Assessing Fracture Network Connectivity of Prefeasibility-Level High-Temperature Geothermal Projects Using Discrete Fracture Network Modelling at the Meager Creek Site, Southwestern British Columbia (NTS 092J)

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Introduction

Geothermal energy represents a clean, renewable, baseload source of energy that is underutilized in Canada. The current status of geothermal energy usage in Canada is limited to heating/cooling systems for residential and commercial infrastructure through the use of low-temperature heat exchangers. Despite having a wide distribution of potential high-temperature geothermal sites, there is currently no commercial electricity production derived from geothermal energy in Canada. The amount of energy stored within Canada's in-place geothermal resources is estimated to be greater than one million times current electrical consumption, although only a fraction of this energy can be accessed. The location of high-temperature geothermal sites that have the greatest potential of being developed are concentrated in the western provinces of British Columbia and Alberta, the Yukon and the Northwest Territories (Grasby et al., 2011).

The Meager Creek geothermal site, located approximately 150 km north of Vancouver, BC, has been characterized as the most promising high-temperature geothermal site in Canada (Jessop et al., 1991), with an estimated net electrical capacity of 250 MW (Ghomshei et al., 2004). Exploration of the site began in the early 1970s and production testing began in the early 1980s. Despite several attempts to develop the resource, the most recent occurring around 2005, sustainable yields of geothermal fluids have never been maintained at the site. The principle reason behind the lack of success of these past attempts is that none of the production wells drilled intersected a sufficiently large, connected, permeable fracture network. To date, no extensive fracture network analysis has been completed of the basement rocks underlying the Meager Creek site and the natural connectivity of the existing fracture network remains unknown.

The viability of high-temperature geothermal projects is largely controlled by the connectivity of the fracture network within the reservoir rocks. The reason for this is that the amount of heat that can be extracted from a geothermal resource is dependent on the rate at which high-temperature fluids can be produced from geothermal wells. The geothermal resource at the Meager Creek site is hosted in low-permeability crystalline rocks and the circulation of geothermal fluids is largely confined to networks of interconnected fractures. It follows that if the connectivity of the existing fracture network can be characterized, the likelihood that the site can be successfully developed can be better assessed.

Fracture network connectivity cannot be measured directly, but must be inferred through the development and analysis of representative fracture models. Discrete fracture network (DFN) modelling is a stochastic method that is capable of simulating the geometric properties of individual fractures and the spatial relationships between fractures that develop within a rock mass. Unlike equivalent continuum methods, which treat the rock mass as a porous medium, DFN models explicitly represent the geometric characteristics of connected fracture networks through the stochastic simulation of discrete fractures across a model volume (Jing and Hudson 2002).

Research Objective

The goal of this research is to use historical geomechanical and hydrogeological data collected from the Mount Meager area to assess the natural fracture connectivity of the reservoir rocks that host the geothermal resource at the Meager Creek site using DFN modelling. This assessment will contribute to a greater understanding of why past attempts to develop the site were unsuccessful and help determine whether specific measures can be taken to increase the like-

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lihood of successfully developing high-temperature geothermal resources in the future.

Sources of Fracture Data

The development of DFN models begins with the collection of individual fracture properties. The fracture data required for the development of DFN models is typically collected from core logging, geophysical surveys of borehole walls and/or structural mapping of exposed bedrock outcrops. The primary source of fracture data used in this study consists of data collected during drilling and outcrop-mapping campaigns that were part of exploratory field investigations conducted in the area surrounding Mount Meager from 1974 to 1982. The initial field investigations of the site were carried out by the British Columbia Hydro and Power Authority (BC Hydro) and the federal Department of Energy, Mines and Resources. Although field investigations at the Meager Creek site occurred intermittently until approximately 2005, geomechanical and hydrogeological data collected after 1982 were not publicly available at the time of this study. The location of drillholes and mapping stations within the Meager Creek project area are shown in Figure 1.

Fracture Data from Exploratory Diamond Drilling

The collection of fracture data from exploratory boreholes, either through oriented-core or televiewer logs, is essential for estimating fracture network connectivity of geothermal reservoirs. This is because fracture properties measured in surface outcrops may not be representative of the characteristics of the fracture network at depth. Geological data collected during exploratory drilling that was used in this study to develop DFN models of the Meager Creek site included

- lithology and alteration logs,
- rock-quality designation (RQD),
- depths at which fluid circulation was lost during drilling, and
- depths of dikes, shears and fault zones.

