken during packer tests on specific fractures. Cross flow can also be measured directly using flow logs under ambient (no pumping) conditions.

Monitoring systems help determine the geometry and connectivity of a fracture network. Every addition or removal of water from a fracture-flow system – rainfall, water-supply pumping, drilling, testing, or sampling – produces head responses across the network. The data from a well-designed head monitoring system map the conductive fracture network by indicating which zones do not respond and which zones do respond, along with the amplitudes and time lags of those responses.

Ideally a monitoring system should be installed in every borehole as early as possible to limit cross contamination between fractures at different depths and to start collecting usable data. Pumping tests and sampling activities, which might be done in an open hole before installing the monitoring system, may be performed better after installation, if the monitoring system allows pumping and sampling access to individual zones.

Although traditional clustered and nested standpipes can still serve this role, new monitoring systems have been introduced over the past thirty years that can isolate large numbers of intervals in a cost effective manner. Canadian companies like Westbay Instruments (now Schlumberger Water Services) and Solinst have been particularly active in these developments. Furthermore, for pressure monitoring only, a simple system of grouted-in pressure instruments can provide a very effective and inexpensive completion.

B.4.1 Nested and Clustered Completions.

Clustered and nested standpipes are the traditional completion methods (Figure B-23). A clustered monitoring site uses separate boreholes for each significant conductor. Unless the depths of significant conductors are known in advance, a clustered system would require drilling the deepest borehole first and using its flow data to determine the depths of shallower conductors to be targeted by later boreholes. Each borehole would be completed with a sand pack around the conducting fracture and then full cementing of the borehole back to the surface.

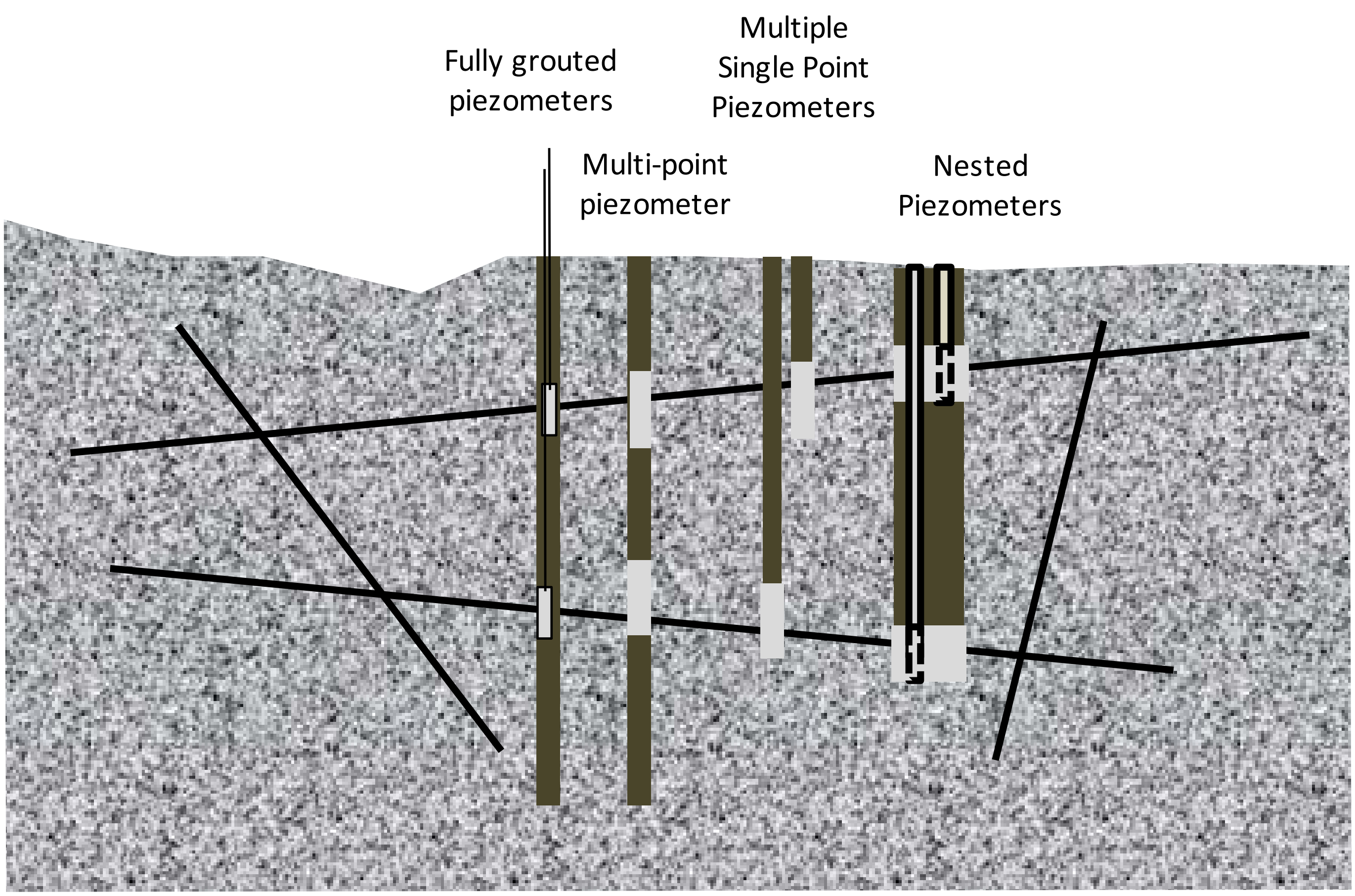
A nested monitoring borehole is an installation in a single borehole with separate standpipes for each monitoring interval. The standpipes are installed from bottom up, sand is placed around the tips and cement or grout is placed in the intervals between the monitoring zones. Nested standpipes can be very effective; however, the number of monitoring intervals is limited by the diameter of the borehole and the ability to force grout effectively around the pipes to provide good seals.

B.4.2 Single Well, Multilevel Monitoring Systems

Multilevel monitoring systems have been in use for about 30 years. They began as research tools, but have gained increasing acceptance especially in the last 15 years. The first commercial installation was the Westbay system in the late 1970's followed by the Waterloo systems of the 1980s, and more recently flexible liner systems from the late 1980's (Parker, and others, 2006).

In addition to these fully integrated multilevel systems, packers and sampling ports are available from packer manufacturers to develop custom systems that can provide more flexibility for different borehole diameters. One drawback of the integrated systems is the use of small diameter tubes and ports that have restricted pumping rates, albeit for smaller numbers of monitoring intervals. Further description of these systems follows.

Figure B-23. Single and multipoint monitoring installations.



