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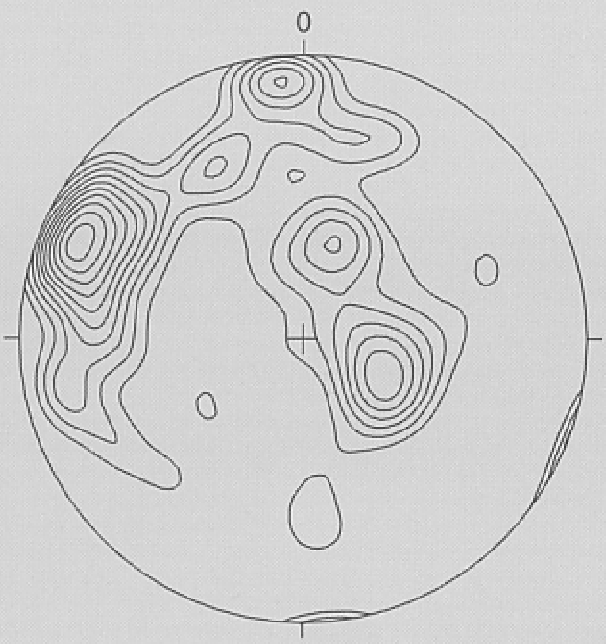
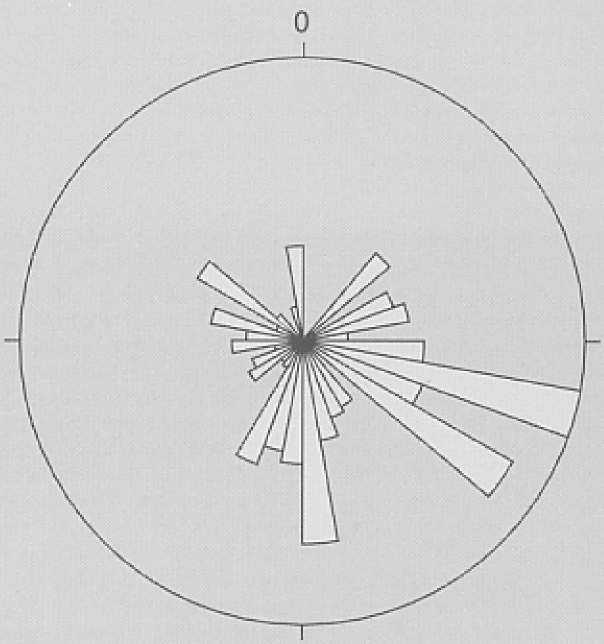
Characteristics of Fractures in Crystalline Bedrock Determined by Surface and Borehole Geophysical Surveys, Eastern Surplus Superfund Site, Meddybemps, Maine

Water-Resources Investigations Report 99-4050



Lower-hemisphere stereonet contour plot



Rose diagram showing dip direction

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By BRUCE P. HANSEN, JANET RADWAY STONE, and JOHN W. LANE, JR.

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Northborough, Massachusetts
1999

U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS

Multiply	By	To obtain
foot (ft)	0.3048	meters
foot per nanosecond (ft/ns)	0.3048	meter per nanosecond
foot per second (ft/s)	0.0003	kilometer per second
foot squared per day (ft^2/d)	0.09290	meter squared per day
gallon (gal)	3.785	liter
gallons per minute (gal/min)	0.06308	liters per second
miles (mi)	1.609	kilometers

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows:

°C = 5/9 (°F-32).

VERTICAL DATUM

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 the United States and Canada, formerly called Sea Level Datum of 1929.

ABBREVIATIONS

MHz	megahertz
mho/m	mho per meter
μg/L	micrograms per liter

Characteristics of Fractures in Crystalline Bedrock Determined by Surface and Borehole Geophysical Surveys, Eastern Surplus Superfund Site, Meddybemps, Maine

By Bruce P. Hansen, Janet Radway Stone, *and* John W. Lane, Jr.

Abstract

Surface and borehole geophysical methods were used to determine fracture orientation in crystalline bedrock at the Eastern Surplus Superfund Site in Meddybemps, Maine. Fracture-orientation information is needed to address concerns about the fate of contaminants in ground water at the site. Azimuthal square-array resistivity surveys were conducted at 3 locations at the site, borehole-acoustic televiewer and borehole-video logs were collected in 10 wells, and single-hole directional radar surveys were conducted in 9 wells. Borehole-video logs were used to supplement the results of other geophysical techniques and are not described in this report.

Analysis of azimuthal square-array resistivity data indicated that high-angle fracturing generally strikes northeast-southwest at the three locations. Borehole-acoustic televiewer logs detected one prominent low-angle and two prominent high-angle fracture sets. The low-angle fractures strike generally north-northeast and dip about 20 degrees west-northwest. One high-angle fracture set strikes north-northeast and dips east-southeast; the other high-angle set strikes east-northeast and dips south-southeast. Single-hole directional radar surveys identified two prominent fracture sets: a low-angle set striking north-northeast, dipping west-northwest; and a high-angle fracture set striking north-northeast, dipping east-southeast. Two additional high-angle fracture sets are defined weakly, one striking east-west, dipping north; and a second striking east-west, dipping south.

