The base map on the front cover shows geophysical survey locations overlaying a geologic map of U.S. Geological Survey, Windham, New Hampshire, 1:24,000-scale quadrangle. Geology is by G.S. Walsh and S.F. Clark, Jr. (1999) and lineaments are from Ferguson and others (1997) and R.B. Moore and Garrick Marcoux, 1998.

The photographs and graphics overlying the base map are showing, counterclockwise from the left, a USGS scientist using a resistivity meter and surveying equipment (background) to survey the bedrock beneath the surface using a geophysical method called azimuthal square-array direct-current resistivity. In the lower left, this cross section is showing the results of a survey along line 3 in Windham, N.H., using another method called two-dimensional direct-current resistivity. In the lower right, the photograph is showing a bedrock outcrop located between red lines 3 and 4 (on base map) at Windham, in which the fractures and parting parallel to foliation have the same strike as the azimuthal square-array direct-current resistivity survey results, and remotely sensed lineaments (purple and green lines on base map). The upper right graphic shows a polar plot of the results of an azimuthal square-array direct-current resistivity survey at Windham for array 1 (red circle on base map).

U.S. Department of the Interior
U.S. Geological Survey

In cooperation with the
NEW HAMPSHIRE DEPARTMENT OF ENVIRONMENTAL SERVICES

Geophysical Investigations of Well Fields to Characterize Fractured-Bedrock Aquifers in Southern New Hampshire

By James R. Degnan, Richard Bridge Moore, and Thomas J. Mack

Water-Resources Investigations Report 01-4183

Pembroke, New Hampshire
2001

U.S. Department of the Interior

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CONVERSION FACTORS, ABBREVIATIONS, AND VERTICAL DATUM

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
	Flow	
gallon per minute (gal/min)	0.06308	liter per second
	Hydraulic Conductivity	
foot per day (ft/d)	0.3048	meter per day

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows:
°F = (°C ÷ 5/9) + 32.

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.

ABBREVIATIONS USED IN THIS REPORT

Ω m	ohmmeter
mmho/m	millimohos per meter
MHz	megahertz
kHz	kilohertz
ft/s	foot per second
mS/m	millisiemens per meter
°	degree
m	meter
nT	nanotesla

Geophysical Investigations of Well Fields to Characterize Fractured-Bedrock Aquifers in Southern New Hampshire

By James R. Degnan, Richard Bridge Moore, *and* Thomas J. Mack

Abstract

Bedrock-fracture zones near high-yield bedrock wells in southern New Hampshire well fields were located and characterized using seven surface and six borehole geophysical survey methods. Detailed surveys of six sites with various methods provide an opportunity to integrate and compare survey results. Borehole geophysical surveys were conducted at three of the sites to confirm subsurface features. Hydrogeologic settings, including a variety of bedrock and surface geologic materials, were sought to gain an insight into the usefulness of the methods in varied terrains. Results from 15 survey lines, 8 arrays, and 3 boreholes were processed and interpreted from the 6 sites.

The surface geophysical methods used provided physical properties of fractured bedrock. Seismic refraction and ground-penetrating radar (GPR) primarily were used to characterize the overburden materials, but in a few cases indicated bedrock-fracture zones. Magnetometer surveys were used to obtain background information about the bedrock to compare with other results, and to search for magnetic lows, which may result from weathered fractured rock. Electromagnetic terrain conductivity surveys (EM) and very-low-frequency electromagnetic surveys (VLF) were used as rapid reconnaissance techniques with the primary purpose of identifying electrical anomalies, indicating potential fracture zones in bedrock.

Direct-current (dc) resistivity methods were used to gather detailed subsurface information about fracture depth and orientation. Two-dimensional (2-D) dc-resistivity surveys using dipole-dipole and Schlumberger arrays located and characterized the overburden, bedrock, and bedrock-fracture zones through analysis of data inversions. Azimuthal square array dc-resistivity survey results indicated orientations of conductive steep-dipping bedrock-fracture zones that were located and characterized by previously applied geophysical methods.

Various available data sets were used for site selection, characterizations, and interpretations. Lineament data, developed as a part of a statewide and regional scale investigation of the bedrock aquifer, were available to identify potential near-vertical fracture zones. Geophysical surveys indicated fracture zones coincident with lineaments at 4 of the sites. Geologic data collected as a part of the regional scale investigation provided outcrop fracture measurements, ductile fabric, and contact information. Dominant fracture trends correspond to the trends of geophysical anomalies at 4 of the sites. Water-well drillers' logs from water supply and environmental data sets also were used where available to characterize sites. Regional overburden information was compiled from stratified-drift aquifer maps and surficial-geological maps.

INTRODUCTION

Many towns and communities in New Hampshire have limited amounts, or an absence of, sand and gravel aquifers, which are favorable for constructing high-yield wells. These towns must look for additional water resources in crystalline bedrock. The average bedrock well yield in New Hampshire is about 6 gal/min. An adequate municipal or commercial well typically requires tens to hundreds of gallons per minute. The U.S. Geological Survey (USGS), in cooperation with the New Hampshire Department of Environmental Services (NHDES), has done a statewide assessment of ground-water resources in the bedrock aquifers of New Hampshire (R.B. Moore and others, U.S. Geological Survey, written commun., 2001), which provides regional and statewide information regarding bedrock aquifer areas that are likely to be favorable for resource investigation. In identified potential high-yield bedrock aquifers, individual boreholes must be targeted to intercept a fracture or fracture zone that could be from 5-10 ft to less than 1 ft wide. The water-resources professional needs additional, site-specific information, to precisely locate boreholes to intercept specific bedrock-fracture zones. If such fractures are steeply dipping, the “target” surface area overlying the high-yield bedrock aquifer can be small. As part of the statewide bedrock-aquifer assessment, the USGS, in cooperation with the NHDES, assessed the use of geophysical methods to identify high-yield bedrock-fracture zones at six sites in New Hampshire (fig. 1).

Purpose and Scope

This report describes the results of surface and borehole geophysical investigations of bedrock aquifers at selected well-field sites in New Hampshire. Included in this report are analyses of the data from various types of geophysical surveys to provide bedrock-fracture zone locations and characteristics and specifically to characterize fracture zones at high-yield well sites. The area of study includes six well field sites that were surveyed with surface methods from February to December 1999. Three sites were surveyed with borehole geophysical methods in December 2000. Geologic and lineament data were used to ensure that a variety of sites were selected, and were considered during the interpretation and discussion of the results of surface and borehole geophysical surveys.

Previous Investigations

The use of geophysical techniques are well documented for water-supply (Haeni, 1995) and contaminant investigations in unconsolidated environments. Whereas fracture zones were correlated with photolinear features in some settings by geophysical methods, for example in karst environments in Florida (Spratt, 1996) and in sandstones in West Africa (Taylor and others, 1999), few publications document the use of geophysical techniques for investigation of water supply in fractured crystalline rock, particularly in the northeastern United States. Previous investigations using various geophysical methods to study high-yield crystalline bedrock aquifers include those of Chapman and Lane, 1996; Mack and others, 1998; and Johnson and others, 1999. Direct-current resistivity and borehole radar techniques were used by Chapman and Lane (1996) to determine the orientations of fracture zones in a crystalline bedrock aquifer in Lawrenceville, Ga. Advanced borehole techniques were used in Rye, N.H., to identify fractures in wells and in the surrounding area. Strikes of fracture sets in the wells in Rye, identified by Johnson and others (1999), were coincident with remotely sensed lineaments identified by Ferguson and others (1997). Complex fracture patterns emerged between two wells using radar tomography results in Seabrook, N.H.,

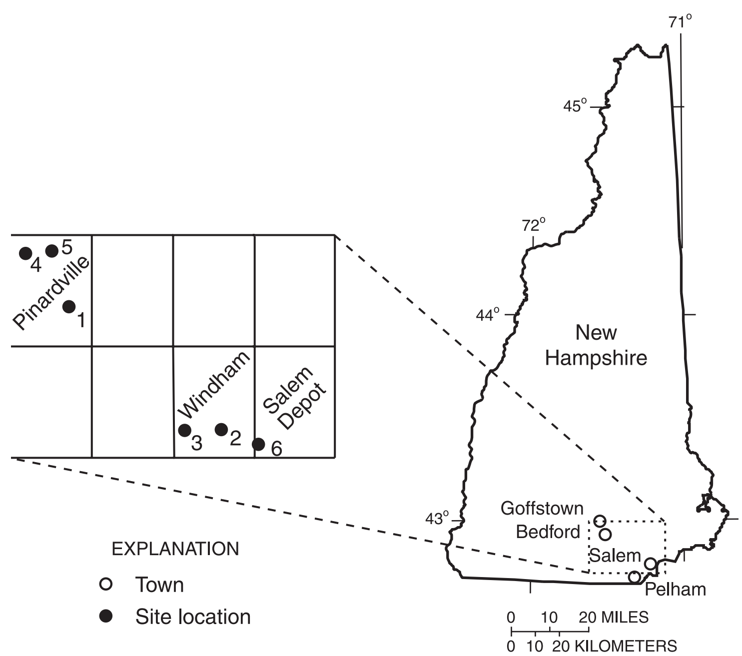

Figure 1. Location of the geophysical study area in the Pinardville, Windham, and Salem Depot 7.5-minute quadrangles in southern New Hampshire. Numbers on the quadrangles refer to sites.

one of which is one of the highest yielding bedrock wells in the State (greater than 560 gal/min). The trend of a lineament at this site (Ferguson and others, 1997) correlated with results of borehole geophysical log interpretations and results of aquifer tests (Mack and others, 1998).

