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In Cooperation with the Town of Seabrook, New Hampshire

Geophysical Characterization of a High-Yield, Fractured-Bedrock Well, Seabrook, New Hampshire

By Thomas J. Mack, Carole D. Johnson, and John W. Lane, Jr.

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CONVERSION FACTORS, VERTICAL DATUM AND ABBREVIATIONS

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
meter (m)	3.281	foot
gallon per minute (gal/min)	0.00006309	cubic meter per second

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

m/µs, meters per microsecond

MHz, megahertz

dB/m, decibels per meter

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Abstract

A 492-foot-deep water-supply well completed in crystalline bedrock in Seabrook, New Hampshire, yields more than 560 gallons per minute on a sustained basis. Borehole geophysical logs from two wells were analyzed to characterize the bedrock aquifer supplying this well. Video camera, caliper, fluid temperature and conductivity, natural gamma, electromagnetic induction, spontaneous potential, resistivity, and deviation logs were used. More specialized geophysical logs included acoustic televiewer and borehole radar. Borehole-radar surveys included cross-hole tomography and single-hole reflection surveys. Analysis of the logs indicated that the upper part of bedrock aquifer, to a depth of 380 feet and especially the upper 150 feet, is more fractured than the lower bedrock. The radar tomogram indicates a complex hydraulic connection between the production well and a nearby test well. The predominant orientation of fracturing in the bedrock aquifer trends northeast-southwest (N 24°–64° E) and generally dips 45° to 85° SE or NW. Fracture zones were compared with lineament data and hydraulic testing at the two wells and at a second well field. A lineament identified on low-altitude photography, trending northeast-southwest (N 17° E), correlates with geophysical log interpretations and aquifer tests at the site.

INTRODUCTION

Many towns and communities in New Hampshire have limited amounts or an absence of sand and gravel aquifers, which are favorable for the development of high-yield wells. These towns must look for additional water resources in crystalline bedrock, which generally yields very little water to a well (a few gallons per minute). Bedrock well 5, a public water-supply well for the Town of Seabrook, was constructed to augment shortages in the town's water supply, especially those that occur during peak demand periods in summer. Bedrock well 5, with a withdrawal rate of greater than 560 gal/min, is currently the highest yielding bedrock well in New Hampshire. An understanding of the hydraulic characteristics of the fractured bedrock aquifer supplying bedrock well 5, and the primary pathways of flow to the well, is needed to protect this resource and to identify those characteristics that may be useful in locating other high-yield wells in fractured bedrock aquifers. The U.S. Geological Survey (USGS), in cooperation with the Town of Seabrook, in southeastern N.H. (fig. 1), used geophysical methods to characterize bedrock well 5, and an adjacent bedrock test well 30 ft away to determine the nature of fracturing in the high-yield bedrock aquifer.

Purpose and Scope

The purpose of this report is to demonstrate how advanced borehole geophysical techniques, in combination with remotely sensed lineament analysis, are applied and used to characterize a fractured bedrock aquifer. The results of the study are the interpretation of the location, nature, and extent of fractures in a bedrock aquifer. Geophysical logs collected from two boreholes are presented and interpreted in order to characterize the bedrock aquifer.

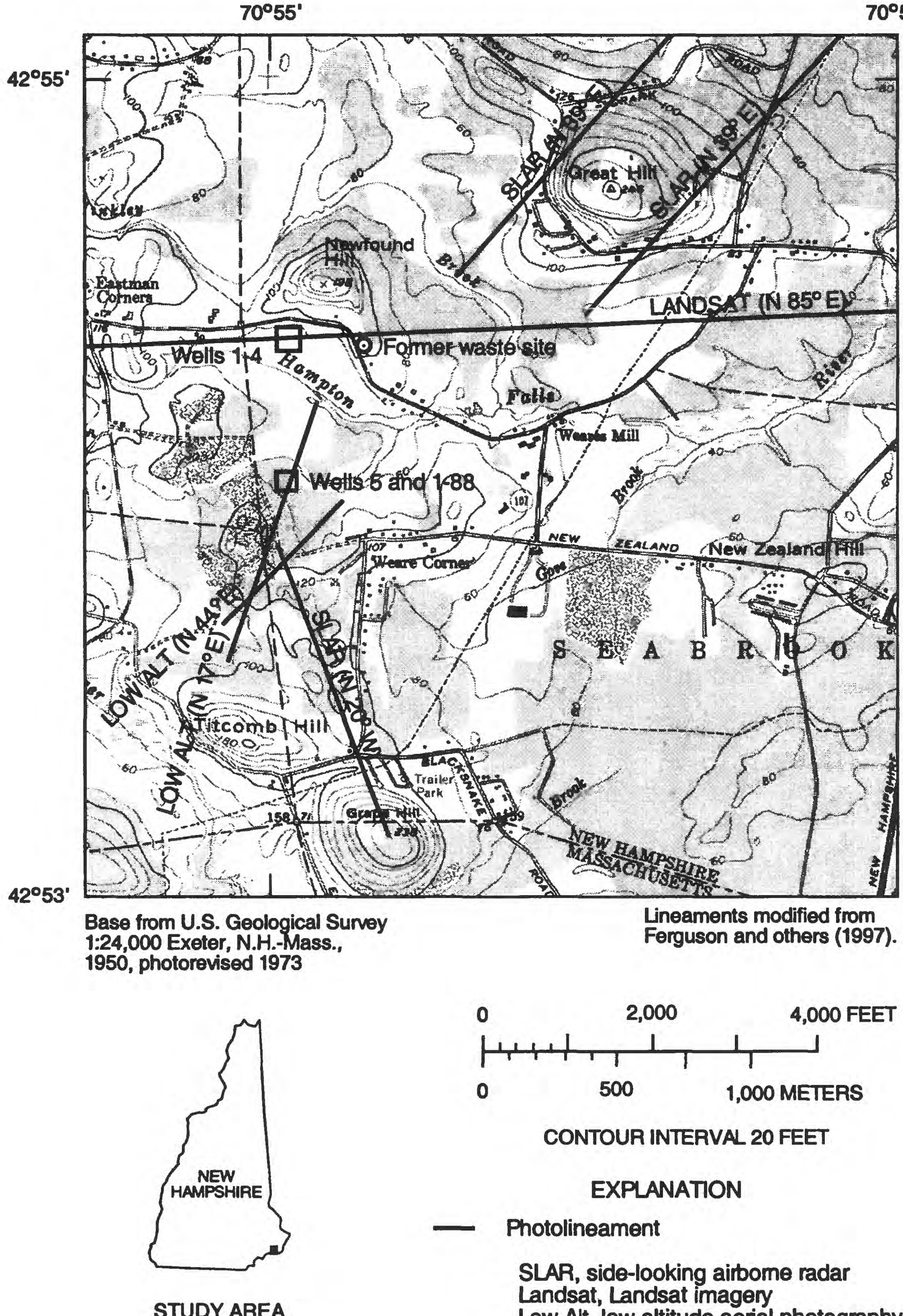

Figure 1. Location of the study area and photolinear data.

Description of the Study Area

The study area is a municipal well field in the northwestern corner of the town of Seabrook (fig. 1). The well field consists of a 492-ft-deep, 12-in.-diameter, municipal supply well, Bedrock well 5 (referred to as well 5 in this report), and a 402-ft-deep, 6-in.-diameter test well TW-1-88 (referred to as well 1-88 in this report) 30 ft east of well 5. Wells 5 and 1-88 are completed in bedrock beneath approximately 73 ft of overburden. The overburden consists of clay and fine sand to 40 ft below the land surface, and glacial till, consisting of compact unsorted sand, silt, clay, and rocks, from 40 to 73 ft below land surface (Douglas DeNatale, Earth Tech, Inc., formerly Whitman and Howard, Inc., written commun., 1997).

A nearby well field, 1/3 mi north of the study area off Route 107, also consists of bedrock supply wells. Bedrock wells 1 though 4 (referred to as wells 1–4 in this report) at the nearby field are completed to depths of up to 500 ft; yields of these wells range from approximately 160 to 500 gal/min (Flanagan and Stekl, 1990). In 1989, a waste site (fig. 1) where engine-repair activities had taken place was identified as a likely source of contamination by volatile organic compounds (VOCs) to wells 1–4. The hydrogeology of this waste site, in relation to the two well fields (wells 1–4 and well 5), is described by Whitman and Howard, Inc. (1991, 1993). The waste site is on the south side of Newfound Hill about 1/4 mi east of wells 1–4 and about 1/2 mi northeast of well 5. The unconsolidated sediments beneath this site include up to 30 ft of beach deposits, consisting of layers of sand, gravel, and boulders near the surface and silt and clay at greater depths. Below the beach deposits are layers of glacial till and marine silt and clay deposits that range in thickness from 55 to 100 ft.

Acknowledgments

Appreciation is expressed to town officials in Seabrook who provided assistance and access to their wells. Special thanks are extended to Douglas DeNatale, of Earth Tech, Inc., for providing assistance and insight throughout the investigation regarding the wells and the bedrock aquifer in Seabrook.

