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SUMMARY OF FIELD RESEARCH EXPERIMENTS AT THE FOREST GLEN (MARYLAND) TEST SITE

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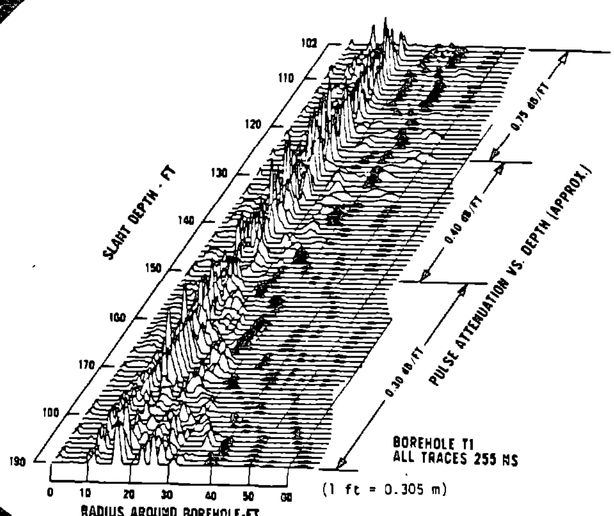

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FOREWORD

Subway construction in the Washington Metropolitan Area has enabled researchers to gather a wealth of information on rock behavior during tunneling. In 1977 a field study was initiated at the then proposed Forest Glen Metro Station at Silver Spring, Maryland, to prove the accuracy of site exploration techniques. Subsequent excavation of this very deep station provided ground truth. This report gives the findings of that study. We are grateful to Metro engineers for allowing us to use the site and to the participating organizations who put their methods to the test.

This report should be useful to geotechnical, structural, and other civil engineers who are planning or designing underground structures.

Copies of this report are being distributed by FHWA transmittal memorandum. Additional copies may be obtained from the National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161.

Richard E. Hay, Director
Office of Engineering
and Highway Operations
Research and Development
Federal Highway Administration

NOTICE

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16. Abstract

The Federal Highway Administration sponsored an evaluation of in-situ site investigation techniques in the Forest Glen (Maryland) Field Research Experiment. Fourteen different organizations participated in the experiment using three general approaches--1) Acoustic and seismic techniques, 2) electromagnetic survey techniques, and 3) mechanical techniques. Nine of these organizations submitted written research reports. Edited versions of all but one of the reports submitted are presented in the appendices to this document. The missing submitted report contained data in the form of colored photographs which, unfortunately, could not satisfactorily be presented in a black and white document.

A conference documenting some of the results from this experiment was held in March 1978, in Alexandria, Virginia. The proceedings of this conference are contained in a previously published report, FHWA-TS-79-221.

The results of acoustic and seismic tests by five different organizations indicated that two investigation techniques provided satisfactory results. Results from three electromagnetic site investigation systems indicated that two of the devices used yielded promising results. Finally, the mechanical devices used in this study, the pressuremeter and borehole jack, can be used effectively in the proper geologic setting.

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METRIC CONVERSION FACTORS

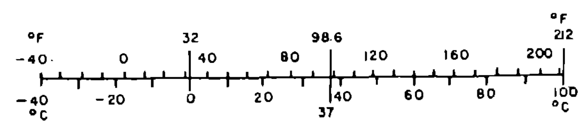
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1.0 INTRODUCTION

In order to evaluate the effectiveness of available in-situ site investigation techniques, the Federal Highway Administration (FHWA) conducted a field investigation at the site of the proposed Forest Glen Metro Station, to be located in Silver Spring, Maryland. The field tests were conducted during the period September 1977 through March 1978. Based on the hardware system used, the testing techniques employed can be subdivided into three groups--1) Acoustic and seismic methods, 2) electromagnetic methods, and 3) pressuremeter and borehole jack methods. Results from these tests were discussed at a conference sponsored by the Federal Highway Administration in March 1978. The report of the proceedings of the conference is listed as Reference No. 1 in this volume.

1.1 Background

The Forest Glen experiments represented the first time that as many as 12 different concepts for subsurface site investigation from single and multiple boreholes were used to conduct site exploration and to make geologic predictions at the same geologic location at the same time. The test site was located in an area which represents geologically median rock (that is, rock formations neither too complicated nor too simple).

Fourteen different organizations participated in the field tests with their various hardware systems and data processing techniques. These organizations were 1) Ocean/Seismic/Survey, Inc. 2) Birdwell Division, 3) Soil Testing Services, Geotechnical 4) Southwest Research Institute, 5) Foundation Sciences, Inc., 6) Holosonics, Inc., 7) Lawrence Livermore Laboratory, 8) Tennessee Valley Authority, 9) West Virginia University, 10) Woodward-Clyde Consultants, 11) Bolt, Beranek and Newman, Inc., 12) ENSCO, Inc. (acoustic system), 13) Waterways Experiment Station, and 14) ENSCO, Inc. (ground-probing radar). A brief description of the various site investigation techniques used in this experiment and the principal investigators for each organization are identified in Appendix A.

Nine of the aforementioned organizations submitted written reports which provided evaluations and predictions of the geologic structure using their probes and data processing techniques. Eight of those reports are included as Appendix C through Appendix J. A summary of these reports is contained in Section 2, and included in Section 3, below, is a discussion and evaluation of these reports.

Since investigative reports of work performed by the remaining five participants--1) Birdwell Division, 2) Tennessee Valley Authority, 3) West Virginia University, 4) Bolt, Beranek and Newman, Inc., and 5) Waterways Experiment Station--were not available, it was not possible to discuss their results in this report. However, brief descriptions of techniques used by the previously mentioned organizations are presented in Appendix A, and significant points are summarized in the following paragraphs.

Tennessee Valley Authority (TVA) used both a nuclear and a sonic probe to survey all four research holes. The data obtained can provide information for the evaluation by cross-hole survey. Based on TVA's reported experience, a specially designed cross-hole sparker can provide high resolution records which will indicate large voids and zones of badly decomposed rock at a maximum borehole spacing between 50 and 75 feet (15 and 23 m).

Bolt, Beranek and Newman, Inc. adapted a high resolution sparker sound source for deployment in the 6-inch (15 cm) borehole and a high resolution boomer sound source which operated near the ground surface. The signals from these sources were recorded on magnetic tape from various accelerometers and pressure sensors were deployed in the boreholes. Using a digital computer, the data obtained was analyzed.

West Virginia University researchers used a shallow, high resolution seismic reflection technique to survey the various earth materials at the site. The pressure and shear wave information obtained was cross-correlated to determine the shear strength and permeability of earth materials.

The Birdwell study included 3-D Velocity and Caliper Logs in each research hole. Cross-hole survey was also conducted. Interpretation included pressure wave velocity, shear wave velocity, elastic moduli (Bulk-Shear-Young's), and fracture identification. Based on Birdwell's reported experience, a 10- to 15-foot (3- to 5-meter) borehole spacing is appropriate for this survey.

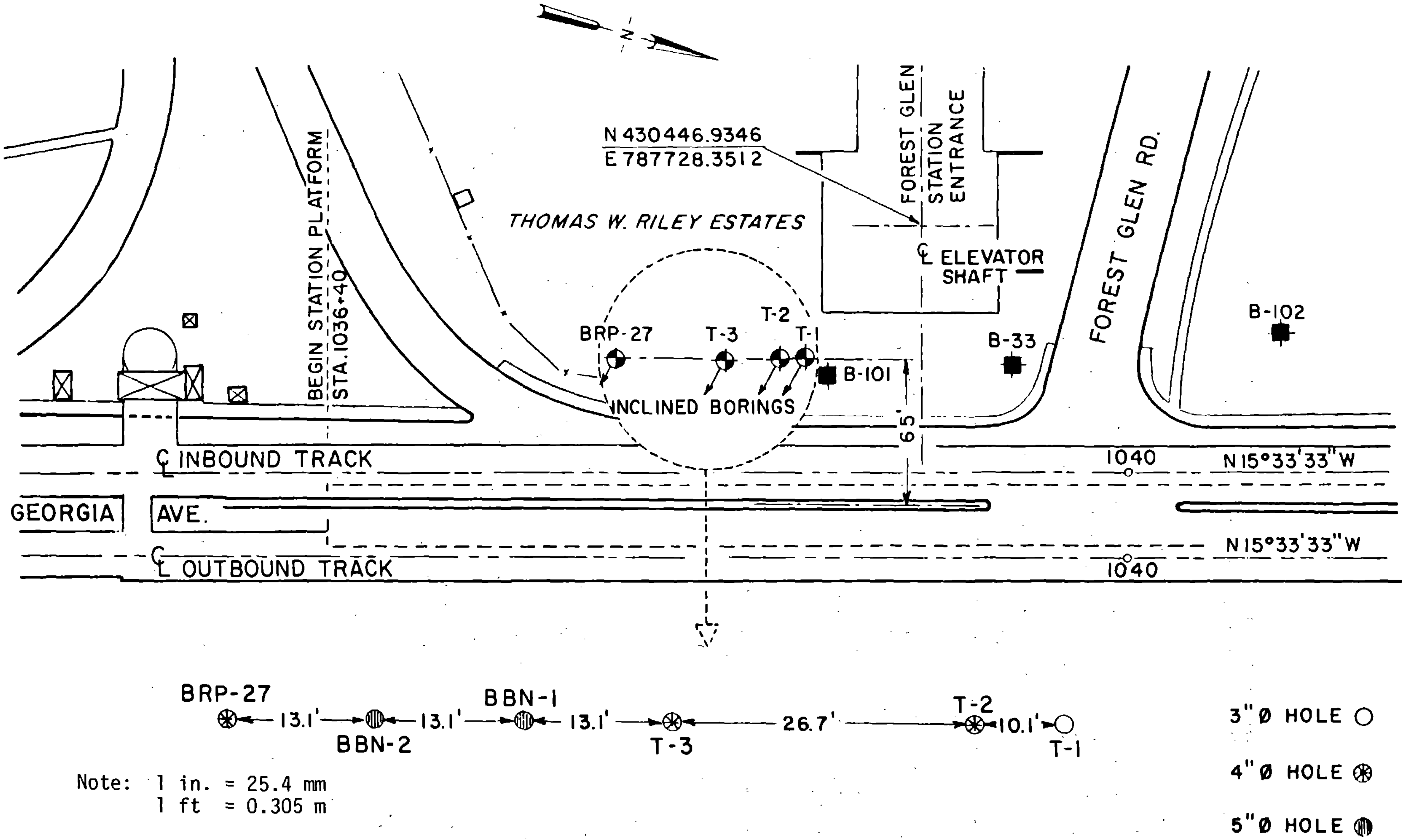
Waterways Experiment Station researchers studied the feasibility of measuring the initial state-of-stress in a rock mass by strain relief measurements without overcoring. The device used was basically a longer version of the Goodman Jack, with a loading capacity of approximately 300,000 lb (1,300,000 N) at 30 ksi (210,000 kN/M^2) line pressure.

1.2 Site Characterization

The selected field test site was the proposed Forest Glen Metro Station in Silver Spring, Maryland, a part of the Washington Metropolitan Area Transit System. The Forest Glen site lies directly north of the north corner of the District of Columbia, just beyond the intersection of Georgia Avenue and Interstate Highway 495. The site geology is fairly typical of the Piedmont region south of New York, wherein residual soil ("saprolite") of varying thicknesses overlies a profile of weathered bedrock. The crystalline country rock is a metamorphosed sediment which is related to the Manhattan and Wissahickon formations, and is common throughout the middle Atlantic seaboard.

The major bedrock type at the Forest Glen site is schist. The principal jointing pattern corresponds with the foliation which tends to form planes of weakness. These planes are often mica-coated, sometimes containing thin clay deposits, gouge, or slickensides.

Four research boreholes were drilled to project into the proposed station volume. The plan view of the boreholes is shown in Figure IN1. A schematic section through the station showing the boreholes and generalized geologic layering is presented in Figure IN2. The borings were inclined to both the vertical plane and the axis of the proposed station opening. However, these borings crossed the dip planes in the rock at approximately right angles. The rock condition, as indicated in the boring logs, was highly jointed and weathered in the upper part of the boring, gradually changing downward to less jointed and sounder rock.



Note: 1 in. = 25.4 mm
1 ft = 0.305 m

Figure IN1. Borehole location plan.
Forest Glen Station.

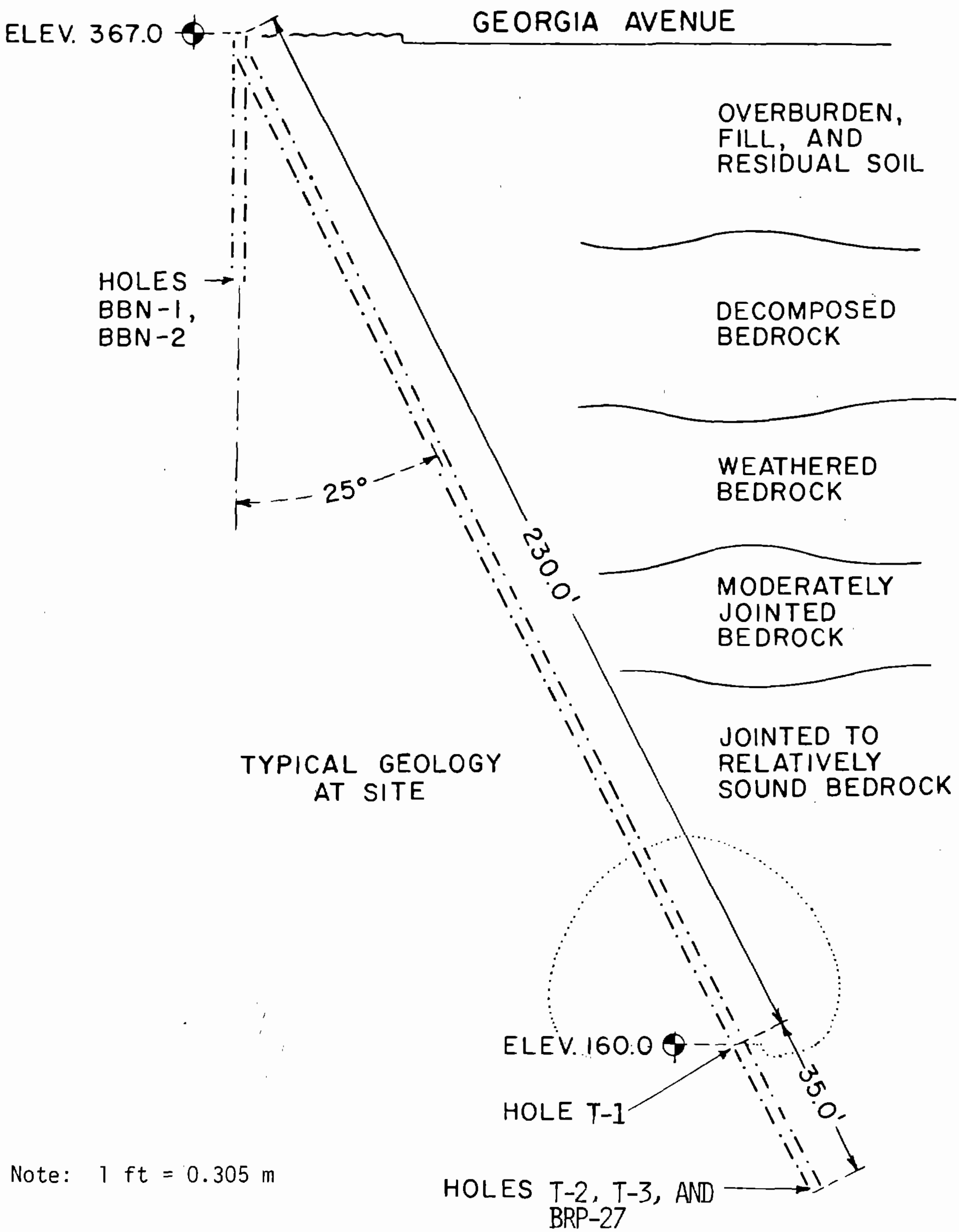


Figure IN2. Section through Metro Station.

2.0 SUMMARY OF TEST PROCEDURES AND FINDINGS

Based on the nature of the tests and the physical properties of the rock formation measured, the 10 test devices utilized at the Forest Glen test site can be categorized into three groups. The first group was basically propagating seismic waves through the rock formation and measuring the resulting wave velocities. The second group was basically generating electromagnetic waves through the rock formation and measuring the resulting wave velocities. The third group was directly measuring the mechanical properties of rocks.

2.1 Acoustic and Seismic Tests

2.1.1 Ocean/Seismic/Survey, Inc.

The seismic experiments conducted by Ocean/Seismic/Survey, Inc. (OSS) consisted of a variety of up-hole and cross-hole surveys. A few of the surveys also were performed with surface layouts of receiving equipment. In addition to providing information on the geotechnical parameters of the soil and rock at the site, OSS hoped to provide conclusions which might aid in the development of standard field procedures for seismic surveys.

The field testing program consisted of thirteen tests, nine of which OSS considered to provide useable data. Test A through Test L were performed using a 200-Joule Sparker source, while the sparker source used for Test M was capable of providing 3000 Joules of energy.

Throughout the testing program, many of the test records were affected by traffic vibrations (primarily those with receivers at the ground surface), erratic seismic wave readings, electrical cross-feed and rainfall which dampened cables and connections causing false electrical signals. Also, some doubt exists as to the validity of both the time recorded for the spark release and the arrival times recorded for the seismic waves. The results of the OSS tests were somewhat discouraging. The following conclusions were presented by the OSS in their test report:

1) Portable seismic refraction systems do not provide useful recordings of seismic compressional or transverse waves.

2) The 200-Joule Sparker sound source was generally too weak to achieve satisfactory signals of compressional waves.

3) For cross-hole testing, the hydrophone was more responsive than the geophone and seismometer.

4) The sparker source did not provide sharp seismic records of compressional wave signals. A high energy sparker source may provide the additional features of making records at closer depth intervals and making a continuous depth record.

2.1.2 Soil Testing Services, Geotechnical

Soil Testing Services (STS) conducted seismic cross-hole surveys at the Forest Glen site. A 6-Joule Sparker source provided the signals, and hydrophones were used as receivers. The sparker source was adjusted to produce one pulse every six seconds.

The testing procedures began with the source placed in Boring T-2 and receivers in Borings T-3 and BRP-27. Observations were made at 5-foot (2 m) intervals between Borings T-2 and T-3, and at 10-foot (3 m) intervals between Borings T-2 and BRP-27. A second observation was made placing two hydrophones in Boring T-3 and the sparker source in Boring T-2. One hydrophone was positioned near the bottom and the other higher within the borehole. Observations were made with the sparker source at 10-foot (3 m) intervals.

The cross-hole surveys provided data from which compressional wave velocities were calculated. Borehole separation distances were determined from a borehole survey and the travel times were scaled from oscilloscope photographs. The recorded data between boreholes T-2 and T-3 produced velocities which increased from 6000 fps (1 800 mps) at the water table, to 22,500 fps (6 800 mps) near the bottom of the boreholes. Considerable velocity variations occurred between the depths of 105 to 125 feet (32 to 38 m) corresponding to very poor to poor rock quality. In general, the seismic studies provided compressional wave velocities that were consistent with RQD values obtained from Boring B-101 (see Figure 2).

2.1.3 Holosonics, Inc.

The Minerals Acoustical Prospecting (MAP) system, used by Holosonics, Incorporated, consists of two basic modes of operation. The first is the Pulse-Echo mode, where the survey is done from a single borehole with one probe. Essentially, the system transmits a pulse of acoustic energy and then receives reflections from veins, faults and other geologic discontinuities. The second mode is referred to as the through-transmission mode which is basically a cross-hole survey. In both modes, the transmission pulse is controlled such that time-of-flight information for returning signals may be easily determined.

The field program was performed in three phases: 1) A pulse-echo survey with a pulse frequency of 25 kHz, 2) a through-transmission survey with a pulse frequency of 18 kHz, and 3) a through-transmission survey using a high energy sparker probe system with low pulse frequency. Through each phase, the orientation of the probe was along the borehole line, and the transmitter was fired four times per foot. The four signals were averaged, to enhance the signal-to-noise ratio, digitized and written on magnetic tape. This raw field data, for both pulse-echo and through-transmission surveying, was later processed and plotted by computer.

Under this program, the through-transmission survey was utilized to produce acoustic wave velocities, which are necessary for analyzing pulse-echo surveys. From the first through-transmission survey, the relationship between compressional wave velocity and depth was obtained from the records, but the shear wave velocities were disguised by other signals (reflections, etc.). From the sparker through-transmission survey, raw data plots exhibited strong compressional wave arrivals. However, the computer output resulting from velocity analysis proved inconclusive. This may have been due to the low frequency of the sparker data and the present high frequency reduction methods used in the computer analysis. The pulse-echo survey showed reflecting horizons that can be directly attributed to the prominent joint patterns in the rock. Because of the inclination of the boreholes, the foliation and its major joint pattern were not detected. However, the survey data correlated well with published geology. In general, the surveys exhibit a lateral increase in compressional wave velocity from approximately 16,000 fps (4800 mps) at Boring T-1 to above 18,000 fps (5400 mps) at Boring BRP-27. The loggings tend to have a constant velocity from about elevation 210 to the bottom of each hole. This information may suggest that the rock at the north end of the site is of lower quality than that at the south end, and the penetration of rock weathering and deterioration extends approximately to elevation 210.

2.1.4 Woodward-Clyde Consultants

A shear wave velocity study was conducted by Woodward-Clyde Consultants (WCC) using the cross-hole technique. Shear waves were generated by a shear wave hammer developed by WCC. The waves propagate in a direction perpendicular to, and radially from, the borehole. Detection of the shear waves are maximized by placing geophones in the plane perpendicular to the borehole containing the source. Shear wave detection is also affected by subsurface stratification.

The site geometry, boring inclination and stratification at Forest Glen did cause some reduction in data quality. However, the tests were completed and the data recorded. The general characteristics of the data records show shot time, compressional (P) wave arrivals and shear (S) wave arrivals. Travel time and source-geophone distance were plotted, and P and S wave velocities were determined from the slope of the plots.

The results of the shear wave velocity study were questionable. This may be attributed to the constraints imposed by the site geometry. In addition, the energy source could not provide consistently legible records from the most distant borehole, BRP-27. The velocities obtained for the P waves appeared reliable, but those for the S waves were not of the standard for engineering applications.

2.1.5 ENSCO, Inc.

ENSCO, Inc. also participated in the Forest Glen research experiment, using a cross-hole acoustic system designed to operate in water-saturated soils. The system may, however, operate effectively in hard rock areas. A high energy sparker source, capable of delivering 1250 Joules of energy, is used with a maximum pulse frequency of 5 kHz. The receiving units consist of crystal accelerometers and preamplifiers. The Forest Glen site provided the first field test for this equipment.

The data obtained from the tests between Borings T-1 and T-2 show that 1) the frequency content of the pulse increases with depth, and 2) the wave velocity at the upper levels of the holes is slower than at the bottom. Such changes in frequency content and velocity should represent changes in the amount of rock fracturing or discontinuities. This study introduced also a fluid (tube) wave that is dependent on the compressional velocity of the fluid and the shear velocity of the rock. The strength of the tube wave, having a tendency to reflect those waves of geotechnical interest, is shown to decrease as hole separation increases, and increase as source depth increases.

In general, the testing program provided reliable wave velocities. Also, the cross-hole techniques used in this survey show major changes in the acoustic velocities throughout the rock mass and, therefore, in the competency of the rock.

2.2 Electromagnetic Tests

2.2.1 Southwest Research Institute

The Southwest Research Institute performed both cross-hole and pulse reflection studies at the Forest Glen site. The test equipment consisted of a transmit-receive probe unit and auxiliary receivers. The probe unit is approximately 12 feet (4 m) long, and capable of operating to a maximum immersion depth of about 500 feet (150 m). The upper half of the probe contains transmitter and receiver electronics; the lower half contains an antenna. The probe operates in the very high frequency (VHF) range and may radiate a useful frequency spectrum of 30-300 mHz from the antenna. Standard auxiliary receivers were used for the cross-hole studies.