Site Selection

Geophysical investigation sites for this study were selected in or near two 7.5-minute quadrangles (Pinardville and Windham, N.H.) where detailed geology (including bedrock-outcrop fracture data) was mapped as a part of this project by Walsh and Clark (1998), and T.R. Armstrong and W.C. Burton (U.S. Geological Survey, written commun., 1999). These quadrangles are the first two quadrangles in New Hampshire mapped in detail by the USGS at the 1:24000 scale. Sites were selected within these quadrangles to provide a more complete geohydrologic setting for the geophysical investigations. Additional lineament data were identified and correlated with fractures in bedrock outcrops within the two quadrangles (R.B. Moore and others, U.S. Geological Survey, written commun., 2001). Lineaments are straight line features observed on the Earth's surface that may represent bedrock fracture zones (Clark and others, 1996). Wells within 500 ft of a lineament were chosen so these data could be included in site characterizations and interpretations. Sites with bedrock-well yields greater than 75 gal/min were selected to ensure the presence of high-yield fractured rock.

Sites were assessed for potential cultural noise and were avoided if the noise potential was high. A total of 17 sites initially were selected for reconnaissance investigations. Techniques that allowed for rapid data collection (ground-penetrating radar (GPR), electromagnetic terrain conductivity surveys (EM) and very-low-frequency electromagnetic surveys (VLF)) were used at the initial sites. Six of the 17 sites were selected for detailed investigation, representing a variety of geologic and physiographic settings, and are the subject of this report.

Geohydrologic Settings

Physiographic settings for the study sites ranged from wetland valleys to mountainsides. Over the two-quadrangle region, elevations of the sites ranged from 150 to 930 ft. The maximum relief between survey lines at a site is 80 ft (at site 4 on the side of a mountain). Two sites had little to no relief between survey lines; a flat field on the side of a hill at site 5 and a wet lowland setting at site 6 (fig. 1).

At all of the sites the crystalline bedrock was covered with unconsolidated materials, which are glacial and glacial fluvial in origin. Four of the sites were covered in till that ranged in thickness from inches to tens of feet. Till generally is an unsorted mixture of clay, silt, sand, pebbles, cobbles, and boulders. Stratified drift overlays bedrock at site 3 and site 6 (fig. 1). It is not known if till is present beneath stratified drift at these sites. Stratified drift at these sites ranged from inches to tens of feet thick. Generally, stratified drift is deposited in streams or quiet water bodies fed by meltwater flowing from glaciers and consists of sorted and layered unconsolidated material.

The bedrock geology of the Pinardville quadrangle includes a suite of metamorphosed intrusives, metamorphosed layered extrusives, and interlayered metasediments (T.R. Armstrong and W.C. Burton, U.S. Geological Survey, written commun., 1999). The rocks range in age from Permian to Late Proterozoic. Sites 1, 4, and 5 were in the Massabesic Gneiss and Rangely Formations. Rocks in the Massabesic Gneiss Complex are coarse grained and include well-foliated felsic and mafic gneiss and weakly foliated to well-layered migmatitic gneiss. Rocks of the Rangely Formation have a strong parallel bedding ductile fabric composed of well-layered pelitic metasediments.

Bedrock in the Windham quadrangle consists of Ordovician and Silurian metasedimentary rocks of the Merrimack Trough, with intrusive rocks as young as Mesozoic (Walsh and Clark, 1998). Sites 2, 3, and 6, in the Windham and neighboring Salem quadrangles are in the Berwick Formation, with site 2 on a contact between the Berwick Formation and the Ayer Granodiorite. The Berwick Formation is a biotite-plagioclase-quartz granofels schist with interbedded calc-silicate rocks and feldspathic quartzite. The Ayer Granodiorite is a Silurian-age intrusive rock. The Ayer Granodiorite is mapped as two phases at site 2, one phase being porphoritic granite to granodiorite, and a second phase of granodiorite (Walsh and Clark, 1999).

Brittle (fracture) geologic data from Walsh and Clark (1999) and T.R. Armstrong and W.C. Burton (U.S. Geological Survey, written commun., 1999) were analyzed on a site-by-site basis to define fracture families. All measurements within a 4,000-ft radius of each study site with a dip greater than 45° were compiled from a geographic information system (GIS) database. Fracture families were defined for each site by plotting azimuth-frequency (rose) diagrams in the Structural Data Integrated System Analyzer (DAISY 2.19) by Salvini (2000). The DAISY software uses a Gaussian curve-fitting routine for determining peaks in directional data (Salvini and others, 1999). Peak orientations, error ranges, and normalized fracture peak heights were compiled for site characterization and comparison with geophysical data. The error range indicates the range of trends associated with the peak. The normalized fracture-peak height indicates how large the peak is, in percent, in relation to the largest (100 percent) peak at a site.

Hundreds of remotely sensed lineaments are present in the study area (Clark and others, 1997; Ferguson and others, 1997). The lineament data used in the analysis for this study were observed based on the methods of Clark and others (1996). Lineaments associated with the sites were observed from the following observation platforms: side looking airborne radar (SLAR), satellite photography (Landsat), low-altitude black and white aerial photography (LOWALT), high-altitude black and white aerial photography (HIGHALT), color infrared aerial photography (CIR), and 1:24,000-scale topographic map (TOPO). Several of the remotely sensed lineaments at the sites have been correlated with physiographic features seen in the field at ground level. Many lineaments were correlated with fractures measured in outcrop; these lineaments are noted in this report when observed at the study sites. Domain-analysis and 1,000-ft buffer analysis fracture-correlation techniques and the full data set are described by (R.B. Moore and others, U.S. Geological Survey, written commun., 2001), a companion report for this project.

High-yield wells at the study sites are used for irrigation, and domestic and public water supply. The reported water yield from the wells ranged from 75 to 630 gal/min. The depth of the wells ranged from 150 to 500 ft. The maximum depth to bedrock was estimated at 22 ft from drilling logs (casing length minus 12 ft). Water-table depth in the bedrock ranged from at the surface (0 ft) to 64 ft deep.

Well-yield probabilities, throughout the Pinardville and Windham quadrangles, were estimated by (R.B. Moore and others, U.S. Geological Survey, written commun., 2001) for a grid of cells, 98.4 x 98.4 ft per cell. Probabilities of obtaining at least 40 gal/min were estimated for theoretical wells drilled 400 ft deep. These estimates were based on a large database of actual bedrock well yields of wells with varying depths and site characteristics. Well-site characteristics were derived from Statewide databases and quadrangle-scale topographic, geologic, and lineament maps. Probabilities at the geophysical sites ranged from 5 to 38 percent. Locations of the high-yield wells at the geophysical sites had probabilities ranging from 12 to 38 percent based on the well-site characteristics.

Acknowledgments

The authors thank the State, Federal, and municipal officials, residents, and well contractors that provided data for this study. Appreciation is expressed to the members of the Geophysical Advisory Committee for providing insight and guidance for the study plans. Members of the Geophysical Advisory Committee include Richard Chormann, James Vernon, Joseph Ingari, Garrick Marcoux, John Jemzeck, and John Brooks. Dr. James H. Vernon provided data examples from surveys at a site just north of the Windham quadrangle. Surface geophysical surveys and analysis by George Willard contributed significantly to this study. Special thanks are extended to the private and corporate landowners and managers who volunteered access to their land and wells making this study possible.