B.4.3 Westbay System

The Westbay monitoring system is a casing-based system (MP casing) specifically designed for isolating multiple monitoring intervals in a well (Figure B-24, second from left). The system includes the well installation, consisting of a casing, pressure monitoring ports, fluid sampling ports, and packers, and tools that run on a wireline inside the casing to take pressure measurements and manipulate ports for pump testing or fluid sampling.

The Westbay system (Black et al., 1986) was developed over thirty years ago in North Vancouver, B.C. Among its early applications was the monitoring of the Downey slide above the Revelstoke Dam on the Columbia River. The multilevel monitoring was key to identifying pressure variations in the critically pressured zones across the plane of the slide. Since then, the Westbay system has seen extensive applications in radioactive waste repository investigations, civil engineering applications, and groundwater contaminant investigations in heterogeneous rocks and soils.

The design of the Westbay system allows the installation of large numbers of monitoring intervals in a single hole. The main constraint on the number of intervals is the packer length, but interval frequencies of 2-3 meters are quite feasible. As an alternative to packers, the Westbay system can be installed with cement or bentonite grouts to provide the seals with sand packs round the ports.

One key attribute of the Westbay system is the small volume of the monitoring intervals. The pressure monitoring system involves virtually no displacement or exchange of water between the monitoring volume and the inside of the casing, minimizing the equilibration times for a reading. Similarly, the small storage volumes in the monitoring interval minimize the need for pumping large volumes to obtain representative samples.

For higher capacity flows, the Westbay system can also include pumping ports that are opened or closed with a special tool lowered from inside the casing.

B.4.4 Waterloo/Solinst Multilevel Monitoring System

The Waterloo Monitoring System came out of the University of Waterloo in the early 1980s (Cherry and Johnson, 1982) and was later adapted for commercial distribution by Solinst of Georgetown, Ontario (Figure B-24 second from right).

The System uses modular casing and monitoring ports. The casing is made of PVC plastic with a flush outer diameter of 56-mm. The ports are constructed of either PVC or stainless steel.

The non-threaded pipe joints connect to one another without turning, with nylon shear wires holding the joints in place and o-rings making the seals.

The annulus between the casing and the borehole wall can be sealed using a variety of methods including:

- Inflatable packers, which allow removal of the system;
- Cement or bentonite grouting with sand intervals at the ports; and
- Self-inflating packers that contain a polymer that swells on contact with water.

The monitoring intervals have several types of completions which involve:

- Single 8-mm tubes;
- Small diameter air-driven pumps that are dedicated to a monitoring port; and
- Pressure transducer for head measurements.

The number of monitoring intervals is controlled by the 50-mm inner diameter of the casing and the choices of port completions. The casing can accommodate up to 15 8-mm tubes or 24 pressure transducer lines. Adding pumps reduces the number of intervals, but still allows up to six zones using open tubes for pressure monitoring or eight zones if pressure transducers are used.

Continuous Multichannel Tubing (CMT) is an approach that allows a single standpipe to monitor up to seven intervals. It was also developed at the University of Waterloo (Einarson and Cherry, 2002) and has been commercialized by Solinst. This system avoids the handling challenges of large numbers of tubes and wires by employing a single high-density polyethylene pipe with six hexagonally symmetric chambers around a central chamber. The 43-mm diameter pipe is flexible and installs in a single continuous length. The monitoring intervals are accessed by drilling holes into the appropriate chamber of the pipe, and covering the holes with screen, except for the central chamber, which monitors the bottom of the hole. The isolation of the intervals is achieved by grouting the pipe into the borehole with sand around the monitoring interval or by using external packers that are inflatable or filled with water-expansive clays (bentonite).

B.4.5 Flexible Liner Systems

Flexible liner systems are a major departure from other monitoring approaches. The developer and provider of this technology is FLUTe (Flexible Liner Underground Technologies, LLC). The technology is about twenty years old, and there is a significant track record of installation and use (Cherry et al., 2006).

The liner is a thin, flexible tube made of an impervious, coated fabric that is emplaced in a borehole (Figure B-24, left). The liner comes inverted, or inside-out, on a reel. The end of the liner is attached to a collar at the wellhead, and the liner is lowered by filling it with water from the surface. Once installed, the internal water pressure of the liner provides a seal along the borehole wall as long as the hydraulic heads at depth do not have values above ground surface elevation.

The descending liner displaces the water in the well into the rock as it is lowered, and the rate of descent depends on the transmissivity of the borehole below the depth where the liner has advanced. When the liner advances past a transmissive fracture, that fracture no longer takes the water being displaced by the liner installation, thus decreasing the installation rate. The changes in the rate of liner descent can be quantified to produce a flow log that identifies the locations and transmissivities of the main fractures (Keller et al., 2006).

As the liner goes into the hole, spacers are added to the liner's outer surface to create a gap between the liner and the borehole wall. These gaps make up the monitoring intervals. Tubes welded into the liner wall from the inside run from the monitoring interval to the surface providing access for sampling and head monitoring. Groundwater sampling uses two tubes. One tube fills with water from the monitoring interval. When the water is to be sampled, the water in the sampling tube is purged with gas, and the water is evacuated through the second tube.

If the main sampling tube has a larger diameter than about 13 mm, a conventional water level probe can be used to measure the head. Otherwise, pressure transducers can be installed with the liner to monitor head values.

B.4.6 Other Approaches and Fully Grouted Piezometers

The integrated systems described above bring the control tubes and access lines up the interior of the casing. An alternative approach brings the lines up the exterior of the casing, or support piping. Baski, Inc., for example, makes packer systems that can be configured for multiple monitoring zones. These commonly use conventional pipe or drill tubing for the support in the well. Baski uses air-actuated pumping ports that open specific intervals inside the pipe to packer-isolated intervals in the well. The advantage of these ports over those used in the modular systems discussed above (with the exception of the Westbay system), is a higher flow capacity for pumping or treatment, albeit with disadvantages of fewer pumping intervals, and a need to purge the pipe when changing pumping intervals.

For pressure monitoring only, a system can often be designed using off-the-shelf packers with pressure or electrical feed throughs. These require more design effort, but can be efficient and cost-effective.