Boring T-1 was the only test hole large enough to accept the 4-inch (10-cm) diameter probe unit. Therefore, all pulse reflection tests were performed from Boring T-1 only. The cross-hole surveys were performed with auxiliary receivers located in Borings T-2, T-3, and BRP-27. Five pulse reflection tests were performed from Boring T-1, scanning from the bottom upward, to the lower end of the plastic casing pipe. It was not possible to perform tests below a borehole depth of about 200 feet (60 m). Nine cross-hole scans were completed in each of the other three boreholes. The primary operating mode utilized common transmit-receive depths such that measurements were horizontally oriented. Data records were logged on both magnetic tape and strip charts (for field inspection).

The processed pulse reflection data revealed evidence of various rock-structure-related reflections at distances to about 60 feet (18 m) from the borehole. However, the apparent rock structure details do not necessarily represent the true rock structure because of the omnidirectional antenna which allows superposition of all received signals from all directions around the borehole. The cross-hole tests revealed useful information on the electromagnetic properties permittivity and conductivity of the rock. Also, the data show a general correlation with the core logs obtained from the test boreholes. The electromagnetic wave velocity profiles also correlate well with fracture conditions in the rock where the lower velocities correspond to highly fractured rock with greater moisture-holding potential.

Verification of specific geologic anomalies and structural details was not possible during the project and, therefore, the validation of the electromagnetically implied rock character was uncertain. However, based on the general fracture conditions observed from rock core samples, the survey data provided a reasonable physical representation of the rock conditions at the test site.

2.2.2 Lawrence Livermore Laboratory

Cross-hole surveys were performed by the Lawrence Livermore Laboratory (LLL) at the Forest Glen test site using continuous-wave (cw) electromagnetic transmissions. LLL has adapted the data collection and interpretation procedures of medical diagnostics, such as brain and body scans, to ground probing with electromagnetic waves.

The interpretation of the collected signals involves modeling the area of interest into a set of zones outlined by arbitrarily spaced vertical and horizontal lines. The transmission path of the signal is assumed straight (ignoring any reflection or refraction of waves), and changes in electrical parameters from zone to zone also are assumed gradual. Computer algorithms, developed by medical researchers, used to reconstruct the area of interest, approximate the electromagnetic equations that describe the subsurface signal behavior. The electromagnetic equations are expressed as a linear system of equations relating signal attenuation and signal travel distance per zone with the unknown electrical properties of each zone.

The electrical properties of the test area were determined using the algebraic reconstruction techniques mentioned previously. From this procedure, attenuation and velocity variation profiles were developed. The attenuation profiles represent the subsurface variations at the site, and correlate well with boring logs. High attenuation and low attenuation correspond to high and low fracture density, respectively. The velocity variation profiles obtained from the Forest Glen survey are of little use. Actual velocity profiles were unobtainable because of calibration problems.

From the results of this cross-hole study, such measurements (attenuation and velocity variation) may provide estimates of the subsurface geological structure. Also, using the cumulative effect of cross-hole surveys, boring data and laboratory tests, it may be possible to better estimate the actual site character.

The LLL report is not included among the appendices because it contains colored photographs of data which would not be sufficiently comprehensible if reproduced in black and white.

2.2.3 ENSCO, Inc.

ENSCO, Inc. also performed a series of electromagnetic tests using pulse-echo and cross-hole techniques. A transmit-receive (T-R) probe, designed primarily for use in horizontal boreholes, was used. The probe provides a pulse of 10 nanoseconds (ns) duration at a frequency of 100 mHz. Only probes having transmit (T) capability were used with T-R probes to perform cross-hole surveys.

The cross-hole surveys were primarily used to determine wave velocities at different depths. Surveys were made between boreholes T-1 and T-2, and boreholes T-3 and BRP-27, at depths of 165 feet (50 m) and 200 feet (60 m), respectively. The mean frequency of the pulses received were plotted, thus revealing a general increase in frequency content with increased integrity of the bedrock. The plots show frequency values between boreholes T-3 and BRP-27 that are higher than those between boreholes T-1 and T-2. This may be attributed to significant differences in material attenuation. The pulse-echo surveys generally produce more useful data when waves are emitted perpendicular to rock discontinuities. Most of the geological features of interest, at the Forest Glen site, lie almost parallel to the foliation. Having performed the tests in boreholes drilled perpendicular to the foliation, very little useful data was obtained. However, those geological features which did show up were reasonably well correlated with the rock core data.

2.3 Mechanical Tests

2.3.1 Soil Testing Services, Geotechnical

A direct exploration technique was performed by Soil Testing Services, utilizing the pressuremeter. A Menard type pressuremeter was used in Boring T-3 to obtain soil and rock information. Tests were performed between the depths of 20 feet (6 m) and 92 feet (28 m). Standard testing procedures were followed, with the probe inflated in increments to a maximum pressure of 74 tsf (70 bars).

From the test data, pressuremeter moduli and limit pressures were obtained. Tests on the highly weathered rock, at a depth of approximately 70 feet (21 m), produced a pressuremeter modulus of 2270 tsf (217,000 kN/m^2). The pressuremeter moduli obtained for the moderately weathered rock, at depths of 80 feet (24 m) and 90 feet (27 m), are 3400 tsf (326,000 kN/m^2) and 3080 tsf (295,000 kN/m^2), respectively.

2.3.2 Foundation Sciences, Inc.

Foundation Sciences, Inc. attempted to determine the engineering properties of the rock at the Forest Glen test site using borehole jacking test and laboratory tests of selected rock core. A borehole jack probe was used for the field tests. The jack is designed to operate in an NX diameter borehole with moveable rigid plates for measuring wall deformation as a function of applied load. A maximum pressure of 9.3 ksi (64,000 kN/m^2) may be applied to the rock surface.

Due to borehole obstructions, only two tests were performed (both at the same depth) in borehole T-2 within the weathered rock zone. Test 1 was conducted with stress applied perpendicular to Georgia Avenue, and test 2 was conducted with stress parallel to Georgia Avenue. The jacking tests produced modulus values that were relatively low. Eleven unconfined compression tests were performed on rock core samples to determine deformation constants. The modulus values obtained in the laboratory for the weathered rock sample compare well with the values obtained in the field.

The unweathered rock exhibits predominantly elastic behavior with no time-dependent strain. The slightly weathered rock exhibits a high degree of permanent deformation and a moderate amount of time dependent strain. During the field tests, the bearing capacity of the borehole wall was not exceeded by stresses above 7.5 ksi (52,000 kN/m^2). The maximum stress levels on laboratory samples were 3 ksi (21,000 kN/m^2) and 5 ksi (35,000 kN/m^2) for weathered and unweathered rock, respectively. In either case, no failure occurred.

3.0 DISCUSSION AND EVALUATION OF TEST RESULTS

3.1 Acoustic and Seismic Techniques

The results of the acoustic and seismic experiments, performed at the Forest Glen test site, were completed and reported by five research organizations. Table 1 provides a summary of the more reliable data obtained from the experiments. Three different types of tests--surface, down-hole and cross-hole--were conducted by the various organizations, each using unique source and receiver probes of varying frequency and energy capabilities.

In general, the tests provided acoustic velocity information which, in a continuous rock mass, is proportional to the ratio of bulk modulus to mass density. Holosonics, Inc. (HI) used the down-hole method to locate the position of discontinuities within the rock mass with respect to borehole location. The effect of the frequency content of an energy source is an important parameter in geophysical exploration. Although physical rock characteristics will have some bearing on the useful frequency content, it has been reported that high frequencies generally yield greater detectability and resolution of rock discontinuities and less rock penetration. Some of the acoustic experiments were excluded from the discussion primarily because the data obtained were not considered to be valid by the investigators.

The majority of the data presented in Table IN1 is considered reliable, and therefore, offers some opportunity for investigation and comparison. The cross-hole surveys were the predominant type of acoustic experiments conducted at the test site. Ocean/ Seismic/Survey, Inc. (OSS) reported compressional (P) wave velocities ranging from 5903 fps (1770 mps) to 8333 fps (2500 mps), with depth (many of the OSS tests were affected by instrument problems such as inaccurate timing of the spark release and electrical cross-field, traffic noise and rainfall). The four other organizations reported much higher velocities. Soil Testing Services (STS) obtained the largest velocity of 20,000 fps (6000 mps), using a 6-Joule energy source and a very small frequency (1 pulse/6 sec.) between boreholes T-2 and T-3. At such a low frequency, the detection and resolution of acoustic waves are questionable. STS did, however, successfully filter out traffic noise interference.

Holosonics, Inc. (HI), and OSS conducted down-hole surveys which, for HI, produced a radius of influence (of acoustic waves) of 60 feet (18 m); the radius of influence determined by OSS was nearly zero. OSS computed down-hole pressure wave velocity and shear wave velocity by using the distance separating the source and the receiver. This procedure may not be appropriate since the main purpose of the down-hole survey is to detect a discontinuity or anomaly some distance away from the borehole wall. Thus, the proper procedure for the down-hole survey should be either to use the average wave velocity from the cross-hole survey or, based on the continuous recording process, to identify the reflection signals from a particular joint to compute the wave velocity. The main problem of the OSS survey is the inaccurate timing of the spark release.

The experiments conducted by Woodward-Clyde Consultants (WCC) provided reasonable compressional wave velocities ranging from 4900 fps (1470 mps) to 11,800 fps (3540 mps) with depth. The subsurface stratification and the borehole inclination significantly affected WCC's determination of shear wave velocities. ENSCO, Inc., however, provided reasonably acceptable compressional wave velocities from their cross-hole studies.

Overall, the investigations provided a good opportunity to evaluate various site exploration systems in a controlled field laboratory. The results of the Forest Glen experiments reaffirmed that geophysical exploration techniques can be viable methods for conducting subsurface investigations.

3.2 Electromagnetic Survey Techniques

The basic principles for using high frequency (average 10^8 Hz) electromagnetic waves to survey subsurface geological formations are that 1) the propagation velocity of these waves is strongly dependent on the water content of rock materials through which these waves pass, and 2) the attenuation of the wave amplitude is directly related to the conductivity of the rock materials. Wave velocity is inversely proportional to the square root of the dielectric constant. At a very high frequency, dry rock has a relative

Table IN1. Summary of acoustic and seismic survey data.

Organization	Test Type	Source Energy (Joule)	Frequency (Hertz)	Receiver Type	Depth	V_p	V_s	Remarks
Ocean/Seismic/ Survey, Inc.	Surface	200	-	Geophone	167.	3,740	-	Source located at 167 ft
	Surface	200	-	Geophone	160.	3,285	1,923	Source located at 160 ft
	Down-Hole	200	-	Geophone	170.	3,750	2,453	V_p and V_s averaged
	Down-Hole	200	-	Geophone	-	-	4,200	V_s averaged
	Cross-Hole	200	-	Hydrophone	230.	8,333	2,940	Between Borings T-1 & T-3
	Cross-Hole	200	-	Seismometer	50.	5,903	-	Between Borings T-1 & BRP-27
	Cross-Hole	200	-	Hydrophone	100.	7,066	-	Between Borings T-1 & T-3
	Down-Hole	200	-	Hydrophone	210.	4,637	-	Source at 50 ft
	Cross-Hole	200	-	Hydrophone	90.	8.079	-	Between Borings T-1 & BRP-27
Soil Testing Services, Geo-technical	Cross-Hole	6	0.167	Hydrophone	177	20,000	-	Between Borings T-2 & T-3

Note: 1 ft = 0.305 m
1 fps = 0.3 mps

Table INI. Summary of acoustic and seismic survey data.
(continued)

Organization	Test Type	Source Energy (Joule)	Frequency (Hertz)	Receiver Type	Depth	V_p	V_s	Remarks
Holosonics, Inc.	Down-Hole	-	25×10^3	-	-	-	-	-
	Cross-Hole	-	18×10^3	-	177	15,000	7,000	Between Borings T-1 & T-2
	Cross-Hole	-	18×10^3	-	-	16,000	-	Actual frequency not stated, but below 18 kH_3
Woodward-Clyde Consultants	Cross-Hole	-	-	Geophone	110	11,800	-	Between Borings T-1 T-2, T-3 & BRP-27
ENSCO, Inc.	Cross-Hole	1250	5×10^3	Accelero-meter	177	13,400	-	Between Borings T-1 & T-2

Note: 1 ft = 0.305 m
1 fps = 0.3 mps

dielectric constant of approximately 2 to 4, while that of water is approximately 81.

Precise correlation between rock electromagnetic parameters and physical rock properties are not yet established. In-situ wave velocity can be determined by performing hole-to-hole measurements. Then, the calculated wave velocity can be used to convert the reflection profile from time scale to distance scale.

As shown in Table IN2, all three organizations used similar high frequency (30-300 x 10^6 Hz) electromagnetic waves. Lawrence Livermore Laboratory, however, sent continuous waves, while the other two organizations used a pulsed transmitter. All three organizations were performing the hole-to-hole type survey. The average pulse propagation velocity was identified by Southwest Research Institute and ENSCO, Inc., as being between 2.4 x 10^8 fps (7.2 x 10^7 mps) to 5.0 x 10^8 fps (1.5 x 10^8 mps). The absolute velocity levels could not be calibrated for the Lawrence Livermore Laboratory experiments, possibly due to the effect of the continuous wave inputs. All three organizations had good qualitative correlation between wave attenuation and rock mass quality, such as fracture density.

Southwest Research Institute and ENSCO, Inc., made an electromagnetic reflection or a pulse-echo survey from a single borehole. This technique seemed very promising, but the data reduction process was not adequate for accurate interpretation. The very large ring-down signal at the beginning of each trace needed to be removed. After removing the ensemble average waveform content of the data from each trace, the retained portion was more directly related to reflections from rock structure conditions. Southwest Research Institute presented a good example for this data reduction step. ENSCO, Inc. presented a quantitative correlation between rock core fractures per foot and received pulse mean frequency for borehole T-3 (over slant depth of 135 feet (41 m) to 170 feet (51 m). Good agreement was obtained.

The technical results obtained in the Forest Glen field tests are encouraging, but some improvements in the borehole electromagnetic probe equipment should be considered. The most significant improvement would be provision for azimuthal directivity around the borehole to avoid the superposition of all reflections from the 360-degree omnidirectional field of view. In addition, development of a technique for separating transmitter and receiver in the same borehole, in order to provide various offsets, would also improve equipment performance.

Finally, one of the most important areas needing further investigation is the behavior of the electrical properties of rocks over a frequency range from 10^6 to 10^9 Hz.

3.3 Pressuremeter and Borehole Jack Tests

The pressuremeter test data obtained by Soil Testing Services, Geotechnical, were correlated with Standard Penetration Test data (N-values) from both the same borehole and borings in other residual soil in the Washington, D.C. area. A least-squares trend line and the average Forest Glen trend line show reasonable correlation. However, since the capacity of the equipment is limited to a maximum pressure of 74 tsf (70 bars), the moduli calculated on the basis of a 100 tsf limit pressure is highly judgmental. Thus, the pressuremeter system used in this test program is adequate only for use in materials ranging from soil to decomposed rock ($N \leq 100$/ft).

Based on the two field borehole jacking tests, the moduli values obtained were

Table IN2. Summary of electromagnetic survey data.

Organization	Test Type	Borehole Tested	Type of Wave	Frequency (Hertz)	Slant Depth (fps)	Propagation Velocity (fps)	Radius of Influence (ft)
Southwest Research Institute	Down-hole	T-1	Pulse Wave	30×10^6 to 300×10^6	102 to 190	2.4×10^8 to 5.0×10^8	60
	Cross-hole	T-1 to T-2 T-1 to T-3 T-1 to BRP-27	Pulse Wave	30×10^6 to 300×10^6	40 to 230	2.4×10^8 to 5.0×10^8	-
Lawrence Livermore Laboratory	Cross-hole	T-1, T-2 T-3 and BRP-27	Continuous Wave	50×10^6	150 to 259	Could not be calibrated	-
ENSCO, Inc.	Down-hole	T-1, T-2 T-3 and BRP-27	Pulse Wave	100×10^6	80 to 250	3.6×10^8	5 to 25
	Cross-hole	T-1 to T-2 T-3 to BRP-27	Pulse Wave	100×10^6	120 to 230	3.6×10^8	20 to 60

Note: 1 ft = 0.305 m
1 fps = 0.3 mps

relatively low. The rock tested exhibited a moderate amount of permanent deformation, and a significant amount of time-dependent strain occurred at the end of each loading cycle. This probably indicated the existence of weathered cracks and crack-closing during each cycle. The elastic moduli determined in-situ were in good agreement with data obtained from laboratory tests on the weathered rock.

The weathered zone is revealed in boreholes T-2, T-3, and BRP-27 by their apparent closure between 107 feet (32 m) and 117 feet (35 m) (inclined depth). Both field and laboratory tests did not reach the failure point of the rock. The maximum bearing pressure for the borehole jack is approximately 9.3 ksi (64,000 kN/m^2). This device may not be suitable for testing the strength of rock, which is approximately 25 ksi (172,000 kN/m^2) on the average. The other disadvantage is the poor mating of rigid plates to the rock surface.

4.0 CONCLUSION AND RECOMMENDATIONS

The main elements measured by the acoustic and seismic survey are the transmission and reflection pressures and shear wave velocities, which depend on the average bulk modulus and density of the material along the path the waves traveled. The main elements the electromagnetic survey measured are the propagation velocity and wave attenuation, which depends on the average dielectric constant and the conductivity of the material along the path the waves traveled. All the aforementioned quantities are indirect measurements of the mechanical properties of the rock mass. Thus, this data must be correlated with conventional boring information. However, after correlation with the related boring data, the geophysical survey, properly used, can provide continuous and average geological information between borings.

Based on a review of the reports from the field research experiment at the Forest Glen site, the following observations can be made:

I. Acoustic and Seismic Techniques:

1. The effect of the frequency content of an energy source is an important parameter in geophysical exploration. Higher frequencies generally yield a greater detectability and resolution of rock discontinuities and lesser rock penetration. However, a higher level of the energy source may improve the distance of penetration.

2. In comparing the five different hardware systems used in the field experiment, the main advantages and limitations can be summarized:

    a. For the Soil Testing Services system, the test frequency appears to be too low and the computed pressure wave velocity appeared to be too high. Further development of this system is not recommended.

    b. For the Ocean/Seismic/Survey system, the computed pressure wave velocity is too low. Inaccurate timing of the spark release may be the main problem. Further development of this system is not recommended.

    c. For the Woodward-Clyde Consultants system, a down-hole shear wave source was used. However, the shear wave velocity was not determiable. Further development of this system is not recommended.

d. For the ENSCO, Inc. cross-hole acoustic system, both frequency and computed velocity were adequate. Further development of this system is encouraged.

e. For the Holosonics, Inc. down-hole and cross-hole system, both frequency and computed velocity were adequate. In addition, the major jointing was interpreted. Further development of this system is encouraged.

II. Electromagnetic Techniques

1. The most significant improvement would be provision for azimuthal directivity around the borehole to avoid the superposition of all reflections from the 360-degree omnidirectional field of view. In addition, the effective radius of penetration needs to be enlarged. Finally, one of the most important areas needing further investigation is the behavior of the electrical properties (permittivity and conductivity) of rock masses over a frequency range from 10^6 to 10^9 Hz.

2. In comparing the three different hardware systems used in the field experiment, the main advantages and limitations can be summarized:

a. For the Lawrence Livermore Laboratory system, a continuous wave was used and only qualitative attenuation results could be interpreted. The absolute propagation velocity cannot be obtained. Further development of this system is not recommended.

b. For the ENSCO, Inc. ground probing radar system, a quantitative correlation between rock core fractures and received pulse mean frequency appeared to be in good agreement for some depth. The effective penetration range was between 5 to 20 feet (2 to 6 m). Further development of this system is encouraged.

c. For the Southwest Research Institute system, the retained received signal, after removing the ensemble average waveform content, directly related to reflections from rock structure conditions. This system had an effective penetration of 60 feet (18 m). Thus, further development of this system is highly encouraged.

III. Direct Measuring Techniques

1. The pressuremeter system used in this test program is adequate for use only in geologic formations from soil to decomposed rock ($N \leq 100$/ft (30/m)) in the standard penetration test.

The maximum bearing pressure for the borehole jack is approximately 9.3 ksi (64,000 kN/M^2). However, the borehole jack can be improved to a 30 ksi (207,000 kNm^2) capacity by using the Waterways Experiment Station system to test the strength of rock masses. No further development of these systems is needed.

REFERENCE

1. Proceedings of Conference on Site Exploration in Rock for Underground Design and Construction, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., 1979, Report No. FHWA-TS-79-221.

APPENDIX A

EXPERIMENT TO EVALUATE NEW SITE EXPLORATION SYSTEMS

Don A. Linger

INTRODUCTION

The Office of Research of the Federal Highway Administration (FHWA) in cooperation with other interested Federal agencies undertook a "Field Research Experiment for Evaluation of Geological Structure and Engineering Properties of Ground Using New Site Exploration Techniques." This project used the various new site exploration techniques currently under development or consideration by the FHWA Office of Research and was the outgrowth of a field test requirement of an ongoing FHWA research project. However, the very interesting geology, the uniquely large and deep tunneling requirements (a Washington Metropolitan Area Transit Authority (WMATA) station is planned for the site), good surface accessibility, the availability of the site, and scheduled geological verification after excavation for WMATA provided so many advantages that the experiment was enlarged in scope. The experiment was unique inasmuch as it contained several novel features:

- It was the first time that as many as 12 different concepts for subsurface site investigation from single and multiple boreholes were used to conduct site explorations and to make geologic predictions at the same geologic location at the same time.
- It was conducted in an area which represents geologically median rock (that is, rock that is neither too complex nor too simple) and which will be the site of a major underground engineering project.
- The work was done at a site which had a very high probability of eventually being mined for an underground structure. It was anticipated that during excavation the geology would be mapped in detail so that the actual geologic characteristics would be available for verification of the predictions.

OBJECTIVES

The principal objectives of this project were (1) to test the various site exploration systems and data processing techniques in a controlled outdoor laboratory with actual geological anomalies which can be identified later by excavation and mapping; and (2) to provide an opportunity to accrue electromagnetic and acoustic (or seismic) reflection and transillumination signature data for future identification libraries and algorithm development.

This project also provided the opportunity for demonstrating developed site exploration technology for geotechnical engineers, design engineers, and engineering and planning executive decisionmakers.

TIME SCHEDULE

The field tests began in the Fall of 1977 and were completed during the first quarter of 1978. In March 1978, a conference sponsored by FHWA was held for the purpose of presenting and discussing the data obtained and the resulting interpretations of same. The proceedings of this conference have been published (Report No. FHWA-TS-79-221, July 1979), and are available through National Technical Information Services, Springfield, Virginia 22161.

COORDINATION

Governmental agency coordination of the project was through the Office of Research/Federal Highway Administration in cooperation with WMATA, the Department of Transportation Tunneling Council, the Office of Rail Technology/Urban Mass Transportation Administration, the Office of Systems Engineering/Office of the Secretary, the Excavation Technology Program/National Science Foundation, and the Interagency Council for Excavation Technology.

RESULTS

The Federal Highway Administration, through its Office of Development, sponsored a conference which addressed the general topic of site exploration in rock and focused on the results of the Forest Glen Field Research Experiment. The conference was held in Washington, D.C., from March 29 through 31, 1978.

PARTICIPATING RESEARCHERS

There were 14 different research organizations who participated in the field test with their various hardware systems and data processing techniques. Each participant is identified in the following brief discussion of the various site investigation techniques used in this experiment.

Principal Investigator: Henry J. Miller
Ocean/Seismic/Survey, Inc.
80 Oak Street
Norwood, New Jersey 07648
(201) 768-8000

Technique.--The Alpine Geophysical plan consists of a nonexplosive type energy source in the borehole. Specifically, a sparker-type sound source was placed in one hole and geophones (or seismometers) placed in nearby and adjacent boreholes. Wave propagation was recorded and studied along (a) horizontal planes, (b) across geological interfaces, (c) paths oriented diagonally to the ground surface, and (d) vertically upward to the top of the hole. Variations included leaving seismometers stationary at these different locations and systematically altering the vertical distance of the energy source in the borehole. Recording instruments were (a) the normal one vertical component geophone of different frequency response characteristics, (b) seismometers capable of detecting the shear waves, and (c) three component seismometers. These recordings supplied data on compressional and transverse wave velocities, characteristics and associated moduli.