APPROACH AND METHODS

Surface geophysical survey methods are useful in water-resource investigations of surficial aquifers (Haeni, 1995). Some of these methods can be applied to fractured-bedrock settings. For this study, surface geophysical techniques were selected that can yield interpretable anomalies if fracture zones are present, and can be detected on the basis of background geologic and cultural conditions. Borehole-geophysical techniques were selected to provide the location and orientation of bedrock fractures at depth for comparison with the results of surface-geophysical surveys. Processed and interpreted geophysical data were compared to geologic outcrop and remotely sensed data.

Many geophysical-survey methods take advantage of the electrical anomaly associated with the large electrical contrast between fractures and the host rock. In general, the electrical conductivity of crystalline bedrock (such as granites, gneiss, and shists) in the State is low relative to other subsurface materials, and a fluid-filled fracture zone is more electrically conductive than the host rock. This electrical contrast creates a dielectric permittivity contrast (Beres and Haeni, 1991), for example, that makes it possible to image fluid-filled fractures with ground-penetrating radar. Sufficiently large fracture zones may have a slower average seismic velocity than competent rock; therefore, average bedrock seismic velocity can be high parallel to the dominant fracture strike. Low magnetic anomalies can indicate weathered fracture zones, which lowers the presence of magnetic minerals in the host rock.

Many other factors can cause geophysical anomalies and must be considered when interpreting fracture zones. Bedrock foliation, geologic contacts, or intrusions may produce electric or magnetic contrasts or anomalies depending on mineral constituents of the rocks. Bedrock and overburden type, ground-water saturation, ground-water chemistry, bedrock and surface topography, cultural, and atmospheric conditions all may have an effect on geophysical data. Variations in electrical properties result from different rock and overburden materials, pore-water chemistry, porosity, and degree of saturation of bedrock or overburden.

Up to seven surface-geophysical survey methods were used to characterize the subsurface at the sites—Primary wave (P-wave) seismic refraction, ground-penetrating radar, magnetics, very-low-frequency electromagnetics, inductive electromagnetic terrain conductivity, two-dimensional direct-current electrical resistivity, and azimuthal square-array electrical resistivity. Technique application was limited on the basis of the natural and cultural conditions at each site. Borehole-geophysical logs also were collected at three sites and included caliper, fluid temperature and resistivity, electromagnetic induction, natural-gamma radiation, and optical televiewer. The following sections describe the surface and borehole surveys.

P-Wave Seismic Refraction

Seismic refraction uses refracted seismic waves to characterize the acoustic or seismic-velocity distribution of layered earth materials. A compression or primary (P) wave is generated at the Earth's surface, travels into the earth and is refracted and reflected back to the surface. The resulting waves are recorded by geophones. Only layers increasing in seismic velocity with depth can be accurately detected with seismic refraction. Thin, intermediate velocity layers are not detectable. A thorough description of theory and interpretation of seismic refraction data is given by Haeni (1988).

Variations in average bedrock seismic velocity were examined between survey lines with different orientations at the sites. Variations in bedrock seismic velocity can be attributed to vertical and sub-vertical fracture zones in which maximum velocity, the average of a line, is along the strike of these fracture zones (Hansen and Lane, 1995). Seismic surveys also were used to search for depressions in the bedrock surface, which might be indicative of a weathered fracture zone.

Seismic-refraction surveys were done at three of the sites primarily to identify seismic-velocity variations, but also to survey the depth to the water table and the depth to bedrock. Nine survey lines were collected at five locations using a geophone spacing of 10 ft. Four of the locations contained two orthogonal lines sharing a common center point. One line was oriented normal and one parallel to the suspected strike of a fracture zone on the basis of previously collected geophysical data. First arrivals of P-waves from 5 shot points on each survey line were recorded using a 24-channel signal enhancement seismograph. A sledgehammer and a metal plate were used to produce the seismic waves. The relative locations and elevation of each geophone and shot point were surveyed for data analysis.

Seismic data were processed using a computer program developed by Scott (1971) that uses time delay and ray-tracing methods. Where possible, identification of the water-table surface and underlying bedrock topography was made during processing to help interpret information gained from other techniques. Variations in seismic velocities and bedrock surface topography were compared with other geophysical data.

Ground-Penetrating Radar

Ground-penetrating-radar (GPR) surveys done with a transmitting and receiving antenna were used to image the depth to bedrock and fracture zones. The antenna generates and detects electromagnetic (EM) waves at a 300 MHz frequency. The radar-wave propagation is affected by differences in electromagnetic properties of the medium. These properties include dielectric permittivity, electrical conductivity, and magnetic susceptibility (Beres and Haeni, 1991), which are affected by water content, overburden type, and lithology. Features identified in this study are bedrock-overburden interfaces and sub-horizontal bedrock fractures. Hansen and Lane (1995) used GPR to identify bedrock-fracture zones and overburden interfaces. The utility of GPR is limited at sites with electrically conductive clay-rich overburden (such as till) because the EM wave can be attenuated before it reaches bedrock (Ayotte and Dorgan, 1995; Ayotte and others, 1999). Where conditions are conducive to successful data collection, GPR provides a rapid means of providing detailed insight into subsurface conditions.

GPR survey design and resulting data presentation for this study differed at each site. Where the land surface was flat and open, the surveys were done in a continuous data-collection mode. Continuous data collection requires that the antenna be pulled at a constant speed while radar pulses are transmitted into the earth. A point-survey mode was used at sites that were heavily wooded or had rugged terrain. During a point survey, the antenna is placed at regular intervals along a line. A 5-ft data-collection interval was used for all point surveys. Repeated measurements at each point are stacked to filter out noise. Continuous and point profiles were adjusted for topographic relief. The results of the GPR surveys for two lines where anomalies indicate features in bedrock are presented in this report. Other GPR surveys are not included.

Magnetics

Magnetometer surveys measure slight variations in the Earth's total magnetic field. Changes in the magnetic field can result from varying types and amounts of magnetic minerals present in the bedrock. Magnetic anomalies also can differ as a result of the sensor and bedrock separation caused by variations in overburden thickness. Magnetic anomalies related to fracture zones could be low if the magnetic minerals of the host rock have been weathered. Magnetic lows were associated with fracture zones in an investigation by Frohlich (1989) of crystalline rocks across New England.

Total field surveys for each line were measured with a proton magnetometer at a measurement interval of 10 ft. Surveys done for this study were completed in less than an hour; therefore, diurnal corrections were not made. Results are reported in nanoteslas (nT) subtracting the regional base of roughly 54,000 nT.

Very-Low-Frequency Electromagnetics

Very-low-frequency electromagnetic surveys (VLF) use very-low-frequency radio (3-30kHz) waves generated by distant transmitters. Measurements of a tilt-angle of the long axis of the primary magnetic field ellipse are made, which are affected by secondary magnetic fields. The secondary fields are a product of electrical galvanic currents induced in conductive media in the Earth from the primary magnetic field. This study used the VLF transmitter in Cutler, Me., that broadcasts at a frequency of 24 kHz at 1,000 kilowatts power. This transmitter provided a consistent and strong signal. Alternate transmitters in Jim Creek, Wa., and Aguada, P.R., were assessed but the signal strength was too weak for use here.

The tilt-angle mode of operation was used to detect conductive features in the bedrock. Measurements were taken every 10 ft along a line. Fracture zones that are fluid filled can produce high electrical conductivity anomalies. VLF surveys are best for detecting conductive anomalies when the feature is linear or elongated and oriented less than a 45° angle from the measurement point to the transmitter. The response of the tilt-angle percent when passing over a conductive feature is a high reading followed by a low reading. The inflection point between the high and low anomalies indicates the location of the feature (Iris Instruments, 1993). The width of the anomaly from peak to trough is proportional to one half of the depth to the top of the feature (Wright, 1994). Surface topography can cause subtle changes in the tilt-angle and must be considered. Ionospheric activity can affect VLF signal strength. VLF was used previously, in conjunction with other techniques, to identify fracture zones at a site in the Mirror Lake area, Grafton County, New Hampshire (Powers, Singha, and Haeni, 1999).

