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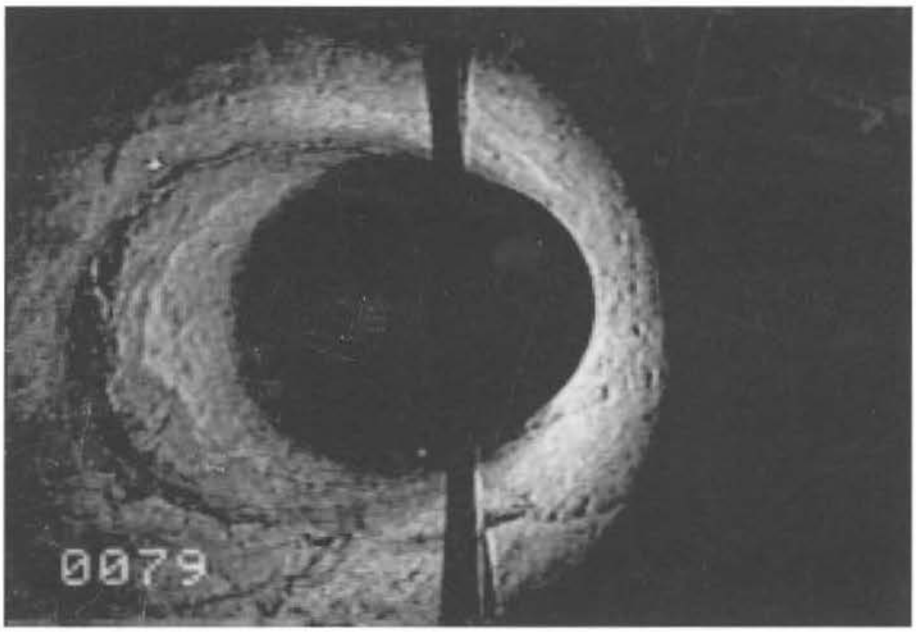
Lithology and Fracture Characterization From Drilling Investigations in the Mirror Lake Area, Grafton County, New Hampshire

Water-Resources Investigations Report 98-4183



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Front cover:* *A photograph from submersible borehole video survey showing a steeply dipping fracture at a depth of 79 feet below land surface in a borehole near Mirror Lake in Grafton County, New Hampshire.

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By Carole D. Johnson and Alicia H. Dunstan

Water-Resources Investigations Report 98-4183

Pembroke, New Hampshire
1998

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply metric unit	By	To obtain inch-pound unit
	Length	
millimeter (mm)	25.40	inch
centimeter (cm)	2.540	inch
meter (m)	0.3048	foot
square kilometer (km^2)	0.3861	mile squared
liter per minute (L/min)	0.2642	gallon per minute

Sea Level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Lithology and Fracture Characterization From Drilling Investigations in the Mirror Lake Area, Grafton County, New Hampshire

By Carole D. Johnson *and* Alicia H. Dunstan

Abstract

The lithology and fracture network of the bedrock aquifer in the Mirror Lake area were characterized from hydrogeologic data collected from 1979-95 in Grafton County, N.H. The collection of these data is an integral part of an ongoing multidisciplinary study by the U.S. Geological Survey to characterize ground-water flow and solute transport in fractured rock. The data provide a physical framework and enable the characterization of the fractures and the rock types in the bedrock aquifer in the Mirror Lake study area. In addition, these data provide a detailed description of the subsurface intersected by boreholes that can be used to compare the results of other borehole testing.

The Mirror Lake area is characterized by steep bedrock uplands that are mostly covered by colluvium, discontinuous stratified-drift deposits, and glacial till that varies locally in thickness from less than 10 meters to as much as 50 meters. The land-surface altitude ranges from 180 meters near the Pemigewasset River to 720 meters on the mountain top on the northwestern side of the study area. The bedrock in the area is predominantly sillimanite-grade pelitic schists that have been complexly folded and intruded by granitoids, pegmatites, and diabase dikes. The bedrock has been fractured in response to local and tectonic stress. The resulting interconnected network of fractures forms the bedrock aquifer.

This report describes the lithologic units in the study area and provides a characterization of the lithology and fractures found in 40 boreholes, which range in depth from 60 to 305 meters, that were drilled for this study. Drilling logs and color video surveys were used to locate and characterize the fractures and rock types in the subsurface. Solid bedrock core was obtained from three of the boreholes. Petrographic thin-section, x-ray diffraction and scanning electron microscope with energy dispersive x-ray fluorescence spectrometry analyses were done on selected samples from boreholes and outcrops. Observations recorded at the time of drilling, descriptions of rock samples collected from the boreholes, interpretation of rock type and fractures based on borehole-imaging surveys, descriptions of rock core and petrographic analyses of selected rock samples are in tables and figures.

Analysis of the data provided information on the distribution of fractures and lithology in the boreholes at Mirror Lake. The relative abundances of the rock types were computed for three groups of boreholes, including (1) the Forest Service Experimental (FSE) well field, (2) the Camp Osceola (CO) well field, and (3) the index boreholes, which are 15 boreholes distributed areally throughout the study area including the deepest borehole from each of the two well fields. The index boreholes are separated by hundreds of meters and are typically 100 meters deep. The FSE well field includes 13 boreholes that are separated by 10 to 40 meters. These 13 boreholes are approximately 100 meters deep, except for one borehole that is 230 meters deep. The rocks penetrated by the FSE wells are predominantly igneous. Approximately 70 percent of the rocks encountered in the boreholes in the FSE well field

were granite, pegmatite, and aplite. The CO well field includes 9 boreholes that range from 60-70 meters deep and one borehole that is 175 meters deep. The rocks encountered in these boreholes were predominantly metamorphic. The distribution of rock types in the CO well field is similar to the distribution of rocks in highway roadcuts, that are approximately 90 to 150 meters east of the well field. Seventy percent of the roadcut exposures are schist. Collectively, in the 15 index boreholes, the metamorphic and igneous rocks are equally distributed. Analysis of the rock types in these boreholes indicates that the rock types tend to "change" every 5 to 9 meters.

Although the metamorphic and igneous rocks each comprise approximately 50 percent of the rock types observed in the 15 index boreholes, 73 percent of the fractures were in the igneous rocks. This indicates that the granitoids tend to be more fractured than the metamorphic rocks. Pegmatite, diabase, quartzite, and gneissic rocks are relatively unfractured.

Boreholes completed in bedrock generally have one or two water-bearing zones, which were identified during the drilling process. At the completion of drilling a borehole, the driller estimated the yield of the borehole with an air-lift test. Yields estimated by drillers ranged from less than 3 to 378 liters per minute. These yields are typical of the yields measured for domestic wells in Grafton County. Water levels measured in the open boreholes after the boreholes recovered from the hydraulic stresses of drilling were usually in the steel casing and were within 10 meters of the land surface. Water levels in eight of the boreholes were above the top of casing or above land surface.

INTRODUCTION

Bedrock in the Mirror Lake area in Grafton County, N.H., is characterized by pelitic schists of Silurian to Devonian age, which were generally metamorphosed to sillimanite grade during the Acadian orogeny. The schists have been complexly folded and intruded by Devonian anatectic granites and pegmatites, and Mesozoic diabase dikes (Lyons and others, 1997), and fractured in response to tectonic stresses (Hardcastle, 1989) and local stresses (Trainer, 1988). The geometry of fracture networks and openness of individual fractures control the flow of fluids in the rocks and the advection, dispersion and storage of solutes.

Approximately 97 percent of the bedrock at Mirror Lake is covered by surficial deposits. Bedrock outcrops generally are limited to the stream beds, ridges, and exposures produced by highway excavations. Hence, detailed characterization of the rock types and fractures relies on data collected during subsurface exploratory drilling and geophysical surveys. Forty boreholes, ranging in depth from 60 to 305 m, were drilled from 1979-95 by use of the air-percussion rotary drilling method (table 1). From June through August 1992, in August 1994, and in August 1995, a color video camera was used to survey the boreholes and improve the interpretation of the subsurface bedrock. Cores were collected from three of the boreholes to obtain representative subsurface samples of rock units and fracture surfaces that could be compared with fracture and lithology interpretations based on borehole logging and borehole imaging methods.

The 40 boreholes were installed as part of an ongoing multidisciplinary research effort to characterize fluid movement and chemical transport in fractured crystalline bedrock in the Mirror Lake drainage basin. The research is supported by the U.S. Geological Survey (USGS) Toxic Substance Hydrology Program. An overview of the research is provided by Shapiro and Hsieh (1991). General descriptions of geologic, hydraulic, geophysical, and geochemical methods used in this investigation are provided by Hsieh and others (1993).

The objectives of the test-drilling program described here were to install a network of boreholes for hydraulic testing, water-quality sampling, geophysical testing, long term water-level monitoring, and for improving the characterization of the distribution of lithology and fractures in the subsurface. Fractures and changes in lithology could be detected and detailed descriptions of the boreholes were generated by using borehole-imaging methods and characterization of rock samples collected at the time of drilling. These characterizations of the boreholes serve as a basis for other work being conducted in the boreholes. The borehole characterizations can be used for statistical analyses of subsurface fracturing and distribution of rock type, for planning hydraulic or geophysical tests, or for comparing the results of other borehole analyses.

Table 1. Description of boreholes installed near Mirror Lake in Grafton County, New Hampshire

[Total length of casing and depth to bedrock are measured from top of casing. Latitude and longitude are in degrees, minutes, seconds; Altitude is based on sea level; --, no data; ~, indicates approximation. All length measurements are in meters. All boreholes are 15 cm in diameter.]

Well name (fig. 1)	Altitude of			Total length of casing	Depth to bedrock surface	Total depth of well	Previous well name	Date drilled	Well location	
	Top of casing	Land surface	Bedrock surface						Latitude	Longitude
CO1	217.69	217.14	211.90	9.14	5.79	175.86	CO87-BR	10/08/89	43° 56' 28.20"	71° 41' 23.77"
CO2	216.87	216.23	211.51	7.62	5.36	61.87	CO89-BR	10/24/89	43° 56' 27.85"	71° 41' 24.24"
CO3	215.41	214.91	210.93	7.92	4.48	64.46	--	07/22/91	43° 56' 27.10"	71° 41' 24.34"
CO4	216.11	215.30	210.11	8.84	6.00	60.65	--	05/26/92	43° 56' 27.15"	71° 41' 23.11"
CO5	217.38	216.71	213.11	8.14	4.27	70.00	--	06/27/94	43° 56' 27.73"	71° 41' 23.18"
CO6	217.37	216.52	212.19	9.39	5.18	70.04	--	06/22/94	43° 56' 27.81"	71° 41' 22.38"
CO7	215.92	215.01	213.18	6.25	2.74	71.05	--	06/29/94	43° 56' 26.66"	71° 41' 22.37"
CO8	217.83	216.98	212.66	8.81	5.80	76.90	--	08/13/94	43° 56' 28.24"	71° 41' 23.04"
CO9	217.85	216.94	213.47	7.16	4.39	76.47	--	08/15/94	43° 56' 28.34"	71° 41' 22.46"
CO10	215.78	214.90	209.38	10.06	6.40	77.11	--	07/28/95	43° 56' 26.83"	71° 41' 21.43"
CO11	225.74	224.92	217.51	12.28	8.23	183.79	--	07/27/95	43° 56' 30.00"	71° 41' 20.64"
FS1	261.88	261.27	247.86	16.46	14.02	137.15	FS-79-BR	08/30/79	43° 56' 44.58"	71° 42' 5.34"
FS2	255.71	255.04	248.34	9.75	7.38	152.39	FS-87-BR	08/28/87	43° 56' 40.62"	71° 42' 3.57"
[1]FS3	274.45	273.84	265.00	12.04	9.44	225.54	FS-89-BR	10/12/89	43° 56' 47.81"	71° 42' 6.87"
FS4	346.12	345.36	342.16	7.62	3.96	305.70	--	07/24/93	43° 57' 4.00"	71° 42' 16.05"
FSE1	240.20	239.83	226.46	16.92	13.75	107.60	FS83E-BR	08/31/83	43° 56' 36.36"	71° 41' 59.98"
FSE2	241.06	240.39	225.91	17.07	15.15	108.00	FS83E2-BR	09/20/83	43° 56' 36.40"	71° 42' 0.39"
FSE3	241.01	240.31	226.42	18.59	14.60	108.20	FS83E3-BR	09/22/83	43° 56' 36.07"	71° 42' 0.03"
FSE4	241.26	240.71	226.38	18.29	14.87	229.50	FS83E4-BR	07/02/84	43° 56' 36.11"	71° 42' 0.44"
FSE5	242.36	241.65	229.16	16.92	13.20	61.26	FSE5-BR	10/26/89	43° 56' 35.50"	71° 42' 1.51
FSE6	242.88	242.21	222.71	22.55	20.18	76.20	--	08/06/90	43° 56' 34.34"	71° 42' 3.56"
FSE7	242.31	241.88	226.34	18.90	15.97	76.50	--	08/06/90	43° 56' 35.88"	71° 42' 1.94"
FSE8	242.27	241.82	227.99	21.03	14.30	76.20	--	07/18/91	43° 56' 35.11"	71° 42' 1.10"
FSE9	242.82	242.13	228.40	20.12	14.42	76.20	--	07/22/91	43° 56' 35.06"	71° 42' 2.28"
FSE10	244.33	243.72	225.44	22.55	18.90	77.11	--	07/24/91	43° 56' 34.86"	71° 42' 4.71"
FSE11	242.59	242.09	221.35	24.99	21.24	84.58	--	06/02/92	43° 56' 34.44"	71° 42' 1.61"
FSE12	243.71	242.92	227.07	20.73	16.64	88.10	--	06/03/92	43° 56' 35.83"	71° 42' 3.13"
FSE13	240.61	239.79	218.15	24.38	22.46	75.90	-	06/04/92	43° 56' 33.73"	71° 42' 1.98"
H1	232.15	231.56	228.51	9.14	3.64	91.74	--	07/16/91	43° 56' 25.61"	71° 41' 51.22"
IS1	224.67	224.13	211.93	17.07	12.74	151.50	--	05/29/92	43° 56' 42.96"	71° 41' 20.09"
K1	215.40	214.15	203.21	15.54	12.19	46.33	Kh-1-BR	08/28/89	43° 56' 31.42"	71° 41' 35.77"
K2	215.18	214.81	201.10	17.37	14.08	48.77	K-BR	08/24/79	43° 56' 28.77"	71° 41' 40.60"
K3	209.28	207.15	187.80	23.77	21.49	53.34	Kh-B-BR	08/22/79	43° 56' 25.69"	71° 41' 39.17"
[2]R1	255.93	255.91	239.76	20.42	16.92	193.54	--	08/08/90	43° 56' 51.83"	71° 41' 53.66"
T1	229.08	228.47	225.42	6.10	3.66	152.39	--	07/25/91	43° 56' 42.36"	71° 41' 50.32"
TR1	249.29	248.56	197.66	53.19	51.63	190.49	TR-BR	09/13/83	43° 56' 49.50"	71° 41' 40.66"
TR2	232.94	232.24	219.74	16.15	13.20	231.64	--	08/08/91	43° 56' 26.50"	71° 42' 6.82"
FS5	~499.2	~498.3	~491.6	7.62	3.90	~ 66.44	--	07/05/94	43° 56' 54.46"	71° 43' 48.80"
[3]FS6	~243.8	~244.1	~232.7	13.47	11.12	182.57	--	07/24/95	43 ° 56' 23.50"	71° 42' 10.00"
RR1	~184.4	~183.5	~153.6	30.78	27.13	183.48	--	08/01/95	43° 55' 58.00"	71° 40' 58.00"

[1]FS3 caved in at 196.6 meters.
[2]R1 caved in at 165.5 meters.
[3]FS6 caved in at 125.0 meters.

Typically, each borehole has two to three water-bearing fractures that were detected during the drilling process. Detailed geophysical surveys of the boreholes indicate numerous fractures in each borehole. Flowmeter testing and hydraulic tests identify only a few hydraulically conductive fractures. All fractures identified in the boreholes by use of geophysical methods are tested for hydraulic conductivity. Straddle-packer tests, conducted over 3 to 5 m intervals, indicate that the hydraulic conductivity (and transmissivity) ranges over six orders of magnitude (Hsieh and others, 1993; Shapiro, 1993; and Hsieh and Shapiro, 1996).

Purpose and Scope

The purpose of this report is to describe the hydrogeology of a bedrock aquifer and to report geologic and hydraulic information resulting from the 1979-95 drilling program at Mirror Lake. The test-drilling program included field observations recorded at the time of drilling, lithologic sampling, and detailed descriptions of rock samples. In addition, borehole-imaging techniques were used to characterize the lithology and the fractures in boreholes. This report describes the lithologic units in the study area and the well-drilling methods and other techniques used to characterize the fractures and rock-types in the boreholes. The fractures and the rock types observed in the boreholes are described, and data are presented in tables and figures.

Location and Description of Study Area

The study area is in the Pemigewasset River Valley and surrounding uplands near the towns of Woodstock and Thornton, in Grafton County in central New Hampshire (fig. 1). The entire study area is approximately 2 km^2 in size. Part of the study area is in the Hubbard Brook Experimental Forest, which is operated and maintained by the Northeastern Forest Experimental Station, U.S. Department of Agriculture (USDA) Forest Service, Radnor, Penn. The Hubbard Brook Experimental Forest has been the site of numerous scientific investigations during the past three decades (Likens, 1991). The study area is in the central highlands physiographic province of New England (Denny, 1982). This area was covered at least twice by glaciers from 2,000,000 to 10,000 years ago, and is characterized by steep bedrock uplands that are covered by glacial till and discontinuous stratified-drift deposits. The Mirror Lake drainage basin has high ridges and steep slopes, with occasional bedrock-cored knobs and sand terraces. The land-surface altitude ranges from 180 m near the Pemigewasset River to 720 m on the mountain top on the northwestern side of the study area. The underlying bedrock is predominantly high-grade metamorphic rocks that have been intruded by felsic igneous intrusions and to a lesser extent by pegmatites and diabase.

Previous Investigations

Several investigators have studied the geology and hydrogeology of the Mirror Lake area. The bedrock geology has been mapped at several scales, ranging from several square kilometers to mapping outcrop faces that are tens to hundreds of meters in length. Lyons and others (1997) mapped the geology at a scale of 1:250, 000. Their map and publication provide a thorough description of the rock units. Hatch and Moench (1984) provided geologic maps at the scale of 1:125,000 of the Wilderness Area, which includes the Mirror Lake area. The bedrock geology of the Plymouth, N.H., 15-minute quadrangle was mapped by Moke (1946) at a scale of 1:65,000. Lyons mapped the Woodstock, N.H., 7.5-minute quadrangle at a scale of 1:24,000 (John Lyons, Dartmouth College, written communication, 1993). In addition, fractures on the highway outcrops and rock exposures within the study area were mapped in detail by Barton (1996 and 1997). All fractures on the outcrops that exceed 1 m in length were individually characterized by six parameters: orientation, length, connectivity, aperture, surface roughness, and mineralization (Barton, 1996). Figure 2, which is modified from Barton (1997), shows the distribution of rock types in the study area at a scale of 1:12,000.