Principal Investigator: W. M. Sturdevant
Birdwell Division
Box 1590
Tulsa, OK 74102

Technique.--The Birdwell study included 3-D Velocity and Caliper Logs in each borehole. An acoustic signal was transmitted from hole-to-hole. This effort was dependent upon the capability of the geologic formation to transmit the acoustic signal. The distance of 10 to 15 feet separation between the boreholes was consistent with the Birdwell experience. Interpretation included pressure wave velocity, shear wave velocity, elastic moduli (Bulk-Shear-Young), and fracture identification.

Principal Investigator:

Marvin D. Oosterbaan
Soil Testing Services, Geotechnical
8305A Merrifield Avenue
Fairfax, Virginia 22030
(703) 573-4846

Technique.--This effort included the use of a pressuremeter (PM) and seismic down hole and cross borehole procedures. These techniques were used to obtain moduli values in situ for the various strata of the geologic profile. The seismic investigation developed gross data on bulk properties including dynamic modulus and allowed correlation of the measured static and dynamic modulus with actual modulus tests of recovered rock core and the fracture frequency of the strata.

Principal Investigators:

Sidney A. Suhler and Thomas E. Owen
Southwest Research Institute
8500 Culebra Road
San Antonio, TX 78284
(512) 684-5111

Technique.--This effort utilized a borehole electromagnetic reflection probe with a relatively high-power, deep-penetrating pulse-echo system designed to detect fault displacements and changes in sedimentary rock structures at radial penetration distances of about 50 feet around a borehole. At the time of the test the system receiver recovery time, which governs the range to the nearest observable target, limited the nearest target range to about 15 feet in sedimentary rocks. Because of uncertainties in the penetration depths obtainable in the schist and gneiss rock materials at the FHWA field site, equipment modifications were made to reduce the minimum detectable target range to about 5 feet. These modifications primarily involved changes or adjustments in the transmitter output pulse waveform and in the receiver electronic circuits.

Principal Investigator:

Donald J. Dodds
Foundation Sciences, Inc.
520 S.W. 6th Avenue
Portland, OR 97204
(503) 224-4435

Technique.--The objectives of this effort were to measure, using a borehole dilatometer, the static deformational properties of the rock at the site of the WMATA Georgia Avenue Station; to allow comparison of measurements with the rock dynamic characteristics to be measured by others in the same borehole and to allow evaluation of both sets of measurements for usefulness in predicted excavation conditions to be found during construction.

Principal Investigator:

Ted O. Price
Holosonics, Inc.
2400 Stevens Drive
Richland, WA 99352
(509) 946-7641

Technique.--This effort consisted of an acoustic pulse-echo and through-transmission survey of the drill holes. Data were displayed on site for field control, and recorded for playback into the computer and data anaysis. The geology of the area was determined after the field test data were analyzed. Data analysis was compared to the mapped geology for verification.

Principal Investigator: R. J. Lytle
Lawrence Livermore Laboratory
Box 808, L-156
Livermore, CA 94550
(415) 447-1100

Technique.--This effort utilized a new technique being developed to map subsurface structure with radio-wave transmissions. Transmitter and receiver pairs were lowered in holes drilled on opposite sides of the underground region to be probed. The signature of the electromagnetic waves propagated between these pairs varied according to the electrical properties of the intervening media. From this signature anomalies were indicated in the electrical properties of the intervening media; and, in many cases, these anomalies can be directly related to geologic structure. Such radio-wave probing has many applications in mapping underground sites.

Principal Investigators: H. C. Harrell and Jerry Wright
Tennessee Valley Authority
Knoxville, TN 37902
(615) 632-2101

Technique.--This effort included the use of a cross-hole sparker designed to give high-resolution records at distances between 50 and 75 feet. The TVA has found this spacing to be optimum for locating targets such as large voids and zones of badly decomposed rock. It becomes more difficult to locate, evaluate, and confirm such targets as the spacing between holes increases. TVA logged all research holes with both a nuclear and sonic probe. This information provided the necessary data base to evaluate the cross-hole surveys.

Principal Investigator: Keith Kirk
West Virginia University
Department of Geology and Geography
Morgantown, WV 26506
(304) 293-5603 or 3477

Technique.--This effort included two shallow, high resolution, seismic reflection (SHRS) surveys, one a P wave survey and one a S wave survey. These surveys were used to determine the layering of and depth to the various earth materials at the site. The P and S wave velocities were correlated with the data obtained by the other researchers on the project in order to determine the interrelationships between dynamic elastic moduli of the earth materials and the seismic velocities. These moduli included Poisson's Ratio, Rigidity, Young's Modulus and Bulk Modulus for the various layers. This information was cross correlated in an attempt to determine earth characteristics and variations in those characteristics such as shear strength, bearing capacity and permeability.

Principal Investigator: Ronald E. Smith
Woodward-Clyde Consultants
12150 Parklawn Drive
Rockville, MD 20852
(301) 881-3940

Technique.--This effort utilized a shear wave velocity measurement technique developed by the staff of Woodward-Clyde Consultants. Included in the testing was both cross-hole and down-hole shear wave measurements. The shear wave velocity was used to determine the shear modulus of material at low strain levels, and an attempt was made to develop correlations between these low strain moduli and large strain moduli to facilitate use of this type of data in situations such as the design of tunnel support systems.

Principal Investigator: B. G. Watters
Bolt, Beranek and Newman, Inc.
50 Moulton Street
Cambridge, MA 02138
(617) 491-1850

Technique.--Adaptation of a high resolution sparker sound source for deployment in a 6-inch borehole and a high resolution boomer sound source for deployment near the ground surface. The signals from these sources were recorded on magnetic tape from various accelerometers and pressure sensors deployed in the boreholes.

The magnetic recordings were analyzed with a digital computer. The processing included: a) pulse shaping using Wiener filtering, b) image reconstruction for sound speed anomalies such as might be caused by boulders in unconsolidated soil, or by faults in rock, and c) reflection profiling using down-hole sensors to delineate bedding in the unconsolidated soil and the top of the consolidated material.

Principal Investigator: James C. Fowler
ENSCO, Inc.
Subsurface Systems
5408A Port Royal Road
Springfield, VA 22151
(703) 321-9000

Technique.--The objective of this test was to use a newly developed acoustic system to map the area for the proposed Metro station. This work consisted of taking both acoustic transmission and reflection tests in the boreholes and providing an interpretation of the results. This interpretation was made in two ways. First, the data were interpreted to obtain all of the possible geologic information, and secondly, were interpreted from the standpoint of making alterations to the newly developed prototype system to provide for better data.

Principal Investigator: Robert D. Bennett
U.S. Army Corps of Engineers
Waterways Experiment Station
P.O. Box 631
Vicksburg, MS 39180
(601) 636-3111

Technique.--The objective of this study was to demonstrate the feasibility of a practical and economical method of measuring the initial state-of-stress in rock masses by strain relief measurements without overcoring. The secondary objective was to determine the mechanical properties of the rock mass in situ. These measurements were compared with other compatible devices to be used in the research experiment. The device used was basically a longer version of the Goodman Jack, with a loading capacity of about

300,000 pounds at 30,000 psi line pressure. The device incorporates friction gauges to measure initial tangential borehole strains and involves impressing friction-strain gauges on two opposite quadrants with a self-equilibrating pair of forces of sufficient magnitude for initiating and propagating fractures of depth adequate to relieve strain. The initial tangential strains on the borehole wall are relieved by the creation of an open axial fracture and measured by the impressed friction gauges.

Principal Investigator: L. A. Rubin
ENSCO, Inc.
Subsurface Systems Manager
5408A Port Royal Road
Springfield, VA 22151
(703) 321-9000

Technique.—This effort utilized electromagnetic (EM) logs from transillumination experiments with ENSCO's borehole radar probe. Parameters measured with respect to depth were a function of the dielectric constant and the conductivity values, and can be used to identify geologic structure discontinuities by novel data processing techniques. The resulting electromagnetic logs were utilized to assess the geologic conditions of the rock.

APPENDIX B

SITE CHARACTERIZATION AND GEOLOGIC CONSIDERATIONS OF THE FOREST GLEN TEST SITE

James P. Gould, Don A. Linger, and Delon Hampton

FIELD TEST SITE

The field test was conducted at the site of the proposed Forest Glen Metro Station in Silver Spring, Maryland, a part of the Washington Metropolitan Area Transit System. This site was selected on the basis of its interesting geology, the unique requirements of a deep rock Metro station, good surface accessibility, and the opportunity, through eventual excavation, to verify the results of the experiments cited herein which later proved to be incorrect due to shifting of the alignment.

Four research boreholes were drilled to project into the actual proposed station volume. The plan view of the boreholes is shown in Figures B1 and B2, and a schematic section through the station showing the boreholes and geologic layering is shown in Figure B3.

GEOLOGY

Figure B4 is a plan showing the general geology of the District of Columbia area. Forest Glen site lies directly north of the north corner of the District of Columbia, just beyond the intersection of Georgia Avenue with the Beltway. The site geology is fairly typical of the Piedmont region south of New York wherein residual soil "saprolite" of varying thickness overlies a profile of weathering in bedrock. The crystalline country rock is a metamorphosed sediment which is related to the Manhattan and Wissahickon formations and is common throughout the middle Atlantic seaboard. A detailed engineering geology report of these sections of Glenmont Route was prepared by Patton (1974) indicates that the materials present are predominantly micaceous schist, schistose gneiss, and amphibolite representing the range from sandy to clayey sediments. The Forest Glen test site lies in a schist of the country rock which dips toward the west at relatively steep angles. While the strike is consistent in any limited area, the dip varies on a vertical line. The principal jointing pattern corresponds with the foliation which tends to form planes of weakness. These planes are often mica-coated, sometimes containing thin clay deposits, gouge, or slickensides.

The pattern of zoning of rock at the site is shown by the geological section of Figure B5 which illustrates, in turn: shallow fill; saprolite zone labeled D; transition zone between saprolite or decomposed rock and weathered rock labeled D to WR; obviously weathered bedrock zone, WR; moderately to highly jointed bedrock zone, labeled J; and jointed to relatively sound bedrock, labeled R. This drawing involves rather drastic generalizations between the borings. Zones in the plane of the boreholes wherein jointing is more intense are indicated by wavy lines on that geologic section.

Original planning called for the typical WMATA rock station, placed at an unusually great depth because of deep rock weathering. This station is a broad arched opening, typically 65 feet wide and 40 feet high at the crown, which is excavated by a

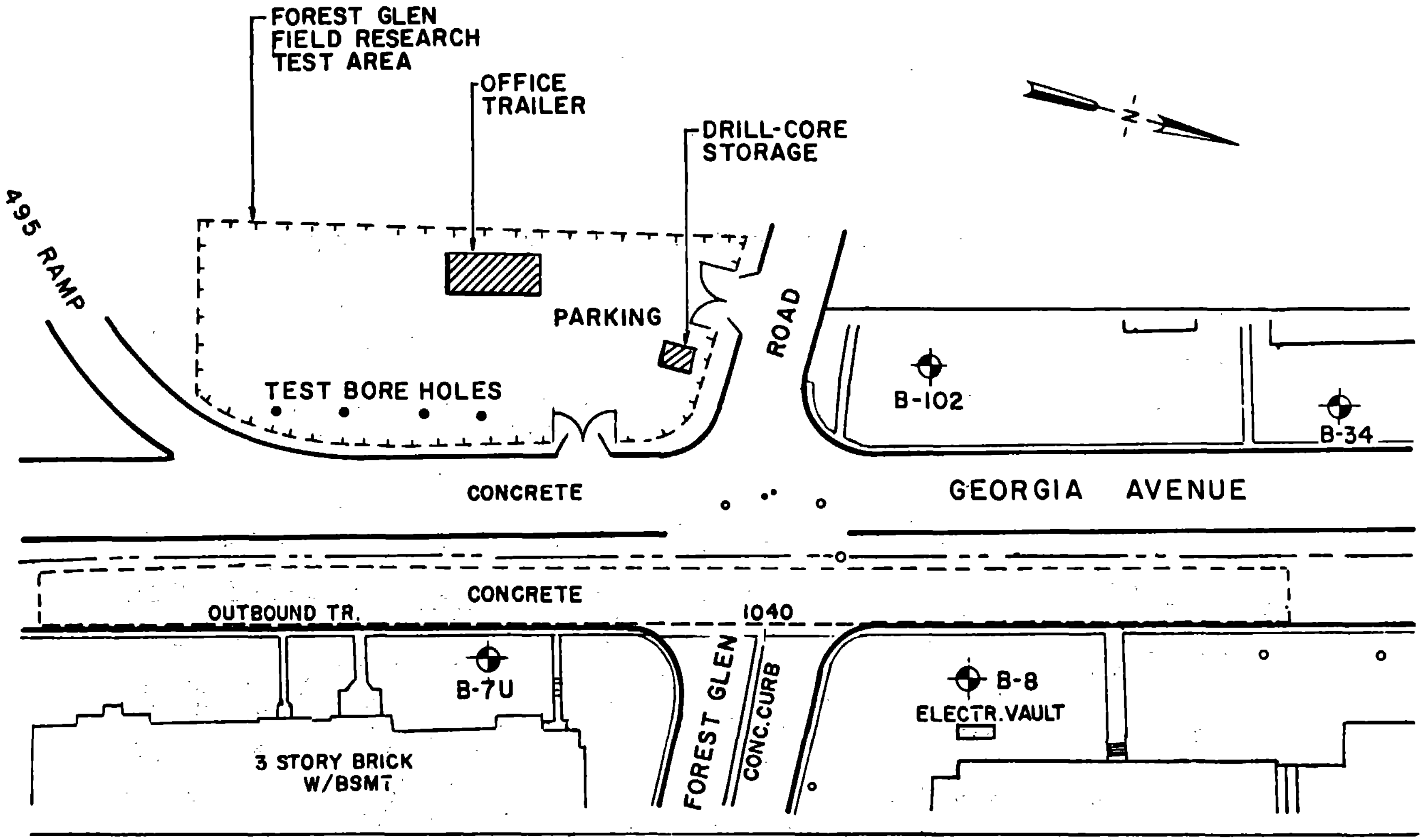
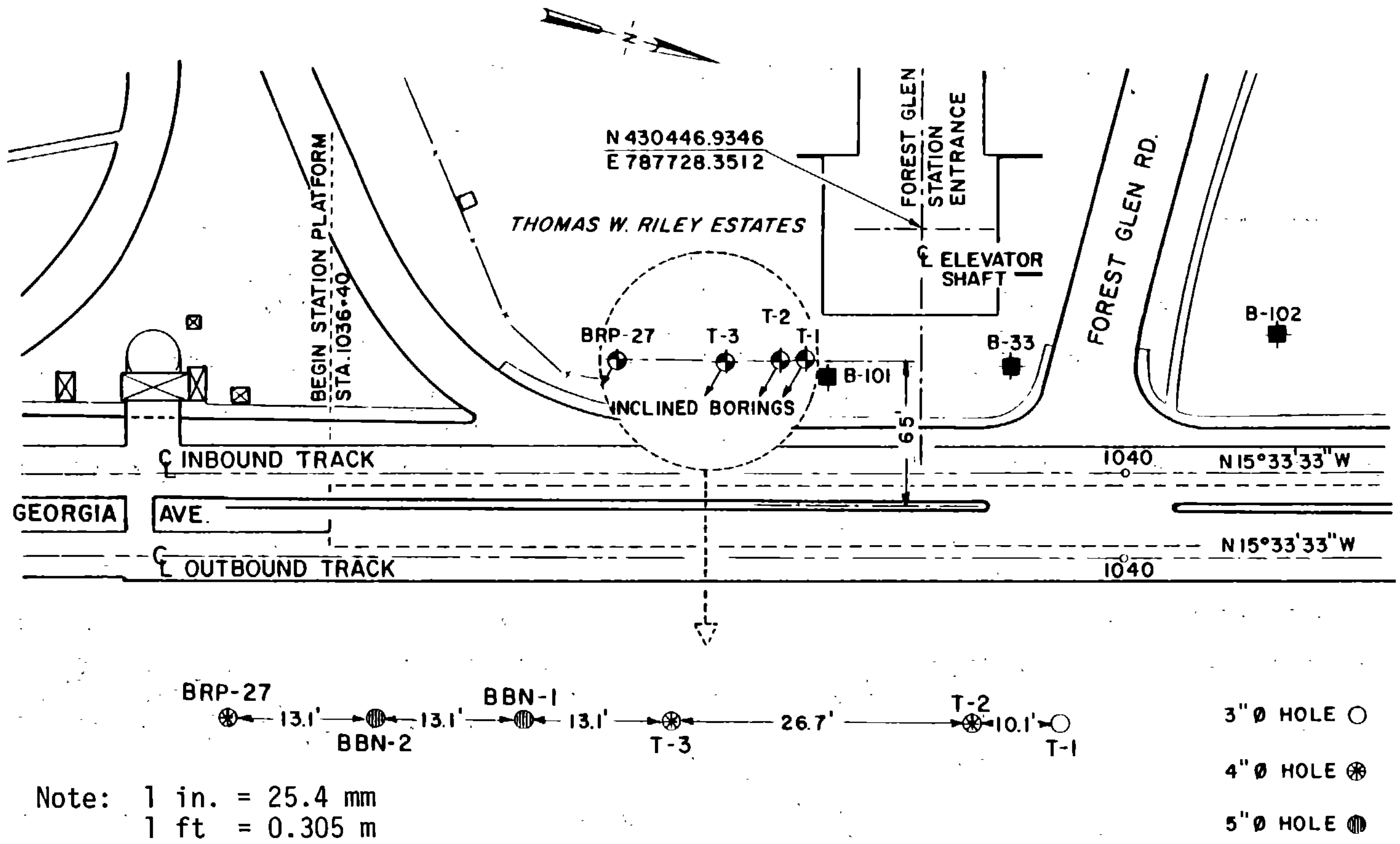
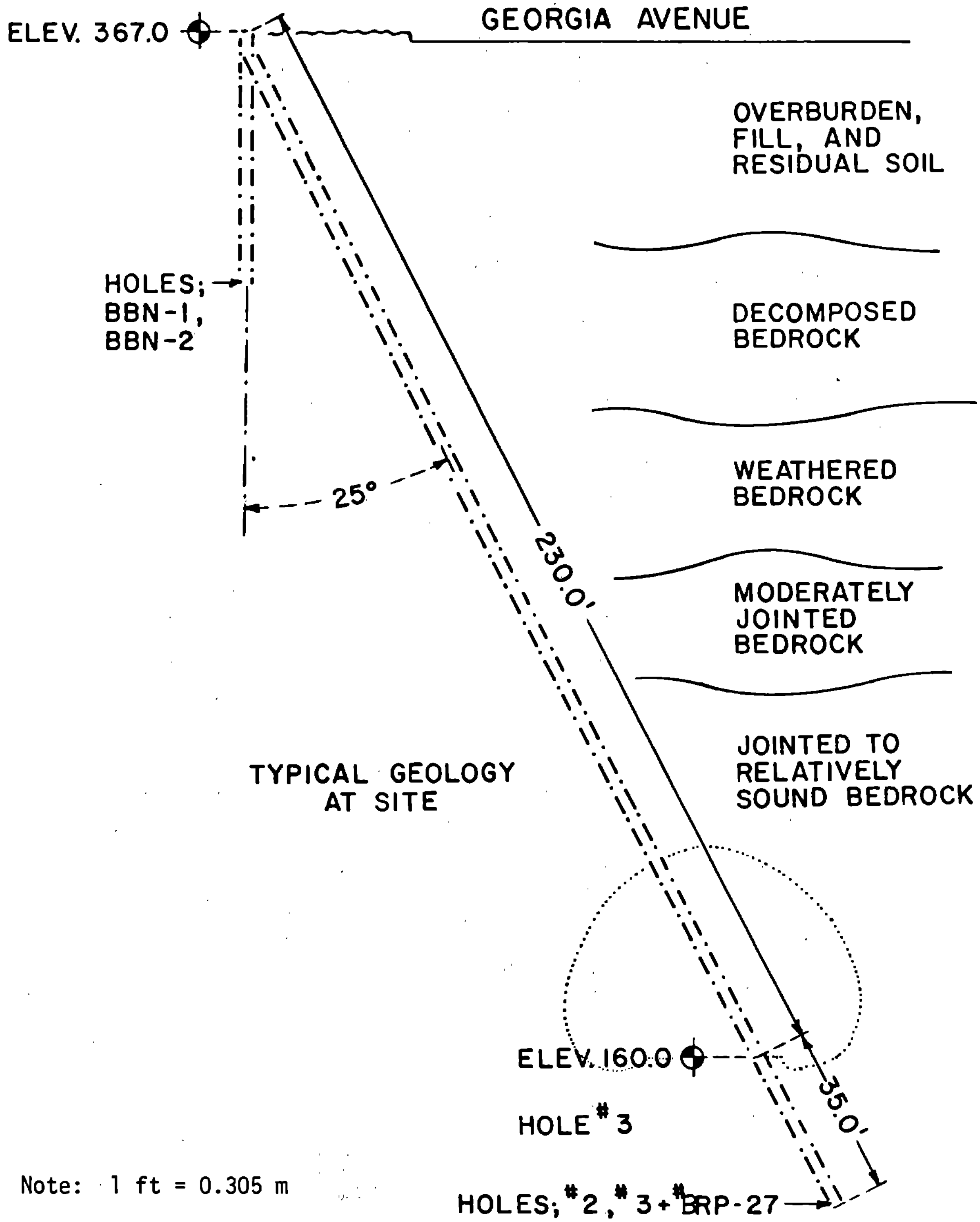


Figure B1. Forest Glen Station. (Alternate "B")



Note: 1 in. = 25.4 mm
1 ft = 0.305 m

Figure B2. Borehole location plan, Forest Glen Station.



Note: 1 ft = 0.305 m

Figure B3. Section through Metro Station.