Integrated results from all of the geophysical surveys indicate the presence of three primary fracture sets. A low-angle set strikes north-northeast and dips west-northwest. Two high-angle sets strike north-northeast and east-northeast and dip east-southeast and south-southeast. Statistical correction of the fracture data for orientation bias indicates that high-angle fractures are more numerous than observed in the data but are still less numerous than the low-angle fractures.

The orientation and distribution of water-yielding fractures sets were determined by correlating the fracture data from this study with previously collected borehole-flowmeter data. The water-yielding fractures are generally within the three prominent fracture sets observed for the total fracture population. The low-angle water-yielding fractures primarily strike north-northeast to west-northwest and dip west-northwest to south-southwest. Most of the high-angle water-yielding fractures strike either north-northeast or east-west and dip east-southeast or south. The spacing between water-yielding fractures varies but the probable average spacing is estimated to be 30 feet for low-angle fractures; 27 feet for the east-southeast dipping, high-angle fractures; and 43 feet for the south-southeast dipping, high-angle fractures.

The median estimated apparent transmissivity of individual water-yielding fractures or fracture zones was 0.3 feet squared per day and ranged from 0.01 to 382 feet squared per day. Ninety-five percent of the water-yielding fractures or fracture zones had an estimated apparent transmissivity of 19.5 feet squared per day or less.

The orientation, spacing, and hydraulic properties of water-yielding fractures identified during this study can be used to help estimate the recharge, flow, and discharge of ground water and contaminants. High-angle fractures provide vertical pathways for ground water to enter the bedrock, interconnections between low-angle fractures, and, subsequently, pathways for water flow within the bedrock along fracture planes. Low-angle fractures may allow horizontal ground-water flow in all directions. The orientation of fracturing and the hydraulic properties of each fracture set strongly affect changes in ground-water flow under stress (pumping) conditions.

INTRODUCTION

Recent sampling (1997) by the U.S. Environmental Protection Agency (USEPA) at the Eastern Surplus Superfund Site in Meddybemps, Maine (fig. 1) detected volatile organic compounds (VOCs) in ground water from surficial deposits and shallow bedrock in two areas (Roy F. Weston, Inc., written commun., 1997). VOCs in one of these areas can potentially flow through fractures in the bedrock to a hypothesized local cone of depression in the bedrock potentiometric surface centered east of the Dennys River (F.P. Lyford and others, U.S. Geological Survey, written commun., 1997). It is postulated that the cone of depression is caused by pumping from a domestic bedrock well. Shallow bedrock wells drilled in the study area in November 1996, ranging in depth from 117 to 240 ft below land surface, intercepted water-yielding fractures. Information about fracture characteristics at the site is needed to determine the fate of contaminants in bedrock and to formulate ground-water remediation strategies.

During 1997 and 1998, the U.S. Geological survey (USGS), in cooperation with the USEPA, studied bedrock fracture characteristics near the Eastern Surplus Superfund Site using several integrated methods, including geologic mapping, surface and borehole geophysics, and aquifer testing. This report describes bedrock fracture orientations and distributions near the Site that were determined by surface and borehole geophysical surveys, including azimuthal square-array resistivity, borehole video, borehole acoustic televiewer, and single-hole directional radar. An integrated interpretation of bedrock fracture orientations and distributions, based on all of the geophysical and geologic information available, is presented. Also described are the characteristics of water-yielding fractures, including orientation, distribution, probable average fracture spacing, and estimated hydraulic properties. Borehole-flowmeter data collected during an earlier study (Lyford and others, 1998) were used to identify water-yielding fractures and, in conjunction with the results of hydraulic testing of bedrock wells (F.P. Lyford and others, 1999), to estimate the hydraulic properties of fractures.

Most of the fracture data in this report are presented on rose diagrams and stereonets, two common techniques used to visually represent fracture data. The rose diagram is a specialized histogram used to represent the distribution of dip azimuth. The data are plotted in an angular fashion. The length of each angular segment is proportional to the number of fractures that have a dip azimuth within that particular segment. The stereonet displays a three-dimensional fracture orientation, showing not only dip azimuth but also dip angle. Equal-area, lower-hemisphere, polar-projection stereonets of data are presented in this report. For clarity, lines of longitude and latitude that normally appear on stereonets have been omitted.