Inductive Electromagnetic Terrain Conductivity

Inductive electromagnetic terrain conductivity (EM) surveys responsed to induced electromagnetic signals to measure the electrical conductivity of subsurface media. A portable transmitter and receiver kept at a fixed distance (coil spacing) were used for EM surveys from point to point along a survey line. The transmitter emits an electromagnetic field by energizing a coil of wire with alternating current (AC). The resulting magnetic field (primary) induces an electrical current in the ground. A secondary magnetic field, caused by the induced current, is measured as a voltage difference from the primary field signal in the receiving coil. This induced voltage is proportional to the apparent conductivity of the Earth. The apparent conductivity measured is that of a hemisphere of all Earth materials between the coils where the effective measurement point is the mid-point between the coils.

The vertical dipole survey mode (VD) was used primarily in this study because it is better at detecting vertical conductive features and has a deeper range of sensitivity than the horizontal dipole survey mode. In the VD mode, the plane of the coils is held horizontally, with the axis of the coils oriented vertically. The VD survey is optimized to be most sensitive at depths of 0.4 times the coil spacing, and measures within a depth range of 0.1 to 1.5 times the coil spacing (McNeil, 1980). The modeled response of a vertically conductive feature detected with a VD survey, consists of a below background (sometimes negative) apparent conductivity measurement centered over a feature positioned between two above-average apparent conductivity measurement peaks. The distance between the inner limbs of the conductivity peaks must be equal to the coil spacing to be able to identify a vertical conductor (McNeil, 1980). The relative height of the above-average measurement peaks to each other can indicate the dip direction of the feature. The dip of a planar conductive feature is towards the higher conductivity peak.

The horizontal dipole (HD) mode is used to obtain a measurement of the near-surface conductivity. In the HD mode, the plane of the coils is held vertically, with the axis of the coils oriented horizontally in the plane of the survey line. The HD is more sensitive to electrical properties close to the surface; a measurement depth range extending to 0.75 times the coil spacing. HD measurements were used to provide a qualitative indication of relative changes in overburden thickness, assuming the overburden is more electrically conductive than the underlying bedrock. Since bedrock generally is much more electrically resistive, a HD high can represent a thickening of the overburden, or a filled bedrock trough. This technique was used by Taylor and others (1999) to indicate depressions in a bedrock surface.

EM measurements were made using a 20-m coil spacing at most of the sites for this study. At sites where electromagnetic noise was a problem, a 10-m coil spacing was used. VD measurements were made every 10 ft and HD measurements were made every 20 ft along a survey line.

Two-Dimensional Direct-Current Resistivity

Two-dimensional direct current (dc) resistivity surveys, termed 2-D resistivity, measure the electrical resistivity of the subsurface. Direct current is induced in the ground by two current electrodes and the voltage is measured at two potential electrodes. A resistance value is obtained by dividing the measured voltage by the induced current. The apparent resistivity is calculated from the resistance value and geometric factors that are different for each array type (arrangement of current and potential electrodes in relation to each other) and takes into account the electrode spacing. Dipole-dipole and Schlumberger array (Zohdy and others, 1974) survey configurations were used. A combination of 28 electrodes and addressable switches were used at a time to collect resistivity measurements. When needed, electrodes were moved from one end of the line to the other end to collect additional measurements. The relative elevation of the land surface at each electrode was surveyed and accounted for in processing of the data.

The apparent resistivity values collected in the field were inverted. Results are adjusted, during the processing, for topographic relief along a survey line. Field and model data sets were processed using RES2DINV version 3.42 (Loke, 1997) to produce inverted resistivity sections from the apparent resistivity data. Inversion gives a more realistic resistivity value projected to a relative elevation.

Model cross sections of the subsurface resistivity distribution were created and data collection was simulated using RES2DMOD version 2.2

(Loke, 1999). The input model cross sections were created on the basis of the known geology and the results and interpretations of the inverted field data. Synthetic apparent-resistivity data were calculated from the model cross-sections and inverted for comparison to the inverted field data. A model solution is reached after numerous iterations, each with a modified model, when the inverted resistivity section from the field data and inverted synthetic resistivity section from the model data approximately match. The model solutions are not unique but, with inclusion of known information to the model, such as depth to water table or depth to bedrock, the solutions represent a likely interpretation.

Azimuthal-Square Array Direct-Current Resistivity

Azimuthal square-array dc-resistivity surveys, termed square-array resistivity, measure the subsurface resistivity in various orientations and allow for the determination of the strike of a conductive anomaly with depth (Habberjam and Watkins, 1967). To determine the strike of near-vertical conductive anomalies in the bedrock, a horizontal-layered overburden must be assumed. This technique cannot correct for bedrock or surface topography; therefore, surveys (arrays) were collected at areas without these conditions

Electrodes are set in square arrays, direct current is produced in the ground by two current electrodes on one side of the square and a potential difference is measured at two electrodes on the other side. The length of the side of the square is termed the A-spacing. From these four electrodes, apparent resistivity is calculated from electrode spacing and a geometric factor. For each square, the current and potential electrode connections are switched 90° to measure resistivity in another orientation using the same electrode locations. Making a measurement by placing the current and potential electrode connections diagonally on the square facilitates an error check.

Resistivity represents an average resistance of subsurface materials between the electrodes. The midpoint of resistivity can be projected to a specified depth and compass direction on the basis of the side length of the square, defined by A-spacing and the array orientation. The effective survey depth is approximately equal to the A-spacing. For each survey, data were collected with array “squares” oriented 15° apart and with a number of different A-spacings. The size of the survey and effective depth of penetration depended on the amount of unobstructed terrain available. After preliminary evaluations of 2-D resistivity data, square array locations were chosen.

Graphical interpretations of the data were made by plotting the resistivity with radial orientation. Resistivity data were collected and interpreted according to the techniques described by Lane and others (1995). Primary conductive strikes are orthogonal to the resistivity maximum. Secondary conductive strikes are orthogonal to the second largest resistivity measurements. If a range of high resistivity measurements is observed, then a conductive range is orthogonal to the range of measurement orientations.

Borehole Geophysical Surveys

Six borehole geophysical logs were collected including caliper (hole diameter), fluid temperature, fluid resistivity, electromagnetic induction, natural-gamma radiation, and optical televiewer. The first five logs can help identify water-bearing fractured zones, whereas the optical televiewer provides the fracture orientation. Borehole geophysical logs were interpreted together to characterize borehole fractures.

The caliper log was used to generate a continuous profile of the borehole diameter. This log shows the mechanically measured diameter of the borehole as a spring-loaded, three-arm caliper tool is pulled up the well. The arms open as they pass borehole enlargements. Increases in the borehole diameter generally are related to fractures, but also can be caused by changes in lithology or well construction. The profile indicates the roughness of the borehole wall. Some enlargements were larger than the caliper diameter (18 in.).

The electromagnetic induction (EM) log provides a profile of the electrical conductivity of the rocks and fluid in the materials surrounding the borehole. The conductivity changes measured by the EM log are caused by variations in the electrical conductance of the fluids in the formation, alteration of minerals, and increases in porosity and borehole enlargements. The log can be used to delineate changes in lithology and electrical properties of water in the formation. In crystalline rock in

New Hampshire, increases in conductivity were associated with fractured zones (Mack and others, 1998), primarily the result of increased water content in the fractures.

The fluid-temperature log displays a continuous measurement of fluid temperature in the borehole. In the absence of ground-water flow, the temperature gradually increases with the geothermal gradient, which is 0.6^{o} C per 100 ft of depth (Keyes, 1988). A continuous plot of the fluid temperature with depth is used to identify zones that deviate from the expected geothermal gradient. Deviations from the gradient indicate locations where ground water enters or exits the borehole.

The fluid-resistivity log records the electrical resistance of the fluid in the borehole. Changes in the electrical resistance of the water in the borehole indicate differences in the total dissolved solid concentrations in borehole water. These differences typically indicate sources of water that have contrasting chemistry and have come from alternate water-bearing zones. Similar to the fluid-temperature profile, fluid-resistivity deviations from a straight-line gradient indicate locations where ground water enters or exits the borehole.