The hydrogeology of the study area also has been the subject of many recent investigations. Winter (1985) provides a detailed description of the hydrogeology and physical setting of the area. Studies of surface- and ground-water processes and interactions were done by Winter (1984) and Winter and others (1989). Other studies have provided information relating to hydraulic and physical properties of the rock. A characterization of the lithology and

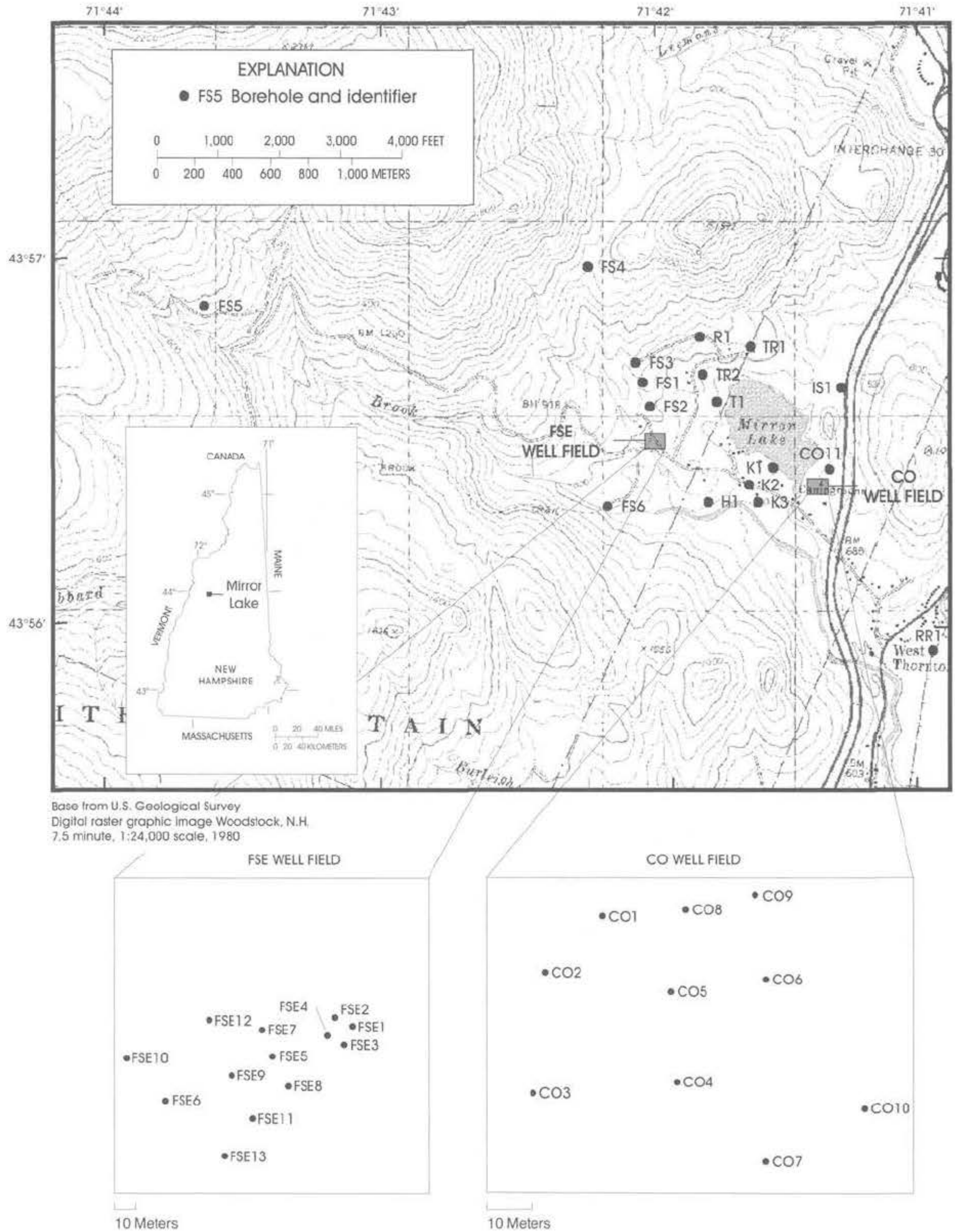
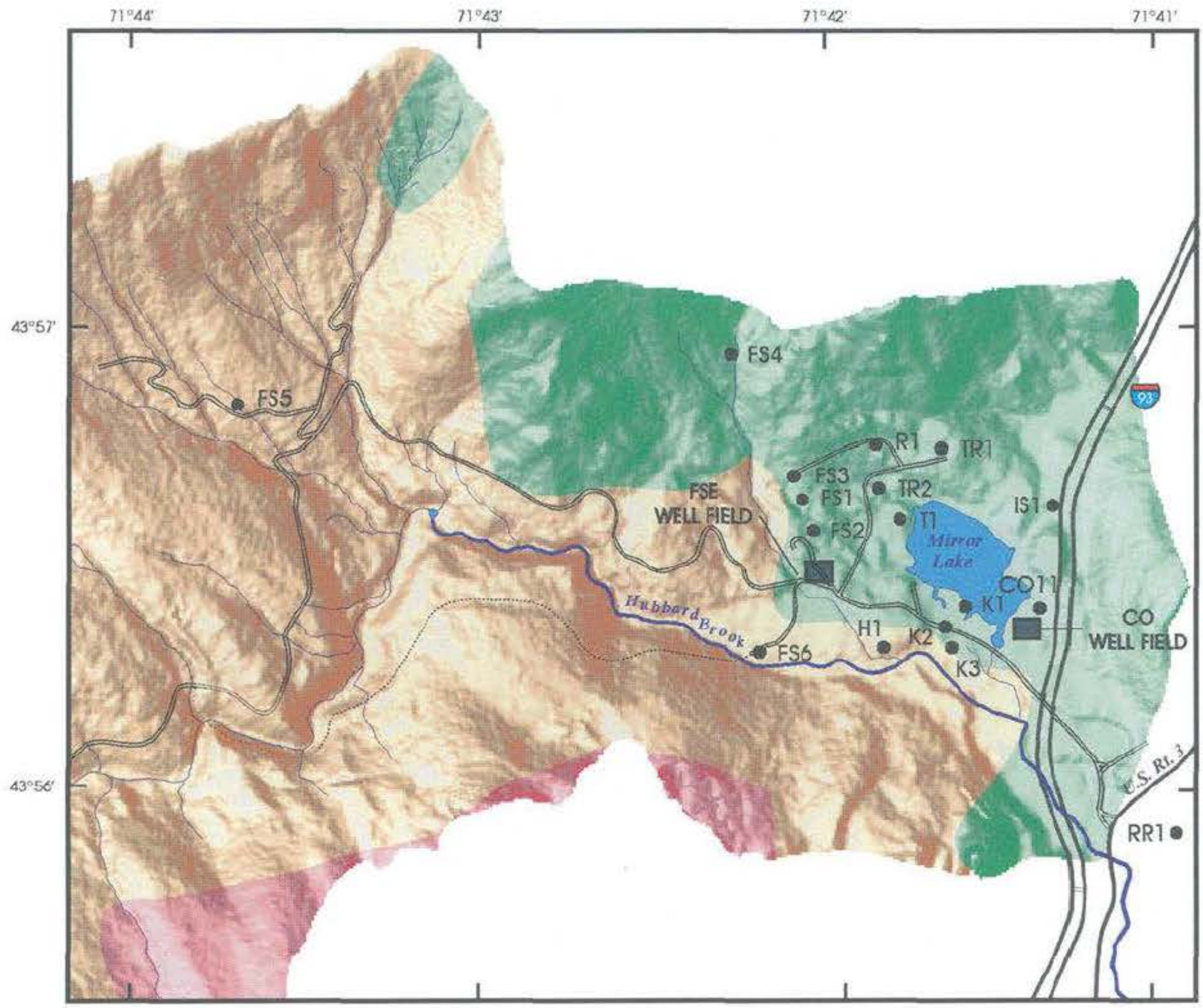


Figure 1. Location of study area and data-collection locations, near Mirror Lake in Grafton County, New Hampshire.



Shaded relief base created from digital elevation model interpolated from digital contour data. Hydrography and roads from U.S. Geological Survey digital line graphs U.S. Geological Survey Woodstock, N.H. 7.5 minute, 1:24,000 scale, 1980

0 1,000 2,000 3,000 4,000 FEET

0 200 400 600 800 1,000 METERS

EXPLANATION

Upper Member of Rangeley Formation (Silurian)

Lower Member of Rangeley Formation (Silurian)

Perry Mountain Formation (Silurian)

● K1 Borehole and identifier

Figure 2. Bedrock geology of the study area, near Mirror Lake in Grafton County, New Hampshire. (Well fields FSE and CO are shown in figure 1.)

hydraulic properties of the overburden and the upper 3 to 5 m of the bedrock, which was not evaluated as part of this study, is reported by Harte (1997). Results of borehole geophysical surveys for selected boreholes in the Mirror Lake Basin have been published in various reports (Paillet, 1985; Paillet and Kapucu, 1989). Borehole identifiers of some boreholes in previous reports are different than the borehole identifiers used in this report. Information provided in table 1 can be used to cross-reference the borehole names in these various reports. Previous work done in conjunction with this investigation is summarized by Hsieh and others (1993).

Acknowledgments

The authors express their appreciation to the employees of the U.S. Department of Agriculture Forest Service, the Institute of Ecosystem Studies, the State of New Hampshire Department of Transportation, and the many private land owners who permitted access to drill boreholes and collect borehole data. The authors are especially grateful to the following individuals and their families: Mr. and Mrs. Herzog, Mr. Ketanna, Mr. Kendal, Mr. Richards, and Mr. Thomas. The authors extend special thanks to Wayne Martin of the U.S. Forest Service for his cooperation and assistance in logistical aspects.

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APPROACH AND METHODS OF INVESTIGATION

All boreholes were constructed using the same technique to reduce differences in hydraulic properties that are caused by differences in borehole installation. In addition, techniques for collecting samples were used consistently at all boreholes. The methods used in this investigation are described in detail in this section. Inclined drilling was not attempted. All of the boreholes that were installed were intended to be near vertical. In some of the boreholes, especially in metamorphic rocks, the boreholes deviated from vertical.

Drilling Through the Overburden and Borehole Construction

The equipment used for the borehole design included a combination of rotary and air-percussion drilling. Rotary drilling was used to penetrate the unconsolidated overburden material and approximately 3 m into competent bedrock. A biodegradable drilling fluid, which is designed to break down after approximately 48 hours, was used when drilling through the overburden in order to hold the borehole open. Steel casing, 15.2 cm in diameter, was set through the overburden and into the rock by use of the following methods. The steel casing, which had a drive shoe affixed to its lower end, was set into the pre-drilled borehole. Lengths of casing were threaded together or welded until the drive shoe reached the bottom of the hole. A mixture of cement and bentonite grout was pumped to the bottom of the hole and into the annular space around the casing, in order to seal the casing and isolate the water in the glacial drift from the water in the bedrock. The entire length of casing was lifted up 1.5 m in the hole and then dropped into place to insure that the grout filled the annular space. The casing was hammered or advanced up to 0.3 to 0.5 m into the rock to assure a tight fit. Once the grout set, an air-percussion tool was used to ream-out the grout in the bottom of the casing and to penetrate the bedrock to the total depth of the borehole. The finished borehole is defined as the open hole from the bottom of the casing to the extent drilled.

Continuous-Core Collection

Cores were taken in selected boreholes in order to collect rock samples from the subsurface that were less disturbed than the samples collected by air-percussion drilling. The cored holes were near vertical as no attempt was made to drill inclined core holes. Bedrock core, which measures approximately 5 cm in diameter, was obtained in three boreholes (FSE5, TR2, and CO7) (fig. 1). After coring was completed, the cored holes were reamed to approximately 15 cm in diameter by air-percussion drilling.

A diamond-impregnated carbide bit was used with a rotary-coring tool to cut the rock. Two coring methods were used to retrieve the core samples. A conventional core-barrel system was used to obtain 46 m of core from borehole FSE5. A wire-line system was used to obtain 46 m of core from borehole TR2 and 15 m of core from observation borehole CO7. The wire-line method allows the drill rod to remain in the hole, while the core barrel is pulled up the borehole through the drill rod on a wire line. This method saves time and also reduces the possibility of the borehole collapsing that sometimes occurs when removing the entire length of drill rod and conventional core barrel at the end of each run (1.5 or 3 m advancement).

Field observations recorded at the time of coring include the rate and smoothness of coring, the loss or gain of circulating wash water, and changes in color of the wash water. The rate of penetration for each core sample was recorded, since the speed of drilling is an indication of the relative hardness of the rock. In addition, changes in the rate of drilling over short distances, the roughness of drilling, or "sinking" of the drill rods indicates incompetent zones, such as fracture zones, faults, very soft rocks, or altered zones. It is important to observe and note these zones at the time of drilling because sometimes the rock samples from these locations are not recovered in the core, and the amount of core recovered is less than the distance that was cored.

Once the core barrel was retrieved, the core was extracted from the core barrel and set in a box. The core was photographed, and the fractures and lithologic contacts were documented. The core was reconstructed by matching the pieces together. Each piece was marked with an arrow that indicated the upward direction, labeled, described, and stored for future use. Core pieces were numbered sequentially with increasing depth. Zones that were completely fragmented and reduced to angular pieces that could not be reconstructed were stored in plastic bags, labeled, and placed in sequence. All breaks in the rock were determined to be either natural fractures or drilling or handling induced (Kulander and others, 1979 and 1990; Pollard and Aydin, 1988). The locations of natural fractures and completely fragmented zones were described in terms of position in the core sample and depth from land surface.

When the amount of core retrieved was less than the distance that was cored, the depth to the fractures along the length of the core was estimated by one of two methods. The first method, which is preferred by the authors, uses the drilling logs to identify the exact location of fractures. The second method uses the depth to the bottom of the drill rod, which is the best known location of the core. The bottom of the core sample is determined as the depth of the bottom of the drill rod, and depth locations of fractures in the core are determined relative to that known depth. This second method attempts to limit possible errors in the depth of fractures over a short interval. For example, if a 1.5 m core were drilled, but only 1 m was recovered, then the pieces would be reconstructed and labeled relative to the position of the bottom of the core barrel. In this method the lost core is positioned at the top of the run. Core recovery from the three cored holes averaged 99.1 percent, and so these two methods were used infrequently.

Fracture faces were examined for weathering and degree of alteration and mineralization, such as, calcite, quartz, clay, and manganese or iron hydroxide. If partial or total coatings or fracture fillings were found, notations were made in the drilling logs. The length of all pieces and fracture angles were measured and recorded. Solid-rock sections were described in terms of rock type, mineralogy, texture, and color. The mechanical aperture of the reconstructed core was not measured.

Air-Percussion Rotary Drilling

Air-percussion rotary drilling uses a hollow-stem drill rod attached to a percussion-cutting tool, which simultaneously rotates and hammers the rock. With this method the drilling fluid, compressed air, and a small amount of water are forced down the center of the drill rods and through the air hammer to evacuate water and rock fragments from the borehole and to cool the drill bit. The air, water, and cuttings are forced up the wellbore annulus to the land surface. If a borehole does not produce sufficient amounts of water, water is added to the drilling fluid to prevent compaction, caking, and collaring of the rock fragments downhole. If a collar of rock fragments adheres to the rods downhole, the evacuation of the borehole can be impeded or completely blocked. The addition of water generally removes the blockage, and cuttings and water are transported to the land surface. Water used for drilling purposes was obtained from Mirror Lake.

Sample-Collection Methods for Air-Percussion Rotary Drilling

In air-percussion rotary drilling, rock fragments (cuttings) and fluids are returned to the land surface under the force of the compressed air. The rock fragments generally measure from a fine dust size to a few centimeters in length. Samples were collected at the land surface over regular intervals of 1.5 m in depth or at any changes in rock units. A sample was collected by placing a sieve at the well head such that a continuous stream of rock fragments was deposited in it. Rock chips measuring 1 to 2 mm in diameter were sieved and washed in a wire-mesh strainer, and were transferred to plastic bags for storage. If the coarse portion of the sample looked significantly different than the fine portion, the fine portion was also sampled. For example, when all of the rock cuttings observed in the wash water were grayish black and the coarse portion of the sample, which was obtained by sieving, was predominantly white, both portions were sampled. In this example, all of the fine-grained dark minerals (biotite) were preferentially removed by washing the sample. Thus, by sampling the fine and the coarse portions of the rock fragments, a representative sample was obtained.

Field observations made at the time of drilling include depth, drilling rates, smoothness of drilling, size of rock fragments, changes in lithology and amount and color of the drilling fluid, and the amount of cuttings returned to the land surface. The rate of penetration indicates the relative hardness of the rocks. When the drilling rate increases rapidly, it indicates that there is a change in rock type or a discontinuity, such as a fracture or fault. A rapid decrease in the rate of penetration is likely caused by a change in rock type. Sometimes weathered zones are indicated by iron-oxide staining and crumbling or friable rocks that are at the bedrock surface or deep in the boreholes. Fracture zones in the bedrock often can be identified in the process of drilling. The drill cuttings in these zones are frequently larger than drill cuttings from more competent rock and are sometimes iron stained or friable. As the drill rod penetrates a fracture, the fracture can cause "chattering" or rough drilling. In addition, the presence of fractures can cause an increase or a decrease in the amount of drilling fluid. These signs, which indicate the presence of fractures, were recorded.

Identification of Water-Bearing Zones in Boreholes During Drilling

Identification of the locations of water-bearing zones can be determined during drilling by carefully observing the volumetric flow rate and the actions of the driller. If the driller has not changed the injection rate of the drilling fluid, then any change in the volumetric flow rate can indicate the presence of underground fractures. An increase in the flow rate indicates the drill bit has penetrated a water-bearing zone. A sudden decrease in the flow rate is caused by the presence of a fracture or fractures that are conducting water away from the borehole. Although this method of observation is not highly quantitative, it can be used for locating the major water-bearing zones in boreholes. One disadvantage is that the method is insensitive to low-yielding zones. During the drilling process, if there was a change in volumetric flow rate, the depth and the volume of the change were noted.

Borehole Development and Drillers' Short-Term Yield

The boreholes were minimally developed at the end of drilling for two purposes: (1) to clean the boreholes of particles and debris and (2) to provide a well-driller's estimate of short-term yield.

Development

Once the borehole was drilled to its completed depth, compressed air was discharged through the drill stem and drill bit and into the borehole. The air forced the evacuation of the water and small rock fragments and particles from the borehole. Each borehole was minimally developed this way until the water cleared of rock fragments or for at least 1 hour. The length of these tests varied but typically lasted 20 to 30 minutes. Water from the drill truck was used to clean the borehole when there was insufficient water production in the borehole. The production rate of water coming from the fractures intersecting the borehole was used as an estimate of short term yield.

Drillers' Short-Term Yield

Short-term yield was estimated by the driller after developing the borehole. This estimate is frequently referred to as the "well driller's yield", the "blow-test", or an air-lift test. The water that is removed from the borehole by compressed air is channeled into a calibrated container for measurement. The rate at which the water is removed from the borehole is monitored, as the rate is increased or decreased, until the maximum rate that can be sustained without dewatering the borehole is determined. Usually, the rate of flow is greatly reduced after several seconds to minutes. This change in flow indicates that the borehole storage has been removed from the borehole. Most often the flow rate stabilizes; in some cases, however, the boreholes are blown dry and the fractures that intersect the borehole are unable to sustain yield. Usually the driller can reduce the force of the air lift such that a sustainable well yield can be measured. Short-term yield is routinely measured by well drillers for home owners and for reporting agencies, and these measurements are considered reliable indicators of yield compared to short-term aquifer-production tests (Paillet and Duncanson, 1994; and Borchers, 1996). Borchers (1996), however, noted that the short-term yields measured in crystalline rocks are not good indicators of long-term sustained production.

Measurement of Water Level

The water level is greatly affected by the drilling process. Sometimes it takes a few days for the water level to rise to a static level after drilling, but generally the water level in the bedrock recovers overnight. All water levels were measured in open holes after the borehole recovered from drilling and before any inflatable packers were installed in the boreholes for long-term water-level monitoring (Hsieh and others, 1996). The water levels were measured using a calibrated electric tape or a steel tape to the nearest one-hundredth of a foot and converted to metric values. The water levels were measured from the top of casing and converted to altitude above sea level.