Fracture frequency (number of fractures intersected per metre) and fracture orientation (dip and dip direction of individual fractures) are two fracture parameters that are necessary for the development of site-specific DFN models. These two fracture parameters have a strong influence on fracture network simulations and, in turn, fracture-network

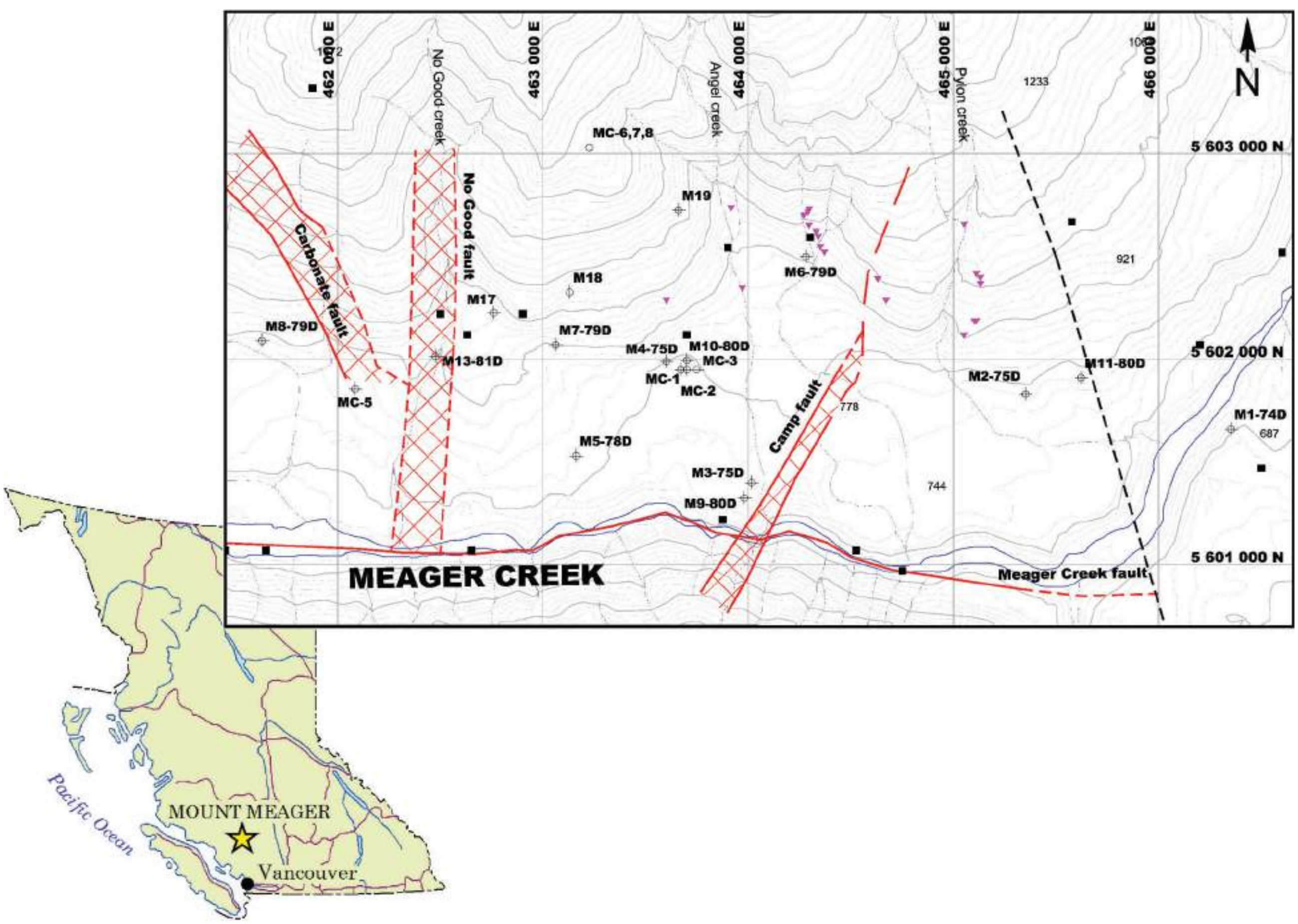


Figure 1. The Meager Creek geothermal project site, southwestern British Columbia, showing drillholes and mapping stations.

connectivity estimates. It follows that the collection of fracture frequency and fracture orientation measurements should be prioritized during exploration drilling.