The natural gamma log measures the natural-gamma radioactivity of the formation surrounding the borehole. Gamma radiation is a natural product of the radioactive decay of potassium-40, and a daughter product of uranium and thorium decay. The gamma log used in this investigation does not differentiate between the sources of the gamma radiation. The gamma log is a count of total gamma-radiation emissions, which may be correlated with the rock type or with fracture infillings. Potassium-40 is abundant in potassium feldspar (microcline and orthoclase), which alters to sericite and clay. In the alteration process, potassium-40 is concentrated in the clay by processes of adsorption and ion exchange. Deviations in the gamma log trace indicate changes in the rock type or the presence of mineralized fractures. Clay minerals, which sometimes form in the fractures, generally have an elevated concentration of potassium-40 minerals from areas away from the fractures and cause an increase in the gamma values.

An optical televiewer (OTV) log was used to map the location and orientation of fractures that intersect a well. The OTV log collects oriented digital pictures of the borehole wall in 360° concurrently with borehole deviation. The product is a high-resolution, digital picture of the borehole wall that can be used to determine the location and orientation (strike and dip) of fractures, lithologic contacts, or other borehole features. Boreholes drilled into crystalline rock frequently deviate from vertical because of variations in rock properties, the fabric of the bedrock, fracturing, or as a result of the drilling process or technique. Deviation is measured by a magnetometer and inclinometer, and is recorded as an azimuthal direction (0-360° from magnetic north) and the inclination of the borehole (0-90° from vertical) with depth. Measurements of borehole deviation are used to correct the apparent strike and dip of a feature in a deviated borehole to its true orientation.

Results of the OTV log for a borehole can be summarized in a fracture stereogram for comparison with surface or remote analyses. The stereogram, a lower-hemisphere, equal-area projection of poles to planes, was used to plot the orientation of fractures and contacts and foliation. Fractures include transmissive fractures, open fractures, contact fractures and cracks. A stereogram reduces each features plane to a point that represents the intersection of a pole, perpendicular to a features plane, with a lower hemisphere. For example, a horizontal fracture would be indicated by a point in the center of the stereogram, whereas a fracture striking 215° with a dip of 89° W would be indicated by a point towards the right (eastern) edge of the outer circle. The orientation of the fracture plane is reported as 215°, 89°, which in the right-hand-rule format implies that a fracture that dips west (89° dip, to the right of the 215° bearing).

ANALYSIS AND RESULTS OF GEOPHYSICAL INVESTIGATIONS OF WELL FIELDS

Six sites in southern New Hampshire were selected for geophysical surveying. Detailed site maps and graphics of the data are used to describe survey results. Surface-geophysical surveys were done along survey lines, and around array centers at each of the six sites. The results are in terms of distance along each line or a trend for an array. Trends are reported in terms of azimuth degrees from true north. Borehole geophysical logs were collected at selected sites where wells were accessible (no pumps were installed), and (or) permission was obtained to remove water-supply pumps. Borehole-geophysical logs provide actual fracture measurements for confirmation or comparison with analyses of surface and remotely sensed surveys.

Numerous anomalies were detected in the survey lines and arrays by various methods. Locations on the survey lines displaying anomalies from multiple methods, or strong anomalies, likely are related to actual features in the bedrock. Multiple geophysical methods, and geologic and remotely sensed data, were used to locate and characterize subsurface features to provide indication of bedrock-fracture zones. Square-array resistivity results, geologic data, and lineament locations and orientations provided information to determine the strike of likely fracture zones.

Site 1, Bedford, New Hampshire

Site 1 on State Route 101 in Bedford, N.H., is a wooded hillside at an elevation of about 360 to 400 ft in the area of the surveys. T.R. Armstrong and W.C. Burton (U.S. Geological Survey, written commun., 1999), mapped the bedrock geology of this area as two variations of the Massabesic Gneiss Complex, specifically a migmatite gneiss and a layered paragneiss and orthogneiss (fig. 2). The bedrock is exposed at the surface on the west end of line 1 and in the central part of the site. The overburden is mapped as a till, which is unsorted to poorly sorted clay silt, sand, pebbles, cobbles and boulders with some gravel (Koteff, 1970). Mapped lineaments at the site were observed from SLAR, Landsat (Clark and others, 1997), and TOPO platforms trending 18°, 33°, and 22° (fig. 2). The SLAR and Landsat lineaments were fracture correlated using the 1,000-ft buffer analysis technique (R.B. Moore and others, U.S. Geological Survey, written commun., 2001). Fracture data within a 4,000-ft radius of the site have three peak orientations: 27°±7° (100 percent, normalized height), 295°±10° (25 percent, normalized height), and 301°±11° (23 percent, normalized height). Fractures in an outcrop between line 1 and line 2 have a strike and dip of 20° and 82°. Lineaments are visible at the site as swales at line 1 trending 5° and 20°.

Drilled to a depth of 485 ft, through approximately 24 ft of overburden, well BIW 889 (fig. 2) has a reported yield of 150 gal/min and a static water level depth of 30 ft. The drillers' log indicates that the high-yielding water-bearing zone is between 420 and 485 ft deep. Probabilities of exceeding a yield of 40 gal/min from a 400-ft deep well at this site ranged from 5 to 29 percent. A 14-percent probability is calculated for the 98.4-ft (30-m) square cell that well BIW 889 is located in (R.B. Moore and others, U.S. Geological Survey, written commun., 2001). Variations in probability at the site appear to reflect lithologic contacts, topography, and lineaments.

Three geophysical survey lines were selected to bisect lineament locations on either side of the well. Line 1 is in the woods to the south of the well, just east of State Route 101 and extending for 480 ft to the east. Line 2 is 900 ft long and begins in an open field east of State Route 101, crosses through a wooded area and into another open field to the north of the well. Two array center locations were placed on line 2 at locations where geophysical anomalies were detected along the survey line. Array 1 was centered at 660 ft along line 2. Array 2 was centered at 450 ft along line 2 (fig. 2).

Geophysical Surveys and Interpretation

Seven geophysical methods were used to characterize site 1. Overburden thickness or physical properties were derived from the (P)-Wave Seismic-Refraction, GPR, EM, and 2-D resistivity survey results (figs. 3-7). Bedrock characteristics and anomalies that could be caused by bedrock fractures are observed in the seismic-refraction, GPR, magnetometer, VLF, EM, 2-D resistivity, and square-array resistivity-survey results.

Seismic-refraction (P)-wave data were collected along line 2 between 335 and 565 ft. The line was interpreted based on a three-layer model: unsaturated till, saturated till, and bedrock. The bedrock surface ranges from 15-40 ft below the ground surface, depending on the velocity chosen for the saturated till. The water table is about 8 ft below the ground surface. Three troughs are indicated in the bedrock surface. The deepest troughs are centered at 375 and 425 ft, with 10-20 ft of relief in the bedrock surface. A minor trough is centered at 525 ft with 5-10 ft of relief. Bedrock seismic velocity normal to the lineament was calculated to be approximately 8,000 ft/s. This velocity is significantly lower than bedrock velocities (10,000 to 20,000 ft/s) typically seen in New Hampshire (Medalie and Moore, 1995).

Ground-penetrating radar (GPR) data were collected along the entire lengths of line 1 and line 2 (fig. 2). The GPR profile of line 1 indicates subhorizontal reflectors at about 10-20 ft below the interpreted bedrock surface. These reflectors likely