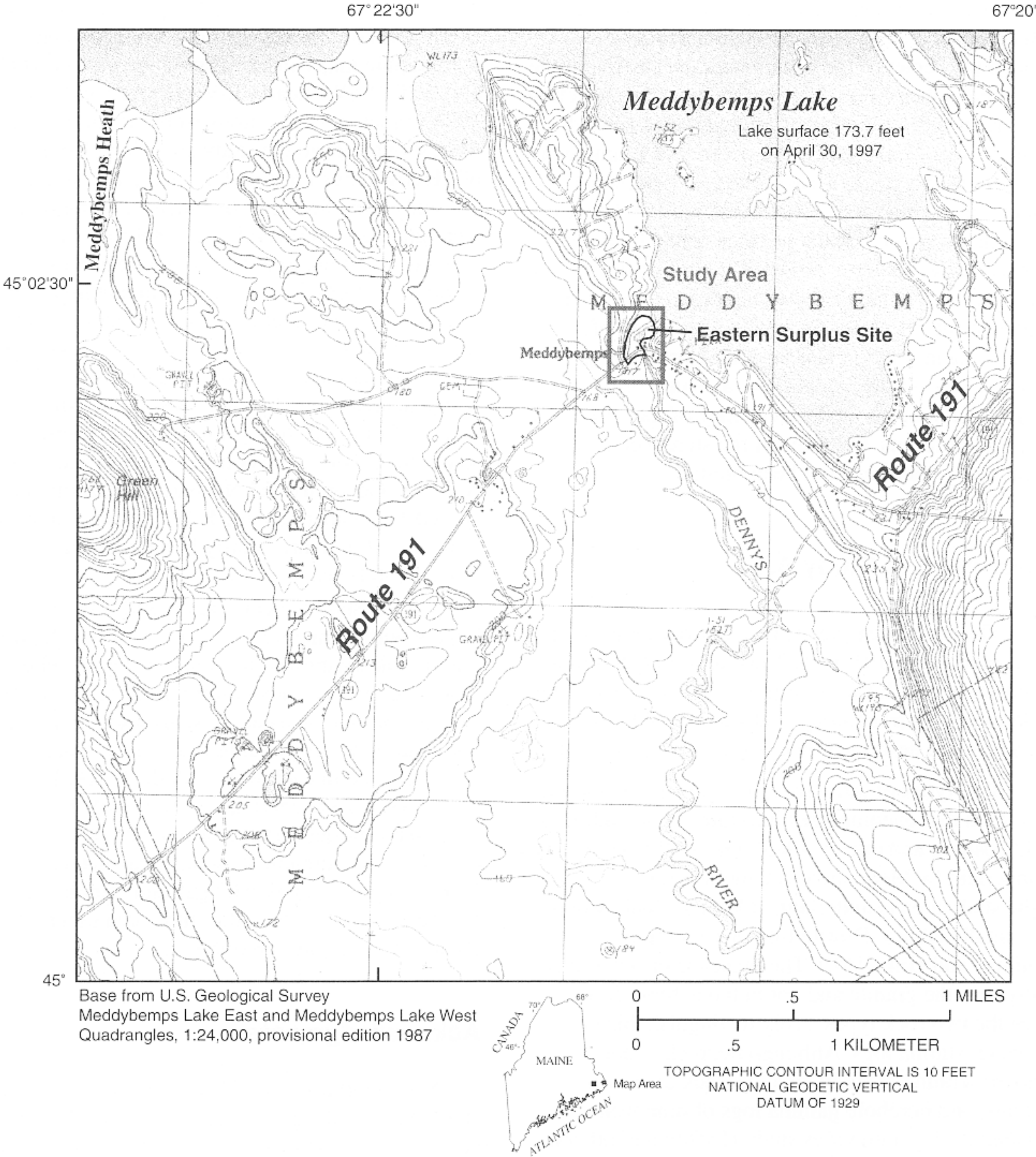


Figure 1. Locations of Eastern Surplus Superfund Site and the study area, Meddybemps, Maine.

Each point on the stereonet represents the intersection of the pole of a fracture-plane surface that passes through the center of the sphere with the surface of the lower hemisphere. The stereonet shows the intersection as if the surface of the lower hemisphere is viewed from the top of the upper hemisphere. For example, a cluster of points on the eastern edge of a stereonet would represent fractures that dip steeply to the west. Horizontal fractures would be represented by points near the center of the stereonet. On most of the stereonets shown in this report the density (relative abundance at any three-dimensional location) of plotted data in relation to a random distribution is shown. These density plots allow a visual determination of the central tendency of the strike and dip of fracture sets. On some of the stereonets, the actual data points have not been plotted.

Description of Study Area

The study area (fig. 1) is in northeastern Maine adjacent to Route 191 in the Town of Meddybemps and encompasses the Eastern Surplus Superfund Site. The background, hydrogeology, and water quality of the study area are described by Lyford and others (1998).