STUDY METHODS

Borehole geophysical logs were used to characterize the geohydrology of the fractured bedrock aquifer. The borehole logs collected in wells 5 and 1-88 included a standard suite of geophysical logs such as video camera, caliper, fluid temperature and conductivity, natural gamma, electromagnetic induction, spontaneous potential, and resistivity. Specialized geophysical logs collected using heat-pulse flowmeter, acoustic televiewer (ATV), deviation, and radar. Borehole-radar surveys included cross-hole tomography between the two boreholes and single-hole reflection surveys in each borehole. ATV and flowmeter logs were not used in well 5 (12-in. well) because the borehole diameter exceeded the operating range for these tools. Depth measurements are referenced to the top of the steel well casing.

Standard Logs

A submersible color video camera was used to examine the borehole to discern rock types, fractures, possible faults, and the condition of the borehole wall. The camera had a digital depth counter, which was incremented in tenths of feet and was superimposed onto the analog picture. Continuous images were recorded on video cassettes. The locations of fractures and rock types were identified directly from the images and were tabulated and plotted. Techniques and equipment for borehole imaging used for the well surveys are described by Johnson (1996).

Enlargements in the borehole diameter generally are related to fractures, but can also be caused by changes in lithology or well construction. The profile indicates if the borehole wall is relatively smooth or rough. Some enlargements may be larger than the caliper diameter.

The fluid temperature log displays a continuous measurement of the temperature, or geothermal gradient, of fluid in the borehole. In the absence of ground-water flow, the temperature gradually increases 0.6°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 concentration of the total-dissolved solids in the water in the borehole. These differences typically indicate sources of water that have contrasting chemistry and have come from alternate water-bearing zones.

The 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, uranium, and (or) thorium decay. The natural gamma log used in this investigation does not differentiate between the source of the gamma radiation. It counts the total gamma-radiation emissions, which can often 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 comprise the infilling of fractures, generally have an elevated concentration of potassium-40 minerals.

The electromagnetic induction (EM) log provides a profile of the electrical conductivity of the rocks and fluids in the rocks surrounding the borehole. The conductivity changes recorded by the EM log are caused by variations in the electrical conductivity of fluids in the formation (such as contaminants or saltwater), alteration of minerals, increases in porosity, or borehole enlargements. The log is used to delineate changes in lithology and electrical properties of water in the formation. Generally, increases in conductivity are associated with total-dissolved solids in water in the rock formation as well as the porosity and clay content of the rock.

The single-point-resistance log measures the resistance between an electrode at depth in the borehole and an electrical ground at the land surface. Single-point resistance is a function of the properties of the formation, as well as the fluids in the formation and borehole. The resistance decreases with an increase in the borehole diameter, weathering, and (or) alteration that sometimes occurs at fracture locations.

The spontaneous potential (SP) log records the natural electric potentials that develop in the borehole between the fluid and the surrounding rock formation. Spontaneous potentials, or voltages, are usually measured in millivolts. The log is most sensitive to changes in the formation and not as sensitive to properties of the fluid in the borehole. It is used to delineate variations in lithology and quality of water in the formation and in fractures. In addition, if there is a significant inflow to the well at a fracture, then the flowing water can generate an electric (streaming) potential. These effects are usually less important than the electrochemical effects (Keyes, 1988).

Boreholes drilled into crystalline rock frequently deviate from vertical due to variations in rock properties or the presence of fracturing. In addition, the deviation of the borehole can be enhanced by drilling techniques. The deviation log records the azimuthal direction (0–360°) and the inclination (0–90°) of the borehole over the depth of the borehole. This log is used to correct the orientation of fractures determined from the acoustic televiewer (ATV) logs and in the analysis of radar cross-hole tomograms.

A flowmeter measures the velocity of vertical flow in the borehole. Used in conjunction with the other geophysical logs, individual fractures or zones of fractures can be identified as the locations where water enters or exits the borehole. The flowmeter used in this investigation makes use of a heat-pulse tracer rather than the more conventional impeller method (Paillet and Williams, 1992). The heat-pulse flowmeter uses a thermal tracer to measure flows as small as 0.01 gal/min.

The ATV tool emits a narrow acoustic beam that rotates 360° and is focused at the borehole wall. The acoustic wave moves through the fluid in the borehole and is reflected off of the borehole wall. The log records the amplitude and travel time of the reflected signal. The product is a high resolution, magnetically oriented, digital image of the location and orientation (strike and dip) of fractures and some lithologic contacts. The travel time can be displayed in the form of an acoustic caliper log that shows the oriented cross-sectional dimensions of the borehole. A fracture that intersects the borehole causes the impedance and scattering of the acoustic wave and a low amplitude response of the signal. The amplitude of the reflected acoustic signal of a smooth and intact borehole wall is higher than the signal response of a rough or fractured borehole wall. A segment of the ATV data collected in well 1-88 is shown in figure 2.

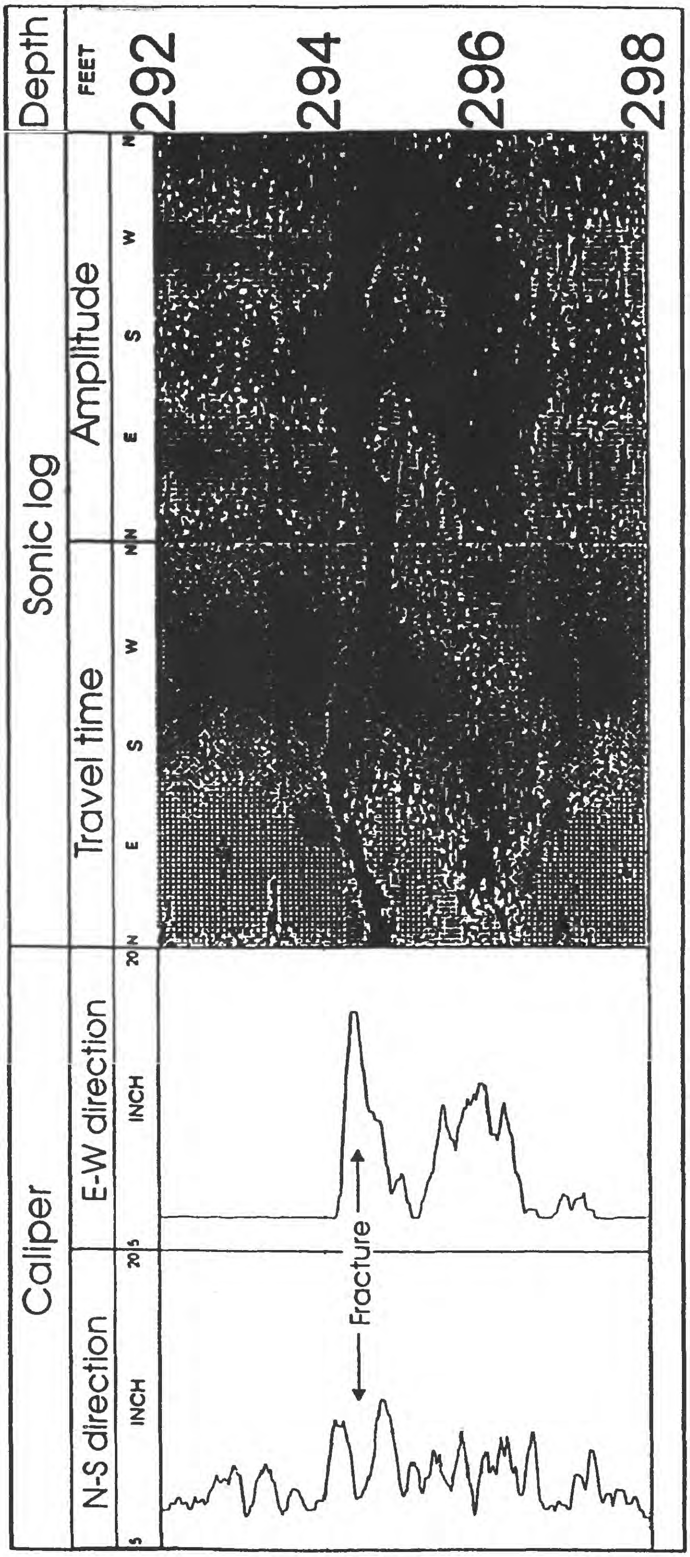

Figure 2. Acoustic televiewer (ATV) log of well 1-88, Seabrook, New Hampshire.

A fracture appears on the image as a high contrast, low amplitude line (dark bands in fig. 2). On the acoustic-caliper log, a fracture is indicated by an increase in the one-way travel time of the wave, which is converted to a borehole diameter (fig. 2). Borehole diameter is shown in two directions, north to south and east to west.

Borehole-Radar Surveys

Borehole-radar surveys were done to detect the orientation and location of discrete fractures or fracture zones surrounding the borehole. Following the methods of Lane and others (1994), directional surveys were conducted in each well and a cross-hole (tomography) survey was run between wells 5 and 1-88. The antennas used in this study were broad-based electric-dipole transmitting antennas, with a center frequency of 22 MHz or 60 MHz, directional and non-directional receiving antennas.