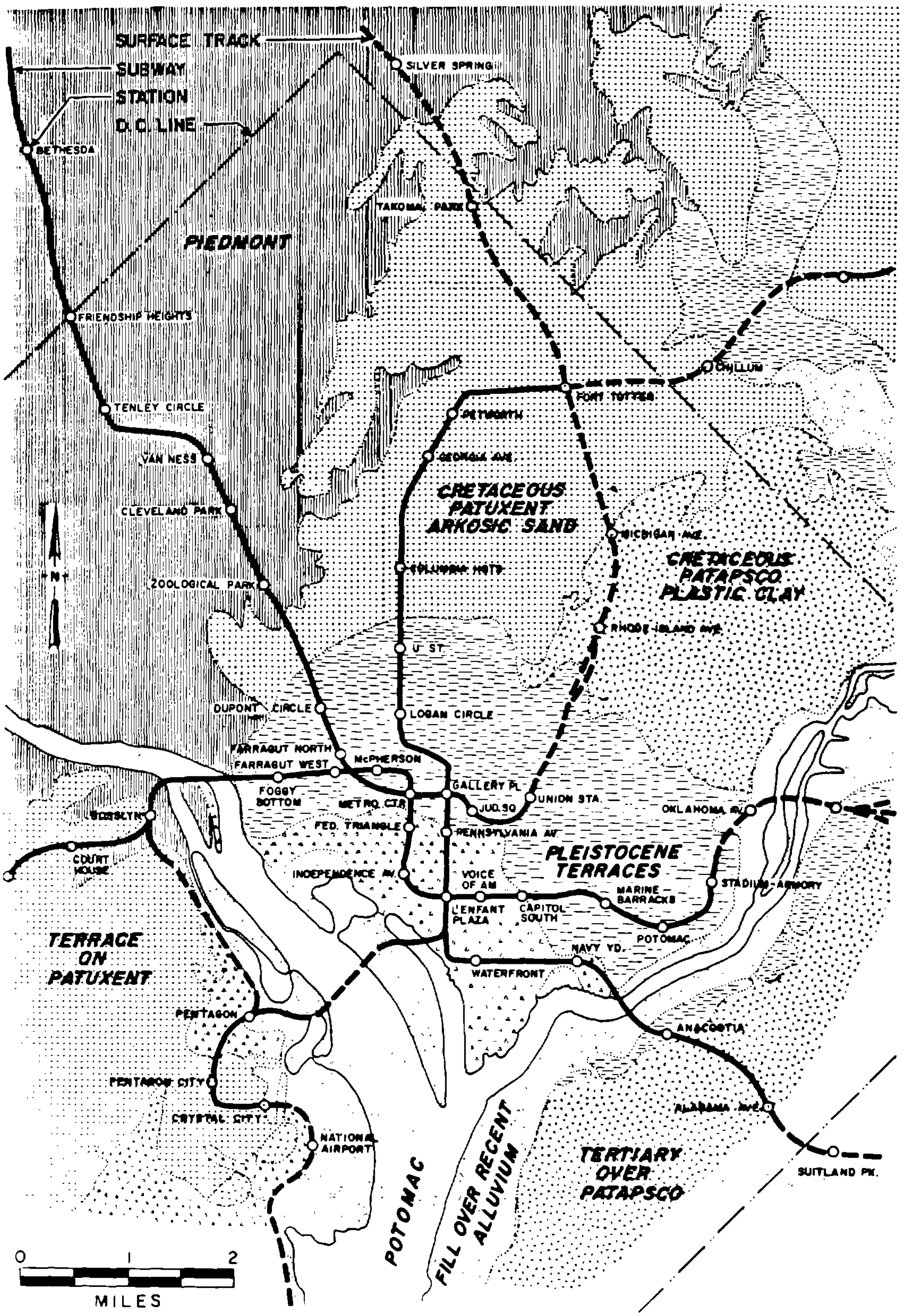
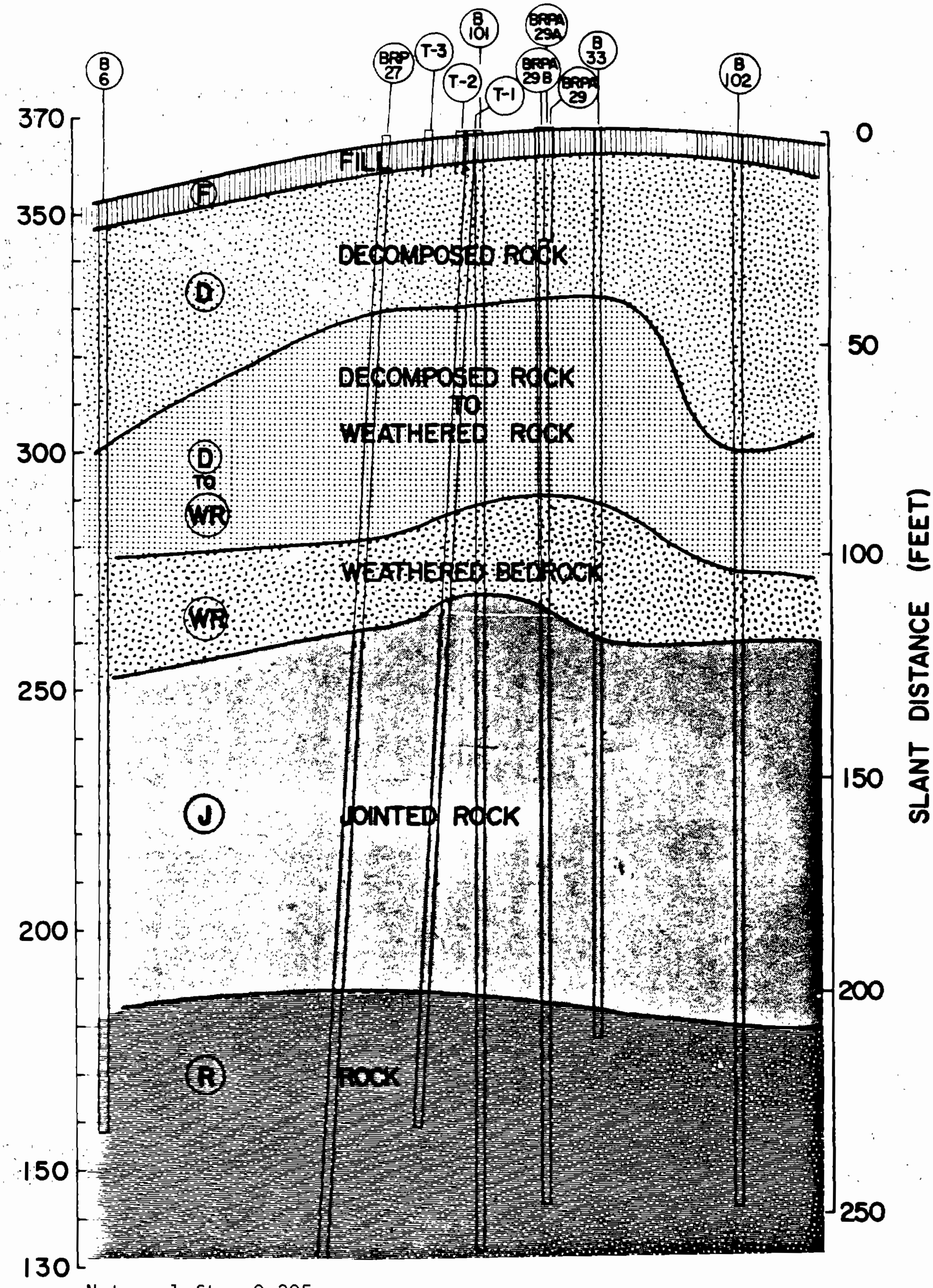


Figure B4. Geological plan of District of Columbia.



Note: 1 ft = 0.305 m

Figure B5. Geological section of Forest Glen site.

series of separate headings. Current excavation procedures call for mining the running tunnels through either lower quadrant of the station and then out the arch above the tunnels. This is obviously an involved procedure, dependent for its cost on rock quality. As an alternative, the possibility was studied of a "Stockholm" type station utilizing the two parallel running tunnels with an opening between them for access.

The exploration program consisted of a large number of conventional borings with rock coring. In addition, four special slant holes were made up to 230-foot depths, sloping downward from the west side of Georgia Avenue to cross through the planned station location. The borings were slanted with respect to the axis of the station opening both in plan and in the vertical plane. These crossed the dip planes in the rock approximately at right angles so that they tended to intersect the chief discontinuities at right angles to the core. Typically, the pattern shown by the borings was highly jointed and weathered rock in the upper part of the coring gradually changing downward to less jointed and sounder materials.

In summary, the Forest Glen test site is important because it represents conditions found extensively in the most urbanized region of the United States. However, an effort to delineate rock quality can be confused by the interaction of two elements: the weathering and intensity of jointing. Changes of rock quality in the profile of weathering tend to be gradational with effects overlapping and it should be expected that it will be difficult to distinguish structural features by geophysical methods.

REFERENCE

1. Patton, F.D., "Preliminary Engineering Geology Study - Glenmont Route Sections B009, B010, and B011, Washington, D.C. Metro System," WMATA Report, NTIS No. PB-238990, July 1974.

APPENDIX C

ACOUSTIC SPARKER TYPE CROSS-HOLE AND UP-HOLE SURVEY

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OBJECTIVES OF SEISMIC EXPERIMENTS AT FOREST GLEN TEST HOLES

The objectives of the experiments conducted in the Test Holes at Forest Glen by Ocean/Seismic/Survey, Inc. (successor to Alpine Geophysical Associates, Inc.) are as follows:

1. To determine if ordinary portable seismic refraction systems could detect and record seismic compression and transverse wave signals with sufficient clarity to provide information on the geotechnical parameters of the rock and soil.

2. To obtain such seismic signals by use of a 200 Joule Sparker System as a source of energy.

3. To evaluate level of Sparker sound source necessary to achieve satisfactory signals of compressional waves.

4. To evaluate interval velocities representative of geologic stratification by recording direct seismic arrivals along a geophone string from various depths.

5. To evaluate the pattern of seismic geophone layout which would provide the best seismic signals.

6. To evaluate the effect of different size spark bag containers for transmitting seismic spark energy.

7. To determine capability of the same system for detecting and accurately identifying compressional wave signals in cross-hole set-ups.

TEST A: HORIZONTAL 100-FOOT SEISMIC LAYOUT

Instrument Set-up

A seismic refraction cable was strung approximately in the same plane as the inclined Test Hole perpendicular to the main highway (Georgia Avenue). Geophone spacing of 12-channel cable was arranged at 10-foot intervals. The first geophone was placed between the sidewalk and the boundary fence, 25 feet from the top of Test Hole T-1 which was evenly located between Nos. 3 and 4 geophones. Additional geophones were placed out to No. 11 cable position, and No. 12 geophone placed alongside No. 11 geophone since there was no further space within the property boundaries.

The energy source for the seismic refraction signals was a 200 Joule Sparker System. The spark tip was enclosed in a cylindrically-shaped plastic tube with an inside diameter of 3 inches, length of 1 foot and walls 3/8-inch thick. A plastic bag served as the container for the salt water solution.

The energy level for the "200 Joule Sparker" was about 180 Joules.

Recording Procedure

A sparker shot was set off in Test Hole T-1 with the spark source at 97 feet below the top of the Test Hole pipe. The reason for this position was to make certain that the shot was immersed in water.

At each depth, several shots were made one after the other at various gains, sometimes two shots at any one gain level.

Initially, high gain settings of 9 were taken, then 2 or 3 records at gain 8, etc., through gain settings of 7 and 6.

The purpose for repeat records was to obtain seismic signals which were more clearly identifiable and which had short incident breaks. Various gain settings were used to obtain the best seismic signal to noise ratio.

Seismic events were recorded at depth intervals of ten feet, ranging in depth from just a few feet above the water line to the bottom of the hole.

Shot depths ranged between 27 feet and 167 feet below the top of the Test Hole. Shots at 27-foot and 37-foot depths were above the water line inside the Test Hole.

Seismic records were made at discrete time intervals, and each record labelled with shot number, time, gain setting, and depth.

No exact time schedule could be used for making successive records since shots had to be made between traffic noises--usually during periods of a red light in the Georgia Avenue direction.

A total of 80 seismic records were made for Test A at Test Hole T-1 with 200 Joule spark source, a large 3 1/2-inch plastic tube for the salt water bag, and a 100-foot seismic geophone layout.

Seismic Signal Quality

A portable seismic refraction system, the SIE 12-channel RS-4 unit, coupled with a 12-geophone cable, is generally capable of producing records of high quality. Seismic events would be sharp incident events, easily recognizable.

In contrast to records of sharp incident seismic events, the seismic events of Test A were far from sharp incident phases, but had an emergent quality of arrival. The seismic signals assumed to be the compressional wave arrivals were more gradual, emergent-type.

Furthermore, it was generally only the first three to five geophones that recorded relatively useful seismic events. Geophones at and beyond the middle of the seismic geophone layout showed generally weak signals of low amplitude and with an emergent pattern.

Identification of Seismic Events

Compressional waves at each geophone of the 100-foot horizontal cable spread were expected to be sharply recognizable so that refraction travel-time-distance graphs could be constructed and analyzed for travel velocities from various travel depths. Because of the poor quality of seismic arrivals at most geophones, the construction of refraction graphs was abandoned.

A different analysis was adopted. Only the seismic event at the No. 3 seismic cable position (which was five feet from the top of the core pipe) was read for travel time. A tabular listing of travel times and corresponding travel distances was made from each pair of measurable quantities, namely travel time and travel distance, and a velocity was computed. This velocity value represents the average velocity of wave travel over the entire direct travel path from Sparker source to geophone. Average velocities were computed for each depth from the arrival time of the compressional wave along its corrected travel distance. Average velocities ranged between 2000 feet per second, evaluated for the 37-foot depth signal, increasing to 4030 feet per second at the 97-foot depth, then decreasing erratically down to 3740 feet per second at the 167-foot depth. The overall average velocity between 37- and 167-foot depths was 3369 feet per second. Incremental velocities for various depths were not computed for this case.

The range of average velocities appears to be geologically unreasonable and low for the types of earth materials found in the boreholes.

TEST B: UP-HOLE, SHORT HORIZONTAL SPREAD

Seismic Pattern

Instruments were set on the ground surface, the first geophone of a 12-geophone string being one foot from the core pipe exposed at the ground surface, and successive phones placed at one-foot intervals. The geophone line was coincident with the surface trace of the vertical plane through the inclined coring pipe.

Energy Source

The energy source for seismic shots was a 200 Joule Sparker. A spark source cable was lowered into the coring pipe. Spark sources were released inside the water filled core pipe at 10-foot intervals. The sparker container was the 3.5-inch diameter bag filled with salt water.

Shot Records

Records were labelled from No. 81 through No. 109. Two successive spark shots were released at each depth position; one at an amplifier gain setting of 9 and the other at 8 for the deeper shots. At shallower depths, gain settings were 7 and 8. Core pipe shot depths ranged between 20 and 160 feet below the ground surface. Shots made at core pipe depth of 20 and 30 feet were above the water line inside the core pipe.

Record Quality

The overall quality of seismic records is classified as fair to poor for the reason that seismic events were not recorded in sharp contrast to background noise.

The pattern of seismic signal of first arrivals caused speculation that the core tube was possibly generating an elastic wave which reached the nearby geophones before the direct seismic earth wave. Because of this ambiguity, Geophone No. 6 was used to read travel times of the apparent direct seismic wave instead of the geophone closest to the core pipe at the ground surface.

A tabular listing (Table C1) was made of (1) shot depths within the inclined core pipe between 20 and 160 feet, (2) travel distances computed graphically from the shot depth to the No. 6 Geophone, (3) the travel time of an event interpreted as the compressional wave labelled as Tp, (4) the travel time of a secondary seismic event interpreted as the transverse wave labeled Ts, (5) average velocities for the compressional wave, Vp and (6) average velocities for the secondary wave, Vs.

Further computations were made from the primary or compressional average velocities. The first seismic events at each record, theoretically, should be the compressional wave travelling along an almost straight line path from point of spark source within the core pipe to the No. 6 Geophone on the ground surface. These first seismic arrivals were not always sharp and distinctive from the background noise. The first seismic arrivals were read in terms of travel time elapsing from the "time zero" event on the record interpreted as the time instant of spark release. The average velocity computed for a given primary-compressional seismic event was simply the corrected travel distance divided by travel time. Since an average velocity for a specific depth is not of particular significance, interval velocities would be more meaningful. Hence, shot records were made at ten-foot increments.

Interval velocities were computed from the ground surface downwards. Table C2 shows the arithmetical sequence of calculations.

Discussion of Data

The accuracy of evaluating the compressional wave travel time, Tp, depends first upon the identification of the "time zero" event and its validity on the seismic record, and second upon the sharpness and definitiveness of the compressional wave event. The seismic event identified as "time zero" is characterized by a sudden displacement of the trace zero line. The assumption exists that the instant of trace displacement also indicated the time of spark release. This assumption is reasonable since we are dealing with the speed of electricity propagation, but no tests were made to verify that the "time zero" mark on the seismic record corresponds precisely to the time of spark energy release into the ground.

The seismic events interpreted as the compressional wave arrivals were not always sharp nor did they have amplitudes significantly larger than background noise.

The interpretation of secondary events proved to be more ambiguous and uncertain. Definite secondary arrivals appeared on the records. An attempt to identify them as transverse waves was based on the ratios between the average velocities of the primary and secondary events, and comparison of these ratios to Poisson predicted ratios.

Table C1. Record travel time at geophone No. 6; One-foot spacing set-up, Test B.

Shot Depth (ft)	Tp (ms)	D (ft)	Vp (ft/sec)	Ts (ft)	D (ft)	Vs (ft/sec)	Vs/ Vp	Vp/ Vs
20	15	18.4	1227	27+	18.4	669	.54	1.85
30	19	28.1	1479	35	28.1	937	.63	1.58
40	20+	38.0	1900	42+	38.0	904	.47	2.10
50	21+	47.9	2281	43	47.9	998	.44	2.28
60	22+	57.8	2627	48+	57.8	1625	.618	1.616
70	24	67.8	2825	53	67.8	1279	.45	2.2
80	25	77.8	3112	54+	77.8	1440	.46	2.16
90	28	87.7	3132	62	87.7	1416	.45	2.21
100	35+	97.7	2791	65	97.7	1503	.53	1.86
101	36	107.7	2991	69	107.7	1561	.52	1.916
120	38	117.7	3097	69	117.7	1705	.55	1.816
130	41	127.7	3114	74	127.7	1725	.55	1.80
140	46	137.7	2993	78	137.7	1765	.59	1.69
150	45+	147.7	3282	79	147.7	1869	.57	1.75
160	48	157.7	3285	82	157.7	1923	.58	1.71

Note: 1 ft = 0.305 m
1 fps = 0.3 mps

Table C2. Interval velocities, Test B.

Core Pipe Depth Range (ft)	Equation	Interval Velocity (Vi) (ft /sec)
0 - 20	V = 18.4 ft/.015 sec. = 1227 ft/sec.	
20 - 30	20 (1227) + 10 (Vi) = 30 (1479)	Vi = 1983
30 - 40	30 (1479) + 10 (Vi) = 40 (1900)	Vi = 3163
40 - 50	40 (1900) + 10 (Vi) = 50 (2281)	Vi = 3805
50 - 60	50 (2281) + 10 (Vi) = 60 (2627)	Vi = 4357
60 - 70	60 (2627) + 10 (Vi) = 70 (2825)	Vi = 4013
70 - 80	70 (2825) + 10 (Vi) = 80 (3112)	Vi = 5121
80 - 90	80 (3112) + 10 (Vi) = 90 (3132)	Vi = 8413
90 - 100	90 (3132) + 10 (Vi) = 100 (2291)	Vi = 5278
100 - 110	100 (2291) + 10 (Vi) = 110 (2991)	Vi = 9991
110 - 120	110 (2991) + 10 (Vi) = 120 (3097)	Vi = 4263
120 - 130	120 (3097) + 10 (Vi) = 130 (3114)	Vi = 3318
130 - 140	130 (3114) + 10 (Vi) = 140 (2993)	Vi = 1420
140 - 150	140 (2993) + 10 (Vi) = 150 (3282)	Vi = 7328
150 - 160	150 (3282) + 10 (Vi) = 160 (3285)	Vi = 3330

Note: 1 ft = 0.305 m
1 fps = 0.3 mps

Since the respective ratios were comparable, the secondary seismic events were interpreted as possible transverse waves.

The table of computed interval velocities shows a pattern of interval velocities increasing with depth down to about 80-90 foot interval, then the next deeper interval having a negative velocity, followed by a large increase; then an erratic pattern of velocity values. Assuming that the averaging equation is reasonable, the erratic evaluation of interval velocities suggests that the selection of signal events on the records is erroneous for at least certain depths.

Furthermore, the values of interval velocities appear to be too small for the type of rock encountered by the seismic waves.

TESTS C & D: UP-HOLE, SINGLE GEOPHONE

Set-up

1. Test Hole was T-1 for both sets of Tests--C & D.

2. The Sparker source was left at a constant depth for both groups; at a depth of 40 feet below ground surface for Group C records, and at 80 feet for the Group D records.

3. At the 40-foot depth the Sparker source was submerged under 13 feet of water and within the confines of the borehole's plastic liner. At the 80-foot depth, the Sparker source was below the bottom of the plastic liner, and within the confines of the cylindrically excavated rock.

4. The single geophone was a marsh-type.

5. Sparker source was the same 200 Joule unit enclosed in a thick-walled plastic bag containing a saturated salt solution.

Recording Procedure

1. Seismic up-hole records were made at increments of 10 feet starting with the geophone at the 235-foot elevation and continuing up the hole to 50 feet when the sparker shot was at the 40-foot elevation, and to 90 feet when the energy source was at the 80-foot elevation.

2. One to four records were made at each 10-foot depth. Generally, three different gain settings were used ranging between gains of 4 to 8.

3. Record labels ranged between Nos. 130 and 142 for Test D.

Discussion of Data, Test C

Seismic records of Test C, wherein the source was within the confines of the plastic liner, show a very prominent secondary arrival with very large amplitude. The large amplitude impulse is sometimes preceded by a definite but more emergent pulse which does not appear on all the records, and because of its erratic appearance it is difficult to be certain that the same seismic event is read.

Another seismic event appears before the secondary event, but is neither consistently recorded nor is it an emergent-type phase. Its amplitude decreased rapidly with depth. The primary seismic event was detectable between 10 and 110 feet below the Sparker source, whereas a secondary event was recorded with its large amplitude from 10 to 190 feet from the source.

Calculations were made of average velocities from both the primary and secondary seismic events. The velocity range of the primary event is between 2500 and 5000 feet per second, and for the secondary event the velocity range is between 1250 near the instrument to 3655 at a distance of 130 feet from the source or at the 170-foot depth.

Further computations of interval velocities were made for both primary and secondary seismic events. The compiled interval velocities range fom 580 to 15,000 feet per second, but there is little or no pattern to the increases or decreases, small values or sudden large values. The erratic distribution of interval velocities suggests that either the same seismic wave was not read from one record to another or that the same portion of the seismic event was not identifiable on each successive record.

Discussion of Data, Test D

The records of Test D, wherein the Sparker source was placed at a depth of 80 feet in a position below the bottom of the plastic liner, were no improvement on the records of Test C. One noticeable feature was the absence of the primary wave of Test C. Average velocities from the wave of large amplitude had a smaller range of values between 3636 and 4800 feet per second. However, the interval velocities computed from the average velocities for the various depth ranges were much more erratic, ranging between 3595 and 13,600 feet per second, as well as two negative velocity computations.

It was concluded from this that the seismic events selected did not represent either the same wave or the same portion of the wave from one record to the next.

TEST E: CROSS-HOLE, SINGLE GEOPHONE

Set-up

1. Test was a cross-hole seismic configuration between Test Hole T-1 used as the shot hole and T-3 for the listening hole.

2. A single geophone, a brass encased marsh phone was used for the tests.

3. A 200 Joule Sparker was used for the generating sound source.

Procedure

1. Both Sparker and geophone were kept at the same elevation for any given shot. Each was lowered an increment of 30 feet starting at a depth of 90 feet and continuing to a depth of 190 feet.

2. Seismic records were labelled Nos. 143 through 148.

Data Discussion, Test E

No prominent, or even slightly identifiable, seismic events could be detected on the records. In addition, the records developed a bad case of electrical cross-feed occurring precisely at the instant of the Sparker break, but it dies out quickly.

TEST F: UP-HOLE, 3-D SEISMOMETER

Set-up

1. Test Hole was T-1.

2. Seismometer--A three-component land seismometer in a cylindrically shaped container was placed on ground surface 16 feet from the top of the core pipe and in the same vertical plane as the inclined pipe.

3. Axis alignment--The north-south component was perpendicular to the core pipe's vertical plane; the east-west component was parallel to the plane.

4. Energy Source—A 200 Joule Sparker was placed down the hole at positions 50 to 190 feet below the ground surface.

5. Six records were made and labelled Nos. 150 through 155.

Data Discussion, Test F

Seismic records were very poor. No strong nor even slightly emergent weak signals appeared at time intervals expected for the arrivals of compressional waves. Weak, low amplitude signals appeared—probably secondary arrivals--with travel velocities of 2275 feet per second.

Signal cross-feed appeared on all the records and on all components occurring at the instant of spark release. The cross-feed was recorded in the form of sharp transient which became damped out according to a typical 0.7 critical damping pattern. Damping of cross-feed signals consumed between 5 and 15 milliseconds. Assuming a compressional wave velocity of 10,000 feet per second, and a travel distance of 50 feet, the compressional wave event should arrive 5 milliseconds after "time zero", therefore, during the damping period of the cross-feed signal. But no disruption of the damping signal was evident.

TEST G: CROSS-HOLE, HALL-SEARS HYDROPHONE

Set-up

1. Hall-Sears--Single hydrophone placed in Test Hole T-3.

2. Energy Source--200 Joule Sparker in Hole No. T-1.

3. Comparative Depths--Hydrophone was placed at a depth of 230 feet in Hole No. T-3, while the Sparker was in Hole No. T-1 at a depth of 190 feet.

4. Seismic records made for this test ranged between No. 160 through No. 168.

Data Discussion, Test G

Except for the first record, the records were of no use because a large amplitude cross-feed signal occurred on the hydrophone trace and lasted through a period of 40 to 60 milliseconds during which the compressional seismic event should have been recorded. After numerous attempts were made to eliminate the cross-feed noise, the test was abandoned.

The single record that appeared to be a valid recording of a primary wave arrival, and which had no cross-feed electric noise, showed a velocity of 8333 feet per second and a secondary arrival with a velocity of 2940 feet per second.