Two types of intrusive igneous bedrock underlie the region that encompasses the study area (Ludman, 1982; Osberg and others, 1985). Generally, the region is underlain by Meddybemps Granite; however, most of the study area is underlain, at least at shallow depth, by a small Gabbro–Diorite Intrusive Complex (Ludman and Hill, 1990). The presence of potassium feldspar in the granite and not in the gabbro-diorite make the two rock types easily distinguishable on borehole gamma logs. Although bedrock is not exposed within the study area, bedrock core, drill cuttings, and borehole gamma logs of nine wells installed during a previous study (Lyford and others, 1998) confirm that the upper 100–200 ft of bedrock is largely gabbro-diorite. Well MW-16B on the eastern edge of the study area (fig. 2; table 1) penetrated 40 ft of gabbro-diorite before penetrating 60 ft of granite, and well MW-14B on the northern edge of the area penetrated about 30 ft of granite at the bottom of the well. As indicated by Ludman and Hill (1990), this small area of gabbro-diorite is probably a detached body of mafic rock floating in the Meddybemps Granite.

The regional strike of bedrock fracturing, as seen in the grain of topography in bedrock hills on topographic maps and areal photographs, is NW-SE and ENE-WSW (nearly E-W) (Lyford and others, 1998). Fracture orientations were measured on the nearest outcrops to the study area along Route 191 east of Meddybemps Lake and on Green Hill to the west of the study area. Some of the outcrops along Route 191 were granite, and several were gabbro-diorite complex with cross-cutting granitic dikes. Green Hill is composed of granite. Two predominant high-angle fracture sets were measured with linear orientations (fig. 3) similar to those observed in the topography. One set strikes approximately NNW (N 25°-30° W) with a near vertical dip, and a second set strikes ranging from ENE to E (almost E-W) dipping steeply south. Several fractures on one outcrop had a strike of N 60° W. Generally, the NW-striking fractures were spaced 1–3 ft apart and the E-W-striking fractures were spaced 2–10 ft apart. Nearly horizontal fractures, spaced 1–6 ft apart, also were present.

In crystalline bedrock, ground water is present largely within fractures, only a few of which transmit measurable quantities of ground water. Borehole-flowmeter measurements were made in 25- to 193-foot sections of nine wells at the study site. Typically, only one to three water-yielding fractures or fracture zones were detected in each well with the borehole flowmeter. One exception was well MW-10B, where 16 water-yielding fracture or fracture zones were detected. The borehole flowmeter can detect changes in flow of approximately 0.02 gal/min. Yields estimated for the bedrock wells in the study area ranged from about 0.1 to 25 gal/min (table 1).

Acknowledgments

The authors thank Terry Lord, Greg Smith, Harry Smith, Madge Orchard, and Mona Van Wart for permission to conduct geophysical surveys on their property; and Edward Hathaway, Project Manager, U.S. Environmental Protection Agency, for facilitating access to survey locations. Appreciation also is extended to USGS employees Peter Joesten, for assisting with borehole radar surveys; Kevin Knutson, for doing borehole-televiewer and television surveys; Forest Lyford, for providing technical guidance and administrative assistance; William Nichols, for assisting with geophysical surveys; and Joseph Nielsen, for monitoring water levels.