The simplest pressure monitoring approach is the fully-grouted piezometer (Figure B-24 right). A fully-grouted piezometer is simply a set of pressure gauges that are cemented into a borehole at different depths of interest (McKenna, 1969; Mikkelsen, 2002; Contreras et al., 2008). This can be a surprisingly effective, low-cost approach if pressure is the only interest for monitoring and the transient pressure changes are not too rapid. The fact that grouted piezometers work at all is somewhat counter-intuitive; however, two factors work in their favour (Economides, 1990; Vaughan, 1969). Even though cements have low hydraulic conductivity, the pore volume of cement that must equilibrate with nearby rock fractures is not large, especially if the sensors are placed at the depths of flowing fractures. The cement can be significantly more permeable than the rock and yet still provide enough isolation to give good head values. This paradox is readily explained by equating a simple expression for the flow, Q_f, from the fracture to the borehole, given by the Theim equation or $Q_f = 2\pi T \Delta h_f / \ln(R/r_w)$, with the flow along the well through the cement seal, Q_w, given by Darcy's Law, or $Q_w = KA\Delta h_w / l$, where T is fracture transmissivity, R/r_w is the ratio of radius of influence to well radius, Δh_f is the head difference between the fracture and the well, Δh_w is the head difference between two fractures along a well, A is the cross-sectional area of the cement, and l is the distance between the monitoring points.

The cement can be more conductive than the rock, even by multiple orders of magnitude, and still give good readings, because the efficiency of flow along the borehole is much less efficient than the flow into the borehole, which has a cylindrical geometry.

Any pressure sensor can be grouted into a borehole in this manner. The approach was particularly promoted by Slope Indicator using their pneumatic diaphragm gauges. Pneumatic diaphragm gauges are non-electronic. Each gauge has two small diameter tubes that run from the surface to the gauge. The tubes port to a surface that is covered by a rubber diaphragm. Water pressure on the outside pushes the diaphragm against the surface cutting off the connection between the tubes. To take reading, a technician applies air pressure to one of the tubes. When the air pressure exceeds the water pressure, the diaphragm lifts from the surface establishing a connection to the second tube, which begins to flow air.

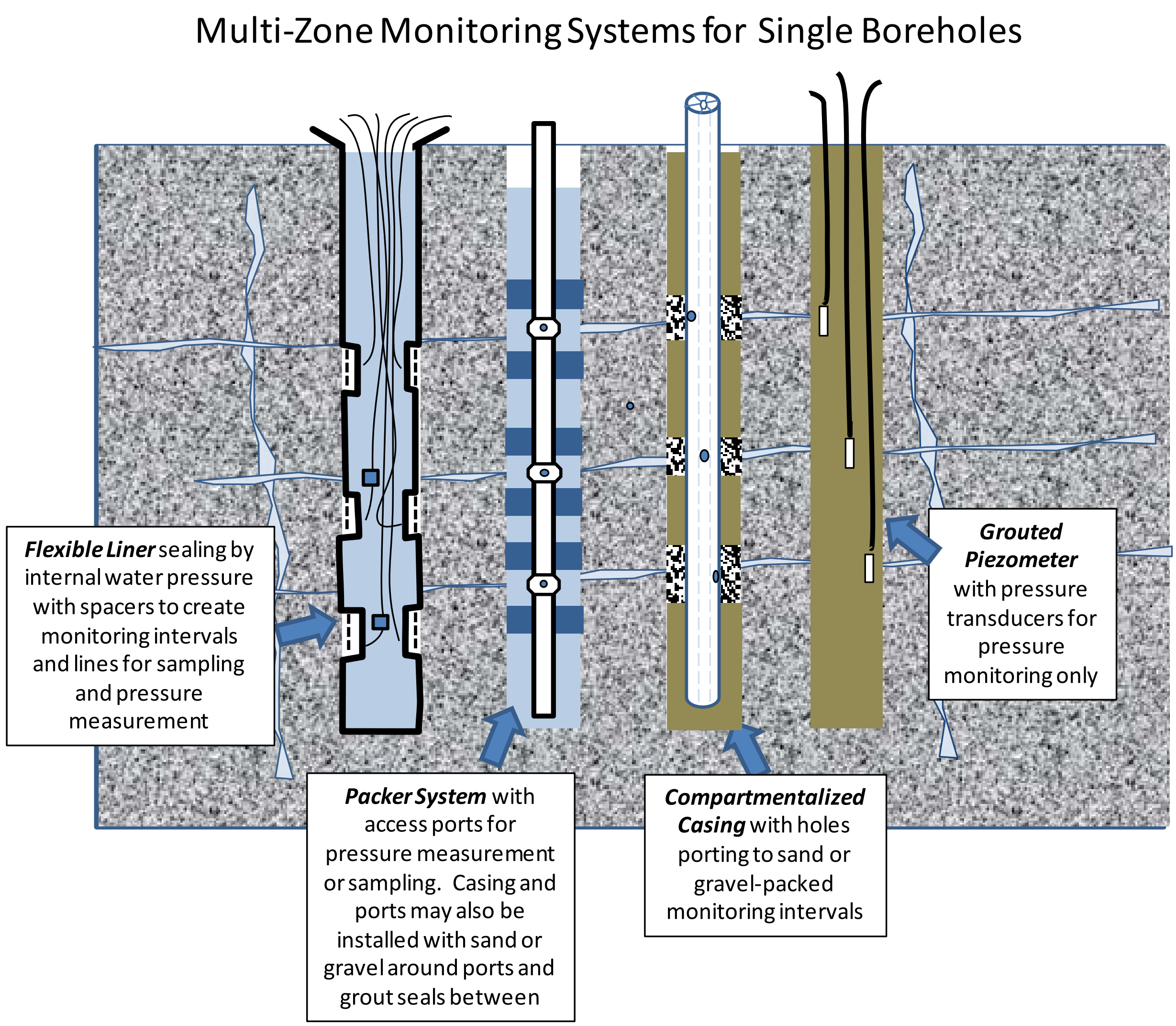
B.4.6.1 Monitoring Systems Summary

The importance of employing multipoint monitoring systems cannot be over-emphasized for both proper management of boreholes to limit their effect on spreading contamination and as a tool for site characterisation and monitoring. Perhaps the greatest sin in site characterisation is leaving wells open to multiple conducting fractures to allow the spread on contaminants to previously unaffected rock.

Monitoring system designs must be conditioned to the key conducting fractures using detailed hydraulic characterization methods such as flow logging or packer testing. The use of other geophysical or geological indicators of conductive fractures is not sufficiently reliable.

Once installed, the pressure should be monitored preferably continuously using automated data acquisition systems to monitor both human and natural perturbations of the site. These responses are extremely valuable tools to delineate the fracture network.

Figure B-24. Single-well, multi-zone monitoring systems.