Borehole radar logs were used to determine location and lateral extent of fractures in the bedrock surrounding the borehole. A transmitting antenna radiates pulses of electromagnetic energy that propagate from the borehole into the surrounding rock. Point or planar reflectors at interfaces between two electromagnetically different materials can be identified in the log. Reflections are caused by water-filled fractures, faults, bedding, changes in rock type, or water quality (Lane and others, 1994). The electromagnetic waves continue to propagate and be reflected until all of the energy is dissipated. The total distance of penetration away from the borehole depends on the frequency, arrangement of the transmitting and receiving antennas, and the electromagnetic properties of the rock.

A single-hole directional survey was conducted in well 5 using a 22-MHz transmitter and a 60-MHz receiver. The directional antenna is used to determine the strike and dip of the reflectors surrounding the borehole. Single-hole-reflection surveys also were conducted in well 5 and well 1-88 using the non-directional 60-MHz transmitter and receiver. The non-directional antenna is used to generate an image of the electromagnetic response of the bedrock surrounding the borehole. The image is a composite response that shows the reflected signal from 360° in a single plane. The location and dip of planar reflectors can be identified using the non-directional tool but not the strike. The non-directional, receiving antenna generally has greater lateral penetration into the bedrock than the directional antenna.

A tomogram is an image of the electromagnetic response in the plane between the two wells. Cross-hole tomography was conducted between wells 5 and 1-88 using the 22-MHz transmitter and 60-MHz receiver. Data was collected every 13 ft (4 m) in the two holes. Cross-hole tomography data were interpreted to produce velocity and attenuation tomograms from a depth of 98 to 460 ft with a 6.6 by 6.6 ft (2 by 2 m) resolution.

BEDROCK CHARACTERISTICS

Lithology

Novotny (1969) has mapped the regional geology as Silurian age metasedimentary bedrock of the Kittery and Eliot Formations. The Kittery Formation consists of dark gray slate, dark gray-green to silvery-gray phyllite, quartz-biotite and biotite-sericite schist, quartzite and feldspathic quartzite, and lime-silicate rock (Novotny, 1969). The Eliot Formation consists of dark-gray slate; dark gray to dark green phyllite; biotite, quartz-biotite, and feldspathic quartz-biotite schist; feldspathic and dolomitic quartzite; and lime-silicate rock containing actinolite (Novotny, 1969). The approximate contact (there are few exposures locally) between the Kittery and Eliot Formations trends approximately north to south through the areas of well 5 and wells 1–4.

The majority of the rocks found in the borehole were metasedimentary rocks that are part of the Merrimack Group (Hussey and Bothner, 1993). Drill cuttings from well 1-88 are described by Douglas DeNatale (written commun., 1997) as gray and gray-green phyllite and quartzite, which is consistent with Novotny's (1969) description of the Kittery and Eliot Formations. Some cuttings from well 1-88 showed dissolution weathering indicative of calcareous rock. Possible bedrock "caverns" were reported during the drilling of wells 1–4 (Whitman and Howard, Inc., 1993), which may be related to dissolution weathering processes.

Fracture-Trace Analysis

Fracture-trace analysis was performed by the USGS as part of a statewide bedrock aquifer-mapping assessment (Moore and Clark, 1995). Fracture-trace analysis identifies straight-line features on the land surface, as viewed on aerial images at various scales, that are most likely related to the surface expression of steeply dipping fractures or fracture zones. These linear features, or lineaments, are noted by the detection of narrow troughs in the topography, truncated geomorphic features, gaps in ridges, straight-line stream segments, and (or) variations in the vegetation or soil. This method provides orientation of the linear feature, but does not provide a measurement of dip angle.

The methods and criteria of the statewide fracture-trace analysis are described by Clark and others (1996). The technique used by the statewide analysis requires the identification of lineaments by two independent observers on multiple scales and types of imagery including black and white aerial photography (at a scale of 1:20,000 and 1:80,000), side-looking airborne radar (SLAR) (at a scale of 1:250,000) and Landsat (at a scale of 1:1,000,000).

Lineaments identified in the study area by Ferguson and others (1997) are shown in figure 1. One low-altitude (1:20,000) lineament (N 17° E) directly intersects the study area. Assuming fracture zones may extend beyond mapped lineaments, other nearby lineaments are also of interest. Other nearby lineaments that can be projected to intersect the study area include two SLAR and one low-altitude (1:20,000) lineaments, bearing N 39°–44° E; and a SLAR lineament bearing N 20° W. Figure 1 includes a Landsat lineament (N 85° E) that more closely intersects the wells 1–4 well field (Richard B. Moore, U.S. Geological Survey, written commun., 1997) than originally located (Ferguson and others, 1997). Although Clark and others (1996) used a standardized process and criteria for lineament mapping, the technique can be subjective. Depending on the platforms observed, and the methods and criteria used, additional or different patterns of lineaments could be mapped for the study area. For example, some of the same lineaments were identified in a previous study, presented in Whitman and Howard, Inc. (1991, fig. 3), in addition to lineaments with orientations other than those shown on figure 1.

INTERPRETATION OF GEOPHYSICAL LOGS

Borehole-radar logs were completed in July 1996. Other logs were collected in November 1996, and February and July of 1997. Initially in November 1996, an obstruction was encountered in well 1-88 at a depth of 156 ft. The video camera was unable to pass the obstruction; however, the caliper, fluid temperature, fluid resistivity, gamma and deviation logs were able to fit around the obstruction to log the entire hole. In February 1997, the obstruction was cleared from the borehole so that video and flowmeter surveys could be completed. After the obstruction was cleared, video and flowmeter logs were collected. An ATV and an additional flowmeter log (with well 5 being pumped) were completed in well 1-88 in July 1997. The logs were examined to identify anomalies or changes in the measured properties that relate to locations of fractures or lithologic contacts. Borehole video, ATV, and radar data are either not shown, or only a segment is shown, in this report. (Original data are maintained on file in the New Hampshire/Vermont District office.)

Standard Logs

Plots of standard logs are shown in figures 3 (well 5) and 4 (well 1-88). Graphic plots of log data indicate lithology changes, water-quality changes or flow, borehole characteristics, and locations of fractures.

Numerous changes in the individual logs of both wells are apparent with depth. Major anomalies in the logs for well 5 (fig. 3) are apparent at a few distinctly corresponding depths. These anomalies, or deflections in the log traces, are most noticeable in the caliper log at center depths of 180, 220, and 380 ft. Significant responses also are noticeable in the EM, temperature, and video logs at these depths. For example, conductivity increases in the EM log at these depths. Slope deflections in the temperature log indicate inflow or outflow of water at these points. The video log was used to confirm the presence of fractures at these locations. Below 380 ft, the caliper, gamma, temperature, EM, and video logs indicate a more uniform, less fractured rock than that above 380 ft.