Fracture Data from Structural Mapping

Fracture data collected from structural mapping of rock outcrops can be used to identify major fracture sets and estimate the distribution of fracture sizes and fracture intensity within the rock mass. Historical structural mapping of exposed outcrops within the Mount Meager area was completed in 1980 and 1981. The structural-mapping database was augmented by geotechnical mapping of rock outcrops located north of the Lillooet River by the author during the summer of 2013. The type of fracture data collected included

- fracture orientation (dip and dip direction),
- fracture type,
- fracture trace length,
- fracture spacing, and
- mapping station co-ordinates.

Interpretation of Fracture Network Characteristics for DFN Model Development

The following fracture network characteristics were interpreted from the geological and hydrogeological data collected from previous field investigations to generate representative DFN models of the Meager Creek site:

- peak orientation and distribution parameters of major fracture sets
- distribution of observed fracture spacing
- distribution of fracture trace lengths
- estimates of fracture intensity

Characterization of Major Fracture Sets

The range of dip and dip direction of major fracture sets that occur within the Meager Creek site was determined by plotting poles of individual fractures on contoured, lower hemisphere, equal-area stereonets for individual mapping stations and comparing peak orientations of observed fracture sets over the Meager Creek site. Peak orientations that were observed over several mapping stations were interpreted as major fracture set orientations. Seven fracture sets were identified and were labelled fracture sets A to G. Figure 2 is a plot of all fractures mapped within the Meager Creek area, along with the range of dip and dip direction for each fracture set. Peak orientations and distribution parameters for each fracture set are summarized in Table 1. The Fisher constant for each fracture set was assessed using a Fisher-distribution analysis, which assumes that all observed fracture orientations within a fracture set are scattered around a single true orientation.

Fracture Spacing Distribution

Fracture spacing is the measured distance between adjacent fractures intersected along a scanline. By fitting a statistical distribution to a population of fracture spacing measurements, inferences can be made regarding the spatial relationship between neighbouring fractures. Fracture spacing was not recorded during the 1980 and 1981 structural-mapping campaigns; however, it was recorded during structural mapping completed during the summer of 2013. It was found that the distribution of fracture spacing measurements could be fit using a negative exponential distribution. The fitted spacing distribution was then used to define the spatial relationship between neighbouring fractures in the DFN model simulations.

Fracture Size Distribution

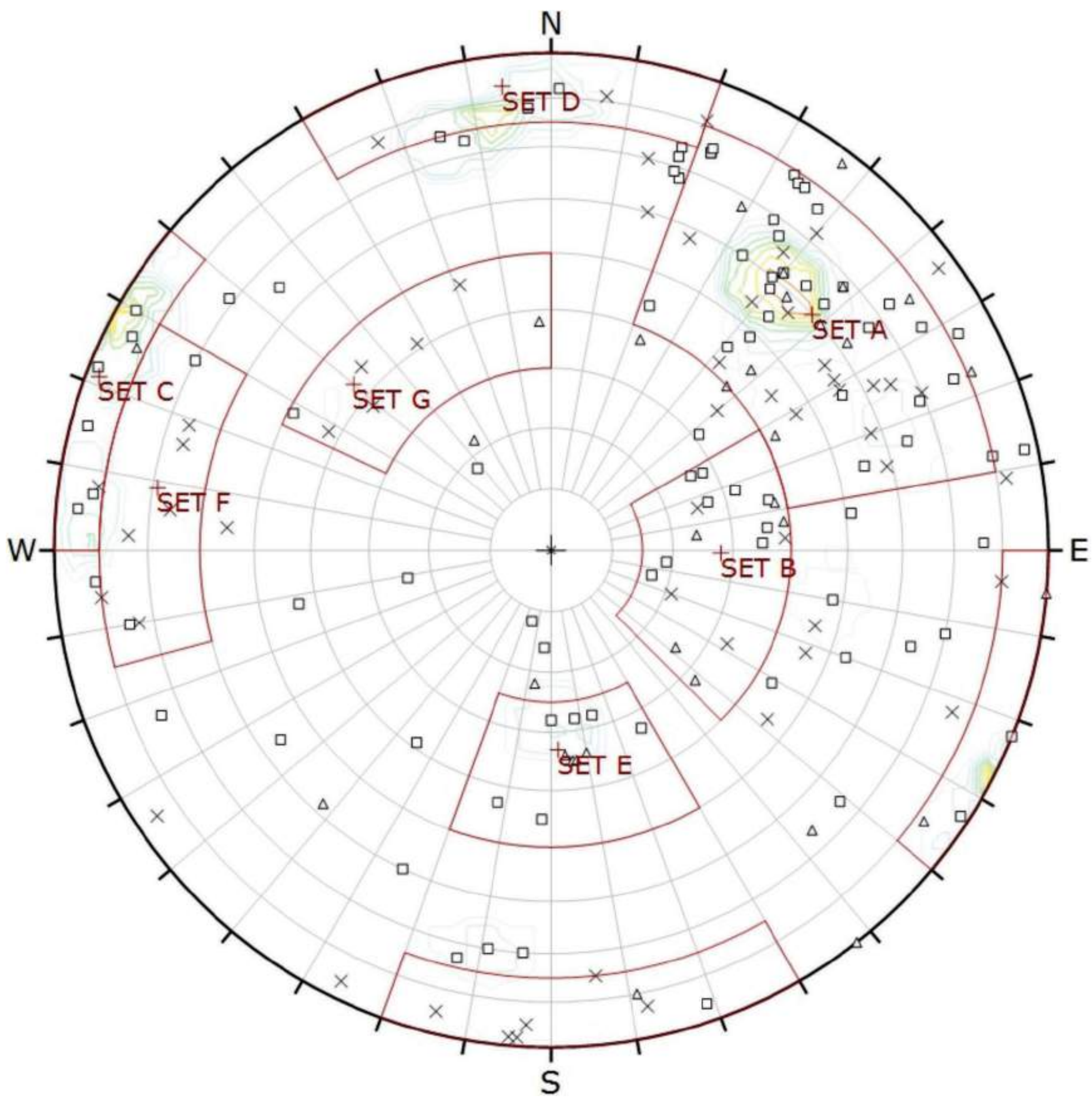
The true size of a fracture is rarely known with a high degree of certainty because direct observation and measurement of entire fracture planes is often impossible or impractical. Fracture size is typically inferred from the length of the line of intersection between the fracture and a two-dimensional plane, referred to as the fracture trace length. The distribution of fracture sizes was determined by estimating an equivalent radius distribution from trace length measurements that were collected during the summer of 2013. The DFN models were populated with fractures using the derived equivalent radius distribution so that the fracture size distributions in the models are statistically equivalent to the distribution of trace lengths observed in the field.