TEST H: CROSS-HOLE, THREE-COMPONENT SEISMOMETER

Set-up

1. Three-component Seismometer placed in Test Hole No. T-4 at a depth of 50 feet within the water column.

2. Sparker source was in Hole No. T-1 at the same depth of 50 feet below ground surface and within the water column.

3. Three sets of recordings were made.

4. Record traces--No. 2 - E-W Component
No. 5 - Vertical Component
No. 9 - N-S Component

5. Distance, T-1 to T-4 (RP-27), measured along the ground surface was 76.75 feet.

Data Discussion, Test H

Of the three records operated, No. 172, with Sparker and Seismometer both at depths of 50 feet, recorded a seismic event free of cross-feed and other electrical noise which was sharp but of low amplitude. Travel velocity of the seismic event was 5903 feet per second. This value would be reasonable for weathered rock.

TEST I: CROSS-HOLE, SINGLE HYDROPHONE, MP-24

Set-up

1. A Geospace Model MP-24, a single Hydrophone, was placed in Test Hole No. T-1.

2. Sparker source was in Hole No. T-1.

3. Sparker shots and recordings were made between depths of 50 and 180 feet below ground surface at depth increments of 10 feet. Sparker and Hydrophone were always at same depth for any one recording.

4. Amplification gain settings ranged between 6 and 9.

5. Record label numbers ranged between Nos. 173 and 188.

6. The set of recordings was made between the hours of 14:25 and 15:10 on Wednesday, November 2, 1977, a period of active vehicular traffic.

The seismic events identifiable provided cross-hole velocities as shown in Table C3.

Table C3. Cross-hole velocities, Test I.

Hydrophone Depth (ft)	Travel Distance (ft)	Travel Time (sec)	Velocity (ft/sec)
50	35.33	.0055	6418
60	"	.0050	7066
70	"	.0045	7851
80	"	.005	7066
90	"	.004	8832
100	"	.005	7066
110	---	--	--

Note: 1 ft = 0.305 m
1 ft/sec = 0.305 m/sec

At cross-hole depths below 100 feet, seismic events were to small to read.

Data Discussion, Test I

The sixteen seismic records varied in quality of recording. All records had a large amplitude overriding sinusoidal noise with 50 to 60 milliseconds period. Superimposed on this noise were the seismic events of fractional amplitude. Very little electrical cross-feed, due to the "zero time" mark, occurred on the Hydrophone channel.

The velocity values computed from the detectable seismic events are geologically within or near the values expected of compressional waves in weathered and partially weathered rock.

TEST J: UP-HOLE, HYDROPHONE MP-24

Set-up

1. Up-hole test using Model MP-24 Hydrophone--single unit in Test Hole T-1

2. Sparker source in T-1.

3. Sparker tip kept at constant depth of 50 feet below ground surface during entire set of recordings.

4. Hydrophone depths ranged between 60 and 230 feet below ground surface. Recordings were made in depth increments of 20 feet.

5. Gain settings ranged between 5 and 9.

6. Time period of recordings was 15:23 and 15:55 on Wednesday, November 2, 1977, a period of heavy traffic noise.

Velocity table for Test J appears in Table C4.

Table C4. Up-hole velocities, Test J.

Hydrophone Depth (ft)	Travel Distance (ft)	Travel Time (sec)	Velocity (ft/sec)
230	180	.048	3750
220	170	.0365	4657
210	160	.0345	4637
180	130	.029	4482
160	110	.023	4782
140	90	.019	4736
120	70	.014	5000
100	50	.1010	5000

Note: 1 ft = 0.305 m
1 ft/sec = 0.305 m/sec

Data Discussion, Test J

Two prominent, sharp seismic events were recorded and identifiable on the records. The later arrival of the two events had an amplitude that went clear off the recording paper. The first of the two large amplitude events was used for the velocity calculations.

TEST K: CROSS-HOLE, T-1 TO T-4

Set-up

1. Hydrophone, Model MP-24, was placed in Test Hole No. T-4.

2. Sparker source in Hole No. T-1.

3. Surface distance between Test Holes T-1 and T-4 was 76.75 feet.

4. During recordings, Sparker tip and Hyrdophone were maintained at the same depth.

5. Seismic recordings were made at depth intervals of 20 feet between 50 and 150 feet below ground surface.

6. Time period of recordings was between 16:08 and 16:34, a time of heavy traffic.

7. Record numbers ranged between 199 and 209.

Velocity table for Test K appears in Table C5.

Table C5. Cross-hole velocities, Test K.

Record No.	Depth (ft)	Travel Distance (ft)	Travel Time (sec)	Velocity (ft/sec)
199	50	76.75	.010	7675
200	60	"	.011	6977
201	70	"	.010	7675
202	80	"	.0095	8079
203	75	"	.010	7675
204	90	"	.0095	8079
205	110	"		
206	130	"		
207	150	"		
208	170	"		
209	190	"		

Note: 1 ft = 0.305 m
1 ft/sec = 0.305 m/sec

Nos. 202 and 203--small amplitude. Nos. 205 through 209--very small amplitude.

Data Discusssion, Test K

The seismic events which were detectable and their arrival times readable, show velocities ranging between 6977 feet per second and 8079 feet per second. These velocity values would be considered within the range expected of a direct compressional wave. It may be significant that detectable seismic events occurred only on records made between 50 and 90 feet deep. When the wave paths became deeper, seismic signals were too weak to read a definite arrival time. This fact may be significant in that previous experience in seismic refraction wave recordings has shown that the amplitude of refracted waves travelling through a hard rock medium has sometimes been very small. The small amplitude travelling through the deeper paths may have been through a medium of harder rock in which there occurred less particle motion.

TEST L: HORIZONTAL, TWELVE-CHANNEL SPREAD

Set-up

1. Test Hole was No. T-2.

2. Twelve geophones were placed on ground surface starting 10.5 feet from T-2 and placed perpendicular to the borehole drilling plane at one-foot spacing.

3. Container for spark source was a small diameter, short length plastic bag--in contrast to the larger thick walled plastic bag used in the previous experiments.

4. Shot depths varied between 40 and 190 feet.

5. Time period of recordings was between 19:40 and 19:50 on November 3, 1977.

Data Discussion, Test L

The geophones experienced severe cross-feed, probably because of the rain which wetted down geophone cables causing extraneous signals to be recorded during periods of seismic events.

The small sparker bag proved to be inadequate. Seismic signals were much weaker than those recorded with use of the larger sparker bag.

All planned seismic experiments were completed and field operations terminated.

TEST M

Further similar tests were made on December 28, 1977. The sparker source was a 3000 Joule System. No usable seismic records were made due to the overriding noise picked up on the records at the instants of recording seismic events.

SUMMARY DISCUSSION

Problems Encountered

Vehicular traffic on Georgia Avenue and Forest Glen Road caused severe vibrations and noise at the geophones. Because of this anticipated problem, plans were made to conduct the seismic test hole experiments at night when the traffic was expected to be diminished. Although the number of cars decreased during certain hours of the night, there was always significant traffic noise.

Seismic recordings were made, generally, during short-period lulls when the traffic lights halted the Georgia Avenue traffic. However, the vibrational noise generated by moving vehicles did not immediately cease when a car came to a halt. Several seconds elapsed before the ground quieted down after a vehicle stopped. General background noise remained relatively high even during temporary vehicle stoppages.

Rainfall, mostly light, dampened the geophone cables and connections introducing spurious electrical signals onto the seismic records. The worst cross-feed signals generally occurred at the instant of, and in connection with, the release of the sparker-generated seismic wave. Efforts were made to eliminate the cross-feed problem by raising the geophone cable connections off the ground, grounding the recording instrument to ground and support vehicle and shielding recording instruments from direct rainfall.

Data Observations

The time of the initial seismic shock must be known very precisely. Although the spark event appeared to be instantaneous, some doubt exists as to the possibility of a delay, maybe of microseconds duration, between "time zero" of the spark firing and actual time recording of the spark release which we assume to occur at the exact same instant. Furthermore, the initial break on the time trace could be read to an accuracy of plus or minus one-half a millisecond. At the short travel distances encountered in these tests, a half-millisecond could correspond to velocity variation of 600 feet per second based on a true velocity of 8000 feet per second. Hence, for short travel distances, the recording of "time zero" should better be evaluated in microseconds rather than milliseconds.

The same holds true for the recording times of the seismic events. The arrival times of direct and transverse waves could be better evaluated if they could be read in microseconds. At best, in the case of a sharp incident wave, reading the arrival instant of the seismic wave can be done to about one-half a millisecond by interpolation.

Evaluation of Objectives

1. Portable seismic refraction geophones did not provide useful recordings of seismic compressional or transverse waves. Furthermore, the 10-foot spacing provided less useful information than the 12 one-foot geophone spacing.

2. The 200 Joule Sparker energy source did not generate a compressional wave of sufficient strength to be recorded sharply and precisely. This was the case for horizontal geophone layout, up-hole and cross-hole, using a seismometer coil type geophone. Compressional wave arrivals appeared to be acceptable when detected by a hydrophone under shallow water pressures.

3. The level of Sparker output is questionable, since a complete range of Sparker output was not conducted. The normal 200 Joule Sparker, actually about 180 Joules, was generally too weak, but the 3000 Joule Sparker should be much more satisfactory. Other operational problems prevented a detailed evaluation of the 3000 Joule Sparker as an adequate source of seismic energy.

4. The evaluation of interval velocities by an arithmetical computation should provide reasonable velocity values for the depth intervals within which recordings are made. The validity of the computations assumes that the values used are consistently correct, i.e., the same type of wave is read and the same part of a wave arrival is read. Conversely, an erratically low, high, or negative value suggests that the wave data used in the computation was not consistent. Therefore, the equations may serve as a check on the proper identification and selection of wave arrivals.

5. Seismic geophone layout patterns apparently are related to the type of pattern of wave propagation. The horizontal layout of 12 geophones at one-foot spacing appeared to provide a group of seismic arrivals which could be read more precisely because of their similarity. In the case of cross-hole tests, the pressure-sensitive hydrophone appeared to be more responsive than the coil type seismometer. Of course, the hydrophone must also be capable of operating under a column of water within the test hole.

6. Spark bag containers apparently play a significant role in the generation and initiation propagation of seismic energy. The larger bag produced seismic records of considerably more energy and amplitude than did a smaller bag which also can blow apart much more readily. The solution of saturated salt water surrounding the spark bag also appears to be important.

7. The up-hole with horizontal geophone cable layout system was tested because a previous survey produced excellent results, albeit a different environment. The previous tests consisted of setting out a 440-foot seismic refraction cable of 12 hydrophones on the ocean--actually a bay—bottom in water depths of 30 to 50 feet, lowering and setting off small (1/4 to 1/2 pound) dynamite charges in the base of completed test hole and working up the hole with dynamite charges as the hole collapsed. The seismic event arrivals were very sharp and clear and computed interval velocities consistent both arithmetically and with geologic structure. It was hoped that a Sparker source of energy could supply seismic records of equally sharp arrivals. The Sparker source would provide the additional feature of (1) making records at closer depth intervals, and (2) making a continuous depth record. Such up-hole velocity tests in connection with newly-completed boreholes in marine areas would provide a relatively quick and accurate evaluation of deeper geologic layering.

APPENDIX D

ACOUSTIC CROSS-HOLE SURVEY AND PRESSUREMETER TECHNIQUES

Marvin D. Oosterbaan and John Fett
Soil Testing Services, Geotechnical

INTRODUCTION

Two devices were utilized in the field testing. First, a Menard type pressuremeter was utilized in the soil and weathered bedrock from depths of 20 to 92 feet (6.1 to 28.0 meters) in Boring T-3, to obtain information with an active testing device. Secondly, a compressional seismic wave was transmitted from borehole T-2 to T-3, and from borehole T-2 to BRP-27 in a "cross-hole" mode to evaluate the seismic wave velocity of the soil and bedrock from depths of 40 to 250 feet (12.2 to 76.2 meters). Testing was also performed with the sparker at 10-foot (3.04 meter) intervals in hole T-2 with one receiver high in hole T-3, and one receiver near the bottom of hole T-3. This provided seismic data from a second orientation.

The compressional wave velocity was correlated with the data obtained from the active pressuremeter device and the classification logs of the rock core.

EQUIPMENT AND PROCEDURES

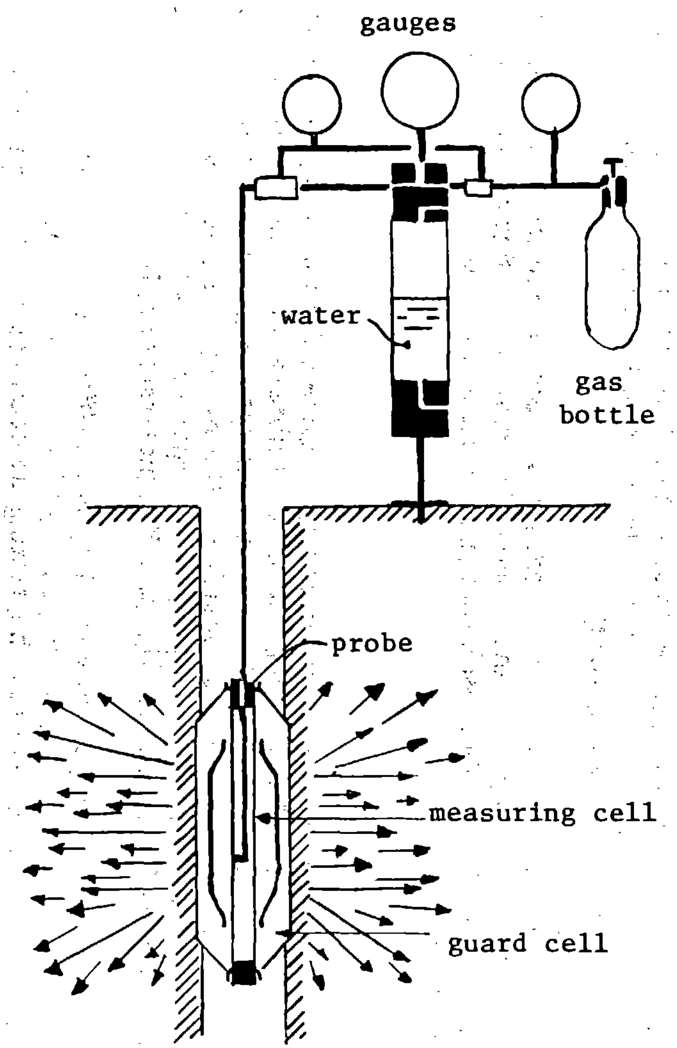
Pressuremeter Testing Equipment

The pressuremeter test equipment consists of a pressure source at the ground surface connected by tubing and valving, and a control panel to the pressuremeter probe. The pressuremeter probe was inserted in a specially prepared test cavity at 10-foot (3.04 meter) intervals as Boring T-3 was drilled during July, 1977. The test cavity was prepared with a 2.5 inch (6.35 cm) diameter split-spoon from depths of 20 to 60 feet (6.1 to 18.3 meters). Below that depth, the residual soil was extremely dense and the cavity was prepared with a 2-3/8 inch (6.03 cm) diameter bit and drilling fluid between depths of 60 to 92 feet (18.3 to 28.0 meters).

After the hole was prepared for the pressuremeter, the probe was inserted and inflated in carefully measured increments to a maximum pressure of 70 bars. The volume of soil displacement, as measured by probe volume at each pressure, was recorded at each test. A sketch of the pressuremeter equipment and a typical curve is included as Figure D1.

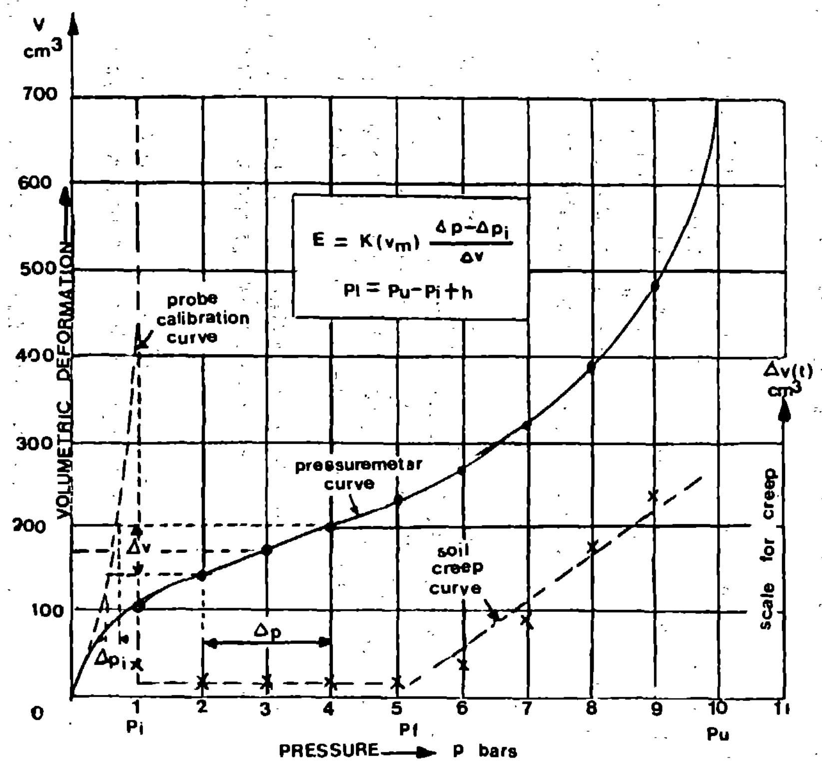
Seismic Testing Equipment

The initial plans for the cross-hole seismic testing were to use a small drop-weight as a seismic source and have clusters of three mutually perpendicular geophones as receivers. However, this source and the geophone receivers can only operate in boreholes inclined 0° to 15° from the vertical. Gimbled geophones are available and could have been used in the Forest Glen boreholes which deviate 30° from vertical. However, gimbled geophones are too large to safely fit into NX size core holes in rock. The normal



MENARD PRESSUREMETER

Note: 1 in. = 2.5 cm
1 in.^{3} = 15.6 cm^3
1 tsf = 0.014 bar



TYPICAL CURVE

Figure D1. Pressuremeter tests and typical curve.

system would be able to determine seismic shear wave velocity as well as compressional wave velocity.

It was therefore decided to develop new instrumentation that would operate efficiently in small diameter boreholes of any orientation. This equipment consisted of a small diameter sparker seismic source and separate hydrophone receivers. A six-joule sparker was fabricated, tested, and found to be adequate for the project. Our calculations indicated a sparker of only a few joules energy would be adequate. The spectrum of traffic noise is almost entirely below 100 Hz and can be removed from the received signals by filtering.

The six-joule sparker consists of a small high voltage power supply generating about 22,000 volts, a nitrogen gas-pressured adjustable spark gap and a few hundred feet of high voltage shielded cable with a weighted spark gap at one end. The spark gap was installed inside a short length of 1-1/2 inch (3.81 cm) PVC pipe streamlined at both ends with machined plastic tips to easily slide up and down the inclined boreholes.

The weighted spark gap is capable of sparking at relatively low voltage. The surge of electricity is adjusted by the number or size of capacitors used and the voltage to which they are charged.

The gas-pressured spark gap was adjusted by increasing the pressure of nitrogen gas to arc at 20,000 volts. With the capacitor used for this investigation, six joules of energy were provided to the borehole sparker.

The receivers were inexpensive commercial hydrophones potted to inexpensive shielded cable. Two receivers were used and each was mounted inside a short length of 1-1/2 inch (3.81 cm) perforated galvanized pipe that provided protection to the hydrophone and also gave weight to allow the hydrophone to slide down the inclined borehole. Again, the top and bottom of the pipe section were streamlined with machined plastic tips. Figure D2 illustrates the field equipment set-up.

The signals received by the two hydrophones were transmitted to simple preamplifiers with adjustable high-cut and low-cut filters. The signals were then transmitted to a dual-track portable oscilloscope and recorded with an oscilloscope camera using Polaroid film.

Field Procedures

Cross-Hole Measurements.--The sparker and hydrophone cables were marked at 10 foot (3.04 meter) intervals with color coded tape to facilitate positioning them in the boreholes. The sparker was placed in hole T-2. Excess sparker cable was placed in a metal garbage can to minimize unwanted radiation. The hydrophones were then placed inholes T-3 and BRP-27 at the same depth as the sparker. T-3 and BRP-27 are, respectively, approximately 25 and 66 feet (7.6 and 20.1 meters) from T-2.

The sparker was adjusted to pulse every 6 seconds. When the oscilloscope traces were adjusted for proper gain, sweep and filtering, a Polaroid picture of the trace was taken for later analysis. This completed the testing at each depth. The depth of the sparker and hydrophone was then changed and another observation made. The cross-hole observations were made at 5-foot (1.5 meter) intervals from a depth of 40 feet (12.2

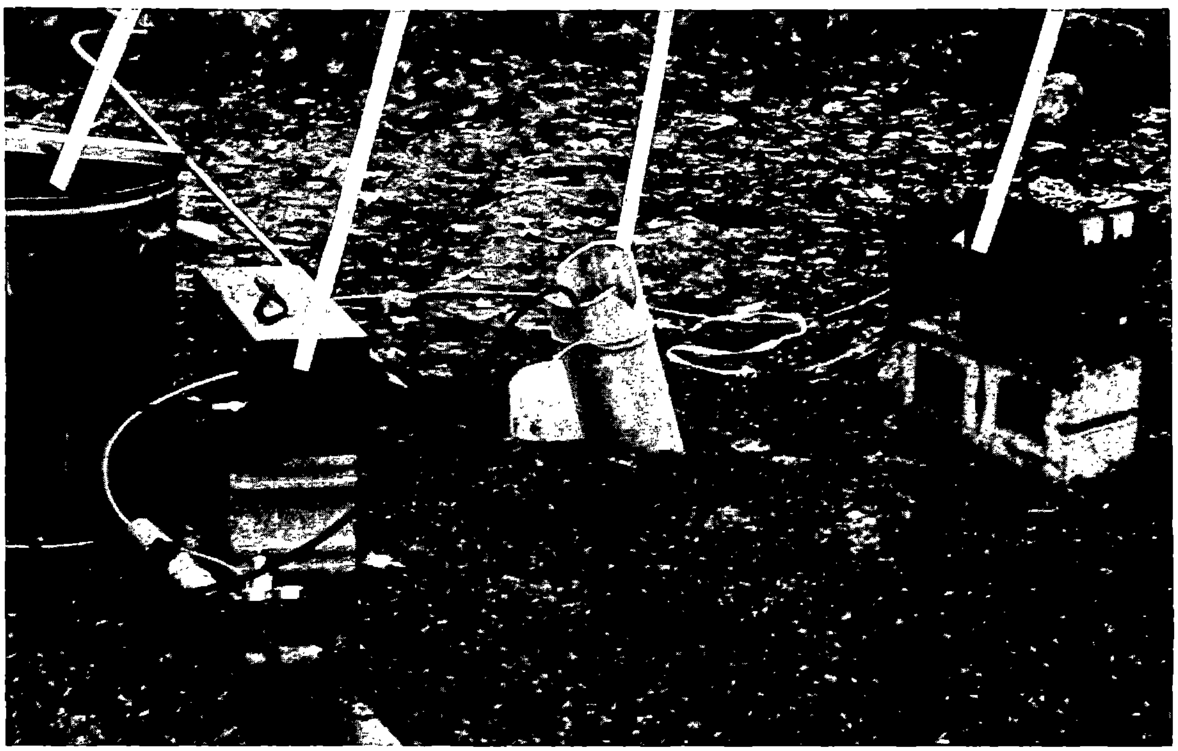


Figure D2. Field equipment for seismic survey.

meters) to the bottom of the borehole for all the observations made between holes T-2 and T-3. The hydrophone could not go deeper than 230 feet (70.1 meters) in hole T-3 because of debris in the bottom of the borehole.

Observations from hole T-2 to BRP-27 were conducted at 10-foot (3.04 meter) intervals from depths of 100 feet to 230 feet (30.5 to 70.1 meters).

Near-Vertical Measurements.—A second orientation of the hydrophone was made with both hydrophones in borehole T-3. One was positioned near the bottom and the other high within the borehole. Observations were made with the sparker at each 10-foot (3.04 meter) interval in adjacent borehole T-2.

