Effects of Lithology and Fracture Characteristics on Hydraulic Properties in Crystalline Rock: Mirror Lake Research Site, Grafton County, New Hampshire

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ABSTRACT

A combination of subsurface borehole imaging data and drilling logs were used to characterize the fractures and lithology in 40 bedrock wells at the fractured-rock research site in the Mirror Lake area in Grafton County, New Hampshire. The purpose of the research was to determine whether subsurface lithology and fractures have an effect on the hydraulic conductivity of the crystalline-rock aquifer in the Mirror Lake area. The distribution of fractures and lithology was quantified with respect to depth, altitude, topographic setting, and spatial distribution. The density of fracturing was described and comparisons were made between lithology, fracture characteristics, and hydraulic-conductivity measurements. Fracturing was found to be related to lithology, depth, and topographic setting. No clear correlation was established between hydraulic conductivity and fracture properties including alteration, oxidation, aperture, orientation, and density.

INTRODUCTION

The problem of investigation and remediation of contamination in fractured crystalline rock has been compounded by a lack of understanding of how to conceptualize and simulate fluid flow and chemical transport in these aquifers. In order to remediate these aquifers, however, the extent and location of contamination and the potential pathways for flow and transport must be understood. In fractured-rock systems, this requires determining the dominant features and processes that control flow. In order to better understand these aquifers, the U.S. Geological Survey established a fractured-rock research site in a pristine area in the White Mountains near Mirror Lake in Grafton County, New Hampshire. The site serves as a field-scale laboratory for developing and testing tools and methods used to characterize flow and transport in crystalline rock. An overview of the research project is provided by Shapiro and Hsieh (1991).

This paper describes the results of research to determine whether subsurface lithology and fractures have an effect on hydraulic conductivity at the Mirror Lake site. The objectives of the research were (1) to characterize the subsurface lithology and fractures and the relation between them; and (2) to use this detailed information to analyze the effects of subsurface lithology and fractures on hydraulic conductivity. Results are described in more detail by Johnson and Dunstan (1998) and by Johnson (1998).

DESCRIPTION OF STUDY AREA

The bedrock at Mirror Lake is predominantly high-grade pelitic schist and gneiss that has been intruded by igneous rocks. Approximately 97 percent of the bedrock is covered with discontinuous layers of glacial deposits that vary in thickness from less than 10 m (meter) to as much as 50 m. Bedrock exposures are generally limited to the streambeds, ridges, and to outcrops exposed by highway excavations. Detailed characterization of the lithology and fractures relies on the limited surface exposures, subsurface exploratory drilling, and geophysical techniques. Forty bedrock wells, ranging in depth from 60 to 305 m were drilled to characterize the subsurface. The investigations at Mirror Lake were designed to observe hydrogeology over multiple scales of interest, including measurements in a single well, measurements between closely spaced wells (over tens of meters) in a well field, and measurements between wells separated by hundreds of meters. This investigation focused on a set of 15 “index” wells, which included 13 deep areally-distributed wells and the deepest well in each of two well fields. Shallow and spatially clustered wells (in the two well fields) were not included in this set of index wells to avoid potential sampling bias.

GEOLOGIC SETTING

The predominant lithology of the Mirror Lake area is the Silurian Rangeley Formation (Lyons and others, 1997). The lower part of this formation is a metapelite, and the upper part is a pelitic schist of sillimanite-grade metamorphism (Lyons and others, 1997). The strike of foliation ranges from N25^{o}E to 45^{o}E, and it dips predominantly 60^{o} to 67^{o}NW and 40^{o} to 80^{o}SE (Barton, 1996). Folding, faulting, metamorphism, and igneous intrusions associated with the Acadian orogeny (and possibly the Alleghanian orogeny) have resulted in a complex distribution of lithology and fractures. The “pavement method” was used by Barton (1996; 1997) on a glaciated surface and four highway road cuts near Mirror Lake. Exposures on highway road cuts exhibit a high degree of lithologic and structural variability.