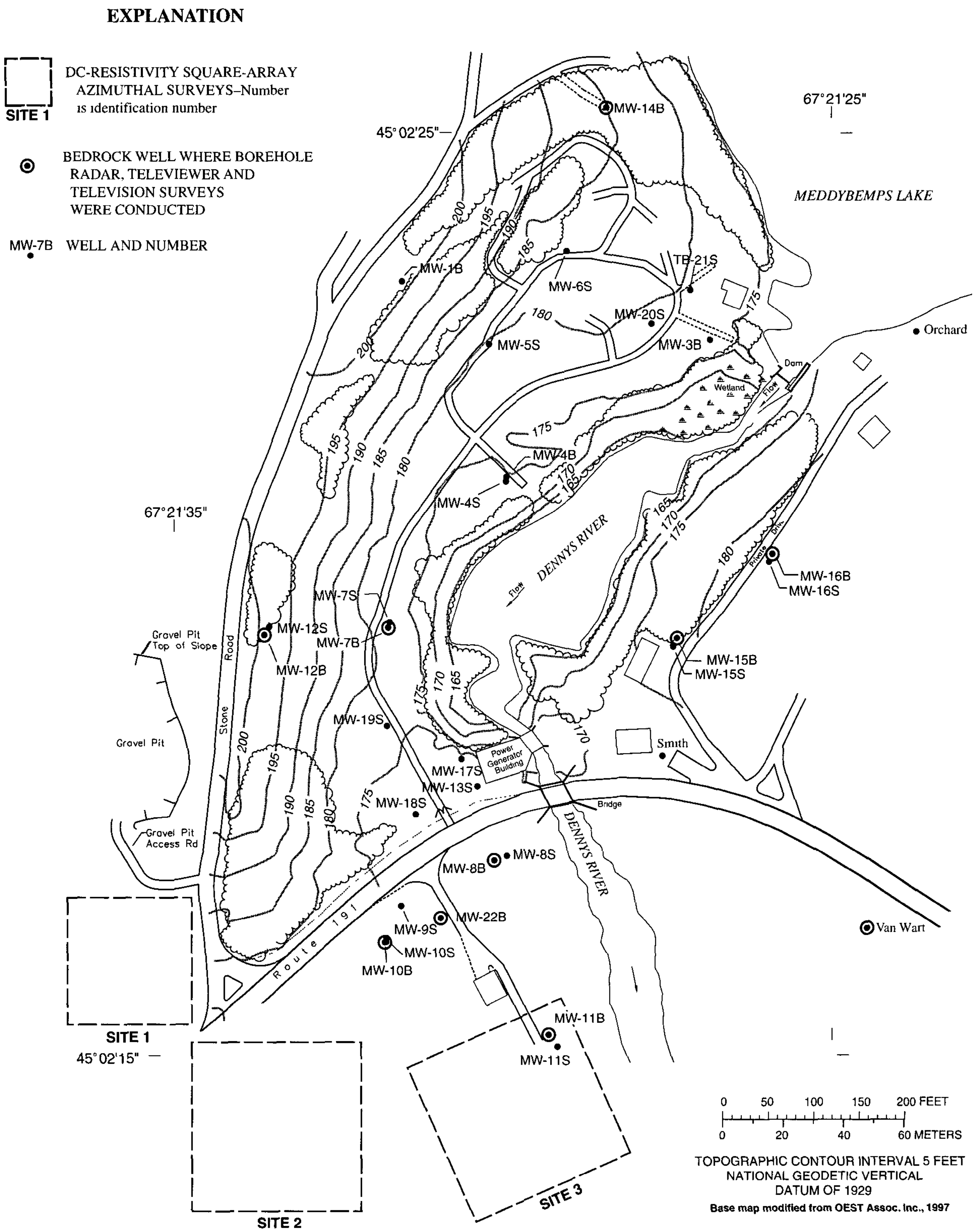
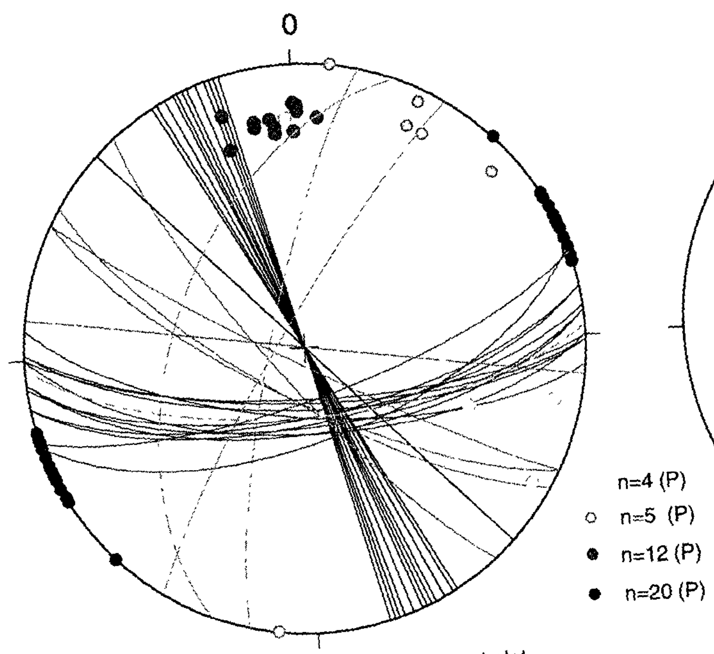


Figure 2. Locations of geophysical survey sites and wells, Eastern Surplus Superfund Site, Meddybemps, Maine.

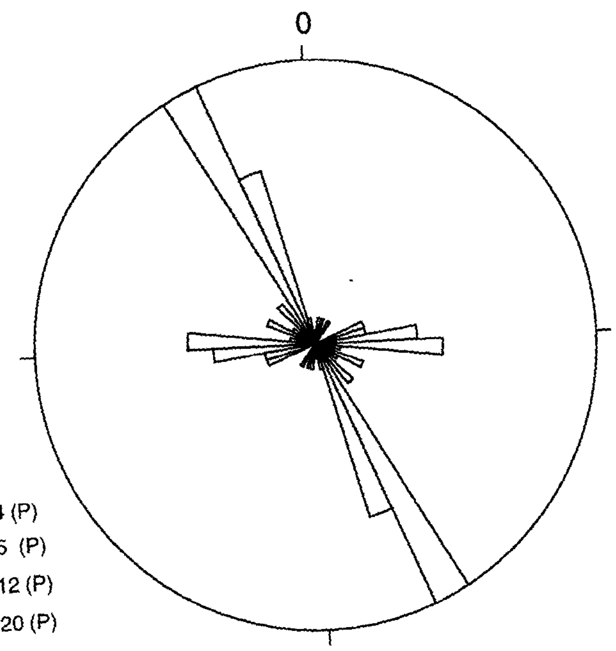
Table 1. Records of selected bedrock wells in and near the Eastern Surplus Superfund site, Meddybemps, Maine