Borehole-Imaging Methods

Borehole-imaging methods were used to improve interpretations of the rock types that previously were based only on initial logs made at the time of drilling and later detailed examinations of drill cuttings. Submersible color video cameras were used to view bedrock and fractures in boreholes to verify and describe rock types in the boreholes. The video images were used to describe texture, grain-size, color, contacts of rock types, occurrence and details of fractures, foliation, folds, and faults, as well as the condition of the borehole wall. Video images provide a direct verification and precise location of contacts between rock types and fractures. In addition, video images can be used to describe fracture zones that are sometimes missing from, or completely fragmented in, the bedrock core. Comparisons of interpretations of borehole video, core, and drilling logs indicate that the interpretations are similar. The similarities indicate that video borehole imaging is an effective, practical, and low-cost alternative to coring for the purpose of characterizing rock types and fractures and for assessing the integrity of the borehole.

Two submersible color video cameras were used in this investigation. From June through August 1992, the camera system with a digital-depth indicator (in whole feet) superimposed on the analog picture was used. In order to evaluate and locate the occurrence of fractures more accurately than one-foot intervals, the distance from the upper expression of a fracture in the borehole to the bottom of the fracture was determined by directly measuring the displacement of the logging cable at land surface, and was recorded in the field. In August 1994 and August 1995, the camera used had digital depth indicators that recorded depths in increments of tenths of feet. For all borehole surveys, the depth measurements were referenced to the top of the steel casing. All depth measurements were converted to metric for reporting.

Techniques and equipment for borehole imaging used in all borehole surveys are described by Johnson (1996). The submersible borehole color video camera systems had two lighthead attachments with two perspectives of the borehole. One lighthead attachment permitted a view of the borehole looking down the borehole, the other permitted a view of the borehole wall. All boreholes were surveyed with the two light attachments.

The dip of planar features (such as fractures or foliation) in the borehole was determined by a combination of measurement and computation. The vertical distance from the top of the feature to the bottom of the feature was measured along the axis of the borehole. A constant borehole diameter of 152 mm was assumed, and the angle at which the fracture intersects the borehole was calculated using right angle trigonometry. Because the borehole can be inclined, this angle is not necessarily the true dip of the feature. In addition, in zones where the borehole has an enlarged diameter, the actual dip of a feature would be less than the angle estimated by this method.

Mineralogic and Petrographic Analyses

Rock fragments collected during drilling were examined using a hand lens and binocular microscope to determine fragment color, texture, and mineralogy. Descriptive colors of the rock fragments are referenced to a standardized rock color chart (Geological Society of America, 1991).

Detailed analyses were performed on representative samples from rock outcrops and rock fragments obtained from boreholes to describe the mineralogy, petrology, and geochemistry of rocks in the study area. Thin sections were made from 11 rock samples from a nearby interstate highway outcrop (fig. 1) and 7 were made from rock fragments obtained from drilling boreholes. The thin sections of the rock fragments were made by embedding the fragments in epoxy. Thirteen thin-section samples were analyzed by use of a polarizing microscope and a scanning electron microscope—energy-dispersive x-ray fluorescence spectrometer (SEM-XRF). Polarizing-microscope analyses were done on the thin sections to provide detailed information about the mineral composition, texture, and structure of the rocks. Point counts, based on a minimum of 500 points, were performed on 10 thin sections to determine the relative abundance of mineral composition. SEM and XRF analyses were used to identify the size and shape of mineral grains, to determine mineralogy and elemental composition, and to characterize the pores between mineral grains. The equipment and methods of analyses are described by Marshal and others (1986). SEM magnifications of 10 to 20,000 times were used in order to obtain information on the mineral shape and morphology of the samples. The general composition of the samples was determined by the XRF tool, which measures the energy dispersion of the samples. Mineral identifications were based on the composition and physical properties of the minerals. The SEM and XRF tools can be used to indicate general or relative abundance of mineral content, but the results should not be considered accurate chemical analyses.

In addition, x-ray diffraction techniques, which make use of the crystallographic spacing of minerals, were used to determine the mineralogy of selected samples. Six samples of rock fragments obtained by drilling were crushed, pulverized, and analyzed by powdered x-ray diffraction techniques. Samples for x-ray diffraction were specifically collected from highly altered, fractured, or faulted zones within boreholes whose mineralogy was difficult to distinguish in hand samples. These analyses provide the relative proportion of the minerals in the sample and are quantitative.

Data-Collection Sites and Borehole-Naming Conventions

Boreholes in the study area were located in order to provide data over various scales. Twenty-three boreholes are clustered in two well fields. The boreholes in the well fields are separated by 10 to 40 m. At least one borehole in each well field was drilled to a depth greater than 175 m. The rest of the boreholes in the well fields were drilled to a depth of approximately 75 m (table 1). Seventeen boreholes are areally distributed throughout the subbasin. The areally distributed boreholes were installed in order to define the geology and hydrology on a scale of hundreds of meters; therefore, these boreholes are spaced several hundred meters apart. Locations of boreholes are indicated on figure 1. These boreholes were drilled to depths of 150 to 305 m, where conditions permitted. In borehole FS5, excessive water production and borehole instability (at approximately 64 m below land surface) prevented drilling the borehole to a depth similar to the other areally distributed boreholes.

In this report, boreholes are referenced by a borehole-numbering system that is unique to this study. Each borehole is classified with a 2- or 3-letter prefix that indicates the landowner, and is followed by a sequential number. The borehole name TR2, for example, was assigned to the second borehole installed on the Town Road property. The prefix "FS" refers to the boreholes that are located on Forest Service property; whereas "FSE" refers to a specific location on the Forest Service land called the Forest Service Experimental well field (fig. 1).

The boreholes were also assigned identifiers consistent with the USGS site-identifying system, which is based on latitude and longitude. The 15-digit identification number consists of 6 digits for latitude, 7 digits for longitude, and 2 digits (assigned sequentially) for adjacent sites located in the same 1-square-second area. Although this borehole-naming convention is based on latitude and longitude, it should not be used for exact coordinate locations. Exact borehole locations are shown in table 1. Boreholes were located using a Global Positioning System (GPS) (Curtis Crow, U.S. Coast and Geodetic Survey, written commun., 1994) and standard surveying techniques. The northern and eastern locations of boreholes are accurate to within 10 m. In the CO and FSE well fields, one borehole was designated as a datum, and all of the other borehole locations were surveyed relative to that datum to a 30 cm accuracy. The altitude of the top of casing and land surface were measured to 0.3 to 0.9 mm accuracy (except for the boreholes noted in table 1) using standard surveying techniques. The altitudes are referenced to local benchmarks that were established by the U.S. Coast and Geodetic Survey.

HYDROGEOLOGIC SETTING

Complex ground-water-flow patterns in the Mirror Lake study area indicate a high degree of interconnection between surface water, unconsolidated deposits, and bedrock (Winter, 1984). The flow patterns also indicate the flow system is highly heterogeneous, and the flow is predominantly controlled by (1) topography, (2) the presence of surface-water bodies, which act as sinks, and (3) the extent and permeability of overburden deposits (Harte and Winter, 1994).

The transmissive properties of the bedrock are primarily controlled by fractures. The hydraulic conductivity of the fractures is much greater than the hydraulic conductivity of the matrix. Hence, ground water is stored and transmitted primarily through the fractures. The bedrock aquifer in the Mirror Lake study area is typical of most crystalline-rock aquifers, which are characterized by a low primary porosity and low hydraulic conductivity. The primary porosity, measured in 20 samples of granite from the Mirror Lake area, ranged from 1.07 to 2.32 percent and had a mean value of 1.46 percent (Wood and others, 1996). Results of detailed hydraulic testing of boreholes indicate a high degree of areal and vertical variation in hydraulic properties. Results of hydraulic testing indicate that the hydraulic conductivity of fractures measured over discrete (3-5 m) intervals ranges over six orders of magnitude (Hsieh and Shapiro, 1996).

Because most of the flow is through the fractures, it is necessary to characterize the geometry of the fracture system in the subsurface. The parameters that are frequently used to describe the fractures—location, orientation, aperture, length, connectedness, and properties of the adjacent rock (Barton and Hsieh, 1989, and Long and others, 1992)—can be collected in boreholes. The next step, which is beyond the scope of this report, is to relate these geologic and geometric data to the hydraulic properties in boreholes.

Bedrock Geology

The Mirror Lake study area lies in the Gander terrane, one of three litho-tectonic terranes in New Hampshire (Boudette, 1990). This region is also assigned to the central Maine terrane (Eusden and Lyons, 1993) and to the Kearsarge-central Maine synclinorium (Lyons and others, 1982), which was formerly referred to as the Merrimack synclinorium by Billings (1956). These various names refer to a northeast-tending belt or region that is comprised of clay-rich sediments that were eroded from the Bronson Hill anticlinorium and deposited in a basin during the Silurian and Devonian. The sediments were subsequently metamorphosed and deformed during the Acadian orogeny and possibly the Alleghanian orogeny. The bedrock has undergone multiple deformations, leaving it complexly folded, fractured, and intruded by igneous rocks. Four phases of deformation and four phases of folding have been recognized to the north (Eusden and Lyons, 1993) and to the southeast (Eusden and others, 1987). Thompson and others (1993) and Eusden and Lyons (1993) provide a detailed history of structural deformation in the central Maine terrane. The general history of structural deformation includes large-scale folding and faulting, the formation of nappes, and doming of pre-existing structures. Partial melting of pre-existing rocks formed migmatites and caused anatectic granites, generally in sheet-like tabular bodies, to be injected into the stratigraphic layers of the metasediments.

The local stratigraphy of the Woodstock quadrangle and the Mirror Lake area, which was mapped by Lyons and others (1997), is predominantly the Silurian Rangeley Formation. The Rangeley here is a pelitic schist of sillimanite-grade metamorphism (Lyons and others, 1997). These metasedimentary rocks, which were previously assigned to the Devonian Littleton Formation by Billings (1955), have been reinterpreted and reassigned to the lower and upper parts of the Rangeley Formation, and are considered to be 438-428 Mega-annum (Ma).

Folding, faulting, metamorphism, and igneous intrusions associated with the Acadian and possibly Alleghanian orogeny have resulted in a complex distribution of lithology and fractures. The variability and complexity of the rock types that are exposed on the highway outcrop are shown in figure 3. The host rock was intruded by granitoids (felsic igneous intrusions), pegmatites, and diabase. The granitoids in the eastern part of the study area are predominantly anatectic, two-mica granite of the Devonian Concord Granite (370-365 Ma) (Armstrong and Boudette, 1984; Lyons and others, 1997). The granitoids also include gneissic textured Bethlehem Granodiorite (Lyons and others, 1997), which was previously referred to as Bethlehem Gneiss (Billings, 1956).

In parts of the area west of Norris Brook, (fig. 2) the granitoids are typically Kinsman Granodiorite (Barton, 1997). Partial melting of the country rocks has resulted in migmatite gneisses, which are found throughout the study area. Pegmatites and aplites (likely differentiates of the granitoids) are intruded into the metasediments and the granitoids (Olson, 1941). The diabase dikes of Middle-Jurassic through Early Cretaceous age (190-95 Ma) (McHone, 1984) are found cross-cutting all other rock units.

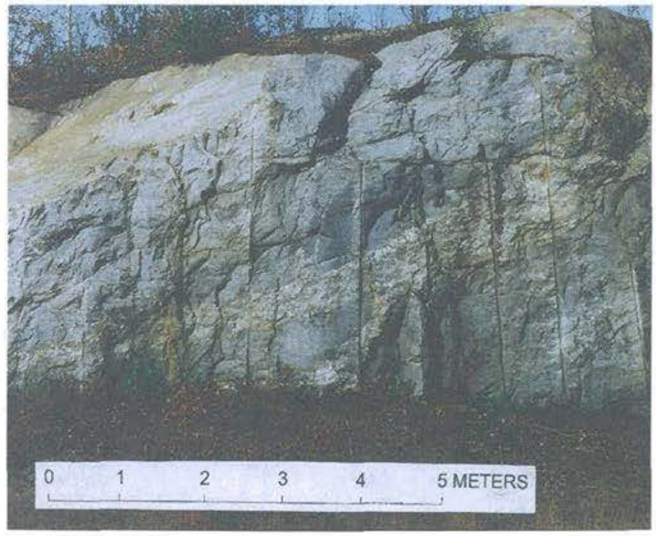


Figure 3. Bedrock in highway outcrop near Mirror Lake in Grafton County, New Hampshire.

McHone (1984) mapped Mesozoic dikes in the northeastern Appalachians, and provided age, composition relations, and the implied history of stress field rotation. Paleostress fields, which McHone (1984) determined relative to the orientation of Mesozoic dike intrusion controlled the orientation of dike and sill emplacement. These fields were similar to the results of a detailed study of brittle deformation by Hardcastle and Albaugh (1990). Hardcastle and Albaugh (1990) analyzed 3,000 mineralized fractures, veins, and dikes, which formed as a result of continental rifting and tectonism in the northeastern Appalachians. These data were used to determine the chronology and implied stress fields during the Mesozoic.

The current ambient stress field is the result of the combination of contemporary tectonic stress and local stresses, such as unloading. Work completed by Borchers and others (1993) and Zoback and Zoback (1989) indicates a correlation between the contemporary stress field and the anisotropy of fracture permeability, with the most open fractures being perpendicular to the minimal stress component. There appears to be some variability in the measurements of the orientation of the current stress field in New England (Gephart and Forsyth, 1985; Zoback and Zoback, 1989). The current state-of-stress has not been measured locally. Plumb and others (1984), however, report the orientation of near-surface maximum compressive stress in New Hampshire is N50^{o}E $\pm$ 33^{o}, based on a statistical analysis of existing stress data.

Surficial Geology

Approximately 97 percent of the bedrock are overlain by Wisconsinian-age unconsolidated glacial deposits characterized by sandy, silty till with some stratified drift deposited in ice-contact, outwash, and alluvium deposits. Till typically ranges from 0 to 10 m thick, but in the topographic saddle or ridge northwest of Mirror Lake near borehole TR2, it is as much as 50 m thick. This sandy till is predominantly ablation till (Carl Koteff, U.S. Geological Survey, oral commun., 1995). The most permeable stratified drift is located in a valley south of Mirror Lake (Winter, 1984) and in the Pemigewasset River Valley (Cotton and Olimpio, 1996). The extent, location, and hydraulic conductivity of stratified-drift deposits in the study area greatly affect the recharge from the overburden to bedrock aquifers (Harte, 1992).

During Pleistocene glaciation, ice sheets scoured the bedrock surface removing weathered bedrock and soils. The bedrock was subsequently covered by glacial deposits. Isolated exposures of saprolite, formed from small pockets of soil and weathered bedrock that were not glacially removed, have been identified in isolated outcrops throughout New Hampshire (Goldthwait and Kruger, 1938). Saprolite, however, was neither identified in boreholes drilled as part of this study nor observed in the shallow boreholes that were drilled through the overburden in a related study in the Mirror Lake area (Harte, 1997).

DETECTION OF WATER-BEARING ZONES AND ESTIMATION OF DRILLERS' YIELD AND WATER LEVELS IN BOREHOLES

The methods and tests described in this section are used routinely by well drillers and hydrogeologists in New England to identify water-bearing zones and estimate yield. Measurements made at the time of drilling, are considered to be "quick and dirty" estimates of hydraulic properties of boreholes. These measurements can be compared to the detailed and precise measurements of flow and hydraulic properties determined from discrete-interval hydraulic and tracer tests, pumping tests, and borehole flowmeter surveys.

Water-Bearing Zones Identified in Boreholes During Drilling

Boreholes were identified during drilling, as boreholes usually have one or two water-bearing zones that can be identified in the drilling process. Water-bearing (and water-yielding) zones that were identified during the drilling generally were confirmed later by borehole flowmeter and hydraulic testing. These geophysical and hydraulic borehole techniques, however, are capable of identifying other zones that have much lower permeability than can be detected in the drilling process. Comparison of water-bearing zones detected during drilling and the results of flowmeter logging for selected boreholes is shown in figure 4. The flowmeter log for R1 (fig. 4a) indicates 3 inflow zones, at depth intervals 20.7 to 24.7 m, 33.5 to 39.0 m, and 45.7 to 50.3 m. These inflow zones also were detected while drilling this borehole, as noted in the figure.

There are some limitations to the identification of water-bearing zones during drilling. The detailed flowmeter log for IS1 (fig. 4b) indicates inflow zones at 24, 30, 111, and 124 m depth. These zones coincide with the major water-bearing zones that were identified while drilling (24 m, 111 m, and 124 m). These three zones are noted on the right side of figure 4b with arrows. Although a fracture at 29.5 m was identified during drilling, it did not produce additional water. The zones at 111 and 124 m were high yielding zones that were estimated at 75 and 375 L/min, respectively. A fracture below these flowing zones would have to add a significant amount of flow in order to be detected during drilling. This method is effective only for identifying the major water-bearing zones in a borehole if they significantly increase the flow. This method is not effective in boreholes that have extremely low yield. The flowmeter log for FSE12 indicates an inflow zone at a depth of 56 m. Inflow zones were not observed while drilling FSE12, however, and the estimated well-driller's yield was 2.8 L/min. FSE12 is an example of the limitation of this method and indicates that specialized tools, such as a borehole flowmeter, are required for the detection and measurement of all water-bearing zones in boreholes.

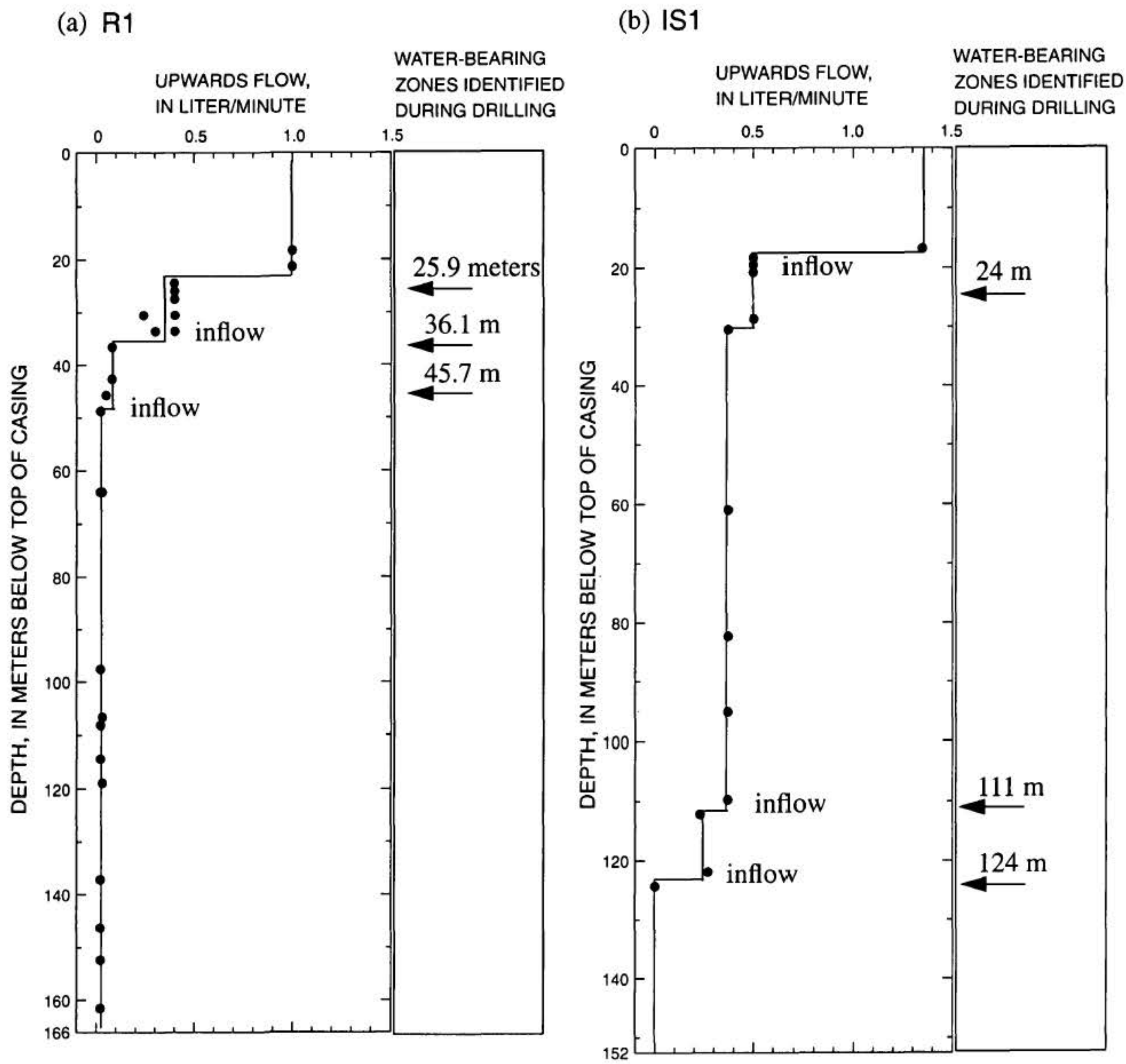


Figure 4. Comparison of flowmeter logs that show upward vertical flow in boreholes R1 (4a) and IS1 (4b) under pumping conditions with water-bearing zones that were identified while drilling the boreholes near Mirror Lake in Grafton County, New Hampshire.