C- APPENDIX C: MODELING

C.1 Overview

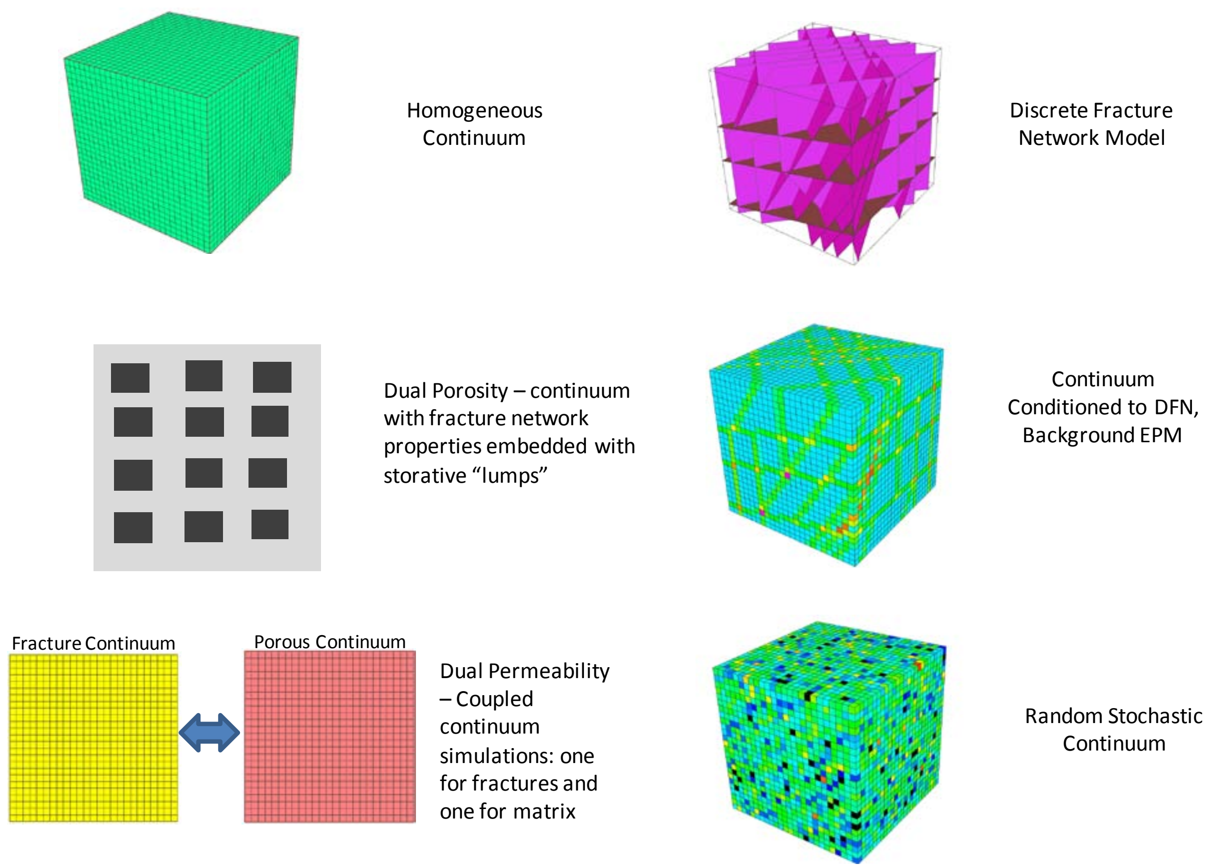
Modeling approaches employ continuum methods, discrete feature methods, or some combination of the two. Continuum means that all points in the simulation region are interconnected. The major portion of groundwater methods developed for porous, layered media, use this approach, hence it is not surprising that many modellers have looked for ways to adapt well-developed codes to fractured media. The discrete feature approach (DFN) represents fracture as two-dimensional features with realistic geometries and properties. These may reduce the simulation to only those elements, or hybrid approaches "pixelate" discrete features into a continuum code.

Among the diverse methods of simulating flow and transport in fractured rock that employ these methods are (Figure C-1):

- *Homogeneous model* – a single continuum that reduce a fractured rock system to a homogenous porous medium.
- *Heterogeneous continuum model* - where properties are applied stochastically or in a structured way that creates fracture-like aggregations (e.g., Neuman, 2005, stochastic continuum).
- *Dual-porosity* - codes usually are represented as "sugar-cubes" after Warren and Root's 1963) paper on the topic; however, the mathematics actually represents a porous continuum in which storative "lumps" are embedded. Besides the "lump" properties, their major variable is their size and shape, hence spherical model represents these lumps as spheres for the purposes of their surface to volume relationships. Dual porosity is the Nelson Type 2 reservoir.
- Dual-permeability codes where a continuum grid representing the fractures is coupled to a continuum grid representing the matrix (or background fractures).
- Discrete fracture network (DFN) models that simulate flow directly on the fracture network (which may also include links to storative volumes for dual porosity effects).

The first route adapts conventional porous media simulators, like MODFLOW, to fractures by creating "equivalent" properties of the fracture network, where equivalent means a set of grid-scale properties that reproduces that same fluxes, velocities, and porosities as a fracture network occupying the same grid-cell volume. Major fracture zones are inserted by creating zones of cells. The flow solvers may use finite-difference or finite-element approaches.

Figure C-1. Modeling approaches.



The second route is where DFN models are used to generate two-dimensional networks of line elements, or three-dimensional networks of plates or non-planar surfaces that represent the fractures. Depending on the mesher and flow solver, these can accommodate considerable complexity of network geometries. Proponents cite these as geologically realistic, while detractors tend to emphasize the difficulty of obtaining the data necessary to build such a detailed model.

Representative codes for these approaches are presented in the following sections.

C.2 Porous Continuum Codes

C.2.1 MODFLOW

MODFLOW is a widely used code for groundwater flow modeling in porous media. It is a three-dimensional block-centered finite difference groundwater flow simulator developed by the U.S. Geological Survey (USGS) since the early 1980's. In the 1990's, the linking of this model to the graphical user interface has facilitated the application of this code.

MODFLOW calculates the transfer of groundwater between porous continuum cells. Each cell has a specific hydraulic conductivity and storativity value. The transmissivity of the cells can be obtained by multiplying the hydraulic conductivity by the saturated thickness. Dry cells, where hydraulic head's elevation is lower than that of the cells, are considered inactive by MODFLOW.

The presence of fractures can be reproduced, in part, by creating an anisotropic porous continuum. For example, an aquifer with a well developed horizontal fracture system could be represented in MODFLOW by a porous continuum having a strong vertical anisotropy. However, only orthogonal anisotropy is considered by MODFLOW. Another way of representing fractures in MODFLOW is to create a zone of high hydraulic conductivity. Mun and Uchrin (2004) do this by assigning higher conductivity cells using a percolation approach that creates preferred connectivities. The thickness of such a zone is usually small and requires a significant refinement of the grid around these features. This could lead to a spatial discretisation error because in MODFLOW, each grid refinement operation made on a layer, column or row is extended to the entire model domain. The process of creating equivalent porous media from fracture networks is called *upscaling* and is discussed fracture under fracture network models.