STUDY METHODS

Analog video images were used to describe the subsurface lithology in terms of color, mineralogy, texture, and size and shape of rock features. The fractures observed in borehole images were characterized by location, host rock, relative size, presence of mineralization, alteration, and (or) oxidation, all of which can be compared to hydraulic properties of the fractures. Techniques and equipment for borehole video imaging were described by Johnson (1996) and Johnson and Dunstan (1998). In addition, an oriented digital borehole camera was used at selected wells to determine the orientation of fractures for comparison to surficial-fracture mapping and to hydraulic conductivity estimated from fluid-injection tests conducted over discrete intervals in the wells. Borehole images consist of a magnetically oriented, digitized, 360-degree, color image of the borehole wall. Because the image is oriented, the strike and dip of the planar features can be determined directly from the image. Methods of data collection and interpretation for the digital borehole camera are provided in Johnson (1998).

CHARACTERIZATION OF LITHOLOGY IN WELLS

The lithologies were described in terms of spatial distribution in the Mirror Lake area, with respect to depth, and in terms of persistence or average length within wells. Analysis of data from the 15 index wells indicates the proportions of the lithologies vary, but collectively, the group of index wells consists of approximately equal amounts of granitoids and schist, with pegmatite and basalt comprising less than 5 percent of the rock. The lithologies change frequently (approximately every 5 to 9 m) over the length of the wells. The length of each rock unit exposed in each well was determined for all index wells. The average length of schist was 5.3 m, and the average length of granitoid units was 4.6 m. The average lengths of pegmatite and basalt units encountered in the index wells were each less than 1 m. There was no apparent correlation between rock type and depth, altitude, or topographic setting.

FRACTURE CHARACTERIZATION AND DISTRIBUTION IN WELLS

Fractures were characterized by density or intensity of fracturing, which was compared to rock type, physical parameters (depth, altitude, and topographic setting), and hydraulic-conductivity measurements. The intensity of fracturing was computed as the distance between all fractures that were observed in the index wells – regardless of the fracture orientation, mode of fracturing, or rock type. This estimate of fracture intensity is referred to as the “interfracture spacing.” The arithmetic average of the interfracture spacings was 2.1 m, which corresponds to an average fracture density of 0.47 m^{-1}. The frequency plot of the 1,244 interfracture spacings observed in the index wells was compared to theoretical frequency distributions, including exponential, power, poisson, and logarithmic functions. The best fit was obtained for the power-law function by the method of least squares, with a coefficient of determination of 0.80 (fig. 1). The fitting parameters for the power function, $y = ax^b$, were a = 20.6, b = -0.85, and x varied as the length (m) of interfracture spacing. The lower cut-off value for this function was 0.06 m. This distribution of fractures, at least in the vertical direction, suggests the fracture network comprises highly fractured zones surrounded by zones that are less fractured.

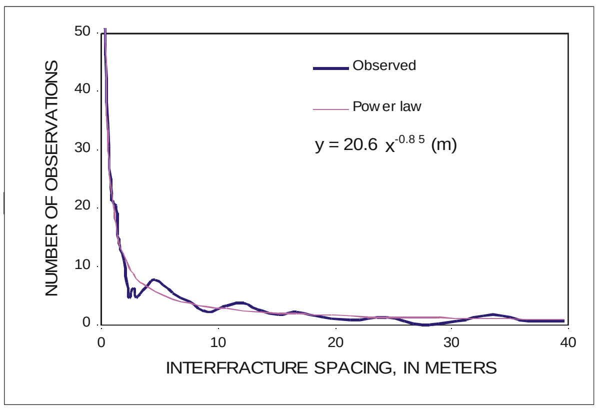


Figure 1. Comparison of observed frequency of interfracture spacing fitted to a power-law distribution.