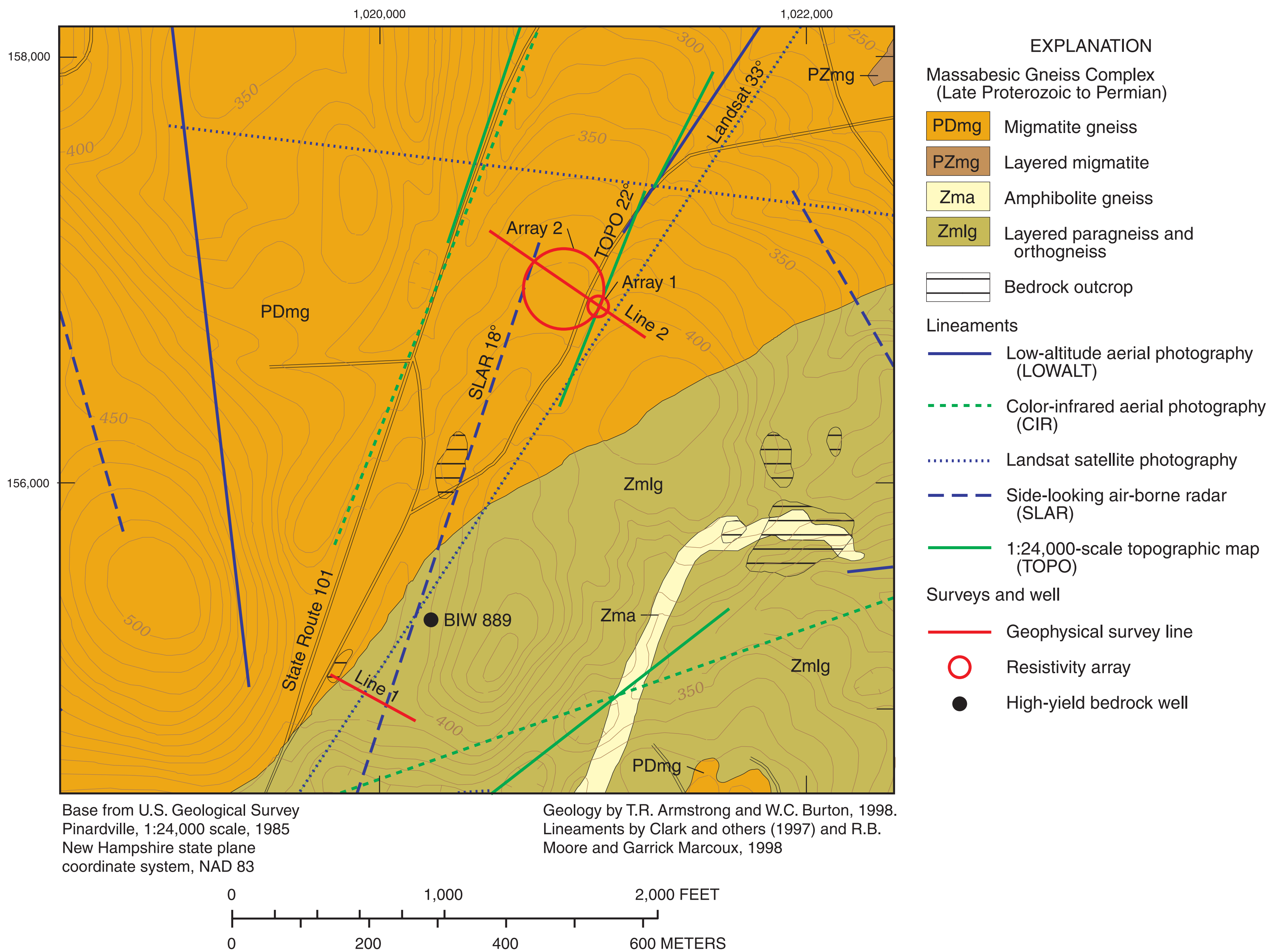

Figure 2. Geophysical survey locations, bedrock geology, and lineaments at site 1, Bedford, N.H. Site location is shown on figure 1.

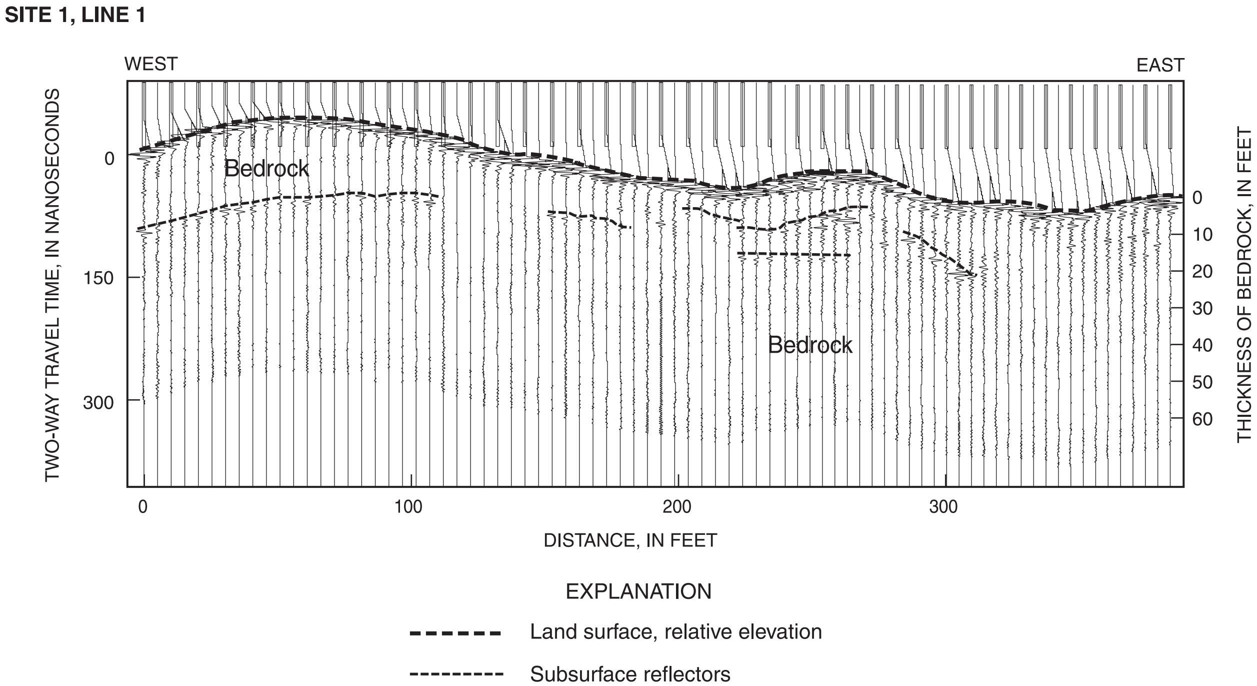

Figure 3. Processed ground-penetrating radar profile at site 1 from line 1, Bedford, N.H. Site and line locations are shown on figures 1 and 2, respectively.

are sheeting fractures (fig. 3). The GPR profile along line 2 indicates a reflector at approximately 10 ft deep from 600 to 900 ft, which is likely the water table in the overburden above bedrock.

Magnetometer measurements were made along line 1 and line 2 (figs. 4 and 5). The average magnetic field measurement (after subtracting the regional trend of 54,000 nT) at this site during the surveys is about 500 nT. Results at line 1 indicate an anomalous magnetic low of 445 nT between 270 and 310 ft; a magnetic low of 470 nT occurs at about 410 ft (fig. 4a). The survey results at line 2 (fig. 5a) indicate a low of 480 nT between 0 and 200 ft. The total field increases to a high of 575 nT at 455 ft. Results at line 2 indicate a low of 525 nT between 640 and 690 ft, and a low of 515 nT at 845 ft (fig. 5a).

VLF tilt-angle surveys at line 1 and line 2 indicate anomalies. Overhead power lines nearby affected results along approximately the first 100 ft of line 1. Line 1 had inflection points at 110, 195, 240, and 310 ft (fig. 4b). Inflections were detected at line 2 at 130, 300, 375, 530, 640, 800, and 880 ft; overlapping anomalies are observed between 300 and 375 ft (fig. 5b).

EM surveys were collected on line 1 and line 2 at site 1. Nearby power lines caused signal noise. To avoid this noise, the survey coil spacing was shortened from 20 (65.6 ft) to 10 m (32.8 ft). Anomalies that likely are associated with vertical conductors were observed on line 1 at 200, 290, 360, and 440 ft (fig. 4c). Similar anomalies on line 2 are at 85 ft and 170 ft (fig. 5c). A combination of deepening overburden interpreted from the HD and potential vertical conductors are noted at 440 ft and 610 ft (fig. 5c).

2-D resistivity surveys were collected at line 1 and line 2. Models were created to check interpretations for both lines. Line 1 survey interpretations indicate conductive anomalies in resistive bedrock that could be a result of near-horizontal sheeting fractures. A vertical conductive anomaly also is found on line 1 at 355 ft (fig. 6). Four major resistivity units from line 2 likely represent an unsaturated, and conductive-saturated overburden, and resistive-competent and conductive-saturated bedrock (fig. 7). Survey results indicate that near horizontal fractures in the bedrock could be present at the southeastern end of line 2. Near vertical, and dipping, conductive anomalies are indicated at 55-95 ft (not modeled), 460-500 ft, and 630-660 ft (fig. 7).