Drillers' Yield

Once the borehole was drilled to the final depth, compressed air was used to remove residual rock fragments and particles from the borehole. The boreholes were only minimally developed. The duration of borehole development varied from 15 min to 1 hour. Estimates of the total yield of the borehole were made during and after development.

The drillers' yields ranged from less than 2.84 L/min to greater than 378.48 L/min for the boreholes (table 2). The depths of these boreholes ranged from 61 to 305 m below land surface. Drillers' yields from boreholes in the study area were compared to yields obtained throughout Grafton County and were found to be similar (Joseph Olimpio, U.S. Geological Survey, written commun., 1996). For this analysis, all boreholes with known yield, diameter, date drilled, depth to water, and total depth were used. The Wilcoxon-Mann-Whitley test was used to compare the two data sets of yield values.

Table 2. Water levels and well-drillers' estimates of yield in boreholes installed near Mirror Lake in Grafton County, New Hampshire

[All length measurements are in meters. Altitudes are above sea level. Depths are below land surface. --, no data; +, indicates water level is above top of casing (flowing); ~, indicates approximation]

Well name (fig. 1)	Altitude of		Depth to water level	Yield, in liters/minute
	Top of casing	Water level		
CO1	217.69	215.83	1.86	--
CO2	216.87	215.75	1.12	--
CO3	215.41	214.86	0.55	56.7-75.7
CO4	216.11	213.83	2.28	7.57
CO5	217.38	215.59	1.79	18.92
CO6	217.37	217.37	0.00	7.57
CO7	215.92	214.33	1.59	7.57
CO8	217.83	214.79	3.04	35.95
CO9	217.85	215.28	2.57	7.57
CO10	215.78	+215.78	Flow	13.25
CO11	225.74	218.88	6.86	11.35
FS1	261.88	255.88	6.00	45.42
FS2	255.71	241.56	14.15	--
FS3	274.45	267.28	7.17	56.77
FS4	350.50	394.04	1.46	13.25
FSE1	240.20	233.79	6.41	15.14
FSE2	241.06	233.28	7.78	3.78
FSE3	241.01	233.62	7.39	2.84
FSE4	241.26	233.73	7.53	--
FSE5	242.36	233.74	8.62	7.57
FSE6	242.88	235.20	7.68	30.28
FSE7	242.31	233.11	9.20	6.62
FSE8	242.27	235.06	7.21	3.57
FSE9	242.82	235.12	7.70	22.71
FSE10	244.33	235.51	8.82	3.78
FSE11	242.59	235.03	7.56	22.71
FSE12	243.71	235.51	8.20	2.84
FSE13	240.61	234.97	5.64	22.71
H1	232.15	217.58	14.57	2.84
IS1	224.67	218.30	6.37	283.9-378.5
K1	215.40	213.57	1.83	--
K2	215.18	211.28	3.90	--
K3	209.28	207.45	1.83	--
R1	256.67	249.69	6.98	30.28
T1	229.08	224.85	4.23	37.85
TR1	249.29	228.44	20.85	--
TR2	232.94	232.94	0	30.28
FS5	~ 499.2	499.20	0	378.48
FS6	~ 243.8	237.97	5.83	45.42
RR1	~ 184.4	181.11	3.29	9.46

Water Levels in Boreholes

The water levels listed in table 2 were measured after drilling the boreholes and represent a hydraulic head value for the entire open hole. Typically, the water levels are in the steel casing. In a few boreholes, the water level is above the land surface or even above the casing, which results in a flowing borehole. The static water levels in boreholes CO3, CO6, FS5, and FS4 are above the land surface, and TR2, FS6, and CO10 flow during most of the year. The water levels in table 2 were obtained as part of a long-term water-level monitoring program (Richard L. Perkins, U.S. Geological Survey, written commun., 1995). The water levels were measured after the boreholes recovered from the hydraulic stresses of borehole drilling and before pneumatic packers were installed for multi-level water-level monitoring.

CHARACTERIZATION OF LITHOLOGY AND FRACTURES

A detailed description of rock units observed in outcrop and in the subsurface is provided in this section. The rocks exposed in the highway roadcut are generally similar to the rocks in the boreholes. The roadcut obviously provides a better opportunity to view the rocks than does a borehole that measures about 15 cm in diameter. Geologic names were not assigned to the rocks in the boreholes but the schists probably correspond to the metamorphic rocks of the Silurian-age Rangeley Formation (Lyons and others, 1997). The granite is most likely anatectic, two-mica granite of the Devonian Concord Granite (Armstrong and Boudette, 1984; Lyons and others, 1982; J.B. Lyons, Dartmouth College, written commun., 1994). Gneissic textured igneous rocks are likely the Bethlehem Granodiorite (J.B. Lyons, written commun., 1994) or the Kinsman Granodiorite (Barton, 1997). The diabase probably corresponds to the lamprophyric intrusions of Middle-Jurassic through Early Cretaceous age (McHone, 1984).

Studies of fractures in the highway rock outcrop (fig. 3) indicate that the fractures in granite are more numerous, more planar, and are shorter than the fractures observed in the metasedimentary rocks (Barton, 1996). Additional work, perhaps employing the method of Terzaghi (1965), would be required to determine if the fracturing observed in the boreholes is similar to the fractures investigated in the highway outcrop. The Terzaghi method accounts for the vertical bias of the fracture sampling that is inherent in vertical to near vertical boreholes.

Description of Rock Units in the Study Area

Six major rock types, including schist, gneiss, granite, pegmatite, diabase, and migmatite, have been identified in the bedrock outcrops, drill cuttings, and borehole video images in the Mirror Lake area. Each rock unit is described in detail in this section. The rock units are distinguished by their color, texture, form, contact relations, and mineralogy. A view of the bedrock outcrop in the exposure along the highway is shown in figure 3.

Schist, Gneiss and Migmatite

The schists and gneisses of the Mirror Lake region contain a foliation comprised of biotite, muscovite, and sometimes sillimanite. Some schists exhibit fine banding or thicker felsic layers, augen, and folded foliation. Characteristic features of schist include boudins, coticule layers, and layers of quartzite and calc-silicate. Layers of fine-grained quartz and garnet, which are referred to as coticule, and impure quartzite layers, which consist of quartz, garnet, diopside, chlorite, and amphibole, are locally abundant in the schist. Petrographic analyses of schist samples from the highway outcrop and rock chips obtained by drilling indicate that the schists are comprised of biotite, muscovite, quartz, and plagioclase with lesser amounts of garnet, ilmenite, zircon, monazite and pyrite (tables 3 and 4). In table 4, minerals that were identified in the sample are denoted with an "X." The relative elemental compositions are shown for selected minerals. The elemental compositions are listed in decreasing proportions below the "X."

The schists are gray to brownish black with some zones that are green, yellow, or white. In borehole video images, the coarse-grained biotites and muscovites reflect the downhole illumination and appear shiny, whereas fine-grained schists appear dark. The schists exhibit moderately to highly schistose foliation. Compositional layering in the schists, where present, is usually less than 2.5 cm in thickness. The schist locally grades to gneiss, which is very coarse grained (with individual grains measuring 1 to 2 cm in length) and exhibits less than 50 percent foliation. The metasedimentary gneiss is overall gray, with alternating bands of white and gray to brownish black layers. The gneisses exhibit compositional banding with quartzo-felsic layering approximately 1 to 25 cm wide with 1 to 5 cm wide foliated, biotite-rich layers. In general, the schists and gneisses exhibit more foliation than the granites and are darker.

Table 3. Results of petrographic point-count analysis of selected rock samples from the highway outcrop near Mirror Lake in Grafton County, New Hampshire

[S indicates schist; G indicates granite; and P indicates pegmatite; --, no data]

Sample	Mineral composition (percent)					
	Quartz	Plagio-clase	Musco-vite and sericite	Biotite	Garnet	Opaques
SCHIST						
S1	10	5	20	60	None	Some
S1-2	10	10	20	60	Some	Some
S1-3	25	15	20	40	Some	Some
GRANITOIDS						
G2	20	15	25	30	Some	None
G2-1	60	10	15	15	Some	None
G2-2	50	20	10	20	Some	Few
G2-3	30	25	20	20	Few	None
G3-1	25	20	15	40	Some	Some
G5	20	20	30	30	Some	None
PEGMATITE						
P2	25	40	30	--	Some	Few

Partial melting of the sedimentary rocks in the study area has produced migmatite and migmatitic gneiss (Winkler, 1979; Allen, 1992; and Dougan, 1981). Migmatites are generally grayish in color. They appear to be a swirly, layered mixture of granitic-looking and schistose-looking units. The felsic-rich granitic layers, which are referred to as leucosomes, were melted and recrystallized. The darker, biotite-rich layers, which were not completely melted, are called melanosomes. Migmatites sometimes exhibit gradational contacts with schist and pegmatite. At outcrop scale, migmatites are frequently ignored and are mapped as part of the adjacent non-migmatized unit. At the scale of a borehole, the view of the rocks surrounding the borehole is limited. Hence, when migmatites were identified in the boreholes, they could not be grouped with the adjacent rock units and were noted in the characterization of the subsurface lithology.

Table 4. Minerals and relative amounts of compositional elements identified by scanning electron microscope and x-ray fluorescence spectrometry for selected bedrock samples obtained from highway outcrops and boreholes near Mirror Lake in Grafton County, New Hampshire

[Minerals identified in the sample are marked by X, and minerals not detected are indicated by N. For selected minerals where data was collected compositional elements are listed vertically below the X in order of decreasing quantity; m, meters; chips refer to cuttings collected at the time of drilling.]

	Minerals															
Sample name	**Biotite**	**Muscovite**	**Quartz**	**Plagioclase**	**Potassium feldspar**	**Garnet**	**Apatite**	**Calcite**	**Ilmenite**	**Zircon**	**Monazite**	**Pyrite**	**Chlorite**	**Pyroxene**	**Sphene**	**Magnetite**
S1(schist)	X	X	X	X	N	N	N	N	X	X	N	N	N	N	N	N
highway	Fe	Al	Si	Si	--	--	--	--	Ti	Zr	--	--	--	--	--	--
outcrop	K	Si	O	Al	--	--	--	--	Fe	Si	--	--	--	--	--	--
sample	Al	K	--	Ca	--	--	--	--	Mn	O	--	--	--	--	--	--
	Mg	O	--	O	--	--	--	--	O	--	--	--	--	--	--	--
	Ti	Fe	--	Na	--	--	--	--	--	--	--	--	--	--	--	--
	O	Ti	--	--	--	--	--	--	--	--	--	--	--	--	--	--
S1-2 (schist)	X	X	X	N	N	X	N	N	X	N	X	N	N	N	N	N
highway	Fe,	Si	Si	--	--	Fe	--	--	Fe	--	La	--	--	--	--	--
outcrop	K	Al	O	--	--	Mn	--	--	Ti	--	Ce	--	--	--	--	--
sample	Si	K	--	--	--	Si	--	--	Mn	--	P	--	--	--	--	--
	Al	Fe	--	--	--	Al	--	--	O	--	Th	--	--	--	--	--
	O	O	--	--	--	O	--	--	--	--	U	--	--	--	--	--
	Ti	Ti	--	--	--	--	--	--	--	--	O	--	--	--	--	--
	Mg	Na	--	--	--	--	--	--	--	--	--	--	--	--	--	--
G2 (granite)	X	X	X	X	N	N	N	N	N	N	X	N	N	N	N	N
highway	--	--	--	Si	--	--	--	--	--	--	Ce	--	--	--	--	--
outcrop	--	--	--	Al	--	--	--	--	--	--	La	--	--	--	--	--
sample	--	--	--	Ca	--	--	--	--	--	--	P	--	--	--	--	--
	--	--	--	Na	--	--	--	--	--	--	O	--	--	--	--	--
	--	--	--	O	--	--	--	--	--	--	Th	--	--	--	--	--
	--	--	--	K	--	--	--	--	--	--	--	--	--	--	--	--
	--	--	--	Au	--	--	--	--	--	--	--	--	--	--	--	--
G5 (granite)	X	X	X	X	X	N	N	N	N	X	X	N	N	N	X	N
highway	Fe	K	Si	Si	Si	--	--	--	--	Zr	Ce	--	--	--	Ca	--
outcrop	K	Si	O	Al	K	--	--	--	--	Si	La,	--	--	--	Si	--
sample	Si	Al	--	Ca	Al	--	--	--	--	--	Si	--	--	--	Al	--
	Al	Fe	--	O	O	--	--	--	--	--	Al	--	--	--	K	--
	TI	Ti	--	Na	--	--	--	--	--	--	O	--	--	--	Ti	--
	O	O	--	K	--	--	--	--	--	--	P	--	--	--	Mg	--
	Mg	--	--	--	--	--	--	--	--	--	Th, Fe	--	--	--	O	--
	Mn	--	--	--	--	--	--	--	--	--	Al	--	--	--	Fe[1]	--
	--	--	--	--	--	--	--	--	--	--	O	--	--	--	--	--

Table 4. Minerals and relative amounts of compositional elements identified by scanning electron microscope and x-ray fluorescence spectrometry for selected bedrock samples obtained from highway outcrops and boreholes near Mirror Lake in Grafton County, New Hampshire—Continued

	Minerals															
Sample name	Biotite	Muscovite	Quartz	Plagioclase	Potassium feldspar	Garnet	Apatite	Calcite	Ilmenite	Zircon	Monazite	Pyrite	Chlorite	Pyroxene	Sphene	Magnetite
D (diabase)	N	N	X	X	N	N	X	N	X	N	N	N	X	X	X	N
highway	--	--	Si	Si	--	--	Ca	--	Fe	--	--	--	Fe	Ca	Fe	--
outcrop	--	--	O	Al	--	--	P	--	Ti	--	--	--	Si	Fe	Si	--
sample	--	--	--	Ca	--	--	O	--	O	--	--	--	Al	Si	K	--
	--	--	--	K	--	--	--	--	--	--	--	--	Mg	Al	Al	--
	--	--	--	Fe	--	--	--	--	--	--	--	--	O	Mg	Ca	--
	--	--	--	O	--	--	--	--	--	--	--	--	--	K	Ti	--
	--	--	--	Na	--	--	--	--	--	--	--	--	--	Mn	Mg	--
	--	--	--	Ti	--	--	--	--	--	--	--	--	--	O	O	--
	--	--	--	--	--	--	--	--	--	--	--	--	--	--	Na	--
[2]P2	N	X	N	X	N	N	X	X	N	N	N	X	N	N	N	X
(pegmatite)	--	--	--	Si	--	--	Ca	Ca	--	--	--	Fe	--	--	--	Fe
highway	--	--	--	Al	--	--	P	O	--	--	--	S	--	--	--	Mn
outcrop	--	--	--	O	--	--	Mn	--	--	--	--	--	--	--	--	O
sample	--	--	--	Na	--	--	O	--	--	--	--	--	--	--	--	--
	--	--	--	K	--	--	--	--	--	--	--	--	--	--	--	--
Diabase	N	N	X	X	N	N	N	N	X	N	N	X	N	X	N	N
TR1 chips	--	--	Si	Si	--	--	--	--	Ti	--	--	--	--	Ca	--	--
(at 57 m)	--	--	O	Ca	--	--	--	--	Fe	--	--	--	--	Si	--	--
	--	--	--	Al	--	--	--	--	Mn	--	--	--	--	Fe	--	--
	--	--	--	Fe	--	--	--	--	O	--	--	--	--	Al	--	--
	--	--	--	O	--	--	--	--	Cr	--	--	--	--	Mg	--	--
	--	--	--	Na	--	--	--	--	--	--	--	--	--	K	--	--
	--	--	--	--	--	--	--	--	--	--	--	--	--	Ti	--	--
														O		--
Granite	N	[3]X	X	X	X	N	N	N	N	X	X	N	N	N	N	X
TR1 99-	--	--	Si	Si	Si	--	--	--	--	Si	La	--	--	--	--	Fe
102-m chips	--	--	O	Al	K	--	--	--	--	Zr	Ce	--	--	--	--	O
	--	--	--	Ca	Al	--	--	--	--	Al	P	--	--	--	--	--
	--	--	--	O	O	--	--	--	--	K	Th	--	--	--	--	--
	--	--	--	Na	--	--	--	--	--	Fe	U	--	--	--	--	--
	--	--	--	K	--	--	--	--	--	O[1]	--	--	--	--	--	--
Granite	X	X	X	X	X	N	X	N	N	X	X	N	N	N	N	N
FSE5, 51.8-	Fe	Si	Si	Si	--	--	Ca	--	--	Zr	La	--	--	--	--	--
54.9-m chips	Si	K	O	Al	--	--	P	--	--	Si	Ce	--	--	--	--	--
	K	Al	--	O	--	--	O	--	--	--	P	--	--	--	--	--
	Al	O	--	Na	--	--	--	--	--	--	Th	--	--	--	--	--
	Ti	Na	--	K	--	--	--	--	--	--	U	--	--	--	--	--
	O	K	--	--	--	--	--	--	--	--	O	--	--	--	--	--
	Mg	Albite	--	--	--	--	--	--	--	--	--	--	--	--	--	--

Table 4. Minerals and relative amounts of compositional elements identified by scanning electron microscope and x-ray fluorescence spectrometry for selected bedrock samples obtained from highway outcrops and boreholes near Mirror Lake in Grafton County, New Hampshire—Continued

	Minerals															
Sample name	Biotite	Muscovite	Quartz	Plagioclase	Potassium feldspar	Garnet	Apatite	Calcite	Ilmenite	Zircon	Monazite	Pyrite	Chlorite	Pyroxene	Sphene	Magnetite
Granite/	N	X[3]	X	X	X	N	X	N	N	N	N	X	N	N	N	N
Pegmatite	--	Al	Si	Si	Si	--	Ca	--	--	--	--	S	--	--	--	--
FS3, chips	--	Si	O	Al	K	--	P	--	--	--	--	Fe	--	--	--	--
195-198 m	--	K	--	O	Al	--	O	--	--	--	--	--	--	--	--	--
	--	O	--	Na	O	--	--	--	--	--	--	--	--	--	--	--
	--	Fe	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	--	Ti	--	--	--	--	--	--	--	--	--	--	--	--	--	--
TR1 chips	X	X	X	N	N	X	N	N	X	N	X	N	N	N	N	N
Schist	Fe	Al	--	--	--	Fe	--	--	Ti	--	--	--	--	--	--	--
136-137 m	K	Si	--	--	--	Mn	--	--	Fe	--	--	--	--	--	--	--
	Al	K	--	--	--	Si	--	--	Mn	--	--	--	--	--	--	--
	Mg	O	--	--	--	Al	--	--	--	--	--	--	--	--	--	--
	Ti	Fe	--	--	--	O	--	--	--	--	--	--	--	--	--	--
	O	Ti	--	--	--	Ca	--	--	--	--	--	--	--	--	--	--
FSE-1 chips	N	X	X	X	X	X	X	N	N	N	N	N	N	N	N	N
Granite	--	--	Si	Si	Si	--	Ca	--	--	--	--	--	--	--	--	--
35 -36.5 m	--	--	O	Al	K	--	P	--	--	--	--	--	--	--	--	--
	--	--	--	K	Al	--	O	--	--	--	--	--	--	--	--	--
	--	--	--	Na	--	--	--	--	--	--	--	--	--	--	--	--
	--	--	--	Ca	--	--	--	--	--	--	--	--	--	--	--	--
FS3, 193 m	N	N	N	N	X	N	N	N	N	N	N	X	N	N	N	N
	--	--	--	--	Si	--	--	--	--	--	--	Fe	--	--	--	--
	--	--	--	--	Al	--	--	--	--	--	--	S	--	--	--	--
	--	--	--	--	K	--	--	--	--	--	--	--	--	--	--	--
	--	--	--	--	Fe	--	--	--	--	--	--	--	--	--	--	--
	--	--	--	--	O	--	--	--	--	--	--	--	--	--	--	--
	--	--	--	--	Ti	--	--	--	--	--	--	--	--	--	--	--

[1] Sphene with scatter of interference from adjacent muscovite.
[2] Iron oxide in fracture filling (along grain boundary - leaching from Magnetite).
[3] Sericite.