Estimation of Fracture Intensity

Fracture intensity is a measure of fracture density within a rock mass. Typically, fracture intensity is inferred from fracture frequency measurements that are measured from core sample downhole surveys of open boreholes. Fracture frequency was not recorded during the exploratory drilling program. Attempts to derive fracture frequency values from logged RQD were unsuccessful. Consequently, a range of fracture intensity values was used as input in the DFN simulations. This led to a wide range of fracture-network connectivity estimates of the Meager Creek site. In future, fracture-network connectivity estimates can be significantly constrained if fracture frequency data is made available.

Results from Fracture-Network Connectivity Assessments

The DFN models were constructed based on two different geological models to analyze the effects of large-scale faults on fracture-network connectivity estimates. The first geological model assumes that regional-scale faults have no effect on fracture network connectivity. The second geo-



Symbol	Area	Quantity
△	East of Camp fault	32
×	North reservoir	81
□	South reservoir	307

Colour	Density concentrations
	0.00 - 1.20
	1.20 - 2.40
	2.40 - 3.60
	3.60 - 4.80
	4.80 - 6.00
	6.00 - 7.20
	7.20 - 8.40
	8.40 - 9.60
	9.60 - 10.80
	10.80 - 12.00
Maximum density	11.54%
Contour data	Pole vectors
Contour distribution	Schmidt
Counting circle size	1.0%

Plot mode	Pole vectors
Vector count	420 (176 entries)
Hemisphere	Lower
Projection	Equal area

Figure 2. Combined, lower hemisphere, equal-area stereonet plot of all fracture data collected from all structural-mapping stations within the Meager Creek area, southwestern British Columbia.

Table 1. Summary of peak orientations and distribution parameters for major fracture sets based on surface-mapping data collected at the Meager Creek site, southwestern British Columbia. Abbreviation: DDR, dip direction.

Major sets	Average orientation		Dip range		DDR range	
	Dip (°)	DDR (°)	Min (°)	Max (°)	Min (°)	Max (°)
Set A	60	223	40	80	200	260
Set B	30	257	15	40	240	315
Set C	89	118	80	90	090	130
			80	90	270	310
Set D	77	172	75	90	330	020
			75	90	150	200
Set E	31	350	25	50	330	020
Set F	66	109	60	80	075	120
Set G	44	124	30	50	115	180

logical model incorporates an extensive east-striking fault that dips toward the north at approximately 50°, with an associated fault-damage zone 100 m in width. The fault-damage zone is assigned a greater fracture intensity value relative to the rocks that constitute the hangingwall and footwall of the fault. The fault geometry used in the model is reflective of the Meager Creek fault geometry, which was mapped in exposed outcrops along the banks of Meager Creek.