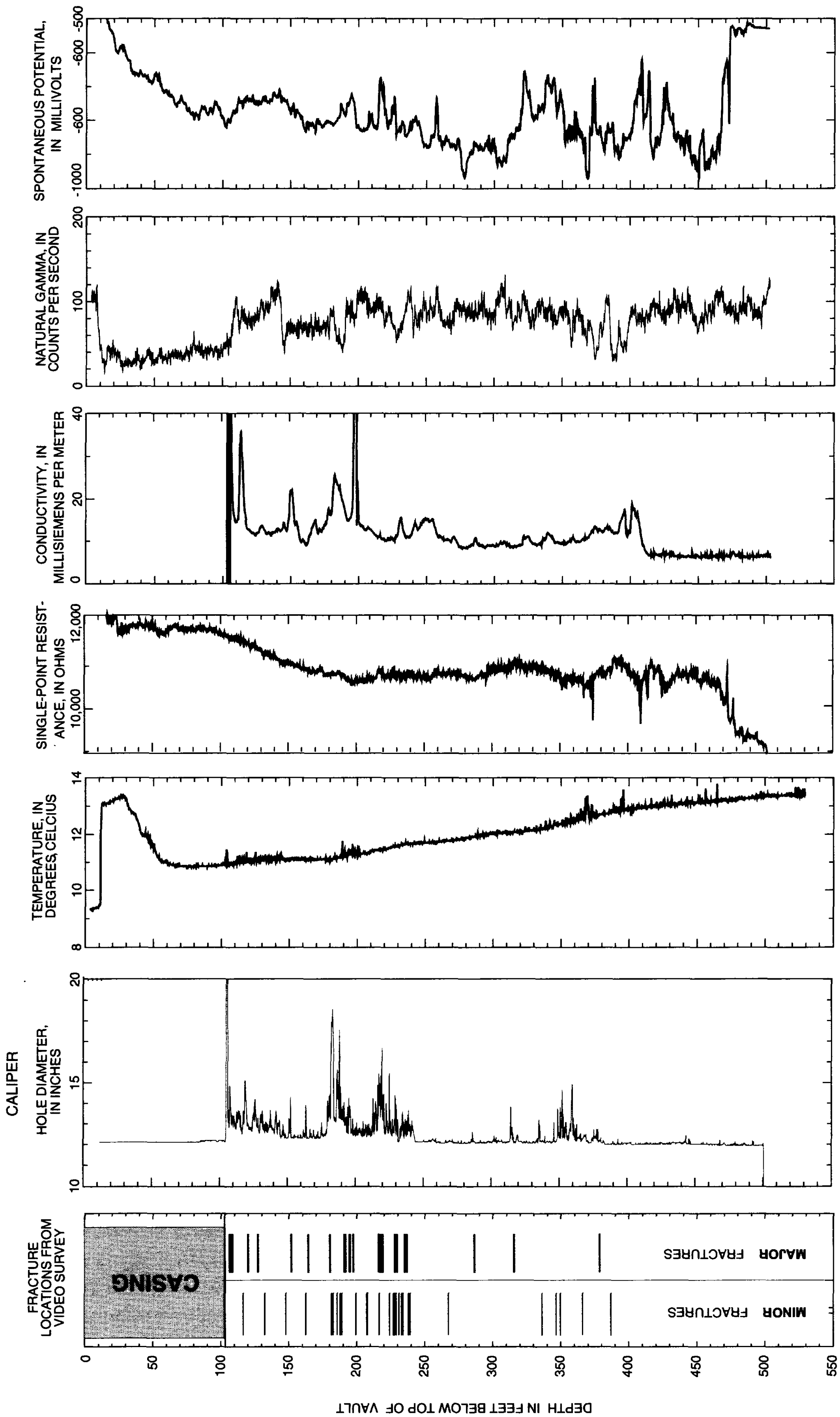

Figure 3. Geophysical logs of well 5, Seabrook, New Hampshire.

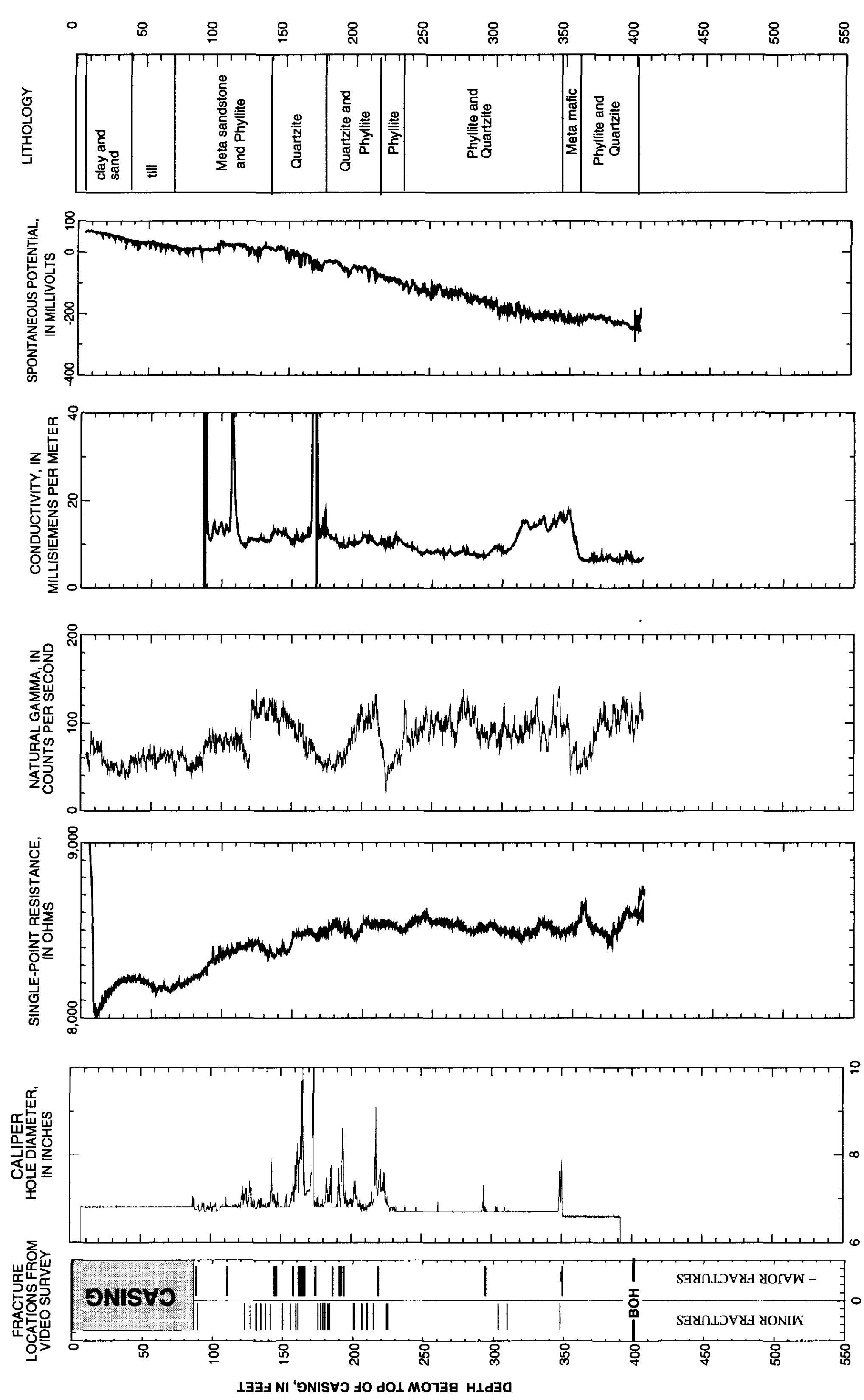

Figure 4. Geophysical logs of well 1-88, Seabrook, New Hampshire.

Major anomalies in the logs for well 1-88 (fig. 4) are less apparent than for well 5, but are noticeable at a few corresponding depths. These anomalies are most noticeable in the caliper log at center depths of 110, 155, and 220 ft. Enlargements measured by the caliper logs correlate well with fractures observed on the video. Interpretation of the video images of well 1-88 indicates that the rock type is a metasedimentary unit that exhibits steeply dipping bands of dark gray green and black layers.

The borehole video surveys indicate that the rock type in the upper 380 ft of well 5 is significantly different from the rest of the bedrock that was found in the two boreholes. It appears to be a felsic-rich igneous intrusion that is almost devoid of dark (mafic) minerals. This unit could possibly be quartz-diorite. Below the upper igneous rock, from 380 to 490 ft, well 5 penetrated metasedimentary rocks similar to the rocks in well 1-88. The natural gamma and EM conductivity logs (figs. 3 and 4), and a description of the drill cuttings (Whitman and Howard, Inc., 1993) support this interpretation of lithology.

The ATV log of well 1-88 (fig. 2 and appendix 1) shows multiple discrete fractures. Many of the fractures, particularly in the upper 200 ft of the well, are in enlarged zones where it is difficult to determine orientations of individual fracture planes. The orientation and mid-point depth of fracture planes that could be discerned from the ATV log are listed in table 1. The ATV data are shown as a plot of lower-hemispherical, equal-area projection of poles to fracture planes in figure 5a. In this plot, or stereogram, each fracture plane is reduced to a point that represents the intersection of a pole, perpendicular to a fracture plane, with a lower hemisphere. For example, a horizontal fracture would be indicated by a point in the center of the stereogram, whereas a north-south fracture with a dip of 89° W would be indicated by a point at the right (eastern) edge of the outer circle. Throughout this report, fracture orientations are described in an azimuthal direction from east of True North where the fracture's dip is to the right of that direction ("Right-hand rule"). By this nomenclature a north-south fracture, with a dip to the west, would have an orientation of N 180°E, as opposed to N 0°.

No singular trend is apparent in the ATV-derived fracture orientations of well 1-88 (fig. 5a); however, the majority of discernible fractures are above 230 ft deep. A broad group of poles from the highly fractured upper zone, above 190 ft, represents fractures with a strike of N 16° E to N 112° E and a dip of 26° SE to 54° SW. Another broad grouping of primarily deep fractures, indicate a south to west fracture strike with moderate (40°) to steep (75°) dips. In general, most of the fractures strike northeast-southwest and dip moderately (40°). Flowmeter-log

Table 1. Midpoint depth, strike, and dip of fractures identified in well 1-88 by acoustic televiewer in Seabrook, New Hampshire

[Strike is reported using a "right-hand-rule" where the direction of the strike is that where the dip is to the right of the strike]

Midpoint depth, (in feet) (figure 5)	Acoustic televiewer		Notes
	Strike (degree)	Dip (degree)	
89.6	331	39	
93.9	148	52	
95.5	333	41	
99.1	318	48	
101.4	332	37	
110.7	304	71	
122.0	210	59	Enlarged zone, 121 to 130 feet
131.0	208	57	
135.3	148	58	
137.2	111	43	
144.5	17	27	
145.4	112	54	
158.6	85	38	
159.9	339	45	
161.0	181	41	
162.2	169	37	
163.2	43	23	Enlarged zone, 163 to 167 feet
174.2	58	29	
187.7	34	31	
191.0	189	37	
197.2	96	48	
219.0	221	53	
294.3	244	58	
303.0	204	32	
309.9	174	13	
348.8	220	76	
350.6	205	43	