Granitoids: Granites and Igneous Gneisses

Granitoids in the study area include the Concord Granite, Bethlehem Granodiorite, and Kinsman Granodiorite (Lyons and others, 1997). These rocks are all igneous intrusions. They are distinguished by their composition and texture. The Concord Granite is a two-mica granite that typically exhibits an equigranular, hypidiomorphic-granular, sugary, fine-to-coarse-grained texture. The composition of the two-mica granite ranges from granite to quartz-monzonite and locally to tonalite. Two-mica granites are generally leucocratic, creamy white to gray with an occasional greenish tinge. These anatectic granites, derived from the melting of pre-existing rocks, were injected into the overlying host rocks. Commonly two-mica granites are found in sheet-like, tabular bodies that have been intruded along preferred zones of weakness that conform to the fabric of the host rock. These tabular bodies occasionally exhibit weak foliation comprised of biotite and muscovite, and sometimes contain strongly foliated biotite schlieren, which are oriented parallel to major structural features in the host rock (Armstrong and Boudette, 1984).

The two-mica granites typically contain quartz, feldspar, microcline, oligoclase, biotite, muscovite, and sometimes chlorite replacing biotite. Petrographic analysis indicates that the two-mica granites are devoid of amphiboles and magnetite. Tables 3 and 4 show that the granitoids include accessory minerals of garnet, pyrite, and apatite. They also contain trace amounts of zircon, monazite, and rarely sphene. Rock samples and borehole images reveal textural and compositional variations in the two-mica granite that produce variations in color and fabric of the rock. The two-mica granite is locally aplitic and grades into gneissic migmatite.

The Kinsman Granodiorite and Bethlehem Granodiorite are strongly foliated igneous gneisses (orthogneisses) that have been assigned to the New Hampshire Plutonic Suite (Lyons and others, 1997). The Kinsman Granodiorite is a porphyritic granodiorite that has a dark-gray matrix and felsic (usually orthoclase) phenocrysts. It ranges in composition from tonalite to granite and contains potassium feldspar and garnet phenocrysts in a matrix comprised of plagioclase, microcline, quartz, biotite, and muscovite. It often contains inclusions of the country rock as xenoliths. The composition of the Bethlehem gneiss ranges from granite to tonalite. It is a coarse-grained, gray unit that contains quartz, plagioclase, microcline, biotite, muscovite, and garnet. The gneiss is strongly foliated and conformable with the foliation of the surrounding country rocks.

Granitoids of this area, including the two-mica granites, Bethlehem Granodiorite, and Kinsman Granodiorite, exhibit moderate to high concentrations of uranium (Lyons, 1964; Gunderson and Schurmann, 1993) and are considered to be potential sources of radon. The SEM and XRF analyses (table 4) indicate that the sources of uranium and thorium are the rare-earth element phosphates such as allanite and monazite. In general, the granitoids have higher radioactivity than the schists (Olson and Overstreet, 1964; Gunderson and Schurmann, 1993). This is also confirmed by a comparison of natural-gamma emissions (Paillet, 1985) and rock types in the boreholes at Mirror Lake.

Granite dikes observed in the highway outcrop vary in strike from N32°E to N78°E and dip from 56°E to 59°NW (Barton, 1996). In the boreholes in the CO well field, which is near the highway outcrop, granite dikes ranged in strike from N25°E to 55°E and dipped 20 to 70°NW (Johnson, 1998).

Pegmatites and Aplites

Pegmatites are characterized by their coarse-grained texture and are generally felsic and are light in color. Large individual crystals (4 cm in diameter) of muscovite, biotite, feldspar, and quartz were observed in video images. Pegmatite frequently occurs in sheet-like, tabular bodies (dikes or sills) that are parallel to the foliation of the host rock. Pegmatites are also characterized as irregular shaped masses, lenses, and pods. Pegmatites and aplites observed in the highway outcrop vary in orientation from N09°E, 34°SE to N68°E, 48°SE (Barton, 1996).

Pegmatite was easily identified in the drill cuttings and in the borehole-video surveys by the characteristically large mica flakes (biotite or muscovite) and felsic minerals. Petrographic analyses indicate pegmatite is comprised mostly of albitic feldspar, microcline, muscovite, quartz, biotite, garnet and trace sphene, magnetite, sulfide minerals, monazite, and (or) allanite. Feldspar is frequently altered to sericite, which is a white, fibrous mica formed during retrograde metamorphism.

Locally, pegmatites correspond to high-gamma-activity counts that are observed in natural-gamma-radiation surveys in boreholes (Paillet, 1985; Paillet and Kapucu, 1989). These gamma-photon emissions are likely caused by the radioactive decay of potassium (^{40}K) in biotites and by radioactive decay of uranium and thorium in the rare-earth element phosphate minerals. The biotites that were observed in the thin-section samples exhibited zone damage from radioactive decay. These observations are consistent with Gunderson and Schurmann (1993) and Lyons (1964) who noted that the pegmatites associated with two-mica granites often had the highest uranium content and radioactivity in the state. The fact that high counts of gamma-photon emissions come from granitoids and pegmatites should be considered when using natural gamma surveys to interpret lithology. The surveys should be used in conjunction with rock cuttings or video surveys in order to avoid inaccurate interpretations.

Aplites have the same mineralogic composition as pegmatites; however, they have a much finer grained texture, which is characterized as an allotriomorphic-granular, or sugary texture. Aplite is generally observed in the highway outcrop and in boreholes cutting pegmatites, granitoids, and metasediments.

Pegmatites and aplites are not abundant in the study area. They comprise less than 5 percent of all of the rocks in the 15 index boreholes. Frequently, pegmatites intruded granitoids rather than the metasediments rocks. The pegmatites and aplites seen in the boreholes varied in size and width. Aplites generally form in sheets or veins that are a few centimeters wide; whereas pegmatites range in width from a few centimeters to several meters. Pegmatites are typically less than 1 meter wide and occur over a range of depths. A massive pegmatite, which extends vertically over several meters, was identified in the FSE well field and in FS6 and RR1. Some pegmatite dikes observed in the borehole images and in the highway outcrops show arrangements of minerals by zone. The form and shape of the pegmatites in the study area are generally similar to those observed in Grafton County (Bannerman, 1943; and Olson, 1941).

Diabase Dikes

Diabase is the least frequently found rock type in the boreholes and in the bedrock outcrops. Diabase dikes were injected into fractures in schist and granitoids resulting in sheet-like tabular bodies. Chill margins along the edges of the diabase dikes and their extremely fine-grained texture indicate rapid cooling of the diabase following injection. Diabase in the boreholes and outcrops cross-cuts the granitoids and schist. Diabase dikes occur in the boreholes over a range of depths, and range from sub horizontal to sub vertical. The diabase exhibits an aphanitic (extremely fine-grained), panidiomorphic-granular matrix. Contacts are sharp and exhibit an extremely fine grained matrix along the margins. The diabase dikes exhibit thermally induced fractures that formed during the cooling process. These thermal joints are numerous but not extensive. Felsic inclusions, including feldspar phenocrysts and cavity fillings, are highly reflective and discernible in video images. A few diabase samples effervesce in hydrochloric acid solution, which indicates the samples contain carbonate minerals. SEM analysis indicates that diabase is comprised of pyroxene, calcic plagioclase, ilmenite, pyrite, chlorite, and sphene (table 4).

Results of X-Ray Diffraction Analyses

X-ray diffraction analyses were used to determine the mineralogy and rock type of fine-grained rock samples that could not be identified in hand-sample analysis. Quantitative x-ray diffraction analyses reveal that the composition of the samples from boreholes FSE5, FSE11, CO5, TR2, and R1 were highly altered and comprised of greater than 95 percent quartz (table 5). The remainder of the sample consisted of plagioclase, illite, and phylosilicates, including muscovite, biotite, phlogopite, clinochlore, and zinnwaldite. The zones represented by these samples appear to be the result of alteration. The fact that quartz remains as a residue indicates normal ground-water removal of feldspars under saturated conditions.

A sample from borehole FS3 had a unique appearance in hand sample and x-ray diffraction analysis. The light-green hand sample with a cement-like matrix with seams of sulfide minerals was collected from the zone in borehole FS3 that collapsed after drilling. This zone, which was not vertically extensive in the borehole, appears to be unique and may be the result of hydrothermal deposits similar to those observed in North Woodstock, N.H. (Cox, 1970).

Table 5. Results of x-ray diffraction analysis of rock samples from selected boreholes near Mirror Lake in Grafton County, New Hampshire

[--, no data; >, greater than; <, less than]

Sample (Well name and depth, in meters, below top of casing)	Greater than 95 percent	Mineral composition (percent)				
		Less than 5 percent of the sample, minerals listed in descending order				
FS5 from 64.0 to 64.5 m (fracture zone in schist)	Quartz	Muscovite	Phlogopite	Clinochlore	Zinnwaldite	--
FSE11 from 49.0 to 50.5 m (fracture zone in schist)	Quartz	Albite	Anorthite	Phlogopite	Biotite	Clinochlore
R1 from 168.0 to 169.5 m (fracture zone in granite)	Quartz	Albite	Biotite	Phlogopite	Clinochlore	--
TR2 from 38 to 39 m (fracture zone in granite)	Quartz	Albite	Muscovite	Clinochlore	--	--
CO5 from 12.5 to 12.6 m (fault zone in schist)	Quartz	Biotite	Clinochlore	Zinnwaldite	--	--

Sample from FS3 taken at 196.6 meters below top of casing	Mineral composition (percent)					
	Muscovite	Pyrite	Potassium feldspar and plagioclase	Quartz	Total clay	Gypsum
FS3 matrix [1] (possibly a gange or hydrothermally altered zone)	> 50	< 20	< 30	--	--	--
FS3 seam[2]	> 20	> 50	< 5	< 10	< 5	< 5

[1] The matrix is the cream colored, clay-like portion of the sample.
[2] The seam is a dark, metallic parting in the sample.

Rock-Core Descriptions

Rock-core samples were collected from FSE5, located in the FSE well field, CO7, located in the CO well field, and TR2, located just northwest of Mirror Lake, in order to obtain representative samples of the study area. The core samples were collected to provide a verification of the interpretations based on video and rock-cutting analyses. The solid core also provides samples for whole-rock analysis and direct observation of the fracture surfaces. These fracture surfaces can be described for mineralization, roughness, alteration, and staining. An estimate of the dip of each fracture can also be measured directly from the rock core. Each fracture in the core samples from FSE5, CO7, and TR2 is listed in table 6 with the presence of the appropriate characteristics and the measurement of the dip noted.

In total, 99.2 percent of the rock-core was recovered from FSE5. Percent recovery for each run ranged from 96 to 101.6 percent. Approximately 44 m of solid core was collected over a depth of 17.3 to 61.4 m below the top of casing. The angles of fractures observed in the core were measured from the plane perpendicular to the axis of the core, which is assumed to be horizontal. The angles of fracture intersections ranged from 10 to 90°. These angles correspond to downhole measurements of fracture dip, which range from less than 20° to 65° (Paillet, 1991). The rock core obtained from borehole FSE5 was a weakly foliated, two-mica granite with several intrusions of pegmatite and aplite.

Interpretations of the lithology of the core samples generally agree with the interpretations based on the analysis of drill cuttings and borehole imaging. A comparison of fractures in borehole FSE5 determined by borehole-imaging methods and coring indicates that approximately 94 percent of the fractures correlated between the two methods. Identification of rock types were also in agreement over approximately 95 percent of the borehole.

A total of 15.2 m of core was collected from CO7 at a depth of 6.6 to 21.8 m below the top of casing. The time for coring a 1.5 m length of core in

Table 6. Description of fractures in core samples from boreholes CO7, FSE5, and TR2 near Mirror Lake in Grafton County, New Hampshire

[Depth is in meters below top of casing; X indicates the presence of a precipitation and (or) alteration; --, no data]

Well	Fracture depth (meter)	Fracture dip (degree)	Precipitate	Alteration	Rock type	Comments
CO7	**(Core collected from 6.61 to 21.85 m from the top of casing)**					
	6.73	14	--	--	Granite	--
	6.91	20	--	--	Granite	--
	6.96	65	X	X	Granite	--
	7.05	80	--	X	Pegmatite	--
	7.17	54	--	X	Schist	Rubble zone, dip taken on bottom of zone
	7.32	70	--	X	Schist	--
	7.88	60	--	--	Schist	--
	9.08	9	--	--	Schist	--
	9.25	4	--	--	Schist	--
	9.30	79	X	--	Schist	--
	9.40	71	--	--	Schist	--
	11.79	41	--	--	Schist	--
	13.17	58	--	--	Schist	--
	20.56	56	--	--	Schist	Sealed fracture
	20.93	39	--	--	Schist	Sealed fracture
	21.40	73	--	--	Schist	Sealed fracture
FSE5	**(Core collected from 17.29 to 61.35 m from the top of casing)**					
	18.85	36	X	--	Granite	--
	20.39	23	--	X	Granite	Greenish clay
	21.31	31	--	X	Granite	Greenish clay
	21.39	53	X	--	Granite	--
	22.54	26	X	--	Granite	--
	24.80	34	X	--	Granite	--
	24.80	34	X	--	Granite	--
	25.18	34	--	--	Granite	--
	25.38	53	X	--	Granite	--
	25.48	14	X	--	Granite	--
	25.54	42	X	--	Granite	--
	27.22	28	X	--	Granite	--
	27.65	40	--	--	Granite	--
	28.22	30	X	--	Granite	--
	28.35	27	X	--	Granite	--
	28.74	20	--	--	Granite	--
	28.81	26	X	--	Granite	--
	28.87	26	--	--	Granite	--
FSE5	**(Core collected from 17.29 to 61.35 m from the top of casing) --Continued**					
	28.87	26	--	--	Granite	--
	29.21	28	--	--	Granite	--
	29.21	28	--	--	Granite	--
	29.38	57	--	--	Granite	--
	29.38	50	--	--	Granite	--
	29.43	44	--	--	Granite	--
	29.57	59	--	--	Granite	--
	29.57	59	--	--	Granite	--
	30.63	59	X	--	Granite	--
	32.03	36	X	--	Granite	--
	32.10	18	X	--	Granite	--
	32.50	24	X	--	Granite	--
	33.10	17	X	--	Granite	--
	33.30	60	X	--	Granite	--
	33.40	65	X	--	Granite	--
	33.50	70	--	--	Granite	--
	33.80	26	--	--	Granite	--
	34.00	20	--	--	Granite	--
	36.00	10	X	--	Granite	--
	37.50	26	X	--	Granite	--
	38.70	56	X	--	Granite	--
	39.10	53	--	X	Granite	--
	40.90	20	--	X	Granite	--
	41.10	10	--	X	Granite	--
	41.50	60	X	X	Granite	--
	42.30	53	--	X	Granite	--
	48.40	14	--	--	Granite	--
	48.50	14	--	X	Granite	--
	49.0	46	--	--	Granite	--
	49.40	20	--	X	Granite	--
	51.90	50	X	X	Granite	--
	52.40	50	--	--	Pegmatite	--
	54.30	56	--	X	Granite	--
	58.20	90	--	X	Granite	--

Table 6. Description of fractures in core samples from boreholes CO7, FSE5, and TR2 near Mirror Lake in Grafton County, New Hampshire--Continued

Well	Fracture depth (meter)	Fracture dip (degree)	Precipitate	Alteration	Rock type	Comments
TR2	**(Core collected from 31.18 to 76.9 m below top of casing)**					
	31.4	--	--	X	Schist	Rubble zone, some sample loss
	31.56	7	X	X	Schist	Some sample loss
	31.67	8	X	--	Schist	--
	32.40	12	--	--	Schist	Some sample loss
	33.30	8	--	--	Schist	--
	33.63	6	--	--	Schist	Sealed fracture
	34.9	5	--	--	Schist	Sealed fracture
	34.93	3	--	--		--
	35.21	8	--	--	Granite	--
	35.31	21	--	--	Granite	Sealed fracture, calcite filled
	35.33	8	--	--	Granite	--
	35.55	3	X	--	Granite	--
	35.62	2	X	--	Granite	--
	35.71	9	X	--	Granite	--
	35.77	10	X	--	Granite	--
	35.85	11	X	--	Granite	--
	36.06	5	--	--	Granite	Sealed fracture, calcite filled
	36.10	10	--	--	Granite	--
	36.13	5	--	--	Quartz	--
	36.18	3	X	--		--
TR2	**(Core collected from 31.18 to 76.9 m below top of casing) --Continued**					
	36.33	13	--	--	Quartz	--
	36.40	40	X	--	Quartz	--
	36.43	25	--	--	Quartz	--
	36.52	9	--	--	Quartz	--
	36.60	1	--	--	Quartz	--
	37.02	2	--	--	Quartz	--
	37.25	5	--	--	Pegmatite	--
	37.25	6	--	--	Pegmatite	--
	37.61	5	X	--	Pegmatite	--
	38.16	10	--	--	Pegmatite	--
	38.24	22	--	X	Granite	Rubble zone
	38.28	15	--	--	Granite	Rubble zone
	38.33		--	--	Granite	--
	39.05	10	--	--	Granite	--
	42.84	13	--	--	Granite	Sealed fracture, calcite filled
	44.38	5	--	--	Schist	--
	44.43		--	--	Schist	--
	44.82	16	X	--	Granite	--
	45.59	60	--	--		--
	45.63	24	--	--	Granite	--
	48.28	62	--	X	Schist	Rubble zone
	49.68	60	--	--	Schist	Sealed fracture, calcite filled
	51.10		--	--	Schist	Rubble zone
	69.44		X	--	Schist	--

borehole CO7 ranged from 8.5 to 21.5 minutes. The rate of coring provides an indication of the relative hardness of the rocks. In CO7, the slowest drilling time was through schist, and the fastest time was through pegmatite. The natural fracture angles measured in the core ranged from 4 to 80^{0} from the axis of the core. Percent recovery ranged from 92 to 100 percent (table 6). A fracture zone was inferred during the drilling process when the drill rods advanced rapidly from 8.5 m below land surface. This zone corresponds to the core sample with only 92-percent core recovery.

A photograph of a core sample from CO7 (fig. 5) shows a fracture that is nearly perpendicular to the axis of the core. The foliation of the schist is steep and almost parallel to the axis of the core. Iron-oxide precipitates are visible as dark areas on the fracture face and in the surrounding rock matrix.