The distribution of all fractures in the index wells with respect to depth does not follow a linear distribution. Highly fractured intervals typically occur in the top 100 m of the wells. Although less numerous, some highly fractured zones exist at depths greater than 100 m. A scatterplot of fracture density (frequency of fractures divided by the interval length for each 3-m interval) plotted as a function of depth are shown in figure 2a. In general, the plot shows there is a higher density of fractures at shallow depths than at deeper depths. Unfractured zones or minimally fractured zones, which plot on or near the x-axis, were observed at all depths. The linear-correlation coefficient between depth and fracture frequency is, therefore, low (only -0.05). To reduce the scatter in the fracture density data, the mean-fracture density was computed and plotted for each 3-m interval of depth in each well (fig.2b). The mean fracture density versus depth has a linear-correlation coefficient of -0.67. Although fractured zones can occur at depth, the probability of encountering them is lower; however, a linear correlation does not lend itself to extrapolation beyond 300 m. Alternatively, an exponential distribution, with a coefficient of determination of 0.51, could be fit to the mean-fracture density plotted as a function of depth. Although the exponential distribution had a poorer fit to the data than the linear distribution, it may be more reasonable to extrapolate the exponential distribution beyond 300 m, because the expected fracture density approaches zero, but does not equal zero or negative values.

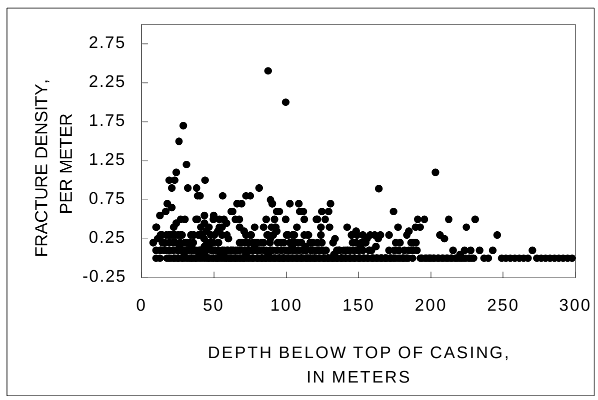


Figure 2a. Fracture density as a function of depth below top of casing in selected wells near Mirror Lake in Grafton County, New Hampshire. Fracture density is shown for each 3-m interval.

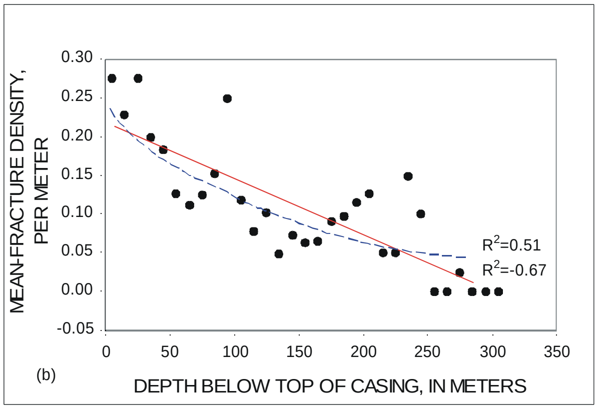


Figure 2b. Mean fracture density plotted as a function of depth and fitted with linear and exponential distributions.

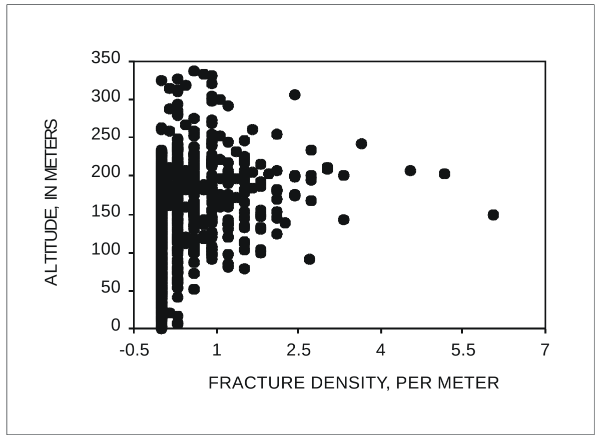


Figure 3. Fracture density plotted as a function of altitude.