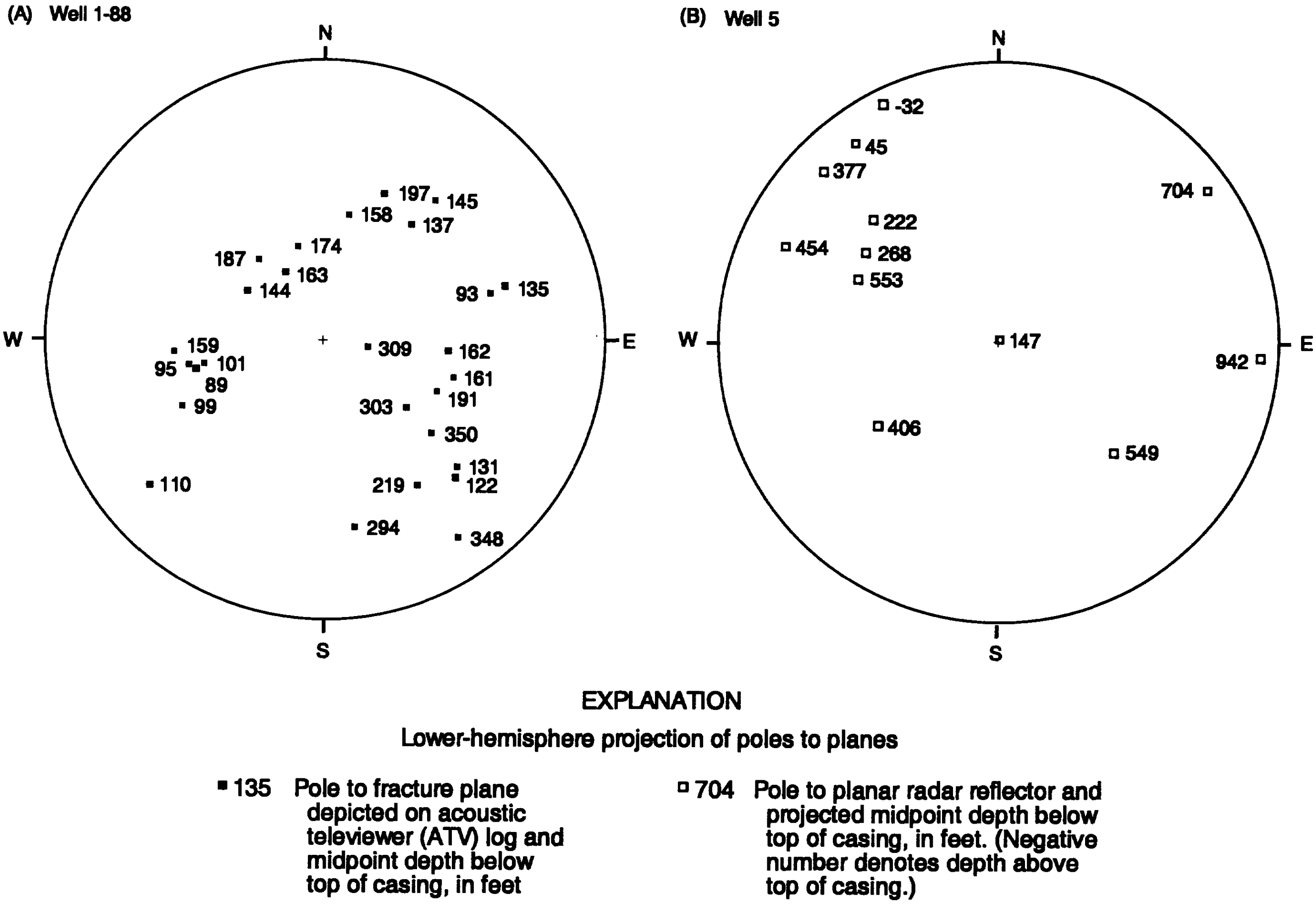

Figure 5. Stereograms of (5A) well 1-88 ATV data, and (5B) well 5 radar data, Seabrook, New Hampshire.

results indicate that fractures appear to connect well 1-88 to well 5 at depths of 145 to 155 ft and 300 to 315 ft. In the enlarged zones (in well 1-88) at 121 to 130 ft and 163 to 167 ft deep, the orientation of discrete fractures could not be mapped.

The deviation of well 1-88 is shown in a radial plot (fig. 6) where the center of the plot is the location of the well at the land surface. Above 200 ft, well 1-88 deviates to the west, below 200 ft, it deviates to the south. The bottom of well 1-88 is at a depth of 390 ft, and has deviated a total of 42.6 ft in an azimuthal direction of N 207° E (SW). Well 5 is less deviated as the result of stabilization measures taken during drilling. The bottom of well 5 is at a depth of 496 ft and had deviated a total of 12 ft in a direction of N 150° E (SE) (fig. 6).

Two sets of heat-pulse flowmeter logs were collected in well 1-88 (fig. 7). In February 1997, when well 5 was not pumped, flowmeter data were collected under ambient conditions and under low-rate pumping (1 gal/min) at the top of well 1-88. There was no measurable vertical flow in well 1-88 under ambient conditions. Under low-rate-pumping conditions minor inflow (0.027 gal/min) to the well was measured at a depth of 218 ft, outflow was at 185 ft. Another set of flowmeter data was collected in June 1997 when well 5 was being pumped. The June 1997 analysis of these data includes qualitative measurements (not shown in figure 7) that were used to identify transmissive zones. The qualitative measurements indicated likely inflow and outflow locations; however, rates of flow were not determined because they exceeded the flowmeter capabilities. In June 1997, when well 5 was on-line,

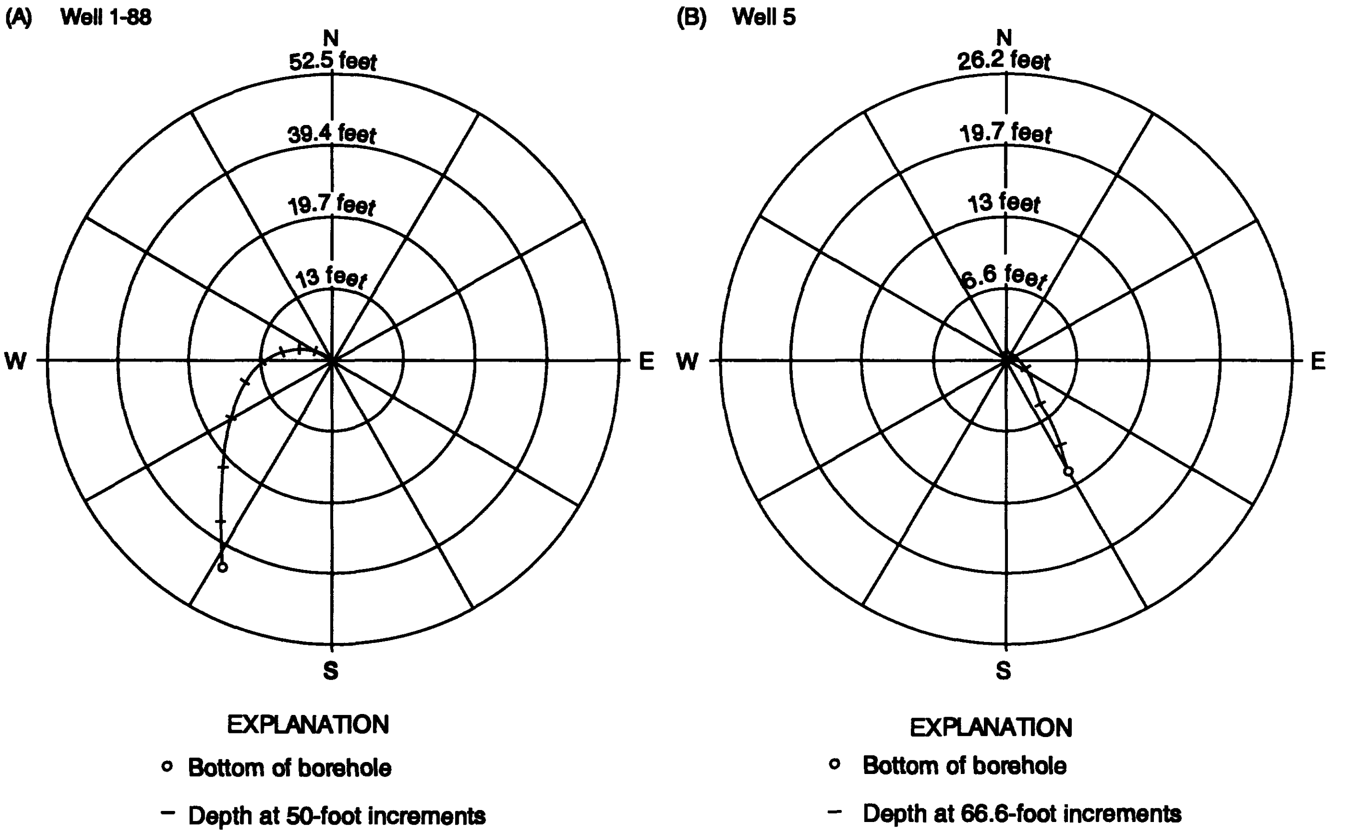

Figure 6. Deviation logs of wells 1-88 and 5, Seabrook, New Hampshire.

flow was primarily into the well at two upper zones (90 and 145 ft), and out of the well at two deeper zones (315 and 350 ft) (Fredrick Paillet, U.S. Geological Survey, written commun., 1997).