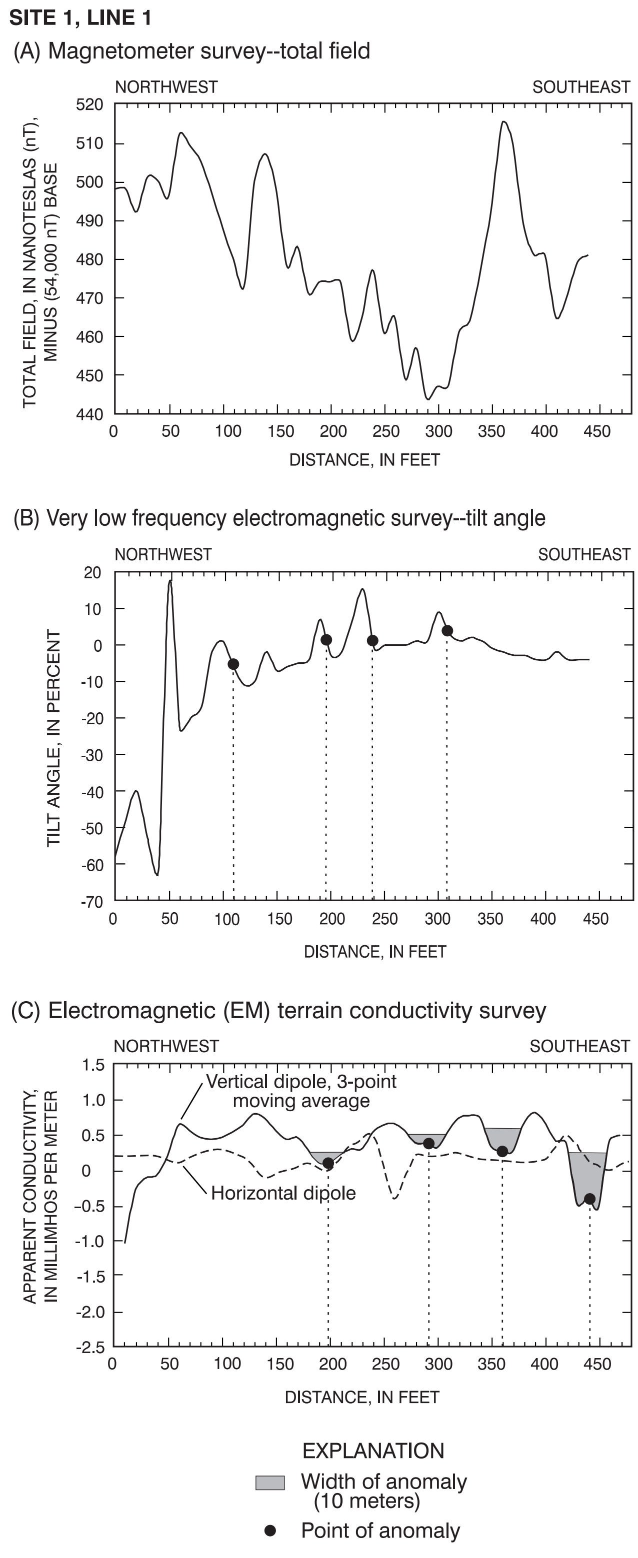

Figure 4. Magnetic and electromagnetic surveys at site 1 from line 1, Bedford, N.H. (A) magnetometer survey; (B) very low frequency (VLF) electromagnetic survey; (C) electromagnetic (EM) terrain conductivity survey with a 10-meter (32.8-foot) coil spacing. Site and line locations are shown on figures 1 and 2, respectively.

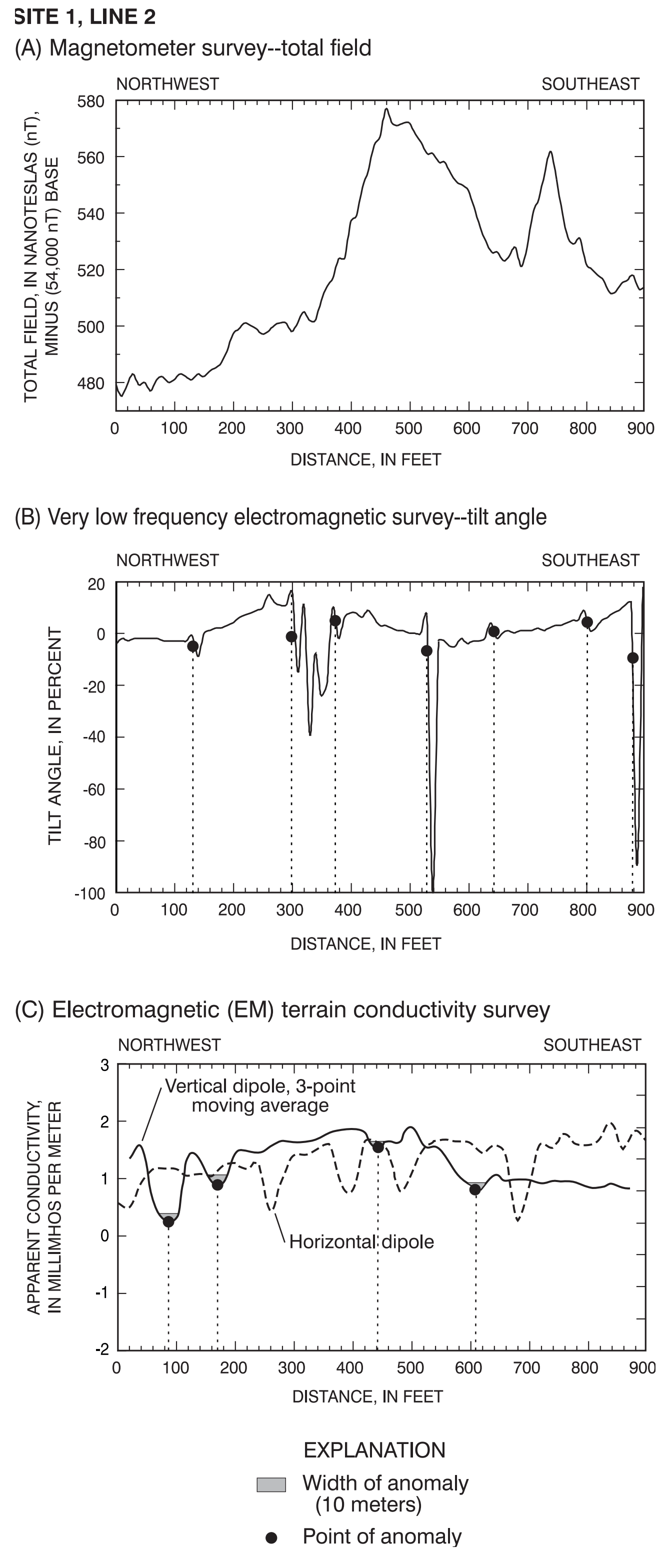

Figure 5. Magnetic and electromagnetic surveys at site 1 from line 2, Bedford, N.H. (A) magnetometer survey; (B) very low frequency (VLF) electromagnetic survey; (C) electromagnetic (EM) terrain conductivity survey with a 10-meter (32.8-foot) coil spacing. Site and line locations are shown on figures 1 and 2, respectively.