[All depths and open-hole intervals are in feet below land surface. **Altitude of land surface:** In feet above sea level. **Depth to water-yielding fracture zones:** Number in parentheses next to fracture zone indicates relative magnitude of yield while pumping, where (1) is the highest yielding fracture zone. **Remarks:** Pumping and drawdown measured by personnel of Roy F. Weston, Inc. (written commun., 1997) while sampling in December 1996. ft, foot; min, minute; gal/min, gallon per minute; --, no data; >, actual value is greater than value shown; <, actual value is less than value shown]

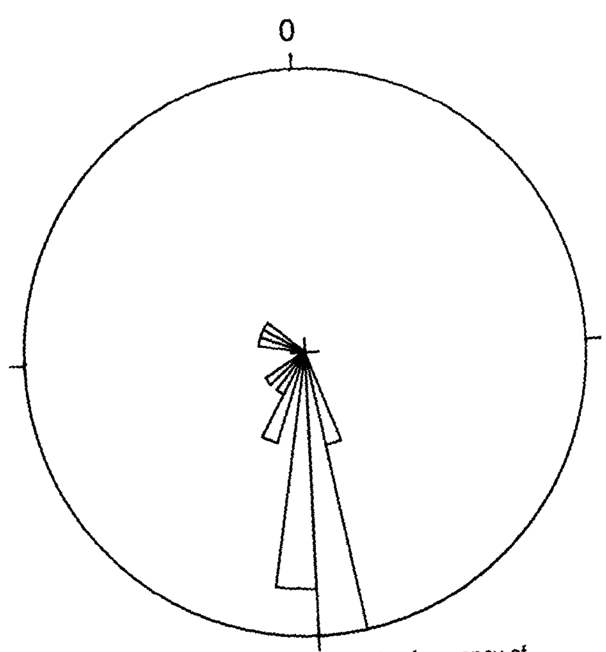
Well No. or name	Date drilled	Altitude of land surface	Total depth of borehole	Depth to bedrock	Altitude of bedrock surface	Open-hole interval	Approximate yield (gal/min)	Depth to water-yielding fracture zones	Remarks
MW-7B	10-28-96	177.81	117.8	18	159.8	21–117.8	>0.004	89	No measurable flow in borehole for static condition. No flow measurements above depth of 48.6 ft during pumping because of drawdown.
MW-8B	11-04-96	169.04	124	20.5	148.5	25.7–124	.06	27–34 (2) 55–65 (1)	No measurable flow in borehole for static conditions.
MW-10B	11-04-96	174.24	120	20	154.2	26.4–120	1.2	30–31 (1) 72–76 (2) 37 (3)	Drawdown of 1.6 ft after 161 min while pumping at 0.07 gal/min. Static flow is downward from fractures from 26 to 60 ft to fractures from 60 to 85 ft. Water-yielding fractures also observed at 33-35, 41-42, 55, 63-66, 80-83, 94-96, 101-107, and 110 ft.
MW-11B	11-04-96	169.69	132	29	140.7	34–132	15	34–41 (2) 71–74 (3) 77–80 (1)	Drawdown of 1.4 ft after 90 min while pumping at 0.42 gal/min. No measurable flow in borehole for static conditions. Water-yielding fractures also at 88 and from 128 to 130 ft.
MW-12B	11-04-96	200.13	138	22.5	177.6	27.7–138	.03	34–37	No measurable flow in borehole for static conditions.
MW-14B	11-05-96	185.70	120	3.5	182.2	9.4–120	.5	25–27	Drawdown of 1.45 ft after 105 min while pumping at 0.21 gal/min. No measurable flow in borehole for static conditions. No flow measurements above 24 ft during pumping because of drawdown.
MW-15B	11-05-96	178.97	240	39	140.0	46.9–240	.06	73–78 (1) 92–95 (1)	No measurable flow in borehole for static conditions. Flow from two zones approximately equal.
MW-16B	11-05-96	182.18	140	38	144.2	42.3–140	.09	45–46 (1) 68–68.5 (3) 108–118 (2)	No measurable flow in borehole for static conditions.
MW-22B	1950s	172.35	49	18	154.4	25–49	25	25.5–30	Former residential well. Yield reported by former owner (E. Gillespie, oral commun., 1996). No measurable flow in borehole for static conditions.
Van Wart	--	171.78	142	29	142.8	39–142	5	--	Residential well. Yield reported by driller (T. Lord, oral commun., 1996).
Smith	--	173.35	420	--	--	--	<.3	--	Residential well. Yield reported by driller (T. Lord, oral commun., 1996)



Lower-hemisphere, equal-area stereonet plot of poles to fracture planes and trace of fracture intersections with lower-hemisphere. Total number of fractures plotted is 41.



Rose diagram showing relative frequency of measured fracture strike, in 15° classes.



Rose diagram showing relative frequency of measured fracture dip direction, in 2° classes.