Radar-Reflection Logs

The average velocity of the radar waves at the site was approximately 130 m/µs and the average attenuation was 2.3 dB/m. Low-velocity zones were identified at depths between 98 and 230 ft, which indicate more permeable rock. An abrupt increase in radar velocity was detected at 360 ft that could indicate the presence of a fault zone at that contact. Radar penetration at the site was at most approximately 80 ft from the borehole, less than observed at other crystalline bedrock sites in New England (Hansen and Lane, 1995; Lane and others, 1994). The low signal propagation is probably caused by attenuation due to the highly fractured nature of this bedrock, which makes it a productive aquifer.

Many reflectors were observed in the directional radar logs of wells 5 and 1-88. Identifying radar reflectors accurately is dependent on the skill and experience of the interpreter. An unprocessed radar record from well 5 is shown in figure 8. Reflectors with low velocity and high attenuation are interpreted as water-saturated fractures or fracture zones. Mid-point depth (mid-point between the high and low point of a dipping fracture), strike, and dip of the major planar reflectors interpreted in the bedrock surrounding the borehole are listed in table 2. The accuracy of an interpreted reflector strike is about ± 10°. Interpreted locations of reflectors (table 2) are shown as a stereogram in figure 5b. A non-directional probe was used in well 1-88; therefore, reflector strikes could not be determined for that borehole.

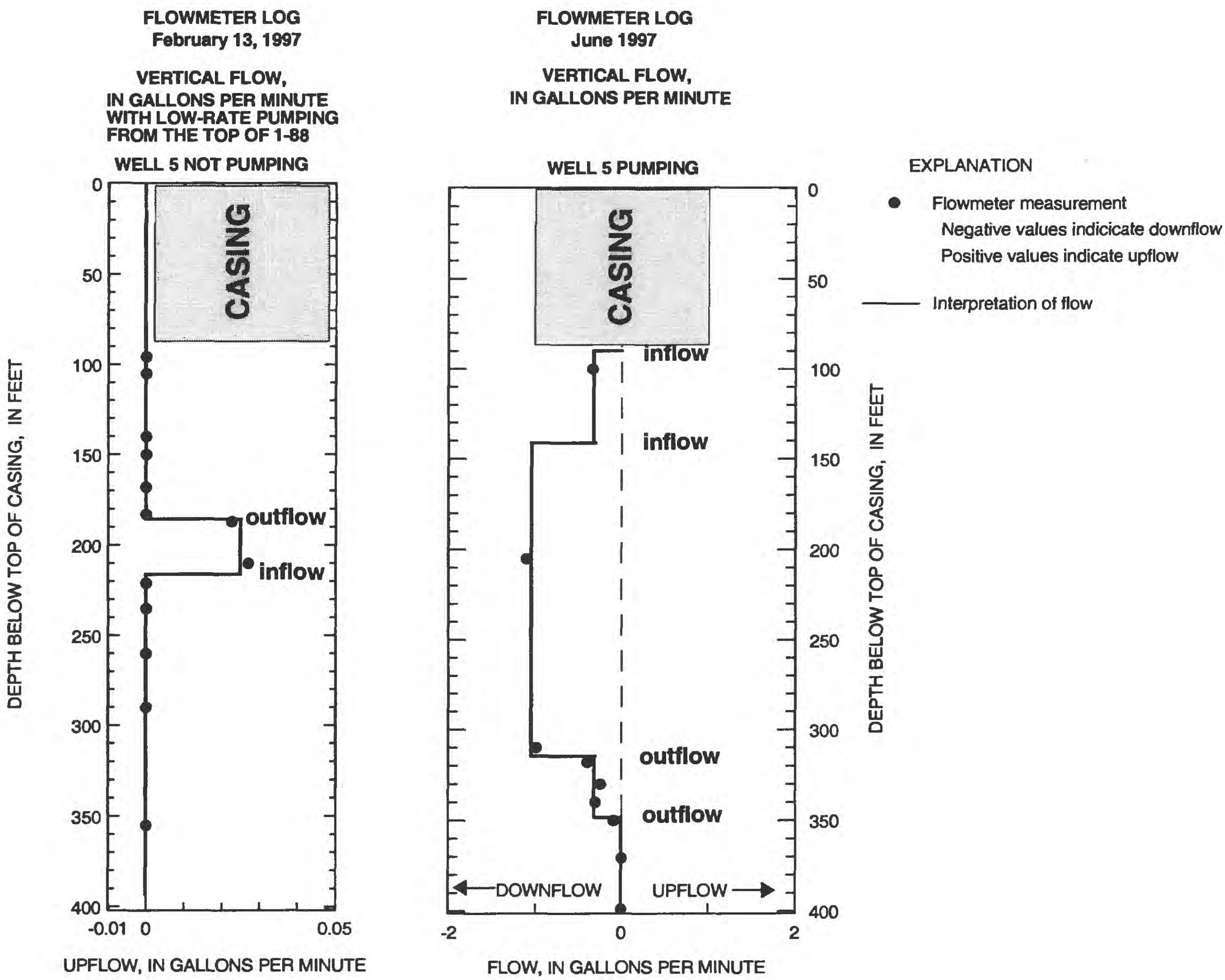

Figure 7. Flowmeter logs of well 1-88, Seabrook, New Hampshire.

The reflectors are projected to the borehole to determine the depth of intersection, a reflector may not necessarily intersect the borehole wall. A negative depth of intersection indicates a reflector that would intersect the well above the land surface or above the top of casing. A feature that has a depth of intersection that is below the bottom of the well is a reflector that was identified at some distance from the well and dips towards the well but does not intersect the borehole. Borehole radar is primarily influenced by large-scale features, up to hundreds of feet from the borehole, whereas the ATV log identifies relatively small-scale features at the borehole wall. These differences can, and at this site do, result in detection of different fracture patterns with investigation scale.

The interpreted reflectors (fig. 5b) have a predominant strike of N 24° to 64° E with an average dip of about 60° SE. These features show considerably less variation than the ATV observations (fig. 5a) indicating more dominant-fracture trends at a large investigation scale. Other less prominent high-angle fractures were observed to strike N 144°E, N 184°E, N 224°E, and N 324° E. [Note: An orientation of N 224°E has the same trend as N 44°E.] In some cases, a strike could not be determined (table 2) because strong reflectors can cause an apparent radar signal from all directions that cannot be resolved.

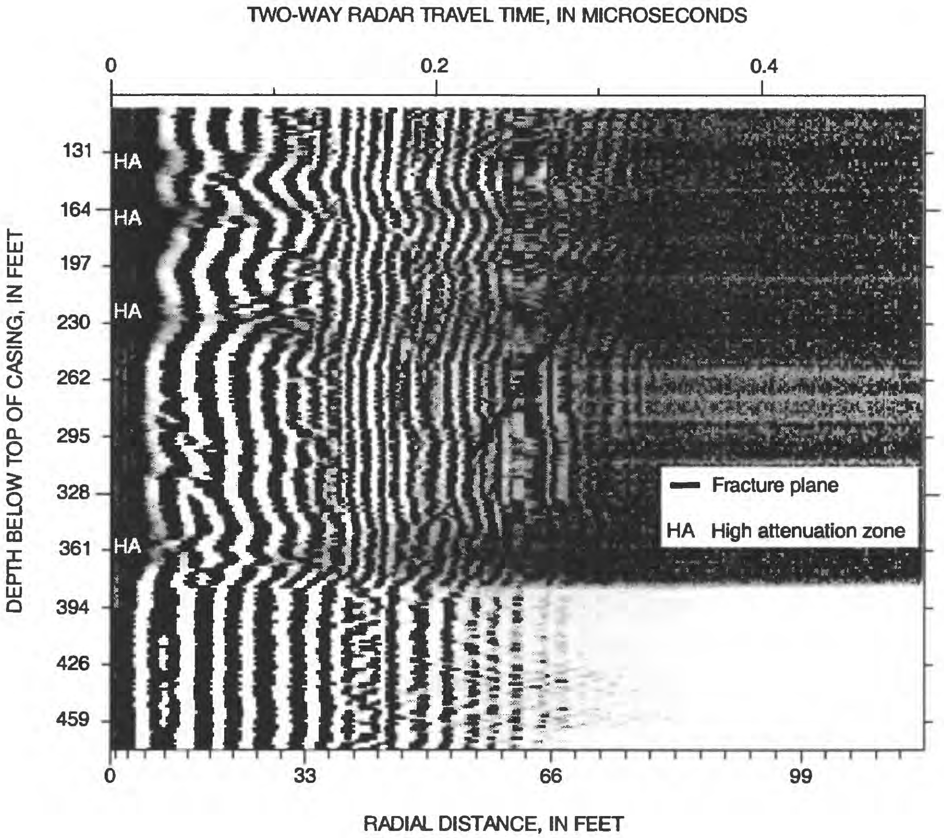

Figure 8. Unprocessed borehole radar log from well 5, Seabrook, New Hampshire.