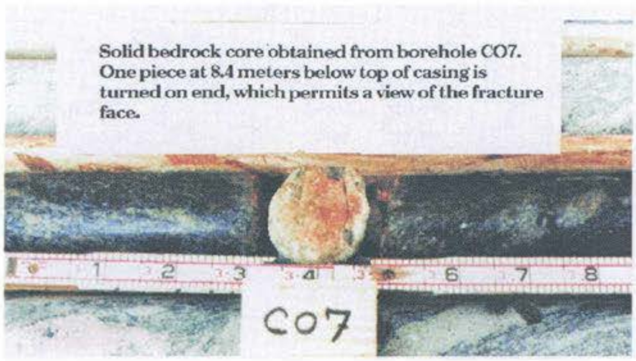


Figure 5. Bedrock core from borehole CO7 near Mirror Lake in Grafton County, New Hampshire (Ruler is in feet).

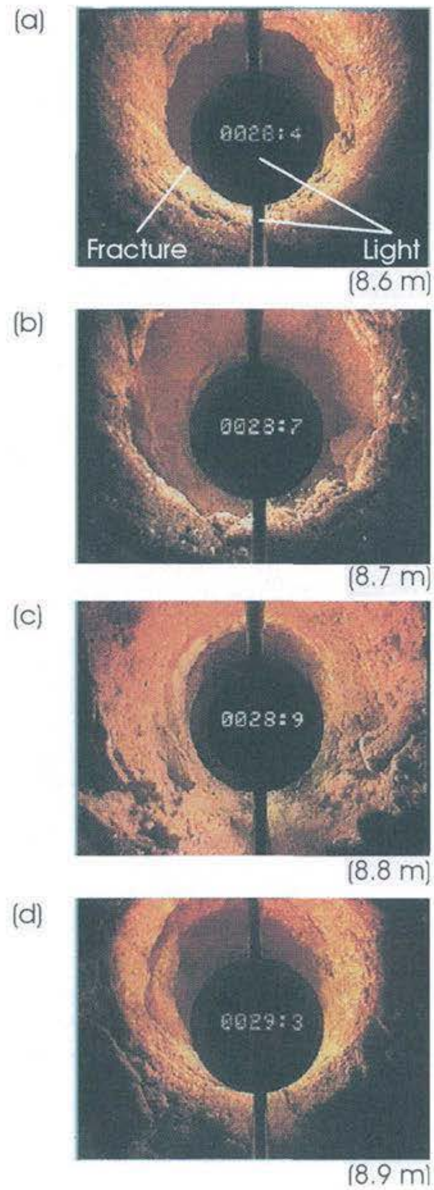


Figure 6. Borehole-video image from CO7 near Mirror Lake in Grafton County, New Hampshire. (The depth, in feet below top of casing, is superimposed on the image.)

The same zone can be observed in the borehole using the color borehole-video camera. The borehole image shows a wide-open fracture that is nearly horizontal. The fracture is not parallel to the foliation of the schist, and the bedrock appears to be oxidized. Borehole-video images of the zone at approximately 8.7 m are shown in figure 6. The depth (in feet below top of casing) is superimposed on the images. A fracture seen in the image at 8.6 m (28.4 feet) (fig. 6a) dips from the lower right side of the image towards the upper left side of the image. The borehole is enlarged and angular at 8.7 to 8.8 m (28.7 to 29.3 feet) (figs. 6b and 6d).

A total of 45.7 m of solid core was obtained from borehole TR2. The coring started approximately 18 m below the bedrock surface at a depth of 31.2 m below top of casing. The bottom of the core sample extended to 76.9 m below the top of casing. In borehole TR2, the rate of penetration ranged from 6 to 86 min per 1.5 m of core. Average time to core a 1.5 m length was 27 min. The hardest and most difficult rock to penetrate was a quartz vein, from 57.2 to 58.7 m below land surface and corresponded to the slowest drilling time. The fastest 1.5-m core sample was obtained from 52.6 to 54.1 m below land surface, which penetrated granite. Fracture angles measured in the core obtained from TR2 ranged from 0 to 62° from horizontal. Several sealed microcracks were identified in the core at approximately 34 to 38 m. Many of these fractures were sealed with calcite deposits that measured less than a few millimeters wide. Four intensely fractured zones, which were reduced to rubble, were identified in the core at the following depths below land surface: 38.24, 38.28, 48.28, and 51.1 m. Percent recovery for each core run ranged from 90 to 100 percent.

Characterization of Lithology in Boreholes

Rock types in all the boreholes were described in terms of color, mineralogy, texture, size, and shape. The characterization of the lithology (appendix 1) is based on descriptions of drill cuttings and interpretations of video images. A graphic log of the rock types also is provided in appendix 1 with lithologic patterns indicating the location and extent of rock types. Each lithologic contact shows the highest and lowest boundaries of the contact in the borehole. The altitude of the contact or the depth below the top of casing (in meters) can be read directly off the scales on the graphic log. The midpoint of the contact was used for all descriptive purposes and for the calculation of the thickness of the unit. For each borehole, the contacts were arbitrarily depicted as sloping from right to left unless they were observed to dip in a different direction relative to adjacent features, such as the foliation of schist or the contact of another rock unit. For example, the granitic dike located at a depth of 11.0 m below the top of casing in CO1 is shown to dip from right to left, which indicates that it does not cross-cut the foliation of the schist; however, the quartz vein at 29.0 m and the aplite vein at 94.8 m are shown dipping left to right (appendix 1, CO1). The actual foliation of the schist is not depicted. Rather the graphic pattern representing schist has a fixed slope dipping from right to left. All borehole logs in appendix 1 are shown with a horizontal exaggeration, in that each column representing a borehole is much wider than it would be if it were drawn to scale. Consequently, the lithologic contacts are steeper in the field than they appear in the graphic log.

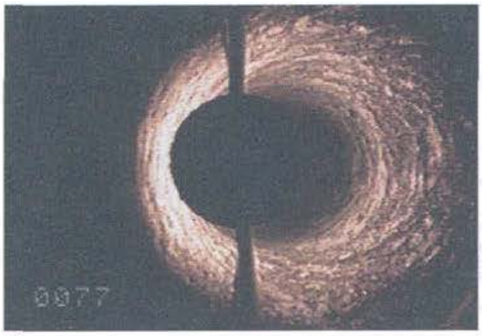
In addition to the graphic log, a description of rock units is provided on the right side of appendix 1 under "DESCRIPTION." The bold text in the description is a generalized log, which identifies all units that were greater than 1 m in thickness. The bold text highlights a general log of the borehole lithology. The detailed description includes information on the rock type, color, grain size, texture, mineral content, foliation characteristics, and thickness of the unit observed in the borehole. Selected terms that were used in the descriptive logs are defined in the glossary.

Figure 7 shows selected borehole-video images for the rock types observed in the boreholes. The images are all taken under water with the light attachment pointed downward in the center of the borehole. The depth, in feet below top of casing, is superimposed on the image. The well name and depth in meters is provided below the image. Typical borehole exposures of schist are shown in figures 7a, b, and c. A fine-grained, strongly foliated schist with steeply dipping foliations is shown in figure 7a. Figure 7b shows a coarse-grained schist with augens and a pegmatite dike below the schist. Figure 7c shows a schist with a coticule (quartz and garnet) lens, which looks uniform and gray. Figure 7d shows a migmatite that is characterized by a gneissic texture and swirled biotite schlieren. Granites are typically light in color, medium to coarse grained and equigranular (figs. 7e and f). Figure 7e shows a granite with a schist xenolith on the left side of the image. Figure 7f shows granite and a diabase dike that intruded the granite. The diabase dike, on the lower half of the image, is characterized by dark color and small white minerals (phenocrysts). Pegmatite that is characterized by large quartz and feldspar crystals is shown (fig. 7g). Figure 7h shows a fine-grained aplite dike that intruded as a schist, which is shown below the aplite dike.

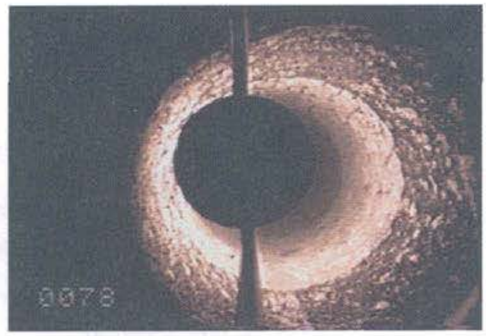
The distribution of the rock types in the well fields indicates the general differences in the FSE and CO well fields. The FSE well field is predominantly comprised of granitoids, whereas the CO well field is predominantly schist. The distribution of rock types was determined for 15 index boreholes, which included 13 of the deep areally-distributed boreholes plus the deepest borehole from each of the two well fields (FSE4, CO1, FS1, FS2, FS3, FS4, FS6, T1, TR1, TR2, R1, H1, IS1, CO11, RR1). The analysis indicates there are roughly equal amounts of granitoids and schist. Pegmatite and diabase comprise less than 5 percent of the rock. The relative abundances of the rock types that were encountered in the boreholes are summarized in table 7.

Fracture Characterization in Boreholes

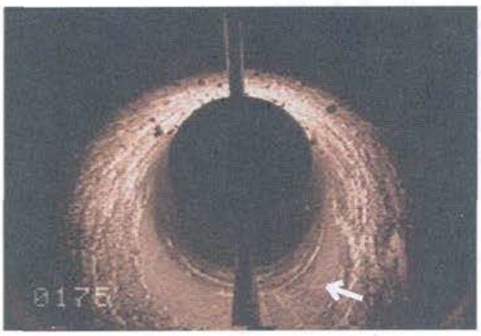
Fractures that were identified in the boreholes using borehole-imaging techniques are shown in appendix 1. Although microcracks were observed, they were not counted as fractures and were not recorded in appendix A. Fractures are represented in the column to the right of the graphic lithology log. Each line in the column that represents a fracture shows the highest and lowest intersection of the



(a) Schist (H1, 23 m)

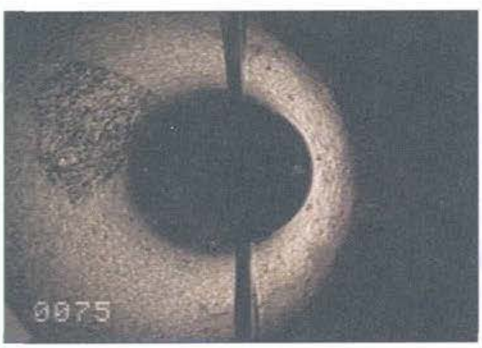


(b) Augen schist (H1, 24 m)

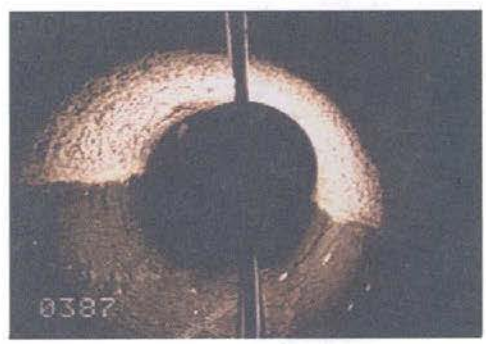


(c) Coticule layer in schist (H1, 53 m)

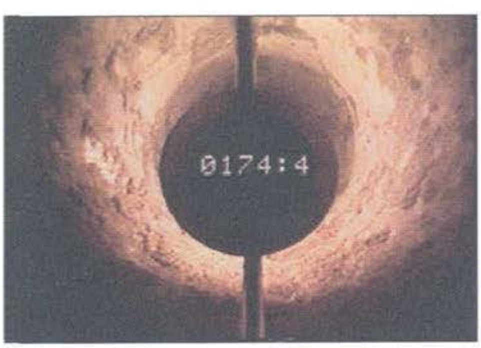
(d) Migmatite (CO7, 39 m)



(e) Schist xenolith in granite (IS1, 23 m)



(f) Diabase dike in granite (IS1, 118 m)



(g) Pegmatite (CO7, 53 m)

(h) Dike in schist (CO7, 54 m)

Figure 7. Selected borehole-video images of rock types near Mirror Lake in Grafton County, New Hampshire.

Table 7. Relative proportions of rock types and fracturing in selected boreholes near Mirror Lake in Grafton County, New Hampshire

INDEX WELLS: Based on 0.3 meter intervals, from the following boreholes: FSE4, CO1, FS1, FS2, FS3, FS4, FS6, T1, TR1, TR2, R1, H1, IS1, CO11, RR1						
	Schist	**Granitoid**	**Gneiss**	**Pegmatite**	**Diabase**	**Quartzite**
Abundance of rock type shown as a percent of the total number of observed intervals	45.5	46.3	2.8	4.7	0.4	0.2
Abundance of fractures shown as a percent of the total number of observed fractures	22.9	72.8	1.0	2.6	0.5	0.2
FSE WELL FIELD: Based on 0.3 meter intervals, from the following boreholes: FSE1, FSE2, FSE3, FSE5, FSE6, FSE7, FSE8, FSE9, FSE10, FSE11, FSE12, FSE13						
	Schist	**Granitoid**	**Gneiss**	**Pegmatite**	**Diabase**	**Quartzite**
Abundance of rock type shown as a percent of the total number of observed intervals	23.0	63.2	1.6	9.2	0.0	0.4
Abundance of fractures shown as a percent of the total number of observed fractures	20.7	73.6	1.0	3.4	0.0	1.0
CO WELL FIELD: Based on 0.3 meter intervals, from the following boreholes: CO2, CO3, CO4, CO5, CO6, CO7, CO8, CO9, CO10						
	Schist	**Granitoid**	**Gneiss**	**Pegmatite**	**Diabase**	**Quartzite**
Abundance of rock type shown as a percent of the total number of observed intervals	65.5	18.7	11.2	4.4	0.0	0.0
Abundance of fractures shown as a percent of the total number of observed fractures	65.7	28.9	3.6	1.8	0.0	0.0

fracture in the borehole. The actual altitude to the top or bottom of the fracture can be read in meters from the scale to the left of the column in meters. Depth below top of casing, in meters, can be read off of the column furthest to the left in appendix 1. As in the lithology column, the column representing the borehole is much wider or horizontally exaggerated than it would be if it were drawn to scale. Also, the fractures were arbitrarily depicted sloping from left to right, unless they were observed to be dipping in a different direction relative to adjacent fractures, lithologic contacts, or to the foliation of the host rock such as schist with a graphic pattern that dips from right to left. If a fracture were parallel to the foliation of the schist, it would be shown dipping from right to left in appendix 1. If a fracture were observed to cross-cut the foliation of schist it would be shown dipping from left to right.

Fracture attributes listed for each fracture are indicated to the right of the fracture column. The attributes' codes used in appendix 1 are summarized in table 8, and example borehole images are provided for frequently used attribute codes (fig. 8a-o). The first column in appendix 1 indicates the dip score, which represents a relative measure of the dip angle. Each fracture is characterized as horizontal, moderate, or steep. Horizontal (h) indicates a fracture that has intersected the borehole between 0 and 30° from horizontal (fig. 8a). Steep (s) indicates a fracture that has intersected the borehole at an angle greater than 60 degrees from the horizontal (fig. 8c), and moderate (m) defines all fractures between horizontal and steep (fig. 8b). These scores were assigned after calculating the dip angle as the inverse tangent of the distance along the axis of the borehole from the highest point of the fracture to the lowest point of the fracture divided by the diameter of the borehole. The diameter was assumed to be a constant 152 cm for all measurements. The dip score is not necessarily the actual dip of the fracture because the deviation of the borehole is not taken into account. The dip score indicates the angle at which the fracture intersects the borehole.

The aperture, or openness, of a fracture can be related to the hydraulic properties of the fracture according to Snow (1968) and Borchers and others (1993). The current regional and local stress fields and fracture infilling can influence the openness of a fracture. However, determining the aperture of a fracture in the subsurface is a problem. Measuring the aperture of a fracture in a borehole is physically difficult and the apparent aperture in a borehole can be greatly changed during drilling. Although the mechanical fracture aperture is affected by the drilling process, a visual estimation of each fracture was made from video logs and is reported for each fracture. The aperture code, which is in the second attribute column (appendix 1), indicates a qualitative score assigned to each fracture. A "narrow" aperture (n) was assigned to all fractures that appeared to be less than 0.5 cm wide (fig. 8d.). Open fractures that appeared to have an aperture greater than 1 cm were assigned "w" for wide (fig. 8f). All fractures that appeared to be wider than 0.5 cm but less than 1 cm were designated as moderate and were assigned the code "m" (fig. 8e). The aperture code is a subjective determination or estimation of the aperture of the fractures.

Table 8. Codes used to describe fractures shown in Appendix 1

[<, less than; °, degree; ≥, greater than or equal to; >, greater than; cm, centimeter]

	Dip	Aperture	Attributes
Dip			
Near horizontal < 30°	h	--	--
Moderate 30° to 60°	m	--	--
Steep > 60°	s	--	--
Aperture			
Narrow < 0.5 cm	--	n	--
Medium 0.5 to 1 cm	--	m	--
Wide ≥ 1 cm	--	w	--
Attributes			
Alteration	--	--	a
Abutting fractures	--	--	b
Borehole enlargement associated with the fracture	--	--	e
Fracture zone	--	--	Fz
Jagged and angular	--	--	j
Multiple fractures (number indicates the number of fractures)	--	--	mf(2)
Oxidation on or near fracture face	--	--	o
Partial fracture	--	--	p
Crosses foliation	--	--	xf
Parallel to foliation	--	--	pf
Sealed	--	--	s
Liesegang bands	--	--	L
White precipitate eminating from fracture	--	--	w
Water-bearing zone during drilling	--	--	y

Several codes are used to characterize the fractures detected in the boreholes. For instance, codes used to describe the physical or mechanical nature of the fractures include "d" for diffuse or porous-looking rock matrix, "e" for an enlarged borehole, "j" for a jagged or angular fracture (fig. 8g), and "p" for a fracture that partially intersects the borehole. Borehole enlargement frequently occurs where the rock has been removed between two or more parallel fractures. Enlargement sometimes occurs where multiple fractures intersect the borehole. These zones also tend to exhibit a jagged or angular appearance. Abutting fractures, which are seen in the video as one fracture that abuts another without crossing, are noted with the code "b" (fig. 8h). Multiple fractures occurring at the same location are noted with "mf." For example, two closely spaced fractures that are observed in the borehole would be annotated with "mf2". Multiple fractures are shown in figure 8i. A zone that is intensely fractured is coded "fz," which indicates a fracture zone (fig. 8j). In one borehole, TR1, some parts of the borehole are extremely fractured. The locations of these zones were noted. The fractures, however, were too numerous to count.

Microcracks that were apparent in the borehole video images were not recorded or counted as fractures in appendix 1. For example, partially sealed microcracks that were observed in the core sample of TR2 were not identified in the video logs as fractures. Microcracks are locally extensive and are too numerous to count.

Several codes were used to describe the fracture relative to characteristics of the adjacent rock mass. A fracture that appeared to be parallel to the foliation of schist or gneiss is noted by "pf" (fig. 8k); a fracture that appeared to cross-cut the foliation is coded as "xf" (fig. 8l). Fractures were also described for the occurrence of mineralizations or coatings. If the rock mass adjacent to the fracture or the fracture face appeared to be iron stained, then the fracture is annotated with "o" (fig. 8m). If the iron-staining occurred in rhythmic bands, it was coded "L" to indicate Liesegang banding. If the matrix around the fracture appeared to be altered, it was annotated with an "a" (fig. 8n). If the fracture appeared to be sealed, it was coded "s" (fig. 8o) and is shown as a dashed line in the graphic column. If there was white precipitate emanating from the fracture and precipitating on the adjacent rock, it was annotated with "w".