MODFLOW does not simulate solute transport, which is modeled with an external finite difference code like MT3D99 and RT3D that reads the advective component from the MODFLOW flow field. Seepage velocity is calculated by dividing the Darcy flux obtained by MODFLOW by the effective porosity of bedrock. This parameter thus represents the porosity of rock available that contributes to the fluid flow. MT3D99 and RT3D can simulate multi-species reactive transport of organic compounds. For example, these codes can be used for the modeling of natural attenuation of petroleum hydrocarbon or chlorinated solvents or for the optimization of bioremediation systems. In summary, MODFLOW is essentially a model applicable to porous media aquifer with a simple geometry. The finite difference discretisation on orthogonal grids restricts the application of this model to more complex aquifers. Furthermore, the finite difference solver becomes unstable when there are large contrasts in properties between adjacent elements, which are common in fracture networks. Documentation on MODFLOW can be obtained online at this address: http://water.usgs.gov/nrp/gwsoftware/modflow2000/modflow2000.html Documentations about RT3D are available at this website: http://bioprocess.pnl.gov/rt3d.htm.

C.2.2 FEFLOW

FEFLOW is a three-dimensional finite element variably-saturated flow, contaminant transport and heat transfer simulator developed by Wasy GmBH since the 1970's. It is a completely integrated system from simulation engine to graphical user interface. This model has gained considerable popularity in the past 10 years and it is now as extensively used as MODFLOW. The main attraction of a finite-element over a finite-difference code is the freedom from the limitations of orthogonal grids, which can reproduce well planar-bedded sediments, but have difficulty representing even relatively simple fracture network geometries.

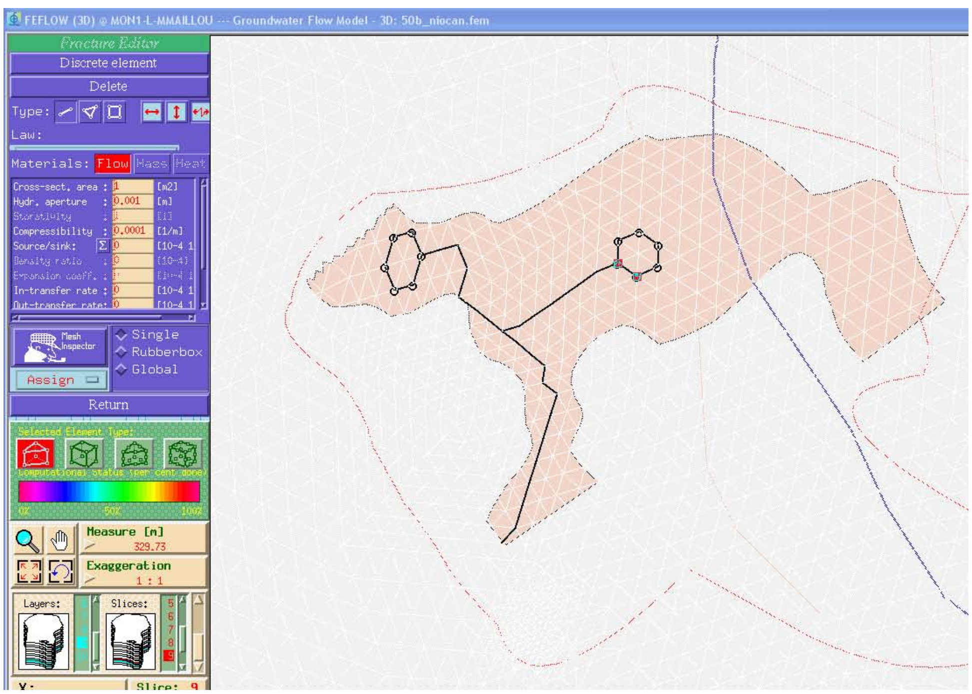
FEFLOW provides 1D and 2D discrete feature elements which can be integrated to (or added to) the porous matrix elements. Different laws of fluid motion can be defined within such discrete features, e.g., Darcy, Hagen-Poiseuille or Manning-Strickler laws. Both the geometric and physical characteristics of the discrete feature elements provide a large flexibility in modeling underground features such as fractures, faults, mine stopes or tunnels (Figure C-2). FEFLOW does not provide random fracture generators; they are assigned manually along element edges. The application of discrete feature elements is restrictive when representing a complex fracture system.

FEFLOW can simulate multi-species reactive solute transport. However, a user-defined chemical reaction module has to be programmed in order to execute the modeling. Dual porosity can be modeled in FEFLOW, using a multi-species approach. In this case, a first species denotes the solute in the mobile pore space and a second species acts as the solute in the immobile pore space. The exchange rate between both species is controlled by a reaction term (similar to that of a chemical reaction).

In summary, FEFLOW is a useful tool for groundwater modeling in a complex geometry porous media aquifer because of its GIS-linked graphical user-interface and finite element discretisation. Fracture flow can be simulated with FEFLOW but the lack of random fractures generators narrows its usage for a simple fracture feature.

Documentation on FEFLOW can be obtained online at http://www.feflow.info/28.html.

Figure C-2. Example of 1-D discrete feature assigned along elements edge used in FEFLOW to simulate the dewatering of an underground mine. The black line represents 1-D horizontal discrete feature (drift) and the black circle represents 1-D vertical discrete feature (stopes).



C.3 Fracture Network Models

C.3.1 Finite Element DFN Models

This section discusses DFN models that mainly address only the fracture network and not the matrix. They tend to honour the fracture network geometry to a high level of detail. The DFN modeling approaches achieve a level of efficiency and practicality in three dimensions by addressing only the fracture network and not discretizing the matrix between the fractures. Thus a DFN model of this type is an assemblage of two-dimensional models, one for each fracture, that link in three-dimensional space, just as real fractures do. Dual porosity behaviours and matrix diffusion are covered by simulating the interactions of each element in the model with a volume of storage that is associated with each element. This approach can reproduce the retardation effects of matrix interactions, without having to fully discretize a complex, three-dimensional volume between fractures.

Transport in DFN models is usually handled using particle-tracking codes that release numerical particles at contaminant source locations and track their progress through the network to the ultimate sinks. In the absence of matrix diffusion or chemical retardation effects, these particles move with the advective velocity of the fracture flow. If there is retardation, the code calculates the diminished velocity that these effects would cause.

Discrete fracture network models rose out of several dissertations in the early 1980's (Long, 1982; Dershowitz, 1984; Dershowitz et al., 1998; Robinson, 1984; Cacas et al., 1990; Andersson and Dverstorp, 1987) among others.