A careful check of the oscilloscope sweep rate calibration was made before and after observations.

Summary.—The observation time for all field experiments required a total of approximately 3.2 hours after the instruments were set up and field tested for operational validity. The cross-hole observations required approximately 2.2 hours, and the near-vertical measurements 1.0 hour.

The equipment used for the seismic investigation is relatively inexpensive and convenient for obtaining in-situ compressional seismic wave velocities between vertical or inclined boreholes. Vehicle traffic noise can be removed by filtering. The equipment was suitable for use in boreholes of 3-inch (7.6 cm) diameter or larger. Subsequent to the tests at Forest Glen, the equipment was modified for use in 2-inch (5.1 cm) diameter or larger boreholes and for use with 12-volt D.C. power supplies.

A limitation of the method is that the portions of holes to be surveyed must be filled with liquid.

ANALYSIS OF DATA

Background Data

The following data were used in evaluation of the pressuremeter and seismic data:

a) Borehole survey data at 10-foot (3.04 meter) station intervals in T-2, T-3 and BRP-27 obtained with a Sperry-Sun multi-shot unit by ENSCO and data reduced by Sperry-Sun.

b) Soil and rock bulk densities measured directly or computed from TVA gamma-gamma logs.

c) Rock quality designation (RQD), rock descriptions and rock classifications provided by Mueser, Rutledge, Johnston and Desimone.

d) Standard split-spoon penetration test data (N-values) from Boring B-101 (which is a vertical borehole drilled about 100 feet (30.5 meters) north of T-2.

Pressuremeter Test Data, Borehole T-3

The pressuremeter test data obtained from the field tests from depths of 20 to 92 feet (6.1 to 28.0 meters) in hole T-3 are presented in Table D1, and graphically presented in Figure D3. Figure D3 also shows the compressional seismic wave velocity measured from T-2 and T-3, and the soil profile and N-values of Boring B-101. The pressuremeter modulus vs. N-Value is presented in Figure D4 along with a least squares fit determined for other residual soils in the Washington, D.C. area. A least squares trend line (Martin, 1977) and the average Forest Glen trend line show reasonable correlation. The current state-of-the-art for use of the Menard pressuremeter for evaluation of in situ conditions is described in Kastman (1978).

Table D1. Pressuremeter results.

Depth (ft)	Modulus E_p (tsf)	Limited Pressure P_l (tsf)
20-22	125.	12.5
30-32	133.	18.
40-42	260.	38.
50-52	325.	32.
60-62	No Data	
70-72	2,270.	100.
80-82	3,400.	100
90-92	3,080.	100

Note: 1 ft = 0.305 m
1 tsf = 0.014 bar

The soils from 22 to approximately 50 feet (6.7 to 15.2 meters) show a gradual increase in pressuremeter modulus. At a depth of 50 to 55 feet (15.2 to 16.8 meters), the N-values change from approximately 45 per foot (0.30 meter) in soil (SM), to 100 per inch (2.51 cm) to 100 per 4 inches (10.11 cm) in very dense decomposed rock and rock fragments. Rock coring started at a depth of approximately 70 feet (21.3 meters) in B-101. At a comparable depth, the pressuremeter moduli are in the range of 2270 to 3400 tsf (2218 to 3329 kg/cm^2). The 2270 tsf modulus corresponds to the highly weathered zone of the quartz mica schist. The moderately weathered materials at depths of 80 to 90 feet (24.4 to 27.4 meters) have moduli of 3000 to 3400 tsf (2932 to 3323 kg/cm^2).

The weathering profile between Borings T-2 and T-3 is somewhat deeper than that shown by Boring B-101. This is indicated by the coring of Borings T-2, T-3, and BRP-27 having started at depths of approximately 92 to 95 feet (28.0 to 28.6 meters) versus about 70 feet (21.3 meters) in B-101 and also by the log of the seismic wave velocity between T-2 and T-3.

The gradation of the weathering zone as shown by the compressional seismic velocity is fairly gradual, changing from a velocity of 6,500 fps (1981 meters per second) at a depth of 50 feet (15.2 meters) to 11,300 fps (3444 meters per second) at a depth of 95 feet (28 meters). Comparatively, the pressuremeter modulus is in the order of 3,000 to 3,400 tsf (2932 to 3323 kg/cm^2) from depths of 80 to 90 feet (24.4 to 27.4 meters) where the velocity changes from 9000 to 11,000 feet per second (2743 to 3352 meters per second). A distinct break (at the strata change) is shown at depths of approximately 50 feet (15.2 meters) where the velocity increases above 6500 fps (1981 meters per second).

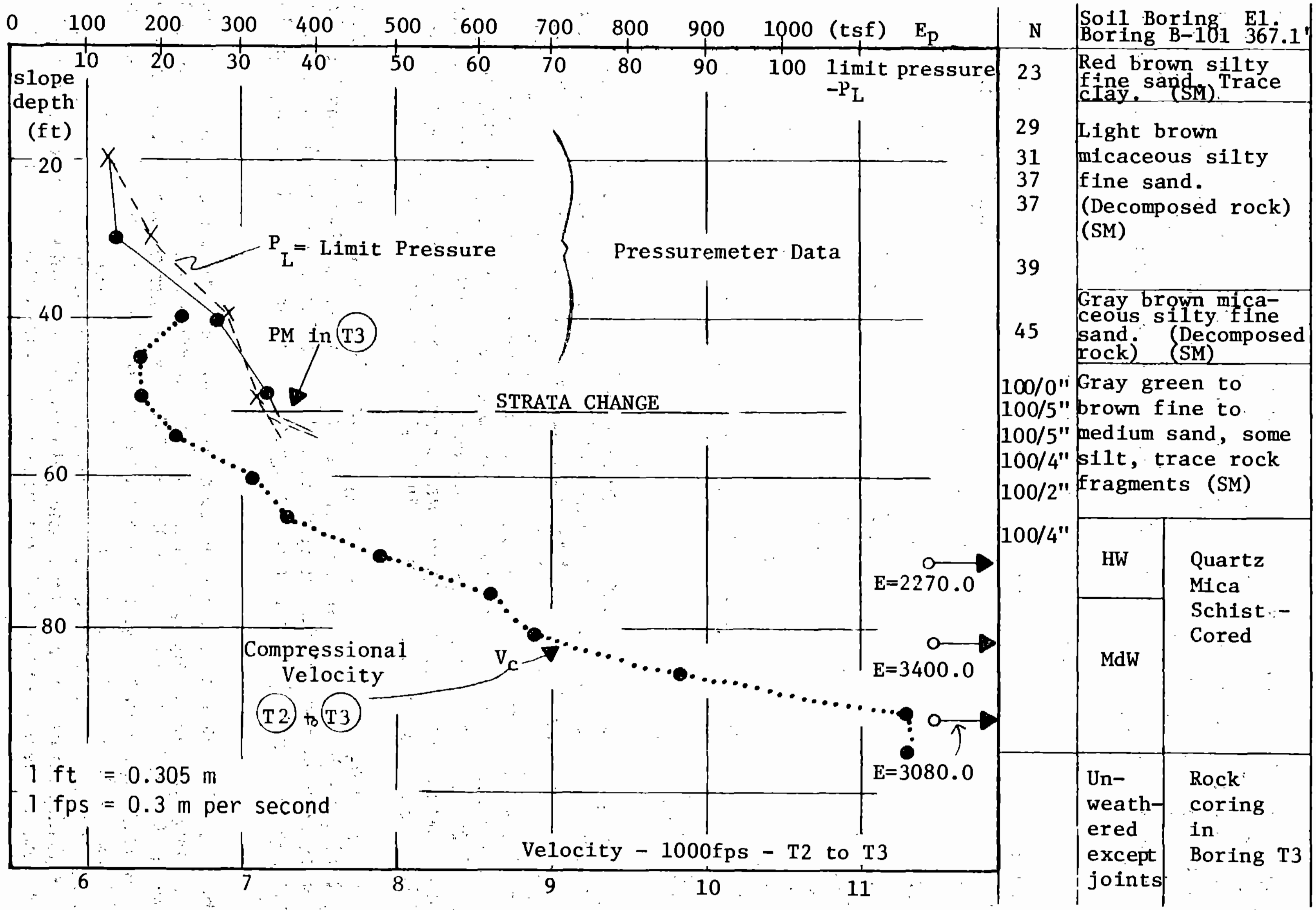


Figure D3. Pressuremeter data and seismic results 20 to 95 feet.

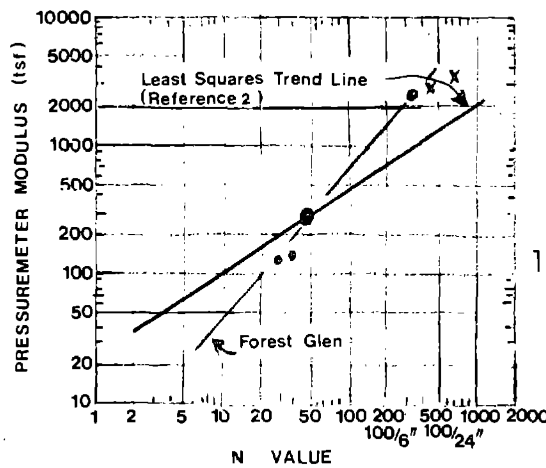
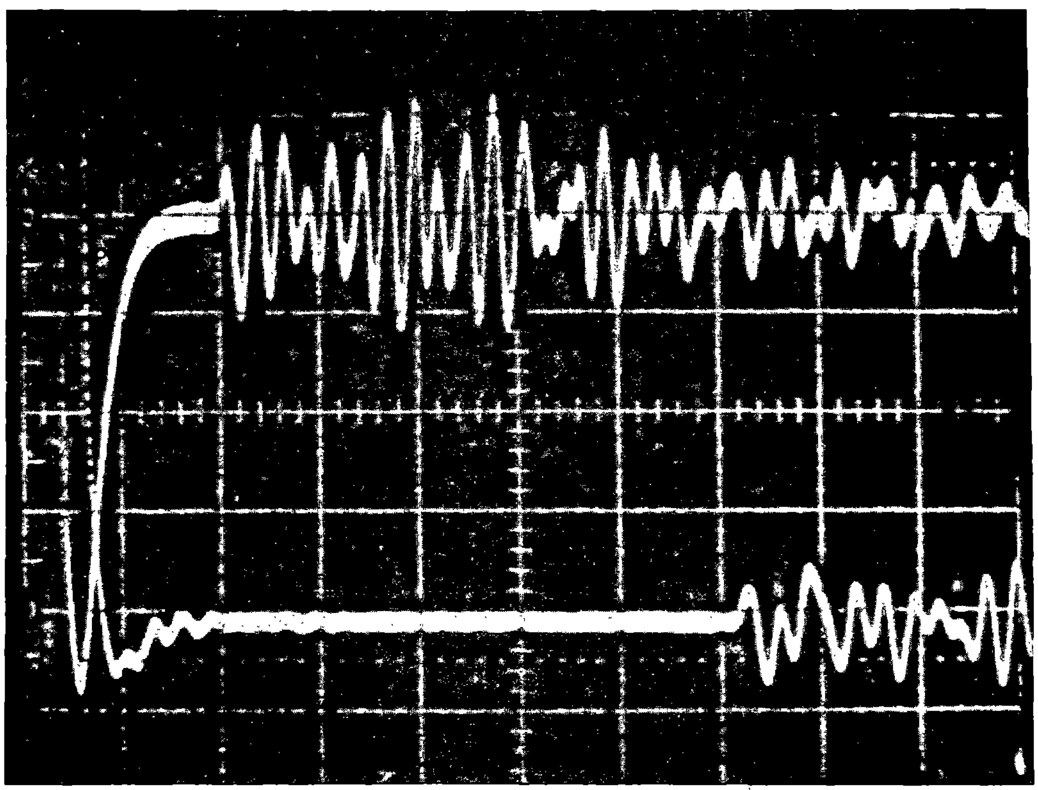


Figure D4. Pressuremeter modulus versus N value data.



Depth 170 feet (51 m)
Sparker in Hole T-2
Upper-trace hydrophone in Hole T-3
Lower-trace hydrophone in Hole BRP-27
Scale 0.5 millisecond per centimeter

Figure D5. Typical seismic record.

Compressional Seismic Velocity

Distances between the boreholes were calculated from the data provided by the Sperry-Sun borehole survey. Seismic travel times were scaled from the photographs of the oscilloscope. A typical oscillogram is shown in Figure D5 for the sparker in T-2, hydrophone is in T-2 (upper trace), and hydrophone in BRP-27 (lower trace).

The compressional seismic velocities are calculated using the distances between boreholes and seismic travel times. An example of velocity data recorded on-site is shown in Figure D6. Cross-hole velocities are shown by data points.

From T-2 to T-3, the cross-hole seismic velocity increased gradually from 6000 fps (1828 meters per second) at the water table to 14,000 fps (4267 meters per second) at a depth of 105 feet (32 meters). From 105 to 125 feet (32.0 to 38.1 meters), there is considerable variation in seismic velocity. This corresponds to rock core with very low RQD values in the "very poor" to "poor" category. From 130 feet (39.6 meters) to the bottom of the hole, the velocity increases from 16,300 fps to 22,500 fps (4968 to 6858 meters per second). The 130 foot depth is noted where unweathered rock was first logged by Mueser, Rutledge, Johnston and Desimone.

The other recorded data from T-2 to BRP-27 showed less variation in cross-hole seismic velocity, as would be expected. The greater separation of seismic source and receiver causes more averaging of small-scale variations in rock properties. A small offset in the data occurs at about 150 feet (45.7 meters), corresponding to a highly jointed and broken zone.

Correlation Between Velocity and RQD

The simplest correlation is directly between RQD, as a common index of rock core quality, and the direct measurement of seismic velocity. Low RQD should directly relate to low seismic velocity.

The measured data were analyzed as follows:

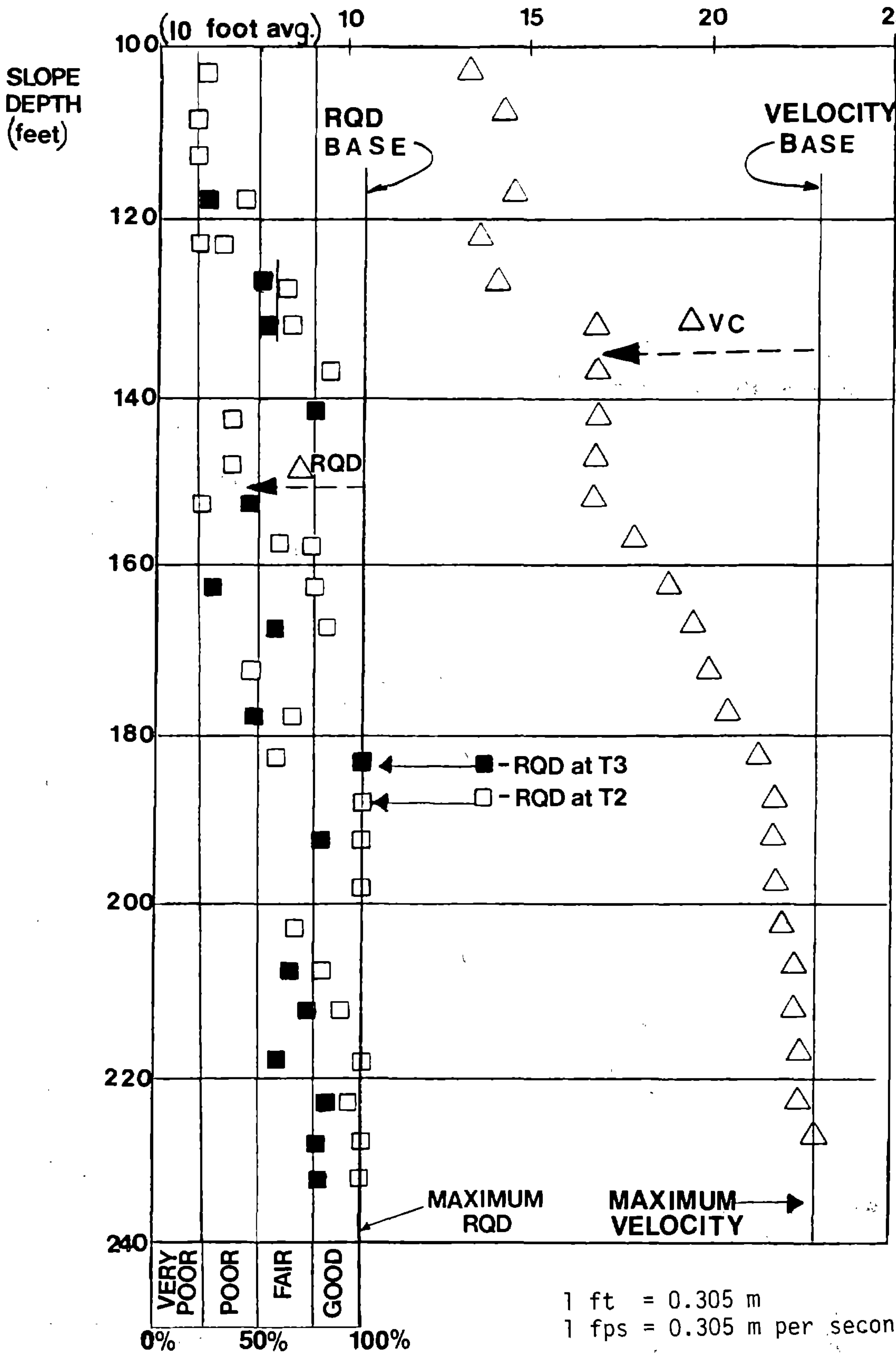
1) A base-line is drawn through the maximum seismic velocity and another base-line is drawn through the maximum RQD (Figure D6).

2) Then, the difference in velocity is plotted from the base-line velocity against a 10 foot (3.04 meter) average of the difference in RQD values from the base-line RQD.

Figures D7 and D8 are the resulting graphs for data recorded at T-2 and T-3, and T-2 and BRP-27, respectively. A strong correlation may be observed between the cross-hole seismic compressional velocity and RQD values. For the Forest Glen site:

$$\Delta \text{RQD} \approx \Delta V_c/112.$$

This specific relationship should be valid only for the rock types and conditions existing at Forest Glen. It should be possible to establish similar relations at other geological settings.



1 ft = 0.305 m
1 fps = 0.305 m per second

Figure D6. Compressional wave velocity for T2-T3 with rock core data.

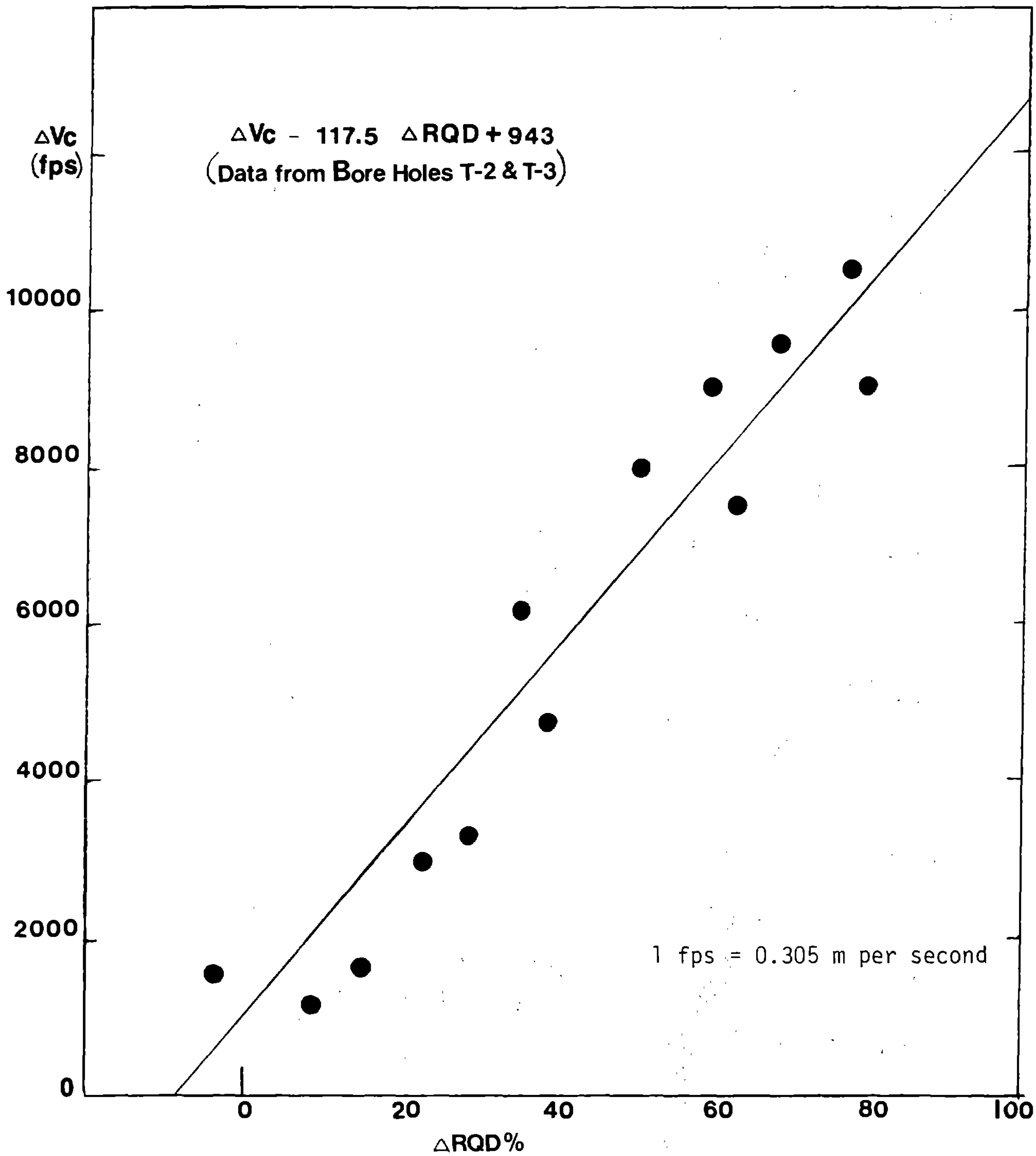


Figure D7. Change of velocity versus change of RQD (T2-T3).

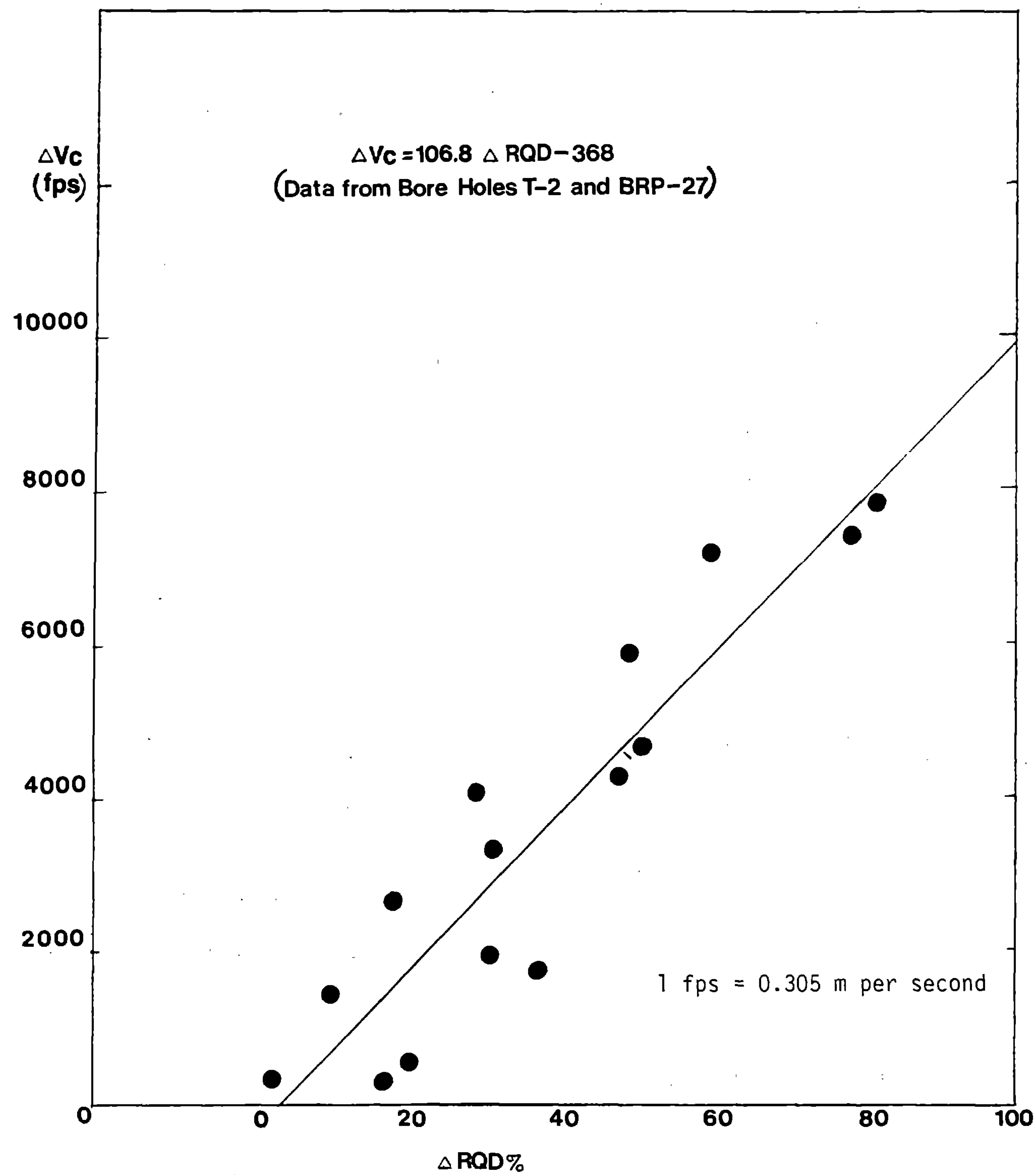


Figure D8. Change of velocity versus change of RQD (T2-BRP-27).