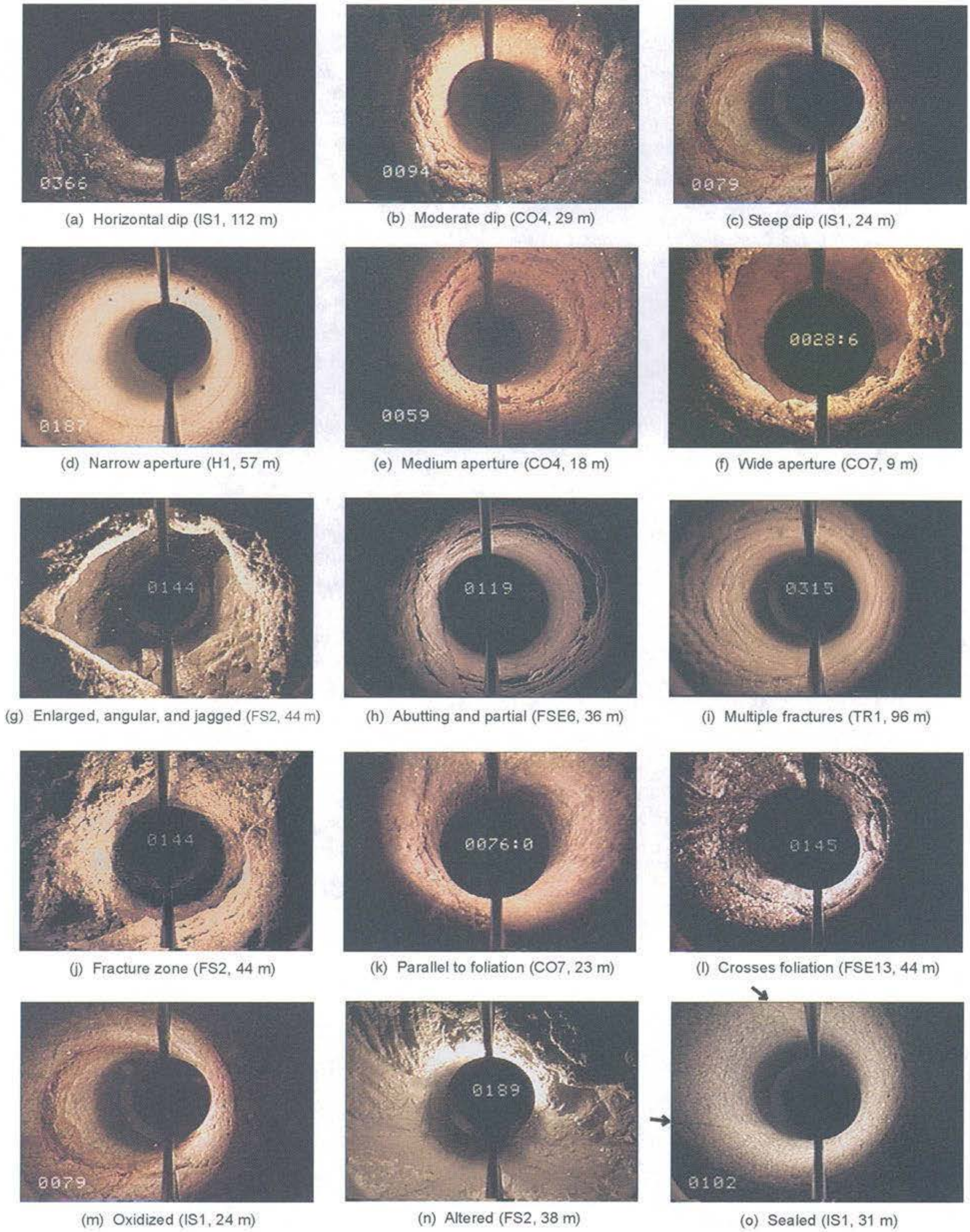


Figure 8. Selected borehole-video images showing frequently used fracture descriptors in boreholes near Mirror Lake in Grafton County, New Hampshire.

This precipitate was only observed in a few boreholes in the FSE well field, where it is thought that the white calcite precipitate was caused by locally high pH levels (P.T. Harte, U.S. Geological Survey, written commun., 1990). Fractures that produced water during drilling were noted with a "y." Any additional fracture characteristics that could not be addressed by codes in the fracture-attribute column were described in parenthesis under the lithology descriptions.

Discussion of Fractures and Lithology

Some general observations that can be made from the detailed logs (appendix 1) are summarized in this section. Some generalizations can be made about the distribution of fractures with respect to spacing, depth, and rock type, as well as the distribution of rock types with respect to location, depth and topographic setting.

Fracture Distribution

The distribution of fracture orientation and frequency is highly affected by the direction of sampling. Subvertical boreholes, such as those drilled in this study, exhibit vertical bias. Subvertical boreholes undersample steeply dipping fractures relative to the total population of fractures and relative to the number of fractures identified in outcrop mapping. Mathematical corrections, which were described by Terzaghi (1965) and Barton and Zoback (1990), can be applied to oriented fracture data to correct or to reduce this bias. Because the fracture data in this report are not oriented, however, the correction cannot be applied.

A borehole represents a near-vertical scan-line along which fracture data can be compiled. Usually, a borehole intersects multiple fractures that belong to different fracture sets. The length between the fractures along the borehole can be computed, and a frequency distribution of the spacing lengths can be generated. For this analysis of fracture distributions, the distance between all fractures (regardless of the fracture orientation) in the index boreholes (appendix 1) was measured. The arithmetic average of the interfracture spacing was 2.1 m, which relates to an average fracture density of 0.47.

The interfracture spacings in all 15 index boreholes were sorted and plotted in a histogram as a function of length. The frequency plot was then compared to theoretical-frequency distributions. The distribution of interfracture spacing length in the index boreholes can be described by a power law. The power-law function was fit to the observed data (the frequency of the histogram) by the method of least squares with a coefficient of determination of 0.80. The fitting parameters for the function $y=ax^b$ were a=20.6, b=-0.85, and x varied as the length of spacing. There were 1,244 observations used in this analysis. Several frequency distributions were tested, including the power, exponential, poisson, and logarithmic functions. The best fit was obtained for the power function.

The power-law distribution, as well as an exponential distribution, has a high frequency of closely spaced fractures and fewer fractures with large interfracture spacing. The results from the Mirror Lake analyses are similar to the results of other investigations in fractured crystalline rock. In other studies, the expected frequency distribution for all fractures, regardless of their orientation or fracture type, were described by exponential distributions (Snow, 1968 and 1970; Priest and Hudson, 1976; Rives and others, 1992).

The frequency distribution of interfracture spacing of all fractures in a borehole is different than the distributions for interfracture spacings of individual fracture sets. In order to analyze the frequency distribution of interfracture spacings for individual fracture sets, oriented fracture data are required. Oriented data can be separated into fracture sets that exhibit similar orientations, and interfracture spacings can be calculated. The frequency distribution of interfracture spacing for fractures that belong to a single fracture set follows a log-normal distribution (Narr and Suppe, 1991) or a gamma distribution (Huang and Angelier, 1989).

Distribution of Fractures With Depth

Several investigators have reported that the frequency of fractures decreases with increasing depth (Fuller, 1905; Clapp, 1910; Ellis 1909; Jahns, 1943; Davis and Turk, 1964; Hansen and Simcox, 1994). These analyses were based on fracture data collected in quarries and from water wells drilled in bedrock. A statement by Cushman and others (1953) is typical:

"The deeper a well is drilled beyond a certain depth the less is the chance of striking fractures....It is probable that [horizontal sheeting joints] do not exist at depths much below 300 ft."

Many of these investigators recommended that because fracture frequency decreases with depth, water wells in New England should not be drilled deeper than 45 to 100 m. A decrease in the frequency of fractures below 100 m can be expected if sheeting joints do not extend beyond 100 m and near vertical wells undersample steep fractures. In other investigations of bedrock in Nevada, South Carolina, and California, however, little to no decrease in fracturing was detected in wells up to 300 m deep (Seeburger and Zoback, 1982).

In this study, the distribution of fractures with respect to depth does not follow a linear distribution. Highly fractured intervals usually are present in the top 100 m of the boreholes. Some less numerous, highly fractured zones exist at depths greater than 100 m. A scatterplot of fracture density (the frequency of fractures divided by the interval length for each 3-m interval) plotted for all index boreholes as a function of depth below top of casing is shown in figure 9. In general, the plot shows a higher density of fractures at shallow depths than at greater depths. Unfractured zones or minimally fractured zones, which plot on or near the x-axis, were observed at all depths. Thus, the linear-correlation coefficient between depth and fracture frequency is low, at only -0.05.

Another way to analyze these data is to view the cumulative fracture frequency for individual boreholes as a function of depth (fig. 10). The cumulative frequency of fractures for all index boreholes that were drilled deeper than 100 m were plotted against depth below top of casing. Each curve in figure 10 a-d represents the cumulative-fracture frequency for an individual borehole plotted against depth. The plots show that the number of fractures per unit length of

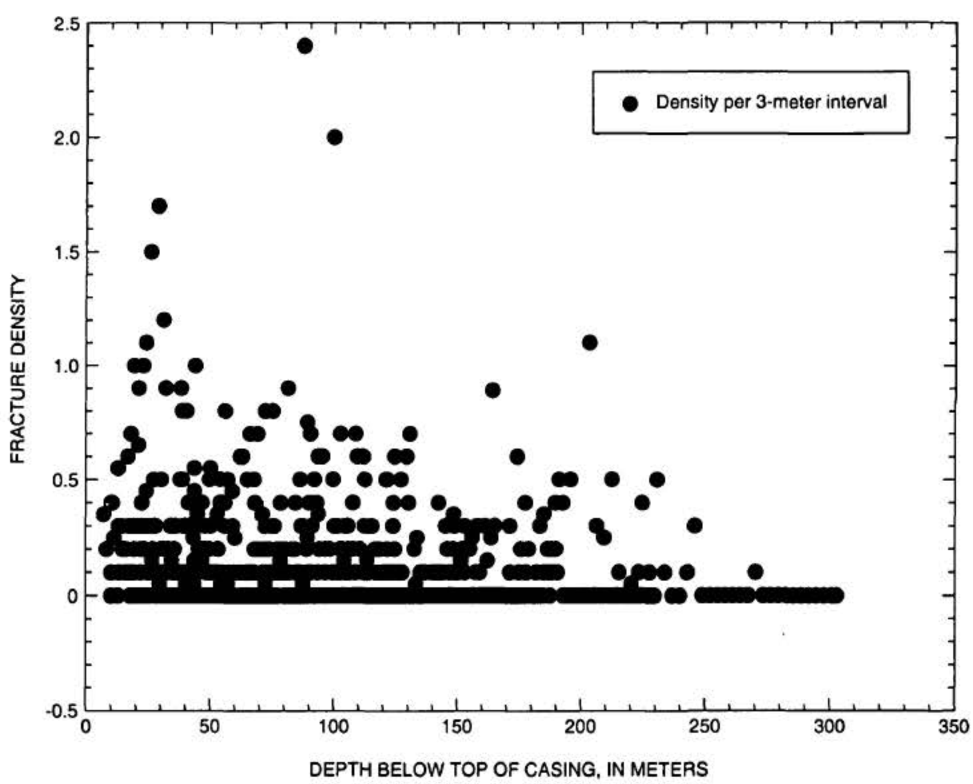


Figure 9. Fracture density as a function of depth below top of casing in selected boreholes near Mirror Lake in Grafton County, New Hampshire. Fracture density is shown for each 3-meter interval in the following wells: FSE4, CO1, CO11, FS1, FS2, FS3, FS4, FS6, IS1, TR1, TR2, R1, RR1, H1, and T1 (fig. 1).

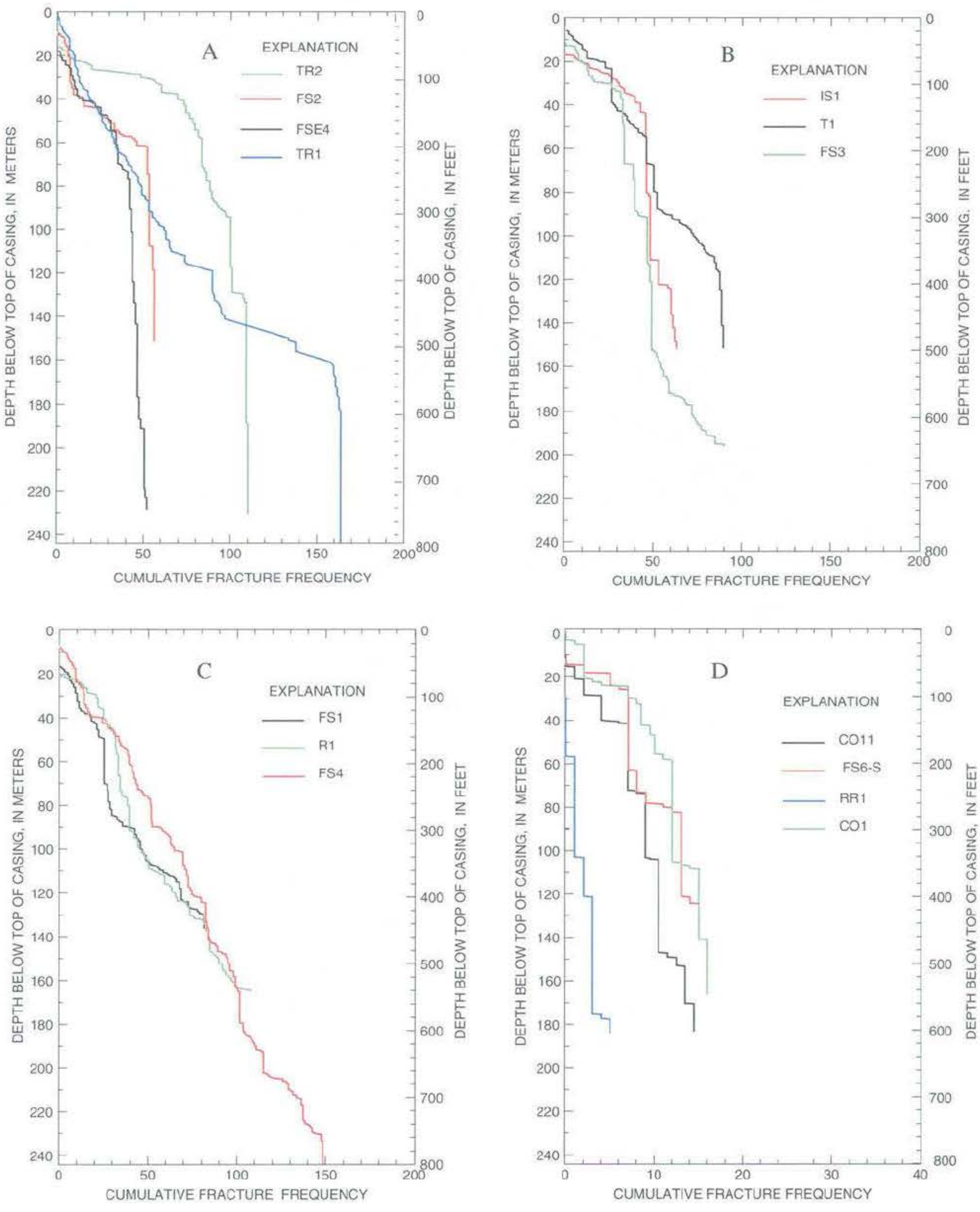


Figure 10. Cumulative-fracture frequency as a function of depth below top of casing in selected boreholes near Mirror Lake, Grafton County, New Hampshire. (The scale for the cumulative frequency in figure 10D is expanded, because there are fewer than 20 fractures in the wells.)

borehole is not uniform. The stair-step shape of the curves indicates slight clustering of fractures. The results were plotted in groups that exhibited similar fracturing characteristics with increasing depths. Figure 10a shows a flattening or reduction in the slope of the curves at greater depths, which indicates a decrease in fracturing with depth. These cumulative-fracture-frequency curves show a significant decrease in fracturing from 60 to 100 m to the bottom of each borehole (fig. 10a). The boreholes in figure 10b exhibit a decrease in the cumulative-fracture frequency in the middle range depths, and then a small increase near the bottom of the wells. Figures 10c and d show little to no decrease in the cumulative-fracture frequencies over the length of the boreholes, from 0 to 240 m in depth. Although the total number of fractures in the boreholes shown in figure 10d is significantly less than all of the other boreholes in the analysis, the curves do not exhibit a decrease with increasing depth. The wells in figure 10d are from the same topographic setting. They are all in valley settings. Borehole IS1, which is also in the valley, does not plot in this group. Collectively, these plots suggest that there is no uniform, simple model that describes the distribution of fractures with depth (up to 240 m) for all of the boreholes.

Detection and Location of Faults

Faults that exhibit displacement were difficult to identify visually in the studied boreholes, but other observations can help to identify faults in the subsurface. In FS5, the fracture zone near the bottom of the borehole at a depth of 65 m exhibited slickensides, quartz, and sulfide minerals. Slickensides, which indicate a fault, are detected only if the rock chips are sufficiently large. These samples from FS5 were approximately 2 to 3 cm in length. In borehole CO5 (at 12.4 m) and in CO10 (at 42.1 m) faults were identified by the presence of fault gouge. The gouge was observed in video images, as well as in the rock cuttings and drilling logs. The fault in CO10 is located along the strike of the prominent (1-meter wide) fault in the highway outcrop, which strikes and dips N40°E, 83°SE (Barton, 1997). Borehole CO10 was drilled with the intent of intersecting this zone. The siting of the CO10 fault was determined by borehole radar surveys in CO7 (J.W. Lane, U.S. Geological Survey, written commun., 1995) and standard surveying methods.

The 50-m thick deposit of till at TR1 was likely fracture controlled (Carl Koteff, U.S. Geological Survey, written commun., 1995). The top 50 m of bedrock in borehole TR1 and the top 40 m in TR2 exhibit numerous and closely spaced fractures (appendix 1). These two boreholes exhibit zones that appear to be unusually fractured relative to other boreholes in the study area.

Fracture Distribution With Respect to Rock Type

Randall and others (1988) reported that fractures in homogeneous rocks such as granitoids are more extensive and more permeable than fractures in micaceous metasedimentary rocks. In general, fractures in the granitoids are more planar and shorter than are fractures in metasedimentary rocks (Barton, 1993). The fractures that were mapped in the granitoids in the highway outcrop exhibit more brittle fracturing and have the highest connectivity (Barton, 1996). The frequency of the fractures observed in the boreholes (appendix 1) generally supports these findings. In the 15 index boreholes, the frequency of fractures with respect to the rock type shows that approximately 73 percent of the total number of fractures were in granitoids, whereas 23 percent were in schist (table 7). Gneiss was relatively unfractured compared to schist and the granitoids, with approximately 1 percent of the total number of fractures. Less than 5 percent of the total number of fractures were in pegmatite, diabase, and quartzite. Although diabase in dikes is intensely fractured with cooling joints, these fractures do not extend into the host rock. These cooling joints were not included in appendix 1, and they were not included in the fracture frequency. The comparison of rock type with respect to fracturing indicates that fractures are lithologically controlled. In general, the granitoids are more intensely fractured than the schist and gneiss, and pegmatites, diabase, and quartzite are relatively unfractured.

Although some fractures were at or near the contacts of rock types, as in CO7 at approximately 28 m (appendix 1), fractures are not typically observed at lithologic contacts. Fractures observed in the borehole generally do not extend from one rock unit to another. These generalizations are corroborated by the observations of Barton (1996) for the fractures on the highway outcrop.

Distribution of Rock Types

Some generalizations can be made about the distribution of rock types based on lithologic data presented in appendix 1. A comparison of the rock types with respect to location indicates that the granitoids east of Norris Brook are equigranular and are likely the two-mica granites. In borehole FS5, which is west of Norris Brook (fig. 2), the igneous rocks exhibit a blotchy-looking, porphyritic texture in a swirled and partially foliated, gneissic matrix, and are likely Kinsman Granodiorite. These rock types, although identified in only one borehole, are consistent with the map of Barton (1997). Schist, gneiss, pegmatite and diabase are found locally throughout the study area. There were, however, varying proportions of the igneous and metamorphic rocks locally throughout the Mirror Lake area.