Fracture Distribution with Altitude

The fracture density for each 3-m interval in the well was referenced to altitude. A scatterplot (fig. 3) of the fracture density plotted as a function of altitude shows a low intensity of fracturing below 100 m. Because the linear-correlation coefficient for density as a function of altitude was only 0.2, the data cannot be described by a linear distribution. There appear to be more fractures at the high elevations beneath the hill slopes than beneath the valleys. Harte (1997) made a similar observation for bedrock core collected from the top 3 to 5 m of the bedrock surface at six locations.

To test this observation, all fracture-density data from the index wells were separated into 2 categories –data below 100 m and data above 100 m. A rank-sum test, or WMW (Wilcoxon-Mann-Whitney) test, had a p-value of 0.0001, indicating the two groups are statistically different. One possible explanation for this distribution of fractures with respect to altitude is that during the two periods of glaciation, the glaciers followed major valleys that were preferentially fractured prior to glaciation. The high density of fractures in the valleys is assumed to be more easily eroded than the less fractured hillslopes, causing the valleys to be preferentially deepened, thereby removing the upper zones of fractured rock. This corresponds to the general finding that wells sited in valley settings are characterized by a lower average-fracture density than the wells sited on hillslopes and terraces.

Fracture Distribution with Respect to Rock Type

A comparison of rock type with respect to fracturing indicates that fractures are geologically controlled. In general in the study area, the granitoids are more intensely fractured than the schist and gneissic rocks, and pegmatite, basalt, and quartzite are relatively unfractured. In the index wells, the count of fractures with respect to the lithology indicates that approximately 72 percent of the total number of fractures were in granitoids, whereas 23 percent were in schist. Only 5 percent of the total number of fractures were in pegmatite and basalt. The average fracture spacing (m) and fracture density (m^{-1}) is summarized for the various lithologies (table 1).

Table 1. Average fracture spacing and average fracture density per meter for individual rock types

Rock Type	Average fracture	
	Spacing (m)	Density (m^{-1})
Schist	3.86	0.26
Gneiss and migmatite	16.06	.06
Granitoid	1.54	.65
Pegmatite	5.35	.19
Basalt	1.26	.79

Fracture orientation

Fracture orientation was determined from inages produced with a digital camera in seven wells in the Camp Osceola (CO) well field. The fractures strike predominantly N40^{o}E and dip predominantly 10^{o}NW and 68^{o}NW and appear to be parallel to subparallel to the foliation of the metamorphic rock. The fractures from the wells in the CO well field were also compared to the fractures mapped in the nearby highway outcrops that are approximately 150 to 275 m east of the well field. The fracture orientations appear to have the same strike but dip in different directions. The outcrop data (Barton, 1997, fig. 2A) shows a mixture of shallow and steeply dipping fracture sets, which have a preferred strike of N30^{o}E, with dips of 7^{o}NW, 50^{o}SE and 82^{o}SE. Although similar fracture orientations were determined in wells CO1-CO7 in acoustic televiewer measurements (McDonald and others, 1997), no geologic structures have been mapped in this area that would explain the difference in fracture dip between the two sites (William Burton, U.S. Geological Survey, oral commun., 1998). Regardless of the physical basis for differences in the dip direction of fractures, these natural variations of dip found over distances of 150 to 275 m indicate the importance of measuring subsurface fractures and emphasize the need for caution in extrapolating outcrop data to the subsurface.

DISTRIBUTION OF HYDRAULIC CONDUCTIVITY

Hydraulic conductivity was estimated by pumping or injection tests conducted within discrete packed-off intervals that were on average 4.6 m long (Shapiro and Hsieh, 1997). The hydraulic-conductivity data were compared to physical parameters of the fracture system, such as the depth, altitude, topographic setting, rock type, fracture density, and presence of altered or oxidized fractures. The comparisons were made using 176 hydraulic-conductivity measurements from 11 of the areally distributed wells for which hydraulic conductivity data were available (Paul Hsieh, U.S Geological Survey, written commun., 1997). The hydraulic-conductivity measurements ranged over 6 orders of magnitude, from the lower detection limit of the equipment at $1x10^{-10}$m/s to $5.0x10^{-5}$m/s. Hydraulic conductivity could not be correlated with altitude or with depth of the measurement intervals.