The DFN model was initially conceived as a stochastic, Monte Carlo approach. During the prior two decades, there was a major advance in the stochastic description of fracture geometries that laid a foundation for describing the probability density functions of size, intensity, and orientation. It was a logical step to move from stochastic descriptions of geometry to create Monte Carlo generators of fractures as either one-dimensional line objects in a two-dimensional space, or planar objects in 3-dimensional space. In principle, a large number of realizations (that is, random generations sampling from the probability density functions) would capture the uncertainty in a fracture network. The nuclear regulatory authorities' taste for probabilistic simulation fit well with this modeling approach, as radioactive waste disposal became a major consumer and driver of fracture-flow simulation from the early 1980s through the present.

The key step toward a DFN flow simulator involved discretizing the generated fractures into line or plane elements and applying a flow solver to simulate fluid movements. The Stripa Project, which was discussed in the introduction, provided a forum for testing DFN codes with site data in the late 1980's until the end of the project in 1992. The countries with crystalline rock repository programs, Sweden, Finland, Japan, and Switzerland, continue to be major developers of this approach.

Some of the commercial DFN codes in use today are FRACAS, which is a French code developed at the Institut Francais du Petrol (IFP), which grew from Marie Cacas' Ecole des Mines dissertation, NAPSAC, from the UK which came out of Robinson's Oxford University dissertation, and FracMan, which came from Dershowitz's (1984) MIT doctoral work. FRACAS is mainly a petroleum code (Cacas et al., 1990), and uses pipe flow networks for its flow simulation. NAPSAC and FracMan fully discretize fractures into finite elements for flow solution.

The main steps in a DFN analysis as applied in FracMan are the following:

- Analysis of fracture geometric data to define probability density functions (pdf's) of intensity, size, orientation, and hydraulic properties;
- Identification of major fractures and fracture zones that are defined in the model deterministically;
- Generation of a stochastic fracture network in three-dimensions by Monte Carlo sampling of the geometric pdf's;
- Discretisation of the network into finite elements for solution of flow and transport; and
- Solving the flow equations and producing visualization of results.

The second step was not part of the original models, but became so during the Stripa Project. The Stripa Project used an experiment called the "Site Characterization and Validation" experiment, which consisted of a series of characterization steps and simulations with the goal of predicting the results of the flow and transport experiments. These experiments focussed on a block of rock, roughly cubic in form with side dimensions of about 100 meters. Within the block were several major fracture zones that clearly controlled the flow in the block and had to be inserted into the model in their correct positions. A purely stochastic model would reproduce features like the major structures, but having them land in their correct locations would require a very high degree of luck.

Except for scales of a few tens of meters, a DFN simulation cannot include all the fractures in a normally-fractured rock mass. The response of modeling larger scales has been to either (1) truncate the fracture population in the model at some low-size cut-off, or (2) upscale the simulation to a continuum simulation.

Upscaling means superposing a MODFLOW-like grid on a fracture network, and determining the equivalent flow and velocity for each grid cell. These flows support the calculations of grid cell directional conductivities and porosities.

The most straightforward means of dong this calculation involves (1) isolating the fractures within a grid cell, (2) applying constant heads to create gradients across opposite faces, and (3) calculating the flux in each of the three orthogonal directions. Rotation of the cell can produce the full three-dimensional tensor. This calculation is, however, sensitive to the boundary condition applied to the remaining four block sides. Using no-flow boundaries on these flow-parallel surfaces disconnects pathways that may pass out of the grid-cell volume and return in the full network. Other boundaries, like linear head with distance create artificial connections that similarly may not exist. Jackson (2000) has proposed using a larger block than the grid cell for applying boundary conditions and then measuring the flux across grid cell face.

Rather than do a flow simulation on each grid block, a faster approach to upscaling analyses the effective permeability tensor directly from the fracture network geometry and hydraulic properties using the Oda tensor (Oda, 1984).

DFN models have achieved a high level of acceptance in the radioactive waste programs, especially in the crystalline rock disposal nations. The models are also being applied extensively in the oil industry, though they have been slow to catch on in contaminant hydrogeology.

C.3.2 HYDROGEOSPHERE

HYDROGEOSPHERE is a finite-element numerical model that solves the three-dimensional variably-saturated groundwater and contaminant transport equations in non-fractured or discretely-fractured media (Theirren and Sudicky, 1996, 2006; Slough et al., 1999; Graf and Theirren, 2007). The code was developed initially out of the University of Waterloo as a two-dimensional code, Frad2D, and later three-dimensional code, Frac 3DVS. This model was initially released in 1995. HYDROGEOSPHERE is the fully-coupled subsurface/surface water version of FRAC3VS with improvements to the graphical-user interface. The user has to prepare a list of commands to be read by a pre-processor. The pre-processor can read Groundwater Modeling System (GMS) or Gridbuilder files for grid generation, boundary conditions and geological material distribution. The linking of HYDROGREOSPHERE to the graphical-user interfaces enables this model to be applied to complex geometry aquifer.

Fractures are represented as idealized two-dimensional parallel plates assigned to a set of selected element faces. The user has to generate a porous media mesh (the matrix) and assign a fracture afterward. A fractures network with random locations, lengths and apertures can be generated with HYDROGREOSPHERE in an orthogonal domain (i.e., composed of 8-node block elements). This means that inclined fractures cannot be generated with this function.

HYDROGREOSPHERE can simulate multi-species reactive solute transport and dual porosity transport. The fact that fractures are integrated into a porous continuum matrix makes it a great tool for assessing fluid and mass exchanges between fractures and matrix.

HYDROGEOSPHERE is a robust model and a good option for simulating variably-saturated flow where numerical convergence problem is expected (complex aquifer geometry, sharp hydraulic conductivity contrast, unsaturated flow, etc). Unlike FEFLOW, HYDROGEOSPHERE can create a random fracture network, although it must be orthogonal as it uses a finite-difference simulator.

Compared with continuum codes like MODFLOW, HYDROGEOSPHERE is explicitly developed for fracture networks and it handles the matrix-fracture interactions. Compared with DFN codes, the orthogonal network limits the possible fracture geometries; however, it does have explicit matrix blocks. What it may lose to fracture geometric faithfulness, it compensates with realistic fracture-matrix interaction.

C.4 Guidance for Model Usage

The topic of modeling fluid flow in fractured rock is not settled in the literature. Fracture network (DFN) models endeavour to reproduce the geometry and properties of the natural system. These methods have advanced beyond being research tools. They are established as the basis for radioactive waste siting studies in Sweden and Finland, and they are seeing widespread application in the oil and gas industry. They are less applied in contaminant hydrogeology; however, the Hydrogeophere model is capable of addressing key issues in multiphase, variable density, and multi-porosity flow, though it is not the code that addresses the most complex fracture networks.