Fracture orientation measurements made on low-relief bedrock roadcuts that are otiented NNW to NNE.

Figure 3. Orientation and distribution of fractures measured on bedrock roadcuts along Route 191 east of the study site in Meddybemps and Baring, Maine.

GEOPHYSICAL-SURVEY METHODS

The geophysical methods applied in this study were azimuthal square-array resistivity, borehole acoustic televiewer, borehole video, and single-hole directional radar. Integration (cross-correlation) of the results from various independent surveys improved confidence in the orientation and location of fractures and also improved resolution (degree to which individual features can be detected) over that of a single method. Individual surveys were made in as close proximity to one another as practically possible, so that the same or approximately similar volumes of bedrock were sampled. The methods used for this study were selected because of their successful use for fracture detection and characterization in previous investigations at other sites in New Hampshire, Massachusetts, and New Jersey (Lieblich and others, 1991, 1992a, and 1992b; Hansen and Lane, 1995; Paillet and Ollila, 1994; Morin and others, 1997).

Azimuthal Square-Array Resistivity

Azimuthal square-array resistivity was used to measure directional variations in apparent earth resistivity. These variations are related to sets of similarly oriented, steeply dipping fractures. The theory, development, and application of this method as it was used in this study is described in Lane and others (1995) and Hansen and Lane (1995).

The square array consists of four electrodes driven into the ground to form a square configuration. The location of all measurements are assigned to the center point of the square. The array size (A) is the length of a side of the square. Each resistivity measurement consists of measuring current (I) between two current electrodes (A and B) and the potential difference between two potential electrodes (M and N). On the basis of these measurements, apparent resistivity is determined using equations presented in Hansen and Lane (1995, p. 6). For each square, three apparent resistivity measurements are taken. Two measurements (alpha and beta) are perpendicular to each other and parallel to the sides of the square, and a third (gamma) is diagonal across the square. The two perpendicular measurements provide information on the directional variations of the subsurface resistivity. The azimuthal orientation of the perpendicular measurements is the line that connects the current electrodes. The diagonal measurement serves as a check on the accuracy of the two perpendicular measurements. In an isotropic medium, the apparent resistivity in the alpha and beta directions are equal and gamma is equal to zero. In a homogeneous, anisotropic medium, the gamma resistivity is equal to the difference between the alpha and beta resistivity. To collect a complete set of azimuthal-profiling data, the array is rotated in equal angular increments around a common center point. To detect vertical (depth) variations in apparent resistivity at each azimuthal orientation, the array is usually expanded symmetrically about the center point. These resistivity soundings can be interpreted as a function of depth. Each array samples a cube of earth with dimensions approximately equal to the array A-spacing.

Fracture strike can be determined graphically or analytically. To graphically interpret fracture strike at a site, each apparent resistivity for a given size square and the azimuth of that measurement are plotted. The principal fracture strike direction is perpendicular to the direction of maximum resistivity. Fracture strike can be determined analytically based on resistivity data from two squares separated by 45° (crossed square array) and applying equations presented by Habberjam (1972; 1975).

Acoustic Televiewer

The borehole acoustic televiewer (hereafter referred to as "televiewer") provides a photograph-like image representing the pattern of acoustic reflectivity on the borehole wall. The image is orientated with respect to the Earth's magnetic field. The irregular surface where a fracture intersects a borehole usually appears as an elliptical line on the televiewer record. The shape and vertical extent of this ellipse can be used to determine apparent fracture strike and dip with respect to the borehole axis. In cases where the borehole is deviated from the vertical, true strike and dip can be determined if borehole deviation is known (Kierstein, 1983; Lau, 1983). The televiewer-logging system used for this investigation collected data on acoustic velocity and amplitude, magnetic orientation, and deviation. All of the data were stored in digital format. The data were interpreted using interactive computer processing that produced a compilation of the true strike and dip of observed fractures, orientated hole-diameter logs, and orientated cross-sectional and plan-view plots of borehole deviation. All fracture orientations were corrected for borehole deviation. All magnetic north azimuths were adjusted to true north. Televiewer instrumentation and interpretation are described in more detail by Keys (1990) and Zemanek and others (1969).

Ten wells at the Eastern Surplus Site were logged with the televiewer. One well (MW-7B) was too small in diameter (2.75 in.) for proper operation of the televiewer, so the record from this well was unusable.

Borehole Video

Borehole video logs were collected for the purpose of visually inspecting the cased and uncased sections of bedrock wells. Video logs were collected by a vertically oriented color video camera that provided a 360-degree image of the borehole wall. A light mounted below the camera illuminated several feet of borehole wall below the camera. The camera was normally focused on the most brightly illuminated section of borehole wall, and the depth encoder was set to record the depth of this point. A video monitor with an onscreen depth display was used to view the optical image of the borehole as the camera was lowered into the subsurface. A permanent record of the video was produced by simultaneously recording the video data onto tape, which could be used for later review of borehole conditions. The horizontal azimuthal orientation of the video camera was unknown and, therefore, fracture strike could not be determined from the video record. A description of a borehole video logging system is given by Safko and Hickey (1992).