COMPARISON OF FRACTURING AND LITHOLOGY TO HYDRAULIC CONDUCTIVITY

Theoretically, the fracture density of the bedrock relates to high connectivity and possibly high hydraulic conductivity. To test this widely held concept, the fracture density and hydraulic conductivity were compared. The scatterplot in figure 4 indicates there is no correlation between the magnitude of hydraulic conductivity and fracture density for the individual measurement zones. Because alteration and oxidation can be indicators of past or present hydraulically active fractures, the density was weighted by codes that include the presence of oxidation or alteration in the rocks. No correlation was found between the presence of alteration and (or) oxidation with fracture density that could be used as a predictor of hydraulically conductive zones.

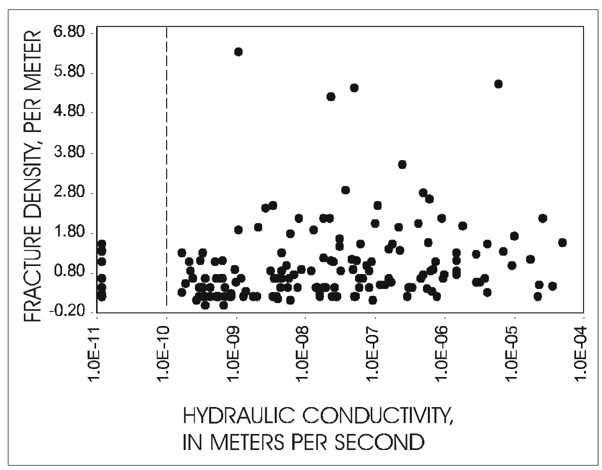


Figure 4. Hydraulic conductivity plotted against fracture density of the measurement zone. (Dashed line indicates lower detection limit of the field equipment.)

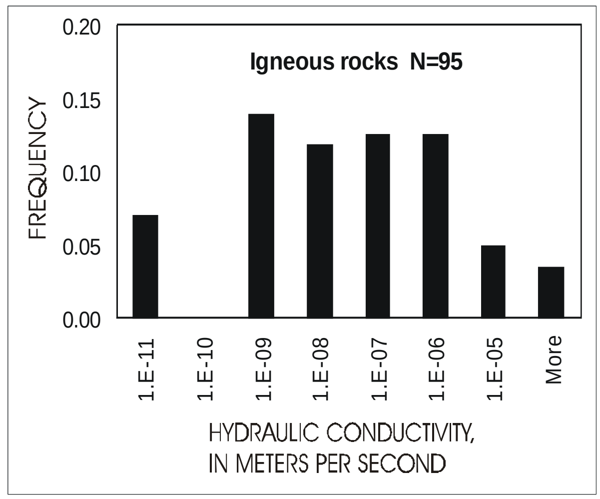
A WMW test was used to test whether the hydraulic conductivity values for the two major lithologies in the Mirror Lake area (igneous and metamorphic) are statistically different. The null hypothesis for this test, which states the values come from the same population, could not be rejected, thus indicating the distributions of hydraulic conductivity for the lithologies are not statistically different. The distribution of measured hydraulic conductivity in igneous and metamorphic rocks is shown in figure 5a and 5b, respectively. The frequency in each histogram has been normalized to 144, which is the total number of tests conducted in the igneous and metamorphic rocks combined. The results indicate hydraulic conductivity is not distinctly different for the different lithologies; however, there is a higher probability of fracturing and higher probability of measurable hydraulic conductivity in the igneous rocks than in the metamorphic rocks.

To determine if there is a preferred orientation to the hydraulically conductive fractures, a comparison between hydraulic conductivity and strike and dip was made for the limited set of wells with oriented fracture data (for wells CO1-CO7). The hydraulically active fractures strike approximately N30^{o}E and dip predominantly towards the NW, with a few fractures dipping SE. Another weak fracture set strikes NW and has a shallow dip to the SW. The orientation of fractures in the zones with measurable hydraulic conductivity was similar to the entire population of fracture orientations for wells CO1-CO7. There was no distinct preferred orientation of fracturing that relates to the magnitude of hydraulic conductivity.