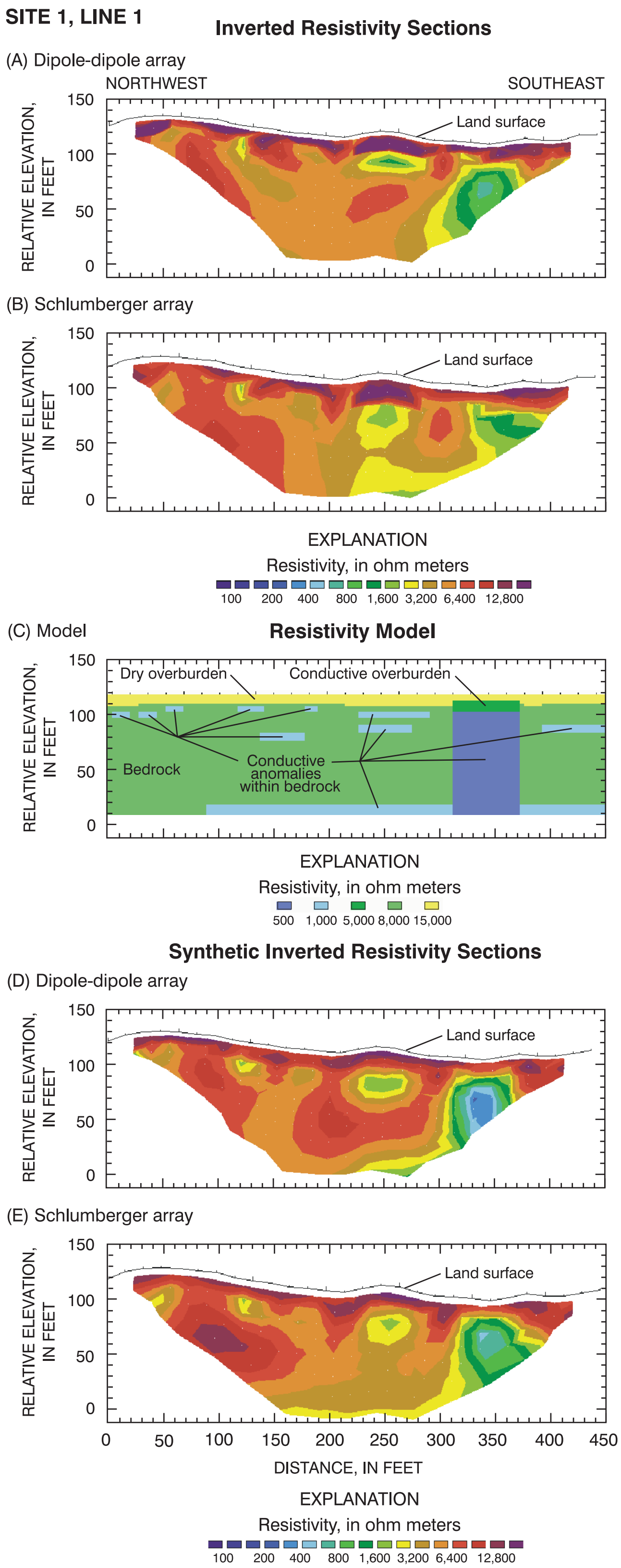

Figure 6. Cross sections showing (A and B) inverted resistivity sections of two-dimensional, direct-current resistivity data at site 1 from line 1, Bedford, N.H.; (C) model based on field data from A and B; and (D and E) synthetic resistivity output data from Model C. Site and line locations are shown on figures 1 and 2, respectively.

Square-array resistivity data were collected at two arrays centered on line 2. At the largest A-spacing of 10 m, array 1 (fig. 8a) shows a prominent primary and secondary conductive strike of 15° and 60°. At the largest A-spacing of 40 m, array 2 (fig. 8b) indicates a weak primary conductive strike of 345°. Measurements from array 2 show a decrease in the average resistivity from the 5-m A-spacing to the 10-m A-spacing, and an increase in resistivity from 10- through 40-m A-spacing. This sounding (fig. 8b) indicates three layers, resistive at the surface (unsaturated overburden), a conductive layer (saturated overburden), and a resistive lower layer (bedrock).

Integration of Results

EM and VLF anomalies, indicative of conductive features in bedrock, appear along line 1 at 200 ft. A magnetic low, a conductive 2-D resistivity anomaly, and VLF and EM anomalies indicative of conductive features in bedrock are found along line 1 between 310 and 390 ft. Line 2 has near vertical, conductive EM and 2-D resistivity anomalies coincident with a magnetometer peak value between 460-500 ft. Fractured bedrock could be bisecting the line as indicated by the low bedrock seismic velocity between 335-565 ft. Conductive anomalies between 610 and 660 ft along line 2 from VLF, EM, and 2-D resistivity coincide with a magnetic low. Conductive features along lines have consistent responses, where the magnetic response varies between high and low with some features, along line 2.

Conductive strikes from square-array resistivity results with the same orientation as fractures identified in outcrop, or remotely sensed lineaments, likely are related to fracture zones. Interpretation of square-array resistivity surveys at array 1 indicate a primary conductive strike of approximately 15°±7.5° at the largest A-spacing, which is the same as the orientations of TOPO and SLAR lineaments (fig. 2). This strike also corroborates with the maximum fracture trend from geologic data. The peak fold axis trends 65° and is correlated with the deepest secondary strike anomaly trends from the square-array resistivity survey at array 1. Mapped lineament orientations at this site of 22° and 33° coincide with the maximum fracture peak from geological mapping data of 27°±7°. These include a 25,054-ft long Landsat lineament striking 33°, and a 10,900-ft long TOPO lineament striking 22°.

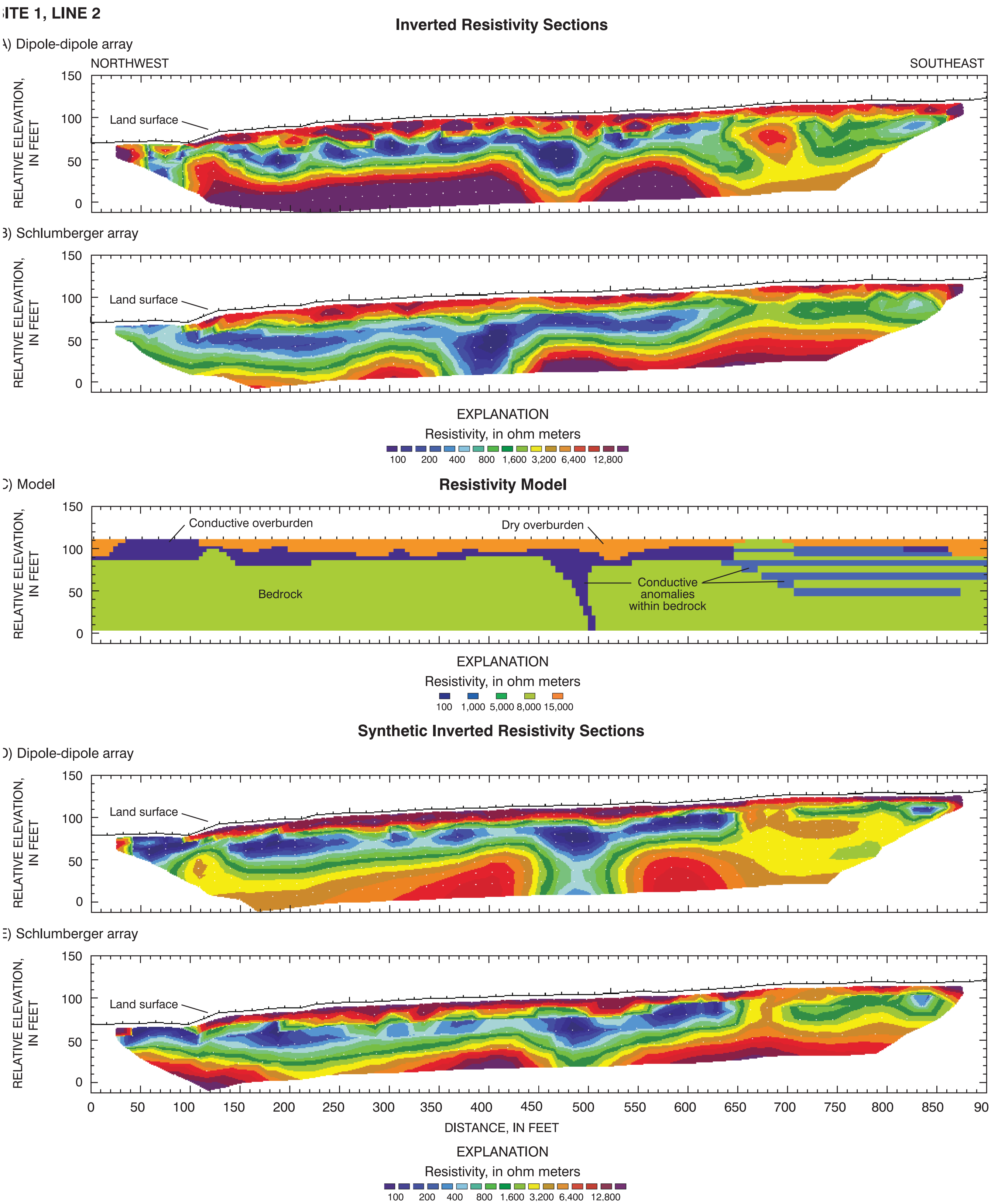

Figure 7. Cross sections showing (A and B) inverted resistivity sections of two-dimensional, direct-current resistivity data at site 1 from line 2, Bedford, N.H.; (C) model based on field data from A and B; and (D and E) synthetic resistivity output dataf from Model C. Site and line locations are shown on figures 1 and 2, respectively.