The clarity of the video images was directly related to the transparency of the water in the borehole at the time of each survey. In general, the quality of the record from most of the 10 wells surveyed was good. However, because of other logging activities that created turbid water, the record from well MW-11B was very poor and the records from wells MW-22B and MW-8B were fair.

The video records were used mainly in conjunction with televiewer logs to clarify fracture geometry, particularly in fracture zones where fractures with different overlapping orientations intersected the borehole. Video records also were used to examine the bottom of the casing for evidence of water leakage. The video surveys are not presented in this report.

Single-Hole Directional Radar

Single-hole directional radar surveys were done to detect the location and orientation of fractures or fracture zones. These surveys were done with an MALA GeoScience RAMAC borehole-radar system. A broad-band electric-dipole transmitting antenna with a center frequency of 60 MHz was used with a directional-receiving antenna consisting of four separate loop antennas oriented orthogonally. Directional information about a reflection is obtained by measuring the phase difference of the incoming wave on the different antenna elements. The frequency used was selected to provide an acceptable compromise between high resolution (the degree to which individual features can be detected) and deep penetration (the distance that the radar wave travels into rock). For this study, the transmitter and directional receiver were lowered into the same well with the antenna center points separated by 27.9 ft. Incremental stacked measurements were made every 0.82 ft along the length of each well. Data were processed and interpreted with MALA software. The analysis software allows the interpretation of the strike, dip, and projected borehole-intersection depth of planar discontinuities. The distance and direction to pointlike discontinuities also can be interpreted.

The velocity of radar waves through the rock adjacent to the borehole was determined by collecting a vertical radar profile (VRP). For this technique, either the transmitting or receiving antenna remains fixed in the borehole and the other antenna is moved away at 0.82 ft increments. Total traveltime of the direct wave between the transmitting and receiving antenna at each station is measured. The traveltime data are used with the known distance between the antennas to calculate the direct-wave radar velocity through each increment of borehole. Theory, development, and previous use of borehole-radar systems is summarized in references cited by Lane and others (1994) and Hansen and Lane (1995).

FRACTURE ORIENTATION AND RELATIVE DISTRIBUTION DETERMINED BY GEOPHYSICAL METHODS

Graphic displays of data from azimuthal square-array resistivity, borehole-acoustic televiewer, and single-hole borehole-radar surveys are presented in this section. Fracture orientations determined with these methods and from examination of bedrock outcrops are summarized.

Azimuthal Square-Array Resistivity

Azimuthal square-array data collected at three sites (fig. 2) indicated variations in apparent resistivity with measurement direction. At each site, these variations changed as the size of the array increased. At small array spacings, resistivity anomalies (resistivity highs with corresponding orthogonal resistivity lows) were small and randomly distributed. These small and random anomalies probably resulted from heterogeneities in the unconsolidated surficial deposits that were investigated (sampled) at small array spacings. Resistivity data from large array spacings, which sample a large volume of bedrock, were used to interpret the large-scale orientation of high-angle fractures. Azimuthal plots of resistivity data for sites 1–3 (fig. 2) at array spacings of 148, 212, and 148 ft, respectively, are shown in figure 4. Resistivity data for an array spacing of 42 ft for site 3 also is shown in figure 4. Data from other array spacings were used for analysis but are not shown. The graphical plots of resistivity data indicate the following:

- At site 1, the primary high-angle fracture strike orientation is generally NNE and probably ranges from N to ENE.
- At site 2, the primary high-angle fracture strike orientation is generally NE and ranges from NNE to ENE.
- At site 3, at shallow bedrock depths (less than 42 ft), the primary high-angle fracture strike orientation is generally NE and generally E at greater depths.

Acoustic Televiewer

Fracture orientation and relative distribution of all fractures observed on televiewer logs from nine wells (fig. 2) are shown in figure 5. Three fracture sets are indicated by the relative distribution of the data on the lower-hemisphere stereonet data plots. A low-angle fracture set (less than 45° dip) generally strikes NNE and dips WNW. The strike of individual fractures in this low-angle set range slightly more than 90° E and W of the centralized strike. This low-angle fracture set has an average dip of 18° but varies from 0 to 45°. Two high-angle fracture sets are indicated by the data plots. In general, these sets strike NNE and ENE and dip ESE and SSE, respectively.

Fracture orientation and density in each of the nine wells logged with the televiewer are shown in figure 6. In general, fracture populations within individual wells correspond to one or more of the three generalized fracture sets shown by the data for all fractures in figure 5 but vary from well to well. A few wells have fracture sets that do not correspond to the generalized fracture sets described above. The absence of observed very high-angle or vertical fractures in any of the wells is probably the result of a very high negative sampling bias because the wells are vertical.