SUMMARY AND CONCLUSIONS

Detailed fracture and lithology data collected from 40 wells at the Mirror Lake research site in Grafton County, New Hampshire were used to compare the occurrence of lithologies, fractures, physical parameters, and hydraulic measurements. A set of 15 index wells was used to summarize the fracture characterizations and to test for statistical correlations. There does not appear to be a correlation between rock type and depth, altitude, or topographic setting. There may be a relation, however, between topographic setting and fracturing; that is, there is a low probability of encountering highly fractured wells in valley settings. In addition, there is a low probability of encountering fractured zones at depth. Although the metamorphic and igneous rocks comprise equal proportions of the rock

(a)



(b)

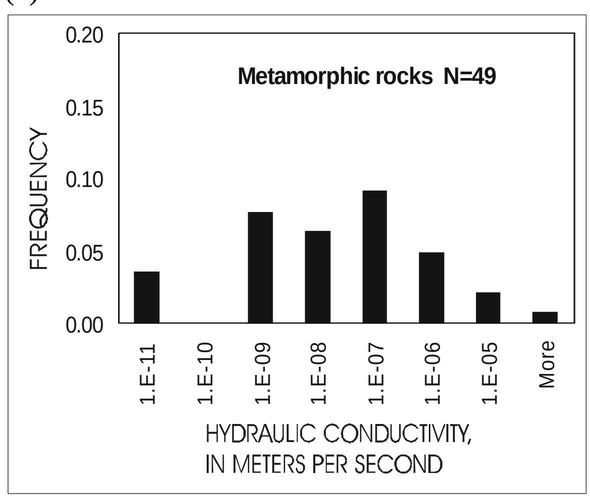


Figure 5. Histogram of hydraulic conductivity for igneous (a) and metamorphic (b) rocks. (N indicates the number of zones in each histogram. The histograms show only the zones measured for hydraulic conductivity and do not show the unfractured zones that were not tested. The lower detection limit for measuring hydraulic conductivity was E^{-10} meters per second.)

types in the index wells, most of the fractures observed in boreholes were in igneous rocks (granitoids), indicating the fracturing is lithologically controlled.

The data from all 15 index wells were combined and statistics were compiled on the distribution of spacing between fractures. The interfracture spacing (computed for the well data) was best defined by a power-law function. This distribution of fractures, at least in the vertical direction, suggests the fracture network comprises tightly-spaced fractures surrounded by zones that are less fractured. Over the scale of a well field, this distribution of fractures would likely cause a spatially variable distribution of hydraulic conductivity.

Digital images were collected in a small subset of wells to describe the lithologies and fracture location and orientation. Analysis of the images indicates a generally good agreement in the strike of fractures measured in the CO well field and on the nearby highway outcrop. Most of the fractures in the subsurface of the CO well field, however, dip in the opposite direction from those on the outcrop. The differences in fracture orientations could indicate fracture variability and a potential weakness in the extrapolation of outcrop data to subsurface fracturing.

Hydraulic-conductivity values available from 11 of the index wells were compared to rock type, fracture density, fracture aperture, fracture density weighted for presence of alteration and oxidation, fracture orientation, and physical parameters such as depth, altitude, and topographic setting. No correlations were established for these comparisons. Fracture intensity alone cannot predict hydraulic properties of fractured rock, because fracture density is not correlated to hydraulic conductivity. This finding indicates that theoretical equations that rely on fracture density are unable to describe hydraulic properties of the aquifer.