Additionally, a number of low-velocity zones were identified where both strike and dip could not be resolved. Low-velocity zones appear to correlate with major fracture intersections with the borehole. For example, in well 5 (table 2), at center depths of 173 and 355 ft low-velocity and high-attenuation zones are observed. The standard logs (fig. 4) indicate significant fractures at or near these depths.

Radar Tomography

Radar-wave velocity and radar-wave attenuation tomograms were prepared from data collected during cross-hole radar surveys between wells 5 and 1-88. The tomogram integrates data collected over the length of the two boreholes and provides one graphical depiction of the plane between the wells. A tomogram can allow for a more readily discernible analysis of the connection between two wells than that provided by borehole directional data from individual wells.

The tomograms shown in figure 9 depict distinct patterns of high and low velocity and attenuation zones. In the upper 150 ft of the tomograms, radar waves are most highly attenuated and velocities are slowest, indicative of highly permeable rock. From 150 to 350 ft, the section is characterized by moderate attenuations and velocities, indicative of moderate permeabilities, whereas at about 390 ft, the section is characterized by low attenuations and high velocities indicative of a competent, resistive, low permeability rock (fig. 9). The transition to a dense competent rock at about 400 ft in well 5, and at the base of well 1-88 at 350 ft, is clearly evident in the tomogram by a sharp transition to a low attenuation/high velocity zone. These findings are consistent with the interpretation of other borehole logs and illustrate the complex connection between the wells.

Table 2. Projected midpoint depth, strike, and dip of reflectors identified by borehole radar in Seabrook, New Hampshire

[Negative number indicates plane intersects above the well; --, indicates orientation cannot be determined; RHR, strike is reported using a "right-hand-rule" where the direction of the strike is that where the dip is to the right of the strike]

Midpoint depth (in feet) (figure 5)	RHR strike (degree)	Dip (degree)	Notes
Well 5			
-32.8	64	85	
-21.3	--	68	Low velocity zone
45.9	54	77	
135.1	--	--	Low velocity zone
147.6	54	0	
172.9	--	--	Low velocity zone
222.1	44	53	
228.6	--	--	Low velocity zone
248.3	--	75	
268.0	34	48	
316.8	--	60	
354.9	--	--	Low velocity zone
371.3	--	46	
377.9	44	77	
406.4	324	44	
445.1	--	65	
454.0	24	73	
459.5	--	64	
542.2	--	57	
549.4	224	49	
553.0	24	46	
599.6	--	54	
704.5	144	83	
942.0	184	86	

Midpoint depth (in feet)	RHR strike (degree)	Dip (degree)	Notes
Well 1-88 (omni-direction receiver-used strike cannot be determined)			
-27.9		82	
47.2		81	
106.6		71	
115.1		--	Low velocity zone
142.4	--	58	
145.3	--	64	
121.0	--	74	
162.7	--	68	
174.2	--	--	Low velocity zone
201.1	--	66	
206.3	--	40	
214.2	--	51	
221.7	--	74	
233.2	--	54	
267.6	--	--	Low velocity zone
273.2	--	66	
300.8	--	60	
313.6	--	41	
333.6	--	64	
338.2	--	--	Low velocity zone
349.0	--	46	
354.6	--	68	
430.7	--	65	
475.9	--	67	
484.1	--	84	
486.4	--	54	

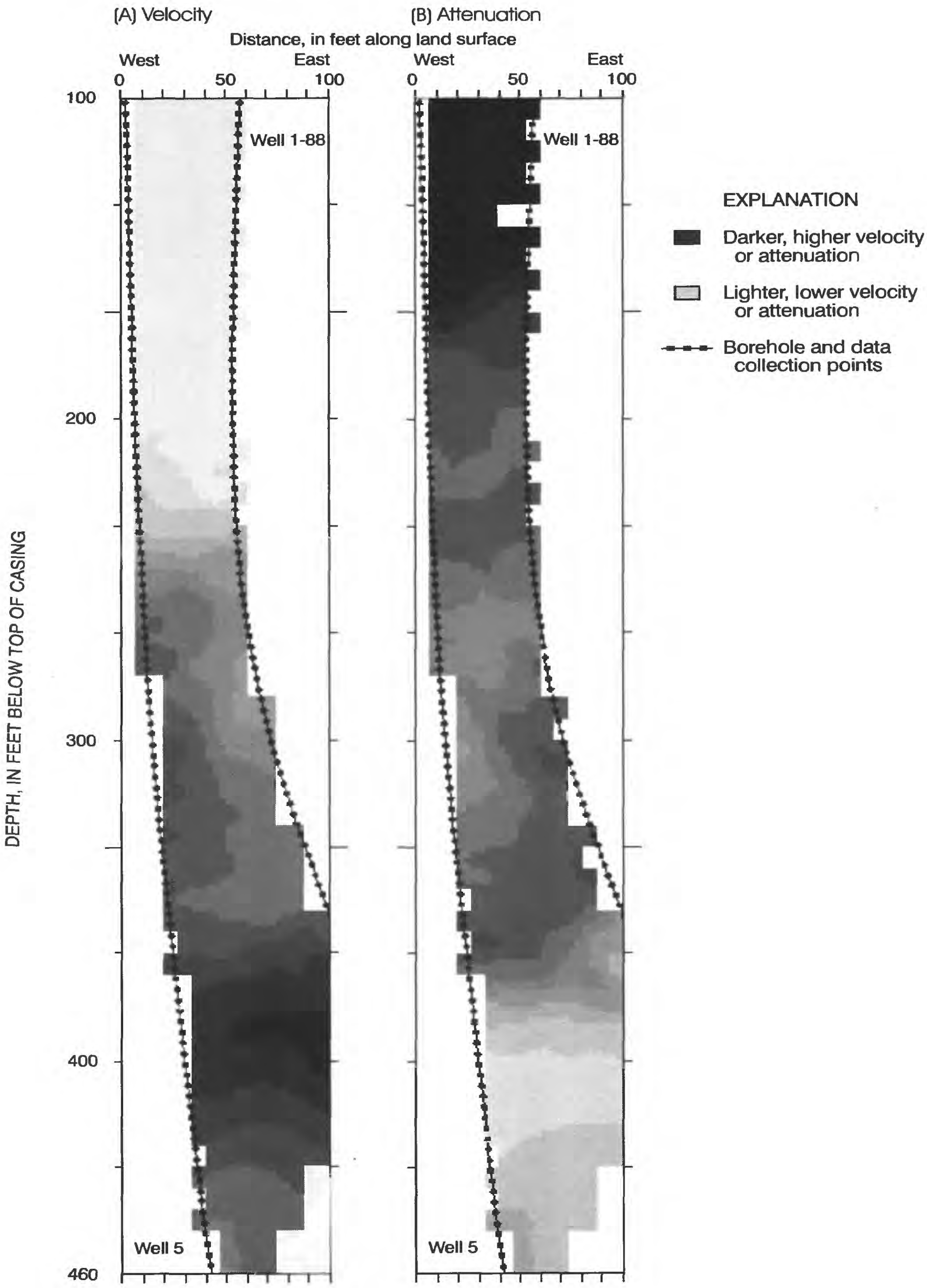

Figure 9. Radar velocity (A) and attenuation (B) tomograms between wells 5 and 1-88, Seabrook, New Hampshire.

CHARACTERIZATION OF FRACTURES

Analysis of geophysical logs indicates that most transmissive (water bearing) zones in well 5 are in the upper 350 ft and especially the upper 150 ft of the borehole. This section of well 5 is characterized as a felsic-rich igneous intrusion, possibly a quartz diorite. At depths greater than 400 ft, the rocks in well 5 are significantly less transmissive than the upper sections.

Drawdowns measured during aquifer tests conducted in and near the study area indicate the direction of predominant ground-water flowpaths under pumping conditions. These measurements provide indications of a large-scale, broadly fractured zone. At well 5, data collected during a 5-day test in 1993 (Whitman and Howard, Inc., 1993) and an 8-day test in 1997 (Douglas DeNatale, oral commun., 1997), indicate a ground-water flowpath at well 5 of about N 40° E (in the general direction of the waste site (fig. 1). The 8-day test of well 5 produced significant drawdowns at the waste site (up to 6.74 ft) and less than 1 ft of drawdown at wells 1–4 (Douglas DeNatale, oral commun., 1997). During the 5-day aquifer test of well 5, drawdown at the wells 1–4 well field was at most 0.37 ft (Whitman and Howard, Inc., 1993). A 5-day aquifer test at the wells 1–4 well field produced a maximum drawdown of 6.2 ft at the waste site, yet a drawdown of less than 0.1 ft at well 5 (Whitman and Howard, Inc., 1993).

At the borehole wall, ATV-determined-fracture orientations are highly variable (fig. 5a) and may reflect small-scale features. In the upper, more highly fractured bedrock, the strike direction varies widely and was centered at about N 40°E with a southeast dip. A more predominant ATV-fracture strike in the deeper less-fractured rock is centered at about N 24° E and dips southeast. The directional radar for well 5 indicates a predominant fracture strike of about N 24° E dipping southeast (fig. 5b). Photolineament (a lineament bearing N 17° E) and aquifer-test analyses support a large-scale northeast-southwest fracture orientation. These results support the interpretation by Whitman and Howard, Inc. (1993) that a broad fracture-zone flowpath provides hydraulic connection from well 5 to the waste site, which is N 22° E of the study area (well 5).