Calculation of Dynamic Shear Modulus

The dynamic deformation modulus, E_s, and the dynamic shear modulus, G, were computed from the measured seismic compressional wave velocities, V_c, and assumed Poisson's ratios, μ. From 20 through 85 feet (6.1 to 25.9 meters) $\mu = 0.33$ was used, and $\mu = 0.27$ was used from 90 to 230 feet (27.4 to 70.1 meters).

The shape of the computed moduli follow closely the graph of measured compressional velocity since the moduli are directly proportional to the square of the velocity (Figure D9). The relations between the moduli and seismic velocity are:

$$E_s = \frac{\gamma t}{g} \frac{(1 - 2\mu)\ (1 + \mu)}{(1 - \mu)} V_c^2$$

$$G = \frac{\gamma t}{g} \frac{(1 - 2\mu)}{(1 - \mu)} V_c^2$$

where g is the acceleration of gravity and γt is the total unit weight of rock or soil.

Relations of E_p and E_s

The ratio between pressuremeter modulus, E_p, and the deformation modulus, E_s, is given below for the data from 40 to 92 feet (12.2 to 28.0 meters). This utilizes the pressuremeter modulus from T-3 and the velocity data from T-2 and T-3.

Depth (ft)	Ratio of E_s/E_p
40	208.
50	163.
70	78.
80	35.
90	65.

1 ft = 0.305 m

A higher ratio is obtained in the soils than in the weathered bedrock. This should be anticipated, since soils with a high water content act incompressible to a seismic compressional wave. The relatively slow application of stress by the pressuremeter allows the water to flow from between the grains as it exerts its pressure on the soil.

CONCLUSIONS

The following conclusions are based on our analysis of the data:

1. The pressuremeter test data in the residual soils show a strata change at 50 to 55 feet (15.2 to 16.8 meters). The relationship of N-value to pressuremeter modulus is consistent with other data reported from the Washington, D.C. area.

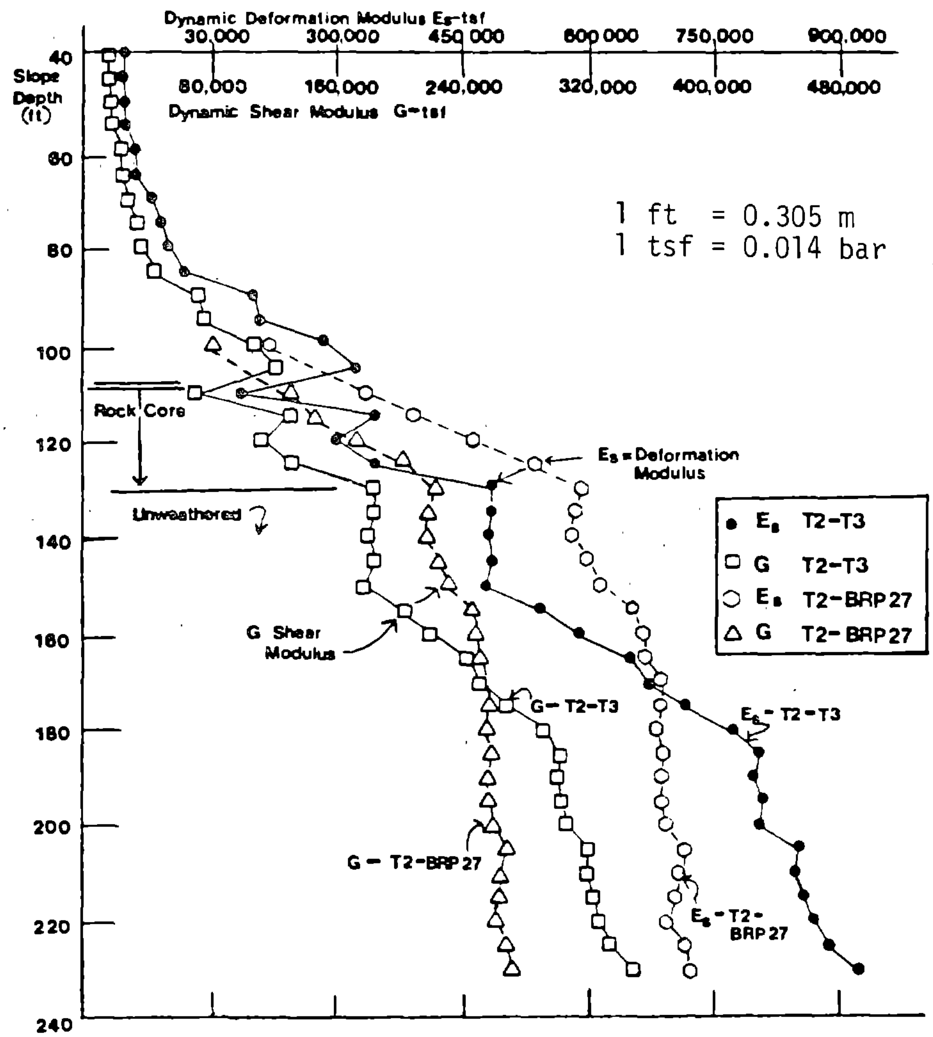


Figure D9. Computed dynamic moduli versus slope depth.

2. The equipment to measure seismic compressional waves in vertical or inclined boreholes proved to be accurate, and gave very rapid measurement of cross-hole soil and rock seismic velocities.

3. Seismic velocities from T-2 and T-3 do not directly show the strata change in the overburden soils at a depth of 50 to 55 feet (15.2 to 16.8 meters). The pressuremeter testing and N-values show more directly the changes in soil modulus and limit pressure.

4. The seismic velocities measured from T-2 to T-3, and from T-2 to BRP-27 demonstrate that rock with low RQD values generally has lower seismic velocities, and good bedrock having high RQD has higher seismic velocities.

5. The seismic equipment is capable of operation in small diameter (2-inch, 5.0 cm, or larger) inexpensive boreholes, provided the holes contain liquid.

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1. Kastman, K.H., "Sensing System for Measuring Mechanical Properties in Ground Masses - In Situ Testing with the Menard Pressuremeter," FHWA Research and Development Report, October 1978.

2. Martin, R.E., "Estimating Foundation Settlements in Residual Soils," ASCE Journal of Geotechnical Engineering Division, Vol. 103, No. GT-3, March 1977.

APPENDIX E

EVALUATION OF GEOLOGIC STRUCTURE AND ENGINEERING PROPERTIES OF GROUND USING A BOREHOLE ELECTROMAGNETIC REFLECTION TECHNIQUE

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BOREHOLE ELECTROMAGNETIC PROBE INSTRUMENTATION

Field equipment used by the Southwest Research Institute (SWRI) in the Forest Glen tests consisted of the Bureau of Mines 4-inch (10.2-cm) diameter electromagnetic pulse reflection probe, a separate 2-inch (5.1-cm) diameter broadband auxiliary receiver probe, an electrically powered wireline logging winch, an auxiliary receiver coaxial cable, the borehole electromagnetic probe surface control unit and a complement of amplifiers and test instruments including a seven channel instrumentation magnetic tape recorder.

Figure E1 illustrates the electromagnetic borehole probe developed for the Bureau of Mines. Physically, this probe is a 4-inch (10.2-cm) diameter sonde approximately 12 feet (3.7 m) long capable of operating either in dry boreholes or in wet holes to a maximum immersion depth of about 500 feet (152 m). This probe operates from a standard 3/16-inch (4.76-mm) diameter 4-conductor logging cable. The upper half of the probe illustrated in Figure E1 contains the pulse transmitter and receiver electronics; the lower half is the antenna.

A simplified block diagram of the borehole electromagnetic probe system is shown in Figure E2. This probe is essentially a baseband short-pulse radar system operating in the VHF frequency range. The transmitter generates a unipolar pulse having a time duration of 10 ns and a peak amplitude of 80 volts at the antenna terminals. The useful frequency spectrum of this pulse as radiated by the antenna is approximately 30-300 MHz. The transmitter repetition rate is 40 kHz.

A balanced hybrid coupler is used at the probe antenna terminals to permit shared use of the antenna for both transmitter and receiver operation. The receiver consists of a 30-300 MHz broadband preamplifier with up to 30 dB gain controllable in 10-dB steps from the surface. The basic threshold sensitivity of the receiver is -82 dBm.

The total electromagnetic pulse-echo transmission loss capability of the system as measured at the antenna terminals is approximately 97 dB.

Time domain sampling is applied to the repetitive received waveform to reduce its repetition rate to either 40 pps for oscilloscope display or 0.1 pps for strip chart recording. The sampled-down 30-300 MHz real-time bandwidth is reduced to 1.2-12 kHz at 40 pps and 3-30 Hz at 0.1 pps.

Time varying gain is applied to the sampled waveform traces to partially compensate for the attenuation losses caused by the rock propagation medium. A

(a) Electromagnetic Pulse Probe—
Initial Field Tests—
San Antonio, Texas

(b) Electromagnetic Pulse Probe—
Field Demonstration Tests in a
Thick Coal Seam
Kemmerer, Wyoming

Figure E1. Photographs of the Bureau of Mines borehole electromagnetic pulse reflection probe.

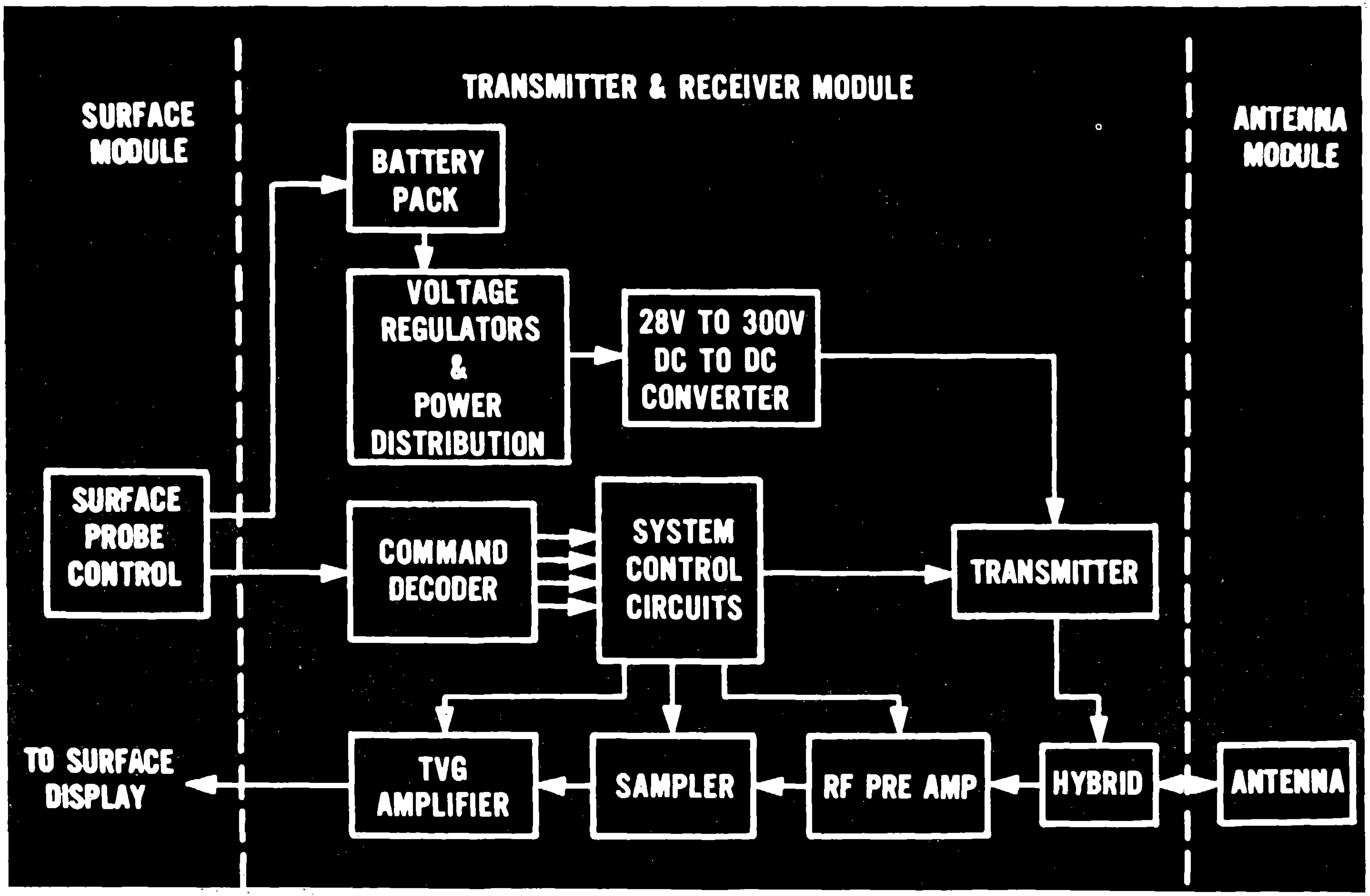


Figure E2. Simplified block diagram of the borehole electromagnetic probe system.

maximum time varying gain rate of 60 dB per microsecond, controllable from the surface, was used in most of the reflection tests giving the capability of compensating for about half of the attenuation caused by the rock materials at the Forest Glen Field Test Site.

Figure E3 illustrates the directivity pattern of the borehole electromagnetic probe operating in a thick coal seam. The antenna is a thick cylindrical insulated traveling-wave radiator with a resistive end termination. The frequency response of this antenna is essentially uniform over the 30-300 MHz range. As shown in the figure, the directivity pattern is omnidirectional with an approximate $\pm$ 60-degree vertical field of view in all directions around the borehole.

Photographs of the field test set-up at the Forest Glen Field Test Site are shown in Figure E4. The electromagnetic reflection probe was handled in Borehole T1 by means of a 24-foot (7.3-m) wooden boom and a portable electrical logging cable drawworks. The auxiliary receiver probe shown in Figure E4(b) consists of a battery operated broadband (1-1,000 MHz) preamplifier, and a 3-inch (7.6-cm) long filamentary wire monopole antenna encapsulated in a 2-inch (5.1-cm) diameter epoxy envelope. The auxiliary receiver is 24 inches (61 cm) in length including space for the self-contained batteries. A 300-foot (92-m) length of RG-9 coaxial cable was handled manually to locate the receiver at the desired depths in the test boreholes. The equipment contained in the mobile laboratory van includes the probe control unit, a Tektronix 7623A sampling oscilloscope, a special variable-density strip chart recorder, a Brush Model 220 strip chart recorder, and a Bell and Howell Model CPR 4010 seven-channel analog magnetic tape recorder. The 24-foot (7.3-m) wooden gin pole boom was assembled on site for the Forest Glen tests.

When operating in the reflection mode, the internal probe receiver, which contains a time-domain sampler down-hole, transmits low-frequency replicas of the received echoes up the logging cable for surface recording. The probe provides, upon surface command, two different signal display rates, either 40 sweeps per second or 0.1 sweep per second. Both rates were used in the tests; the fast rate for magnetic tape recording and the slow rate for on-site strip chart displays of the reflection traces.

When operating in the hole-to-hole transmission mode, the auxiliary receiver output is connected to the sampling oscilloscope which is synchronized to the probe transmitter. A low-frequency replica of the received RF pulse input to the oscilloscope is available from the sampler for recording on magnetic tape or strip chart recorder. A separate RF amplifier is available to amplify extremely low level signals from the downhole receiver.

The electric logging winch used in the tests is a part of the Bureau of Mines Underground Logging System developed for operating logging tools in horizontal drill holes in underground mines. The up-hole end of the cable is coupled from the reel by slip-rings; the downhole end is fitted with a Gearhart-Owen four-conductor cablehead. A variable-speed reversible electric motor drives the reel. A mechanical odometer gives a visual indication of feet and tenths of feet of cable displacement. For the Forest Glen tests a photo-chopper shaft encoder was added to the mechanical output of the odometer to provide an electrical signal of 60 pulses per foot (196.8 pulses/m) of cable displacement. This odometer count was recorded together with the received signals.

EXPERIMENTAL TEST PROCEDURES

Borehole T1 was the only test hole large enough to accept the 4-inch (10.2-cm) diameter electromagnetic probe. Therefore, all of the Forest Glen field tests were

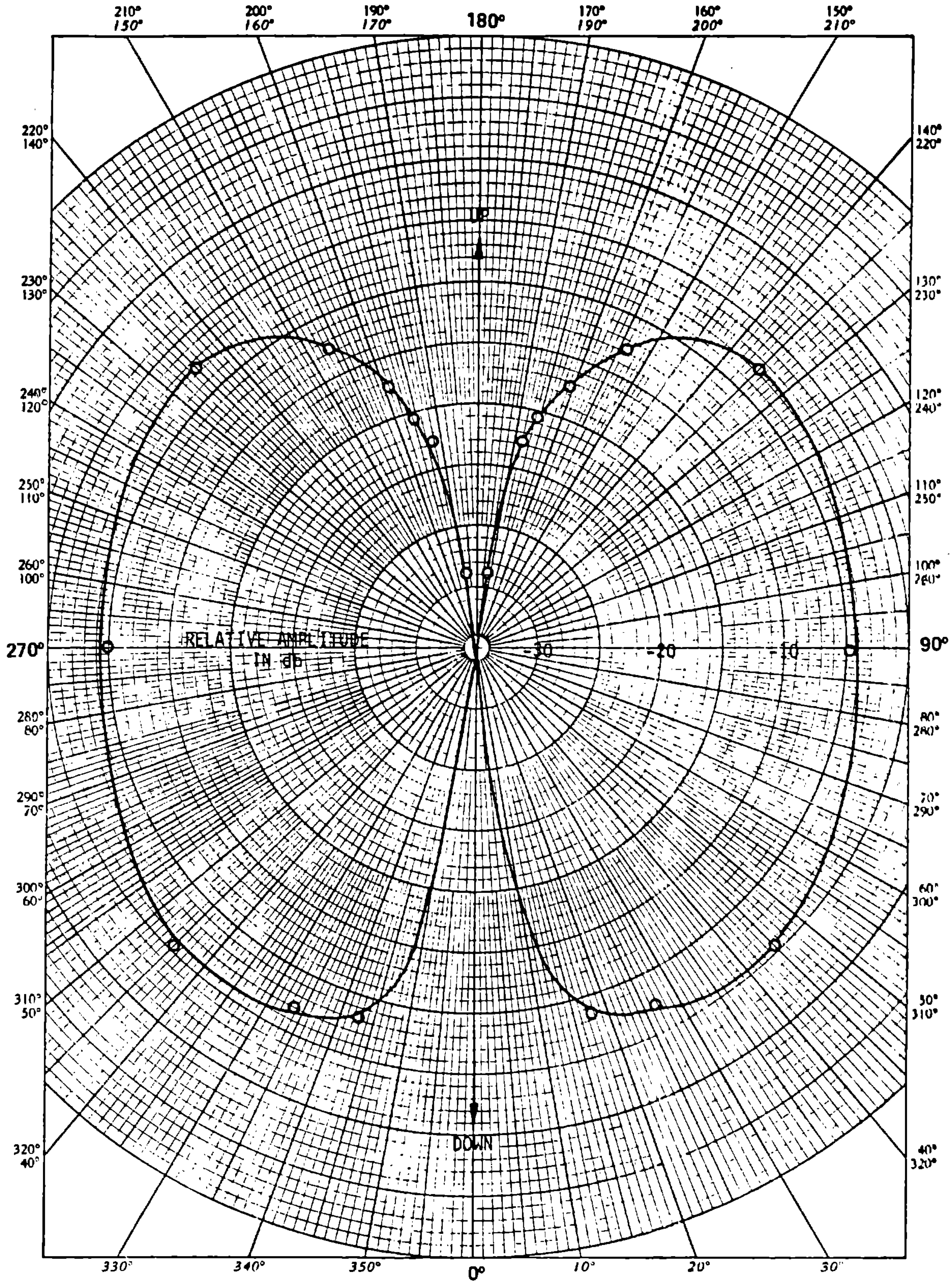


Figure E3. Antenna directivity pattern of the electromagnetic pulse reflection probe measured in a thick coal seam.

(a) Looking North Parallel to Georgia Avenue—Probe in Borehole T1

(b) Looking South Parallel to Georgia Avenue—Auxiliary Receiver Probe at Borehole T3

(c) Mobile Laboratory and Wireline Logging Winch

Figure E4. Photographs of electromagnetic reflection probe tests in progress at the Forest Glen field test site.

performed with the transmitter-receiver probe in Borehole T1 only. Hole-to-hole tests were performed with the probe in Borehole T1 and the 2-inch (5.1-cm) diameter auxiliary receiver located in each of the other Boreholes T2, T3, and BRP-27. The shallow vertical holes, BBN-1 and BBN-2 were not used. A test plan was established at the beginning of the program which served as the guide for the actual field tests. The field experiments varied somewhat from the original plan and several additional recordings were made to assure complete data.

Electromagnetic Pulse Reflection Tests

Five electromagnetic pulse reflection scans were performed in Borehole T1. In each case the borehole was scanned from the bottom upward to the lower end of the plastic casing pipe. Although caliper logs of Borehole T1 did not show a reduced hole diameter, the 4-inch (10.2-cm) diameter probe would not go below a slant depth of about 190 feet (58 m) as measured from the surface to the center of the antenna radiating element.

In the first probe scan, the downhole receiver was operated at full gain. In the second scan, the receiver gain was reduced 20 dB to minimize receiver saturation from transmitter feedover and borehole effects. In the third scan, the gain was reduced further to facilitate the detection of close-in targets. The data from these scans was sampled down to 40 sweep presentations per second and were recorded on magnetic tape together with pulse synchronizing signals from the transmitter and odometer pulses indicating the position of the probe.

Two additional scans of Borehole T1 were made at high and low receiver gains using the slow sampling and display rate for purposes of making on-site strip chart records of the reflection output. Table E1 summarizes the electromagnetic pulse reflection data recorded.

Hole-to-Hole Transmission Tests

Nine different hole-to-hole test scans were performed with the 4-inch (10.2-cm) diameter electromagnetic probe in Borehole T1 and the auxiliary receiver probe in each of the other three boreholes. The primary hole-to-hole operating mode utilized the transmitter and receiver located at common slant depths in their respective boreholes so that the transmission measurements were horizontally oriented. Several scans were also made with the auxiliary receiver held at a fixed depth while the probe transmitter was scanned from the bottom of Borehole T1 to the lower end of the plastic casing in T1. Table E2 summarizes the measurement conditions and data recorded in the hole-to-hole measurements.