The rock types that were mapped in the index boreholes were compared with physical parameters, such as depth, altitude, and topographic setting. The linear correlation coefficients for these analyses are less than 0.2, indicating that no significant linear correlation exists between rock type and depth, altitude, or topographic setting.

The rock types change frequently (approximately every 5 to 9 m) in the index boreholes (appendix 1). The length of each rock unit exposed in each borehole was determined and averaged for all the index boreholes. Only those rock units that spanned 30 cm or more of the borehole length were used in this analysis. The average length of schist exposed in the index boreholes is 5.3 m. The average length of granitoid units is 4.6 m. Pegmatite and diabase units in the index boreholes were less than 1 m long (appendix 1).

Observations of Drilling and Its Effect on the Boreholes

The locations of lithologic changes and depths of fractures that were noted in the drilling logs were generally within a meter of the locations determined from the video-camera images. This correlation indicates that there is no significant lag in the delivery of rocks to the land surface during the drilling process. Observation of drill cuttings during drilling only allows for the identification of major changes in rock types. Additional testing, such as borehole video camera logging, is needed to obtain detailed interpretations of the lithology and locations of fractures.

A common notion among drillers is that percussion drilling chokes fractures in boreholes with sediments and rock fragments. This theory is not supported by the video images. Direct inspection of the fractures in the boreholes shows that generally there are no drill cuttings on the fracture surfaces.

Boreholes that were logged with the video camera multiple times sometimes showed some precipitation of manganese and (or) iron oxides and some sedimentation. These minerals and detrital particles all coat the walls of the borehole and obscure the view of the rock type and fractures. Therefore, it is preferable to log the borehole soon after drilling to avoid these problems.

With the video camera, no particles or sediments were seen flowing from the fractures. Fractures that were identified with the borehole flowmeter as flowing did not appear to exhibit flow in the video images. If the water was pumped below an inflowing fracture, the video camera would likely "see" cascading water. If the water level was above an inflowing fracture, however, the video camera would not necessarily "see" the inflow. The method of looking for flow in fractured crystalline rock, therefore, does not appear to be a reliable method for describing the flow regime.

SUMMARY AND CONCLUSIONS

Forty boreholes, ranging in depth from 60 to 305 m, were drilled into crystalline bedrock in the area of Mirror Lake in Grafton County, N.H. The country rock is predominantly comprised of pelitic schists that have been intruded by younger granitoids, pegmatites, aplites, and diabase.

The drillers' estimates of yield for the boreholes drilled for this study ranged from less than 3 L/min to 378 L/min. These estimates are similar to those for wells drilled for domestic supply in Grafton County. Generally, 1 to 3 water-bearing zones were identified in each borehole at the time of drilling. These observations of yield made at the time of drilling, were frequently confirmed by flowmeter surveys, and appear to be accurate preliminary indicators of water-bearing zones.

Open-hole water levels in the boreholes tend to be in the steel casing. These measurements were made in boreholes that were open over the entire length of the borehole. Eight of the boreholes exhibit water levels that are above the land surface. Three of the boreholes (TR2, FS6, and CO10) flow during most of the year.

All boreholes were inspected visually with a submersible color video camera in order to produce detailed profiles of the subsurface lithology and fracturing. These video images were used to describe the distribution of lithology and fractures in the subsurface. In addition, these data were used to compare fracturing, lithology, and physical parameters such as alteration and oxidation. No linear correlation was found between rock type and depth, altitude, or topographic setting. Correlation coefficients for these analyses were less than 0.2.

The distribution of interfracture spacing lengths between all of the fractures in the index boreholes at Mirror Lake can be best described by a power function. In this distribution, there are numerous closely spaced fractures and decreasing amounts of fractures separated by large, unfractured intervals of rock. A coefficient of determination of 0.80 was obtained with a least squares regression analysis.

The distribution of fractures with respect to depth was examined. The distribution data do not show a significant relation between fractures and depth; however, there is a weak linear correlation of 0.05. Cumulative-fracture frequency plots provide a graphic method for analyzing the distribution of subsurface fractures. Fracture-frequency plots for selected boreholes show that some of the boreholes show little to no decrease in cumulative-fracture frequency. The boreholes that were used for this analysis were between 120 and 300 m deep. Some boreholes exhibited a decrease in fracturing below depths of 60 to 90 m. Half of the index boreholes that were used for this analysis exhibited a decrease in the cumulative-fracture frequency. These analyses suggest that no simple model of fracture density and depth correlation would fit all of the boreholes in the study area.

The distribution of rock types is spatially heterogeneous. Drill logs and borehole images indicate the boreholes penetrate varying amounts of schist, gneiss, granitoids, pegmatite, aplite, and diabase. The FSE well field is predominantly igneous and the CO well field is mostly metamorphic. Approximately 70 percent of the rocks in the boreholes in the CO well field were schist. In the FSE well field, approximately 70 percent of the rock units were igneous, including granite, pegmatite, and aplite. The 15 index boreholes, which include the deepest borehole in each of the two well fields and are boreholes that distributed throughout the study area, consist of 50 percent metasedimentary rocks and 50 percent granitoids. The rock types change frequently over the length of the boreholes (approximately every 5 to 9 m). The average length of schist in the index boreholes was 5.3 m, and the average length of granitoid units was 4.6 m. The average lengths of pegmatite and diabase units in the index boreholes were each less than 1 m.

Although metamorphic and igneous rock each comprise 50 percent of the rock types in the boreholes, the majority (73 percent) of fractures were in boreholes in granitoids. Approximately 23 percent of the fractures were in schist. Less than 5 percent of the fractures were in pegmatite, diabase, quartzite, and gneiss. These results indicate that the fracturing is lithologically controlled. There was no preferential fracturing along the contacts of the rock types, and few of the observed fractures in the boreholes crossed multiple rock types. The composition of the boreholes is consistent with the composition of bedrock outcrops in the study area.

The borehole drilling and borehole imaging data provided in this report can be used for more detailed analyses of fracture distributions and to determine the interrelations between characteristics of fractures (in outcrops and the subsurface), lithology, and hydraulic properties of bedrock. These additional analyses, which are beyond the scope of this report, would enable a quantitative assessment of geologic controls on ground-water flow and the transport of dissolved chemicals.

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GLOSSARY

Air-hammer rotary drilling. See percussion rotary drilling.

Allotriomorphic granular. Crystalline texture of an igneous or metamorphic rock characterized by crystals that are mostly anhedral, or without crystalline form.

Anhedral. A descriptive term for a mineral grain that does not exhibit its own crystal outline.

Anatectic. A term that is used to describe a rock that has undergone anatexis, which is a partial to complete melting of existing rocks.

Annulus. A drilling term used to describe the space in a borehole around the casing or around the drill stem.

Aphanitic. Texture of an igneous rock in which the crystalline components are not distinguishable by the unaided eye.

Aplite. Light-colored igneous rocks characterized by a fine-grained allotriomorphic-granular texture. They consist essentially of quartz, potassium feldspar, and acid plagioclase.

Augen. A large lenticular mineral grain or cluster of grains in foliated metamorphic rocks. In cross-section the augen is eye-shaped.

Diabase. A general term for a group of igneous rocks that are rich in mafic minerals and are typically dark in color. They can be intrusive (as in a dike) or extrusive (as in volcanics).

Borehole. An open hole created in the subsurface by drilling. It is synonymous with well.

Borehole development. A procedure followed after drilling a borehole in order to remove fine particulate rock fragments and drilling fluids from the borehole.

Boudin. Sausage-shaped, elongated structures that are formed along bedding planes from the stretching, pinching, and failure of competent layers, which are surrounded by less competent material. The boudins observed in this sudy area are rich in diopside (a calcium silicate).

Brecciated. A descriptive term for a rock structure that exhibits an accumulation of angular fragments.

Chill margin. The border or marginal area of an igneous intrusion, characterized by finer grain than the interior of the rock mass, owing to more rapid cooling.

Clinochlore. A magnesium-rich mineral in the chlorite group. It is usually green. It is common in metamorphic assemblages and is frequently an alteration product of pyroxenes, biotites, and garnet in igneous rocks.

Contact. A plane or irregular surface between two different types or ages of bedrock or unconsolidated sediments.

Core. A cylindrical sample of bedrock obtained by use of a special drilling bit and retrieved by use of a core barrel.

Core barrel. Two nested tubes above the drill bit, the outer rotating with the bit, the inner receiving and preserving a continuous section or core of the material penetrated.

Coring-induced fractures. Fractures caused by the drilling process. The occurrence is related to the stresses imposed during drilling and to the location of structural flaws in the rock matrix.

Core recovery. A measurement of the length of the core that was obtained relative to the length that was drilled. The core recovery is expressed as a percent.

Coticule laminae. A layer of fine-grained quartz and spessartite garnet that is found in metasedimentary rocks.

Coticule layers. Metamorphosed, fine grained quartz and spessartite garnet that usually are formed in layers.

Cuttings. Drill cuttings are fragments of rock that were created by drilling.

Dike. A planar or tabular intrusive that is usually discordant with the surrounding country rock.

Drilling fluid. A fluid (or gas) that is used in the drilling process to remove cuttings and naturally occurring fluids from the borehole.

Drive shoe. A steel collar that is fixed to the lower end of the casing. It serves as a protective leading edge of the casing as it is hammered into solid bedrock.

XRF. Energy dispersive x-ray fluorescence spectrometry (XRF) uses a electrons from x-ray beam to interact with the sample. Outer shell electrons on the sample are forced to drop to a lower shell, which causes a characteristic release of energy. Energy detectors sample all elements at the same time, and count the occurrence of each element. XRF is used in conjunction with scanning electron microscope.

Euhedral. A descriptive term for a mineral grain that is bounded by its own rational crystal face.

Exfoliation. A process of weathering in which sheets of rocks are removed from the rock mass.

Fault. A fracture or a zone of fractures along which there has been displacement of the sides relative to one another parallel to the fracture.

Feldspar. A group of aluminosilicate minerals containing potassium (as in orthoclase), or a mixture of sodium (albite) and calcium (anorthite).

Felsic. An igneous rock having abundant light-colored minerals in its mode.

Felsic stringers. In this report the term has been used to describe very thin (< 2 cm) usually irregularly shaped veins comprised of felsic minerals.

Flowmeter. A downhole tool used to measure vertical flow within a borehole. The most sensitive flowmeters use a chemical or thermal tracer that moves upward or downward under the influence of vertical gradients in a borehole.

Foliation. A general term for a planar arrangement of textural or structural features in any type of rock; especially the planar structure that results from flattening of the constituent grains of a metamorphic rock.

Fracture. A generic term for a break, crack, or opening in bedrock along which water may flow.

Fracture set. A group of fractures that exhibit similar orientations as they formed in response to the same stress or stresses.

Gamma-photon emissions. Gamma photons, which are a form of electromagnetic radiation, are natural products of radioactive decay of uranium, thorium and potassium-40. The emissions occur as one radioisotope is transformed to another in the decay process.

Global Positioning System. Global Positioning Systems (GPS) make use of satellite and land-based radio signals to determine geographically referenced locations. [The accuracy of the coordinates determined using a GPS depend on the tool and the number of satellites used for the determination of the location.]

Gouge. Fault gouge is soft, pulverized, clay-rich material that is found along some faults.

Gneiss. A coarse-grained metamorphic rock that exhibits less than 50 percent foliated minerals. A banded gneiss exhibits alternating bands of granular and micaceous minerals.

Gneissic. A descriptive term for rocks that exhibit texture that is similar to gneiss.

Granite. A coarse-grained, light-colored, igneous intrusive rock comprised of quartz, feldspar, and mica.

Granitoid. A granitic rock, or a plutonic rock with 20-60 percent quartz, and frequently with gneissic texture.

Grout. A cement slurry of high water content, which can be poured or injected and used to fill or seal spaces.

Hypidiomorphic-granular. A texture of igneous rock that is comprised of a mixture of euhedral, subhedral, and anhedral crystals.

Igneous. Descriptive term for rocks or minerals solidified from molten or partially molten material, that is, formed from a magma, such as a granite, monzonite, or diabase.

Joint. A surface fracture or parting in a rock along which there has been no displacement.

Lens. A tabular layer that is thickest at the center and pinches out at the edges.

Leucocratic. Light-colored igneous rocks with few mafic minerals.

Leucosome. The light-colored, equigranular part of a migmatite, usually coarse grained and rich in quartz, feldspar (plagioclase), and muscovite. Generally it does not exhibit foliation.

Liesegang bands. Bands of iron migration within the matrix of rock.

Lineation. A term used to describe the parallel alignment of linear structures within a rock.

Mafic. A term used to describe minerals that are rich in iron and magnesium (ferromagnesian). A mafic rock is typically dark in color.

Matrix. (igneous rock): A descriptive term that refers to the interlocking mineral grains that comprise the solid fine-grained part of a rock. In igneous rock this is also called the groundmass. (general term): The matrix also refers to the solid rock that bounds a fracture.

Melanosome. The dark-colored, foliated part of migmatite, rich in mafic minerals.

Metamorphic. Descriptive term for rocks such as gneiss and schist, that have formed, in the solid state, from other rocks due to changes in temperature and pressure.

Metamorphism. The process of rocks, such as gneiss and schist, forming in the solid state from other rocks as the result of changes in temperature and pressure.

Metasedimentary rock. A metamorphic rock whose original material was sedimentary.

Migmatite. A rock that is a product of partial melting. Usually, it exhibits a coarse-grained mixture of igneous and (or) metamorphic characteristics. The felsic igneous part is called a leucosome, and the foliated mafic section is the melanosome.

NAD of 1927. North American datum of 1927 is a horizontal, surveying datum that is used to reference cartographic locations. All locations that are referenced to NAD27 can be converted to the more recent datum (NAD of 1983). It is important for spatial relations that features be referenced to the same datum.

Nappes. A sheet like mass of rock that has been moved in a horizontal direction either by thrust faulting or recumbent folding.

Orogeny. The process of mountain formation.

Outcrop. A part of the bedrock that is exposed at the land surface.

Oxidation. A process that causes alteration of minerals and (or) water as a result of electron transfer. The species that loses electrons in the oxidation-reduction process is said to be oxidized.

Panidiomorphic granular. A rock texture comprised almost completely of euhedral crystals. It is most often exhibited in intrusive mafic rocks such as lamprophyres.

Pegmatite. Extremely coarse-grained igneous rock with interlocking crystals. The composition is usually granitic.

Pelitic. A term used to describe metamorphosed aluminium rich (argillaceous) rocks.

Percussion rotary drilling. A method of drilling in bedrock. The drill bit pulses, or hammers, and simultaneously turns its way into the rock, causing it to fragment. Compressed air or water is forced down the center of the drill rods in order to evacuate rock cuttings and fluids from the borehole.

Petrographic. A descriptive term that refers to the classification of rock types usually by means of microscopic examination of thin-section samples of rocks. Petrographic analyses can also include x-ray diffraction and SEM analyses.

Phenocryst. A large, conspicuous crystal in a relatively fine-grained matrix.

Phlogopite. A magnesium-rich, iron-poor phyllosilicate that is copper-colored to reddish brown.

Phyllosilicate. Mineral and crystalline structure of silicon-oxygen tetrahedra arranged in sheets. "Mica", muscovite, biotite, phologopite, and chlorite are phyllosilicates.

Pneumatic packer. A device that is positioned in the borehole and inflated in order to seal or "pack-off" portions of the borehole. One or more packers can be used at the same time to isolate discrete sections of the borehole for hydraulic testing or water sampling.

Porphoritic. An igneous rock texture that exhibits several phenocrysts (relatively large crystals) in a fine-grained matrix.

Primary porosity. The porosity that developed during the final stages of sedimentation or that was present within sedimentary particles at the time of deposition.

Quartzite. A metamorphic rock consisting of quartz and other impurites such as sulfide minerals. Quartzite formed from the metamorphism of quartz-rich deposits such as sandstone.

Rare-earth element phosphate. A mineral comprised of rare-earth metals such as cerium, lanthanum, yttrium, thorium, and phosphate. Monazite is a rare-earth element phosphate that is comprised of 1 to 20 percent thorium, which is radioactive.

Rotary drilling. Method of drilling deep boreholes using a drill bit attached to the bottom of a rotating drill pipe.

Saprolite. A clay-rich, decomposed rock formed by chemical weathering of igneous, sedimentary, and metamorphic rocks. It is commonly called "rotten rock".

Schist. A metamorphic rock characterized by strong schistosity and foliation.

Schistosity. A characteristic texture or cleavage or rock comprised of platy minerals whose long axis lies in the same direction and forms a lineation in the rock. It imparts a planar fissility in the rock.

Schlieren. Restites or residuals of mafic-rich, foliated minerals, which occur in wispy-looking layers usually less than 2.5 centimeters wide.

Secondary porosity. Porosity caused by secondary features such as fractures or solution cavities.

SEM. A scanning electron microscope (SEM) uses a focused beam of electrons, which is moved across the sample, to produce a magnified view of the rock sample. The SEM is used in conjunction with energy dispersive x-ray fluorescence spectrometry (XRF) in order to measure the elemental composition of a sample.

Sericite. Product of alteration or retrograde metamorphism of potassium feldspar to white fibrous mica.

Slickenside. Shiny, striated surface that is caused by the polishing action along a fault surface.

Stress. The resultant forces, expressed in force per unit area, acting on any point within a solid.

Stress field. The state of stress for a given domain or region.

Subhedral. A descriptive term used to define the degree to which a mineral exhibits its crystalline form. A subhedral mineral exhibits some of its crystal form. Subhedral is intermediate to euhedral and anhedral.

Syncline. Folded stratified rocks that dip downward from opposite directions and meet in the middle of a trough. Younger sediments are folded towards one another.

Synclinorium. A regional fold that is concave upward and whose younger stratigraphic layers are in the core of the fold.

Texture. General physical appearance or character of a rock caused by variations in grain size, crystalline shape and orientation, and fabric of the rock.

Thin section. A very thin slice of rock that enables light to pass through so that the optical properties of the rock can be analyzed for purposes of describing and identifying minerals.

Till. A predominantly nonsorted, nonstratified sediment deposited directly by a glacier and comprised of boulders, gravel, sand, silt, and clay mixed in various proportions.

Unconsolidated rock. A sediment in which the particles are not firmly cemented together, such as a sand, in contrast to sandstone.

Vein. A tabular or sheet-like igneous body that has been intruded into a pre-existing rock along a joint or crack. In this report, the term vein has been used for igneous intrusions that are less than 20 cm wide.

Verging, vergence. A structure in crystalline rock that exhibits an inclined or overturned fold.

Vesicular. A term used to describe a rock texture that is characterized by vesicles or cavities formed by expansion of gases during solidification of the igneous magma.

Wilcoxon-Mann-Whitney, test. A statistical test used to determine if two different sample populations come from an identical population. It is also called the rank-sum test and is a non-parametric alternative to the two-sample *t* test.

Wire-line core barrel. A core barrel that can be retrieved from the borehole by use of a steel cable and a winch. The advantage of using a wire-line core barrel over conventional tools is that all of the drill rods can remain in the borehole while the core sample is retrieved.

Xenolith. The inclusion of a pre-existing rock in an igneous rock, usually a piece of the non-igneous surrounding, or "country" rock.

X-ray diffraction. A method that uses a beam of electromagnetic radiation focused at a rock sample. Minerals in the sample are identified by the characteristic interference patterns caused by the x-rays and the crystalline structure of the minerals.

Zinnwaldite. A phyllosilicate mineral that is often associated with lithium-bearing minerals such as monazite, flourite, beryl, or tourmaline.