Numerous studies have reported that fluid flow in fractured media is typically limited to a small percentage of the total number of observed fractures (Long et al., 1991; Cohen, 1995). This was accounted for in the DFN simulations by assigning transmissivity values to individual fractures and utilizing transmissivity thresholds to exclude a certain percentage of fractures from contributing to the development of connected fracture networks. Table 2 summarizes the range of total connected surface area that may exist at the Meager Creek site for various fracture intensity values and transmissivity thresholds.

Discussion of Results

Fracture-network connectivity analysis results indicate that although the geothermal resource at the Meager Creek site is hosted in low-permeability reservoir rocks, the presence of the Meager Creek fault may provide sufficient connectivity for the upwelling and circulation of heated geothermal fluids to possibly permit the future development of a commercial geothermal project at the site. The higher fracture intensity value assigned to the fault-damage zone allows clusters of connected fractures to develop along the fault plane, even in a scenario where only a low percentage of transmissive fractures are present in the model. The effect of the Meager Creek fault on fracture network connectivity is shown in Figure 3.

Significant uncertainty is associated with the fracture connectivity assessments of the Meager Creek site due to the absence of certain geological information that was not collected during the initial field investigations. This data included measurements of fracture orientation and the depth of all fractures encountered during drilling. The data collected from structural mapping could not be corrected for sampling biases, which increases the potential margin of error in the delineation of fracture set orientations and trace length distribution. Sampling biases can be easily corrected if a more rigorous mapping methodology is adopted, which would require that the following data be recorded at each mapping station:

- orientation of the mapping station (dip/dip direction of the mapped surface)
- type of sampling method used, more specifically line mapping (where the orientation and length of the sampling line should be recorded) vs. window mapping (where the total area and shape of the window, whether rectangular, square or circular, should be recorded)
- minimum trace length that was measured
- number of fractures that extend beyond the boundaries of the mapping station
- number of observable fracture termination points, if any, for each fracture

Summary

The collection of geological data for the purpose of characterizing fracture networks can be costly, and at times impossible, due to the extreme depths of geothermal reservoirs and the effects of high temperature on borehole-instrumentation performance (Armstead and Tester, 1987). Moreover, these costs are incurred early in the project lifetime, when there is minimal geological data available for fracture network characterization. It follows that geothermal projects at the prefeasibility-level suffer from high developmental risks due to high exploration costs, coupled with high geological uncertainty associated with the nature of fracture-network connectivity assessments. The use of DFN modelling provides a means to manage part of this risk by allowing the connectivity of natural fracture net-

Table 2. Estimated ranges of connected surface area derived from fracture connectivity analyses of simulated DFN models.

	Fracture intensity: total surface area of fractures per cubic metre of rock (m^2/m^3)	Percentage of transmissive fractures (%)	Total connected surface area (m^2)
Uniform rock mass model	0.5	100%	5.41E+08
	0.5	30%	1.22E+08
	0.5	25%	7.39E+07
	0.5	20%	1.91E+06
	0.5	15%	0.00E+00
Meager Creek fault model	0.5	100%	2.791E+08
	0.5	30%	6.200E+07
	0.5	25%	3.405E+07
	0.5	20%	1.385E+07
	0.5	15%	1.359E+06
	0.5	10%	0.000E+00