A Wilcoxon-Mann-Whitney test was performed on the hydraulic conductivity measurements for the two major lithologies – igneous and metamorphic. Although there are more zones of measurable hydraulic conductivity in the igneous rock, the ranges, means, and variances were similar between the igneous and metamorphic rocks. The test indicated that evidence is not sufficient to conclude that the hydraulic-conductivity data for the two different lithologies come from different populations. Because of the high probability of fractures occurring in granitic rocks, there is a higher probability of finding hydraulically conductive fractures in granitic rocks than in metamorphic rocks.

Fractured-crystalline aquifer systems are extremely heterogeneous and complex. The data and interpretations presented in this paper indicate there is no simple relation or predictor that describes fracture occurrence and probability of hydraulic conductivity. Although some properties of the fracture system have been described, and relations have been defined between fracture occurrence and physical parameters of the aquifer system, the results can be viewed only in a probabilistic sense.

REFERENCES

Barton, C.B., 1996, Characterizing bedrock fractures in outcrop for studies of ground-water hydrology—An example from Mirror Lake, Grafton County, New Hampshire, *in* Morganwalp, D.W. and Aronson, D.A., eds., U.S. Geological Survey Toxic Substances Hydrology Program—Proceedings of the Technical Meeting, Colorado Springs, Colo., September 20-24, 1993: U.S. Geological Survey Water-Resources Investigations Report 94-4015, v. 1, p. 81 - 88.

——— 1997, Bedrock geology map of Hubbard Brook Experimental Forest and maps of fractures and geology in roadcuts along Interstate 93, Grafton County, New Hampshire: U.S. Geological Survey Miscellaneous Investigations Series MAP 1-2562, 1 sheet, 1:12,000 scale.

Harte, P.T., 1997, Preliminary assessment of the lithologic and hydraulic properties of the glacial drift and shallow bedrock in the Mirror Lake area, Grafton County, New Hampshire: U.S. Geological Survey Open-File Report 96-654A, 56 p.

Lyons, J.B., Bothner, W.A., Moench, R.A., and Thompson, J.B., Jr., 1997, Bedrock geologic map of New Hampshire: U.S. Geological Survey State Geologic Map, 2 sheets, scales 1:250,000 and 1:500,000.

Johnson, C.D., 1996, Use of a borehole color video camera to identify lithologies, fractures, and borehole conditions in bedrock wells in the Mirror Lake Area, Grafton County, New Hampshire, *in* Morganwalp, D.W. and Aronson, D.A., eds., U.S. Geological Survey Toxic Substance Hydrology Program—Proceedings of the Technical Meeting, Colorado Springs, Colo., September 20-24, 1993: U.S. Geological Survey Water-Resources Investigations Report 94-4015, v. 1, p. 89-94.

——— 1998, Subsurface lithology and fracture occurrence and their effects on hydraulic conductivity: Mirror Lake Research Site, Grafton County, New Hampshire: Durham, N.H., University of New Hampshire, unpublished master's thesis, 159 p.

Johnson, C.D., and Dunstan, A.M., 1998, Lithology and fracture characterization from drilling investigations in the Mirror Lake Area: from 1979 through 1995 in Grafton County, New Hampshire: U.S. Geological Survey Water-Resources Investigations Report 98-4183, 210 p.

McDonald, G., Paillet, F.L., Barton, C.B., Johnson, C.D., 1997, Borehole sampling of fracture populations - identifying flow paths and correcting borehole bias in bedrock aquifers: ISRM International Symposium, U.S. Rock Mechanics Symposium (36th) N.Y., June 29-July 2, 1997, Columbia University, 6 p.

Shapiro, A.M., and Hsieh, P.A., 1991, Research in fractured rock hydrogeology: Characterizing fluid movement and chemical transport in fractured rock at the Mirror Lake drainage basin, New Hampshire, *in* Mallard, G.E., and Aronson, D.A., eds., U.S. Geological Survey Toxic Substances Hydrology Program Proceedings of Technical Meeting, Monterey, Calif., March 11-15, 1991: U.S. Geological Survey Water-Resources Investigations Report 91-4034, p. 155-161.

——— 1997, How good are estimates of transmissivity from slug tests in fractured rock?: Ground Water, v. 36, no. 1, p. 37-46.

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