Fracture network models have strong critics, especially Neuman (2005) who argues instead for geostatistically-conditioned stochastic-continuum approaches. The most common critiques of fracture network models focus on a perceived impracticality of obtaining sufficient data to build the models. This concern has been addressed partly by the development of flow logging methods that provide much of the needed detail. There is also misconception that fracture network models are purely stochastic models and only build fracture networks by Monte Carlo methods.

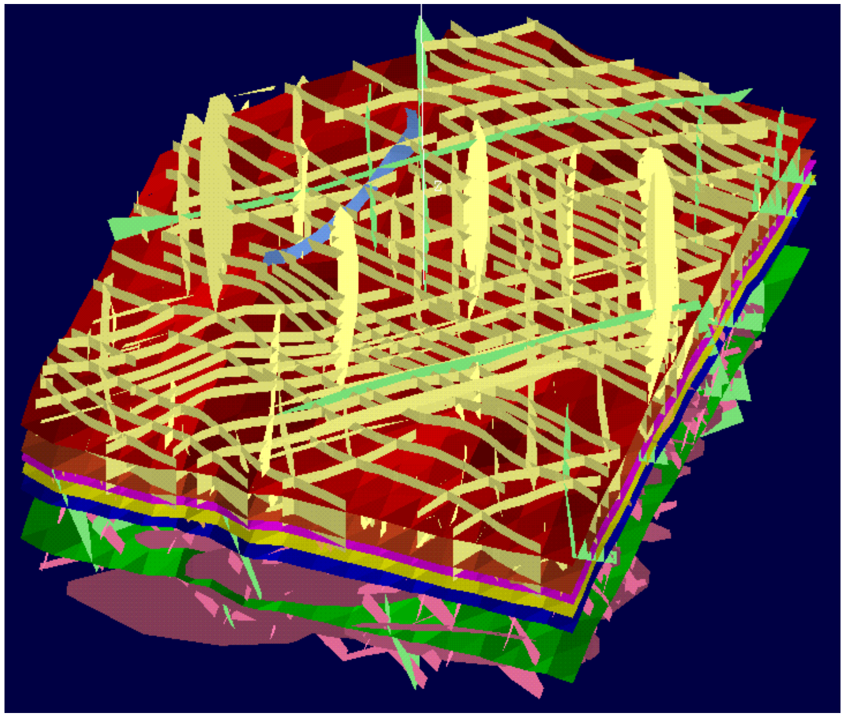
Where there is a consensus, including Neuman (2005), is the need for models to include the important or controlling fractures. Just as a hydrogeologist would be ridiculed for building a MODFLOW simulation by lumping all the aquifers and aquitards into a homogeneous model, so a fracture model cannot be considered adequate unless it captures the essential properties and geometries of the key fractures.

The key fractures will be different in different settings. They may be faults, exfoliation joints, bedding or foliation fractures, solution-enhanced karstic features, or fold-hinge concentrated fractures. The list of possible features is extensive. Some can be simulated within the constraints of orthogonal finite-difference grids, while others may require a complex geometry that only a finite-element grid can provide.

This does not mean the smaller fractures can be ignored. They are often key for providing storage, connectivity, and diffusion-space. But they are more amenable to be treated either as stochastic background features in a DFN model, or as continuum cells with equivalent, or upscaled stochastic properties. Either approach is well established in practice.

The choice of model must be conditioned by its ability to represent the geometry of the controlling features and the physics of the important processes. If matrix diffusion is important, the model must be able to simulate it. If the issue is density-driven multiphase flow, the model must simulate that as well.

Figure C-3. Example of discrete fracture network model: Top: Layered North Sea reservoir with major faults, Bottom, well test simulation with simulated derivative curve (Golder Associates).



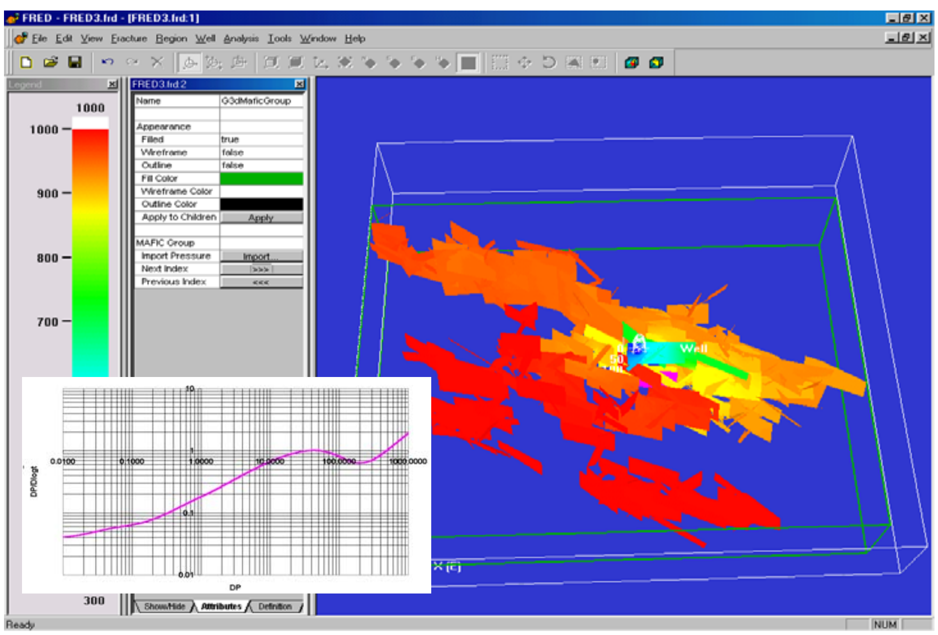


Figure C-4. Upscaling fracture network models.