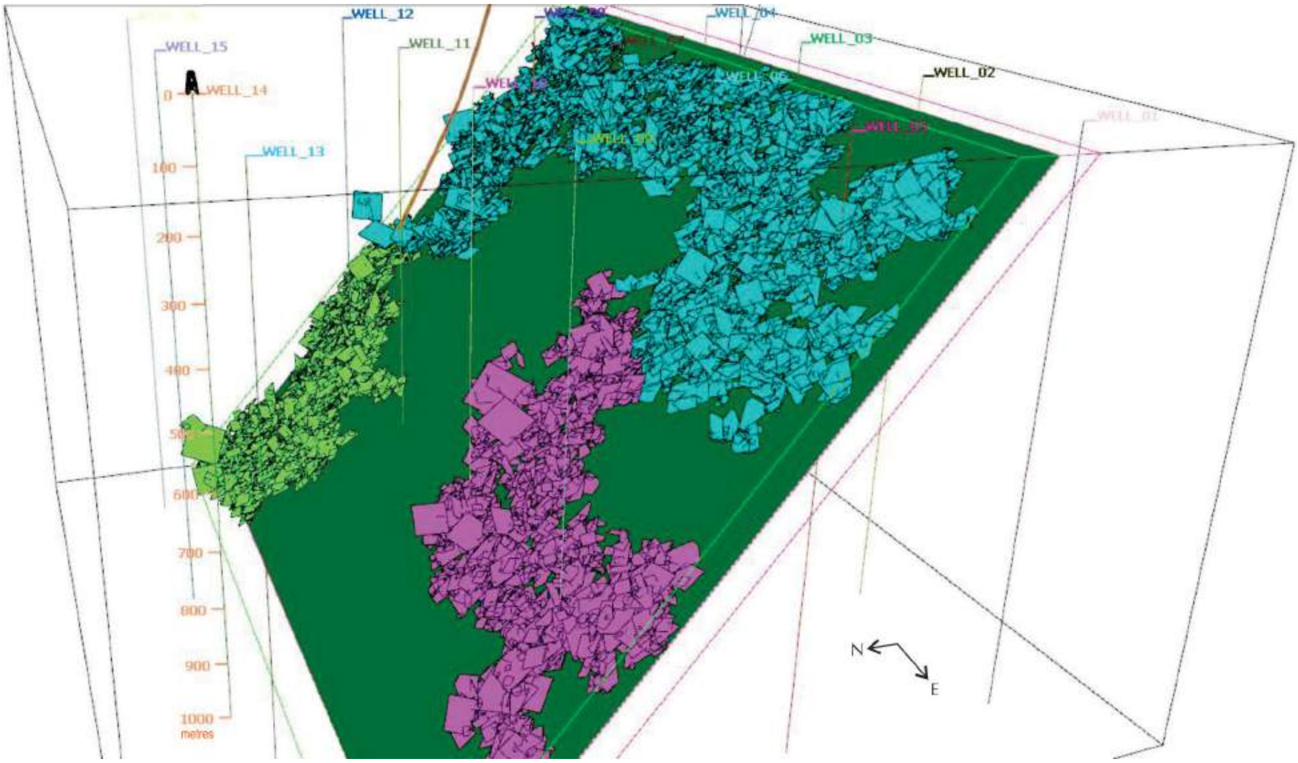


Figure 3. A DFN (discrete fracture network) model simulation, showing the development of three connected fracture networks (in green, blue and magenta) along the damage zone of the Meager Creek fault, southwestern British Columbia. Each polygon represents a single discrete fracture.

works to be assessed using fracture information that can be easily collected during exploration or prefeasibility-level field investigations.

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References

Armstead, H. and Tester, J. (1987): Heat Mining: a New Source of Energy; E. & F.N. Spon Ltd., New York, p. 478.

Cohen, A. (1995): Hydrogeologic characterization of fractured rock formations: a guide for groundwater remediators; Report LBL-38142, p. 144, doi:10.2172/219408

Ghomshei, M., Sanyal, S., Macleod, K., Henneberger, R., Ryder, A., Meech, J. and Fairbank, B. (2004): Status of the South Meager Geothermal Project British Columbia, Canada: resource evaluation and plans for development; Geothermal Resources Council Transactions, v. 28, p. 339–344.

Grasby, S.E., Allen, D.M., Bell, S., Chen, Z., Ferguson, G., Jessop, A., Kelman, M., Ko, M., Majorowicz, J., Moore, M., Raymond, J. and Therrien, R. (2011): Geothermal energy resource potential of Canada; Geological Survey of Canada, Open File 6914, 301 p.

Jessop, A., Ghomshei, M. and Drury, M. (1991): Geothermal energy in Canada; Geothermics, v. 20, issue 5/6, p. 369–385.

Jing, L. and Hudson, J. (2002): Numerical methods in rock mechanics; International Journal of Rock Mechanics and Mining Sciences, v. 39, issue 4, p. 409–427.

Long, J., Karasaki, K., Davey, A., Peterson, J., Landsfeld, M., Kemen, J. and Martel, S. (1991): An inverse approach to the construction of fracture hydrology models conditioned by geophysical data: an example from the validation exercises at the Stripa mine; International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, v. 28, issue 2/3, p. 121–142, doi:10.1016/0148-9062(91)92162-R