SUMMARY AND CONCLUSION

Two wells were logged in Seabrook, New Hampshire, to characterize a high-yield bedrock aquifer. A number of borehole geophysical logs were collected to identify and determine the orientation of water-bearing fracture zones. The investigation determined that the bedrock aquifer above 380 ft deep is more highly fractured than the aquifer below that depth. Recharge to the well is primarily from above 380 ft deep and the upper 150 ft is most highly fractured. The bedrock aquifer is highly fractured with many fracture orientations; borehole radar appears to identify more large-scale features than other logs. The predominant fracture, and fracture zone, orientation in the bedrock aquifer trends N 24°–64°E and generally dips 45° to 85° SE or NW. Fracture zones were compared with lineament data and hydraulic testing at two well fields. A lineament identified on low-altitude photography trends N 17° E and appears to correlate well with geophysical log interpretations and aquifer tests at the site. This lineament could represent a fracture zone that provides a hydraulic connection to a nearby waste site.

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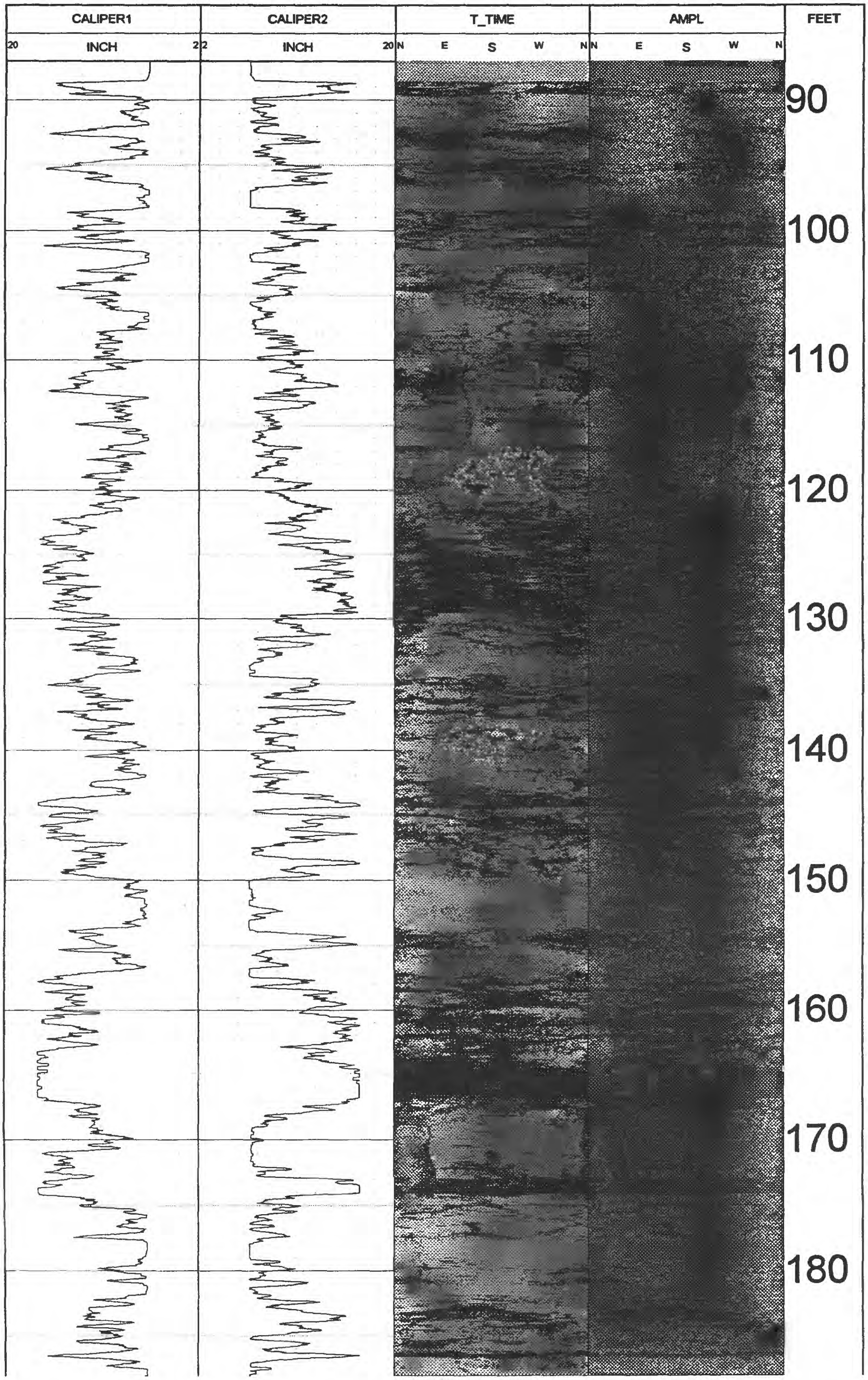
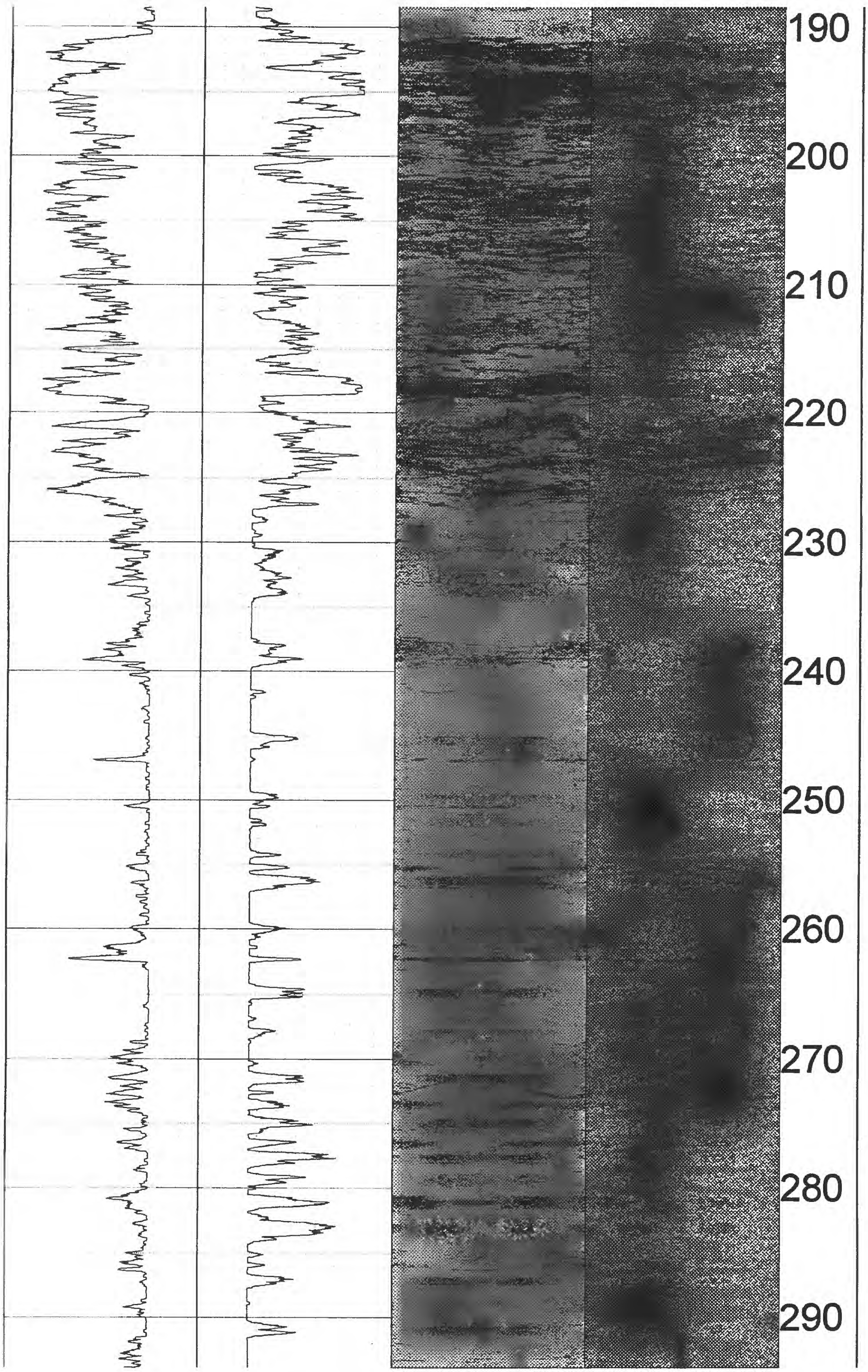
APPENDIX

APPENDIX 1. ACOUSTIC TELEVIEWER LOG OF WELL 1-88, SEABROOK, NEW HAMPSHIRE

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APPENDIX 1. ACOUSTIC TELEVIEWER LOG OF WELL 1-88, SEABROOK, NEW HAMPSHIRE--Continued