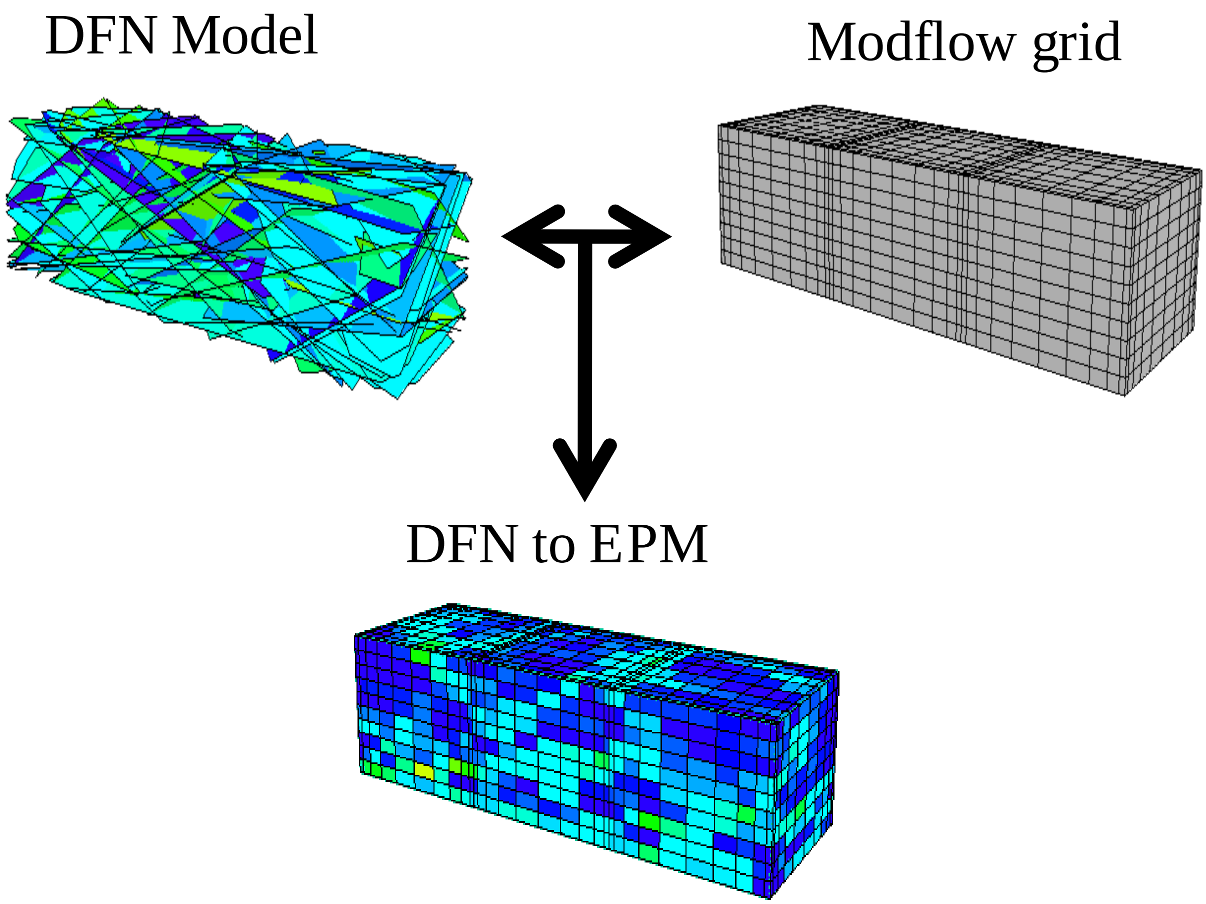
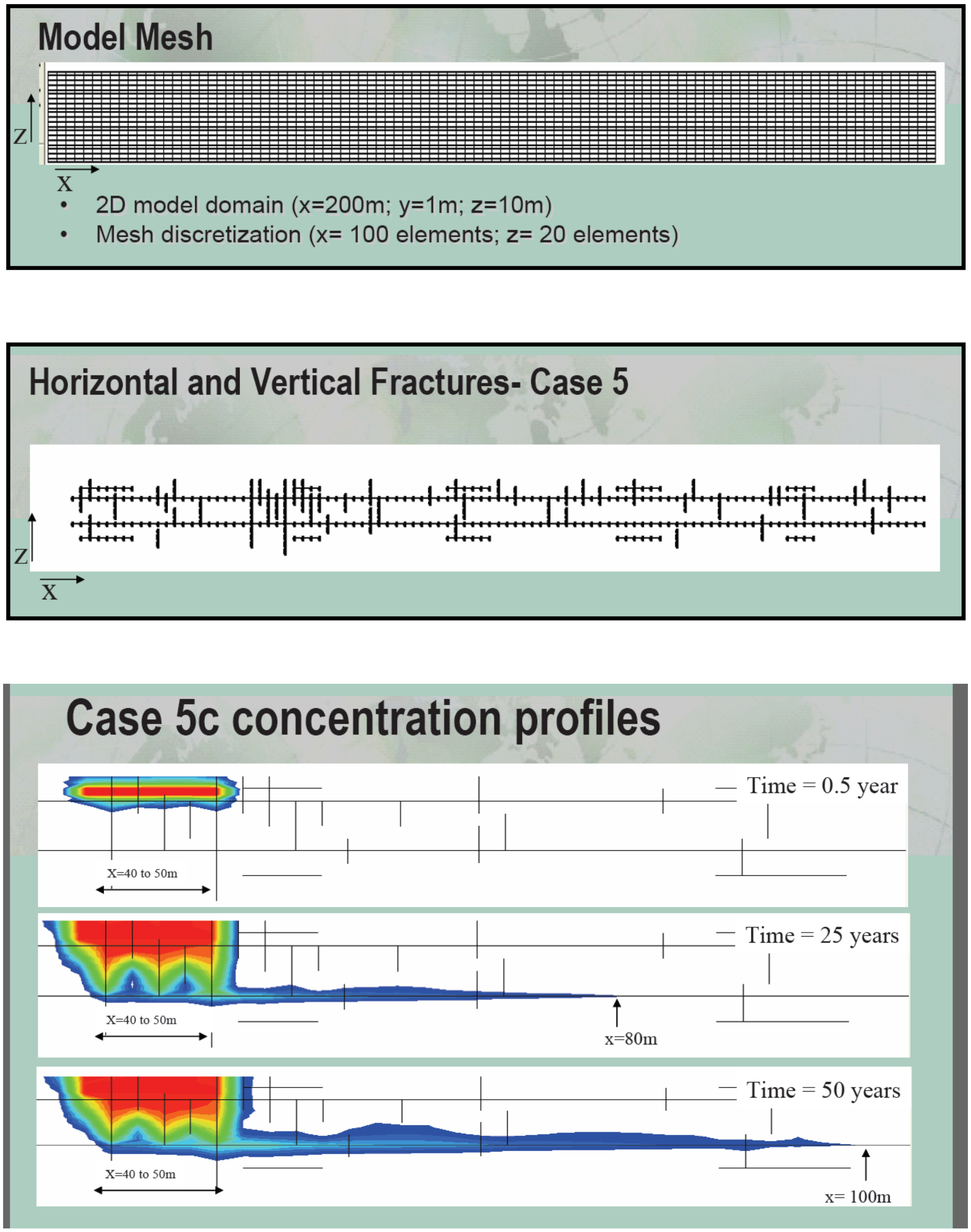


Figure C-5: Example of a finite-element mesh, discrete fractures, and contaminant transport simulation using HYDROGEOSPHERE.

The fractures (middle picture) are assigned to faces of a pre-defined porous continuum mesh (top pictures).



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