DATA ANALYSIS AND RESULTS

Raw Data

Observations of the raw data were made during the field measurements for purposes of evaluating the general performance of the borehole electromagnetic probe and to determine the quality of the test data being recorded. Samples of the raw data records used for this purpose are described below.

Table E1. Summary of electromagnetic pulse reflection data records.

Run #	Probe Borehole	Surface Recorder	Remarks
1	T1	Mag. Tape, 4 channels 15 IPS, Chan. 1 -- raw data. Chan. 2, 3, 4, -- 400-4000 Hz.	40 Hz sample output, full preamp gain (+ 40 dB), full postamp gain (+ 40 dB), continuous log, 198' to 35' below collar.
2	T1	Mag. Tape, 4 channels 15 IPS, Chan. 1 -- raw data. Chan. 2, 3, 4, -- 400-4000 Hz.	Same as "1" above except: reduce postamp gain 20 dB.
3	T1	Mag. Tape, 4 channels 15 IPS, Chan. 1 -- raw data. Chan. 2, 3, 4, -- 400-4000 Hz.	Same as "1" above except: reduce preamp gain to 0 dB and postamp gain to 0 dB.
4	T1	Same as "1" except: Chan. 1-- raw data Chan. 2, 3, 4, -- 1 to 30 Hz.	Sample output = 0.1 Hz Logged slowly ∿ 5'/min Preamp gain, + 40 dB (full), Postamp gain, + 20 dB (Pos. 3).
5	T1	Same as "1" except: reduced filtered channels to 1 to 20 Hz.	Same as "4" above except: set preamp gain to 0 dB and postamp gain to 0 dB.

Note: 1 ft = 0.305 m

Table E2. Summary of electromagnetic pulse transmission data records.

Run #	Transmitter Borehole	Receiver Borehole	Surface Recorder	Remarks
6	T1	T2	Strip Chart	Common Depth transmitter and receiver. Logged up from 190' in 5' intervals. External sync on sampling scope.
7	T1	T2	Strip Chart	Receiver fixed at 160'. Transmittter scanned from 190' up. Internal sync.
8	T1	T2	Strip Chart	Same as #7 above, except 60 Hz pick-up problem solved. External sync on sampling scope.
9	T1	T3 added surface RF amplifier	Strip Chart	Run 9A--Transmitter at 190'. Receiver at 230', 220', 210', 200', and 190'. Run 9B--Receiver at 150'. Transmitter at 190' to 130'. Run 9C--Transmitter and receiver at common depth. 5' intervals 190' to 65'.
10	T1	BRP-27 w/surface amplifier	Magnetic Tape	Transmitter and receiver at common depth. 5' increments 190' to 40'.
11	T1	T2 no surface amplifier	Magnetic Tape	Transmitter and receiver at common depth. 5' increments 190' to 40'.
12	T1	T2	Magnetic Tape	Repeat Run 11, stopping winch motor at each increment.
13	T1	T2	Magnetic Tape	Receiver at 160'. Transmitter scanned 190' to 130'.
14	T1	T3	Magnetic Tape	Transmitter and receiver at common depth. 190' to 40' in 5' increments.

Note: 1 ft = 0.305 m

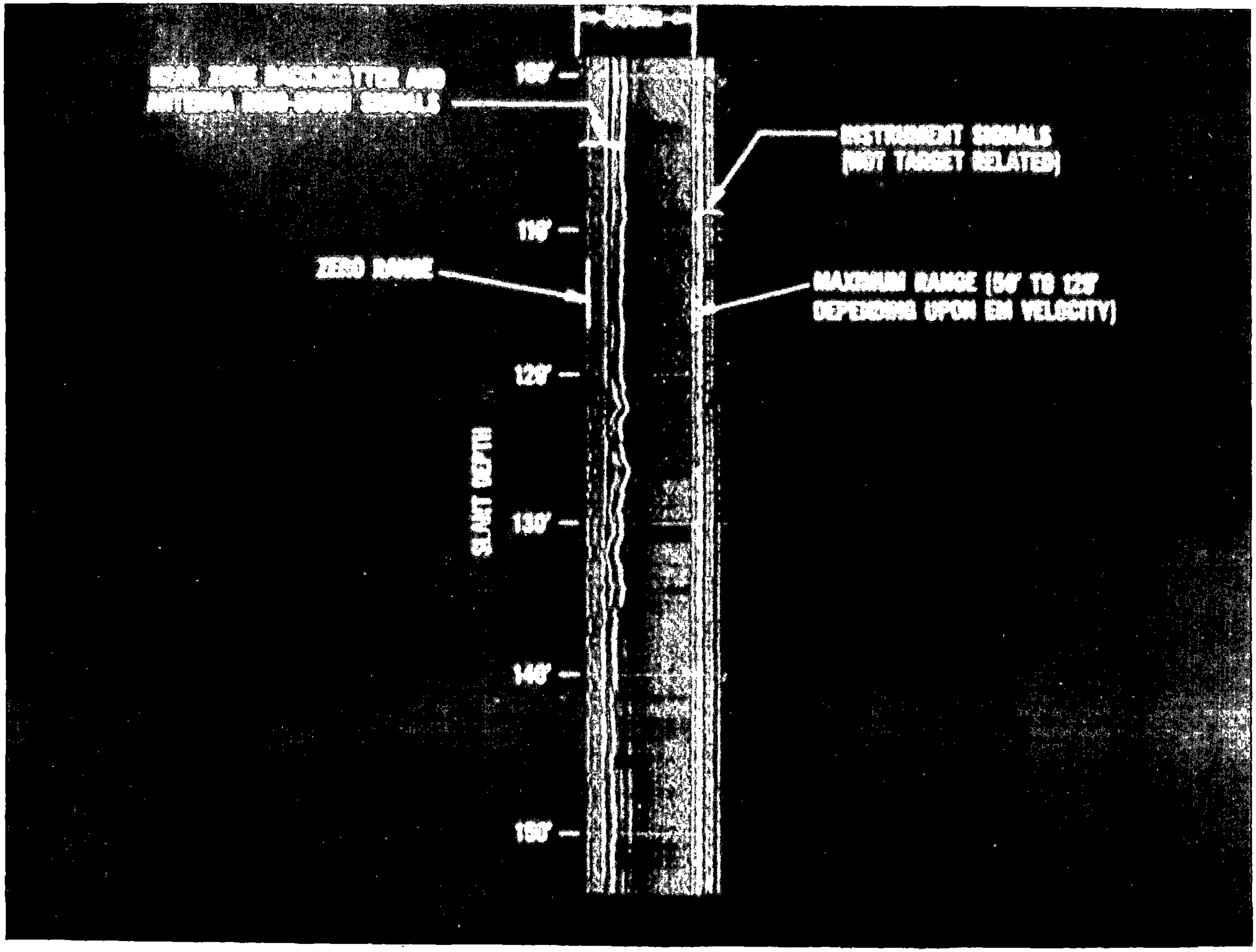
Pulse Reflection Tests.--The electromagnetic pulse reflection signals were displayed on the variable-density recorder to provide a continuous omnidirectional echo trace image versus borehole slant depth. Figure E5 illustrates the reflection signals observed along a 50-foot (15 m) scan of Borehole T1 showing the strongest reflections occurring within the first 10-15 feet (3-5 m) around the borehole. Much of the early time portion of this display is pulse-excited antenna ring-down but it is also noticeably influenced by the variations in rock structure and related rock electromagnetic parameters along the borehole. For example, particularly strong short-range disturbances are noticeable in Figure E5 in the slant depth range of 120-135 feet (37-41 m) in Borehole T1, representative of variations in antenna radiation impedance caused by changes in the rock electromagnetic parameters immediately along the borehole wall. In this particular case, the disturbed signals were caused by a highly jointed and fractured zone of rock penetrated by Borehole T1. The limited dynamic range of this form of variable density display is insufficient to show any significant reflections at the more distant echo ranges.

Figure E6 shows a hidden-line computer display of raw data reflection probe output waveforms recorded at 9-foot (2.7 m) intervals along Borehole T1. This display shows the very strong antenna ringdown effects in the early part of the trace and, because of the greater dynamic range in this data display, weaker reflections are also observed at later times in the traces corresponding to greater distances away from the test borehole. The information contained in these and other similar raw data traces can be processed, as described later, to reveal more of the apparent rock structure and detail.

Hole-to-Hole Transmission Tests.--Hole-to-hole electromagnetic pulse transmission signals were observed on strip chart recordings during the field measurements. Figure E7 shows samples of received pulses observed at four different depths along horizontal paths between Boreholes T1 and T3 separated by a distance of approximately 37 feet (11 m). These waveforms show the effects of attenuation and the distortions in pulse shape caused by the frequency-dependent propagation effects of the intervening rock materials. In particular, the significant increase in transmission loss at the 100-foot (30.5 m) depth corresponding to weathered rock conditions is readily noticeable in comparison with the more competent rock at the deeper depths.

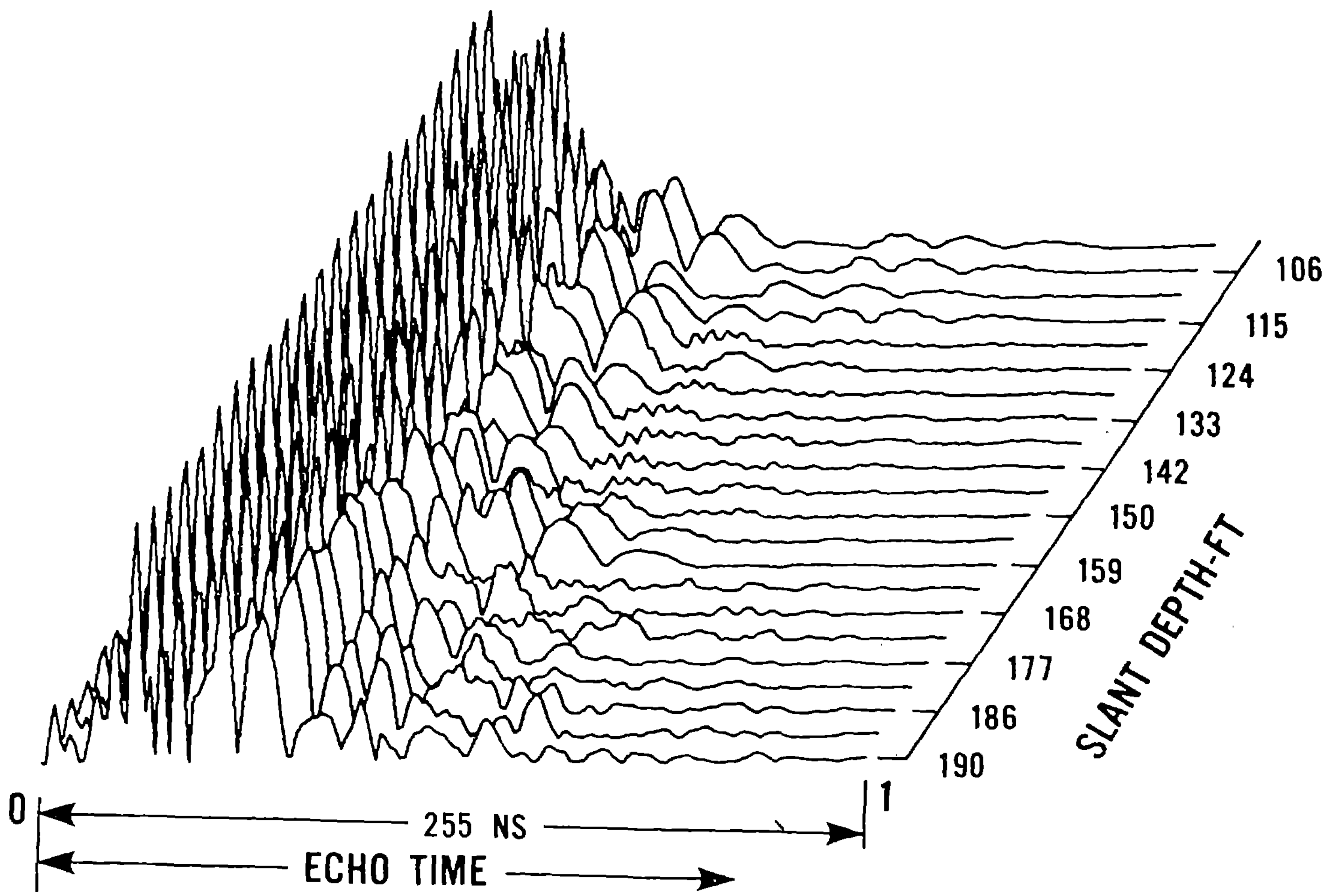
Analysis of hole-to-hole transmission records such as shown in Figure E7 permit the computation of the pulse propagation time over known distances and, hence, determination of the electromagnetic pulse propagation velocity in the intervening rock materials. Also, an analysis of the pulse amplitudes observed in two different boreholes at receiver depths corresponding to known raypaths can yield the electromagnetic attenuation of the rock materials. These parameters are directly relatable to the average permittivity and conductivity of the drilled rock and, hence, are indirect measures of the bulk physical properties of the geologic materials and rock structure.

Precise interrelations between rock electromagnetic parameters and physical rock properties are not yet established in detail. However, certain inferences can be made regarding weak rock condition such as fracture zones and highly porous rock. That is, in these specific cases fractured or otherwise porous rock materials will generally have an anomalously high moisture content in comparison with more competent rock and, hence, will exhibit a large relative dielectric constant (causing a decrease in propagation velocity) as well as a high conductivity (causing an increase in attenuation). As will be evident in later analyses comparing the electromagnetic parameters and some of the core analysis and conventional wireline resistivity logs, these porosity-related effects are verified reasonably well.



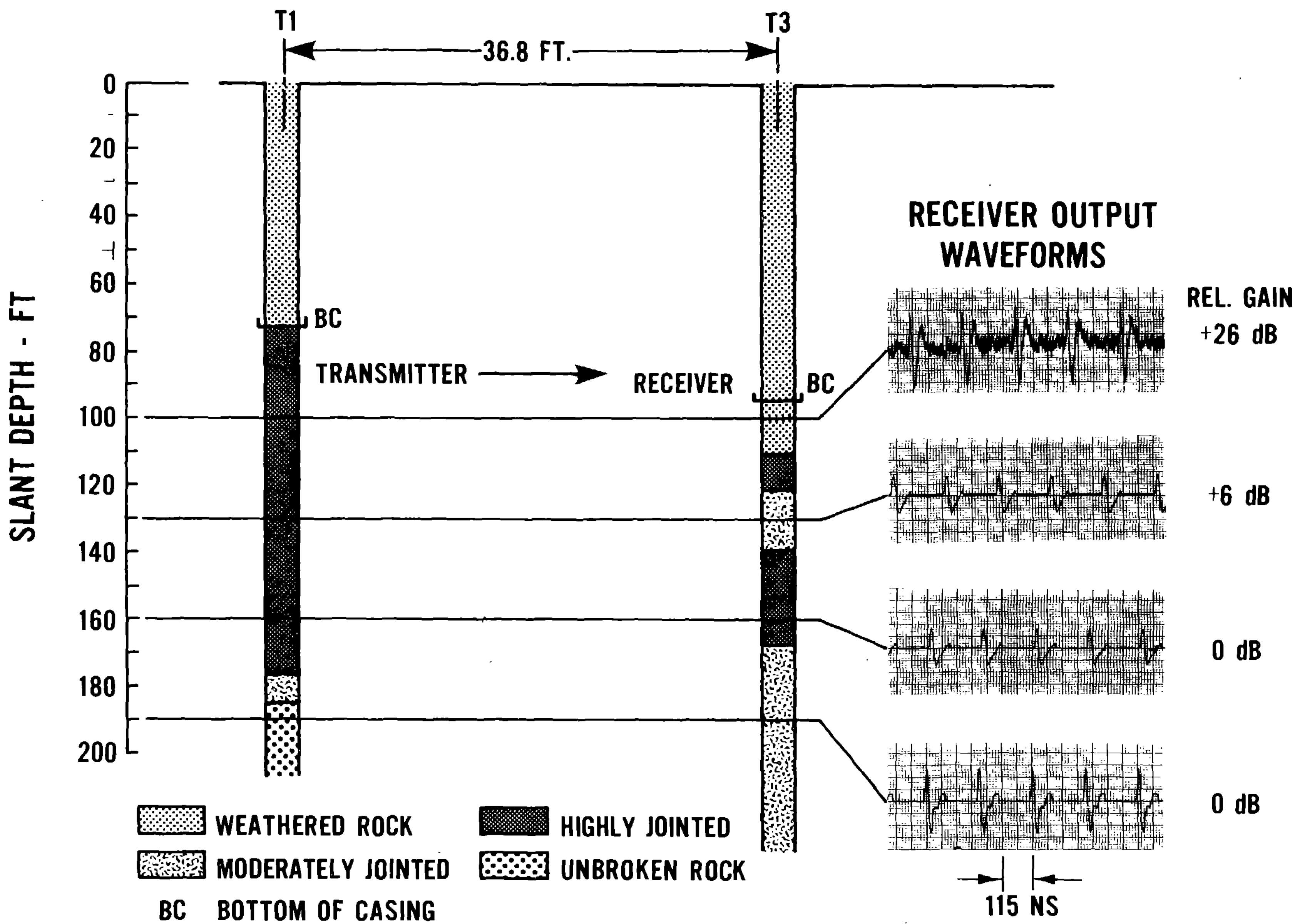
Note:
1 ft = 0.305 m

Figure E5. Sample variable density recording of electromagnetic reflections observed in Borehole T1.



NOTE: 1 FT = 0.305 m

Figure E6. Electromagnetic reflection probe output waveforms--Borehole T1.



Note: 1 ft = 0.305 m

Figure E7. Typical receiver output waveforms observed in hole-to-hole electromagnetic transmission tests--Borehole T1 to Borehole T3.

Data Reduction and Analysis

The magnetic tape records obtained in the Forest Glen field tests were selectively processed in the laboratory to remove the signal clutter caused by antenna ring-down and to take maximum advantage of the dynamic range available in the recorded data. The amount of signal processing applied to the data was limited by the technical scope of the project and, to a degree, by field testing constraints which prohibited operating the reflection probe in more than one borehole. The analyses to follow are representative of the advantages to be gained by a simple form of reflection signal enhancement obtained by ensemble trace averaging and clutter rejection. Also, the hole-to-hole transmission data are analyzed to yield the rock electromagnetic parameters consisting of the pulse propagation velocity and pulse attenuation as functions of slant depth along the boreholes.

Pulse Reflection Tests.--The first step in processing the electromagnetic pulse reflection data was the selection of certain recorded scans from raw data chart displays on the basis of proper signal amplitudes and minimum noise conditions which govern the quality of the data. The selected reflection scans were then digitized from the analog tape playback signals and prepared for computer processing.

In all of the reflection signals the dominant feature in the data was the very large ring-down signal at the beginning of each trace. The consistency of these signal ringing characteristics in each successive trace along the borehole scan indicates the disturbance to be largely unrelated to reflections occurring at larger distances from the borehole. Thus, the weaker reflections from more distant points around the borehole can be enhanced substantially if the strong undesired disturbances occurring early in the traces can be removed.

The ring-down clutter was effectively removed by deriving an ensemble average of the traces obtained along the borehole scan and then subtracting this average from each individual trace. Thus, by removing the average waveform content of the data from each trace only differences more directly related to reflections from rock structure conditions were retained for display and further analysis.

Figure E8 shows the results of this clutter rejection process as applied to the reflection data contained in Run #3 listed in Table E1. The ensemble average used in this case encompassed all of the data contained in the borehole scan. The improvement gained by the process is obvious by comparing the result in Figure E8 with the unprocessed display of the same waveform traces presented earlier in Figure E6. In this first result the decluttering process improved the display but, because of vertical inhomogeneities in the rock medium along the borehole, the full ensemble average correction of the data is not optimum.

An improved clutter rejection result was obtained by subtracting a 15-trace running average trace from each individual trace. Figure E9 illustrates a complete array of reflection traces taken at one-foot (30.5-cm) intervals along borehole T1 processed to remove the 15-trace running average trace. This process permitted the display amplitude to be increased for purposes of revealing more characteristics of the later reflection arrivals. As may be noted from this figure, the early disturbances in the traces are substantially reduced; whereas at the late time extremes in many of the traces several weak but systematic echo patterns can be observed. Further, the echo returns in the mid- and late times of the traces appear to be sharper in the deep section of the borehole scan corresponding to the higher resolution capabilities of electromagnetic signals in the lower attenuation rock materials occurring at depth.

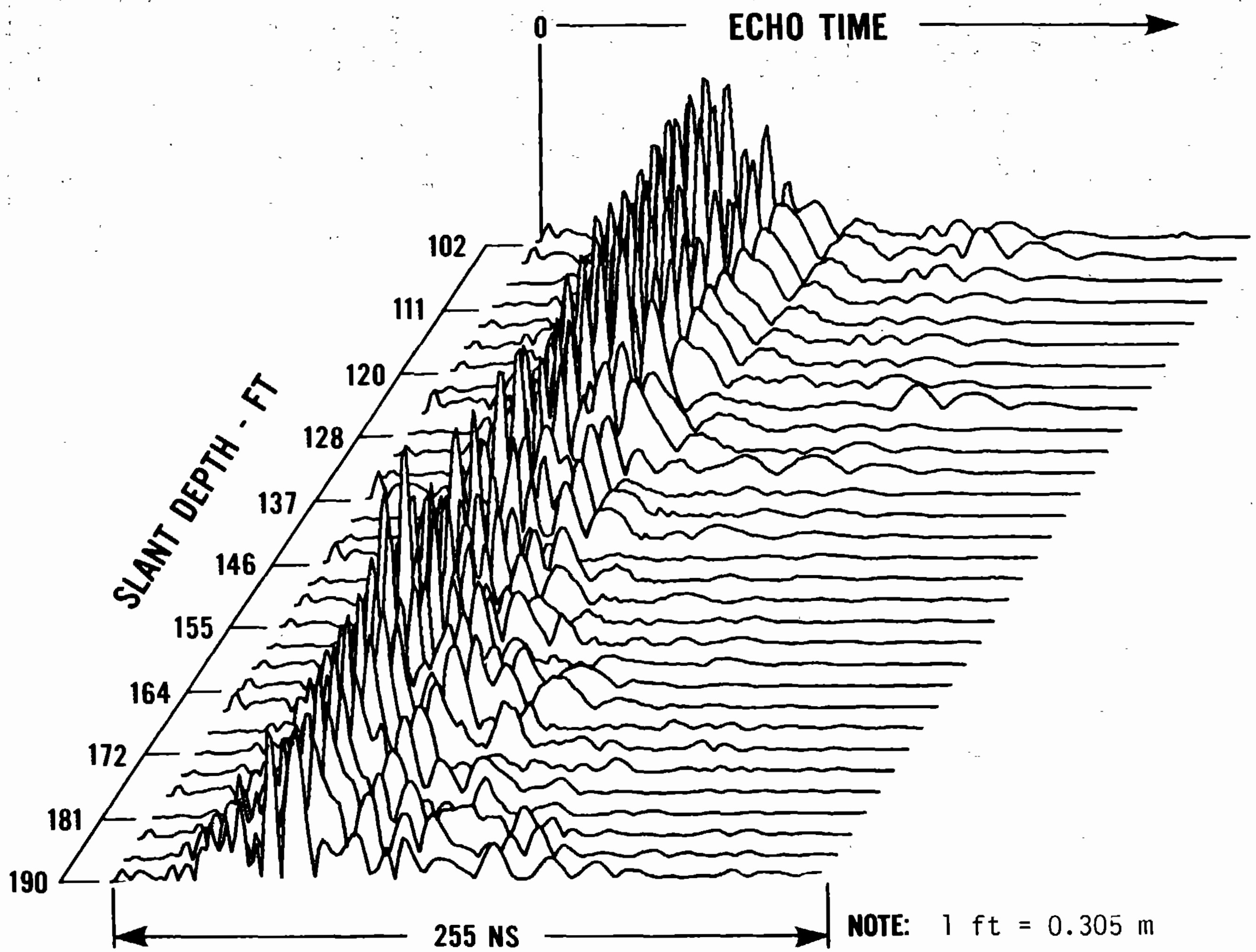


Figure E8. Electromagnetic pulse reflections observed in Borehole T1 processed to remove complete ensemble trace average.

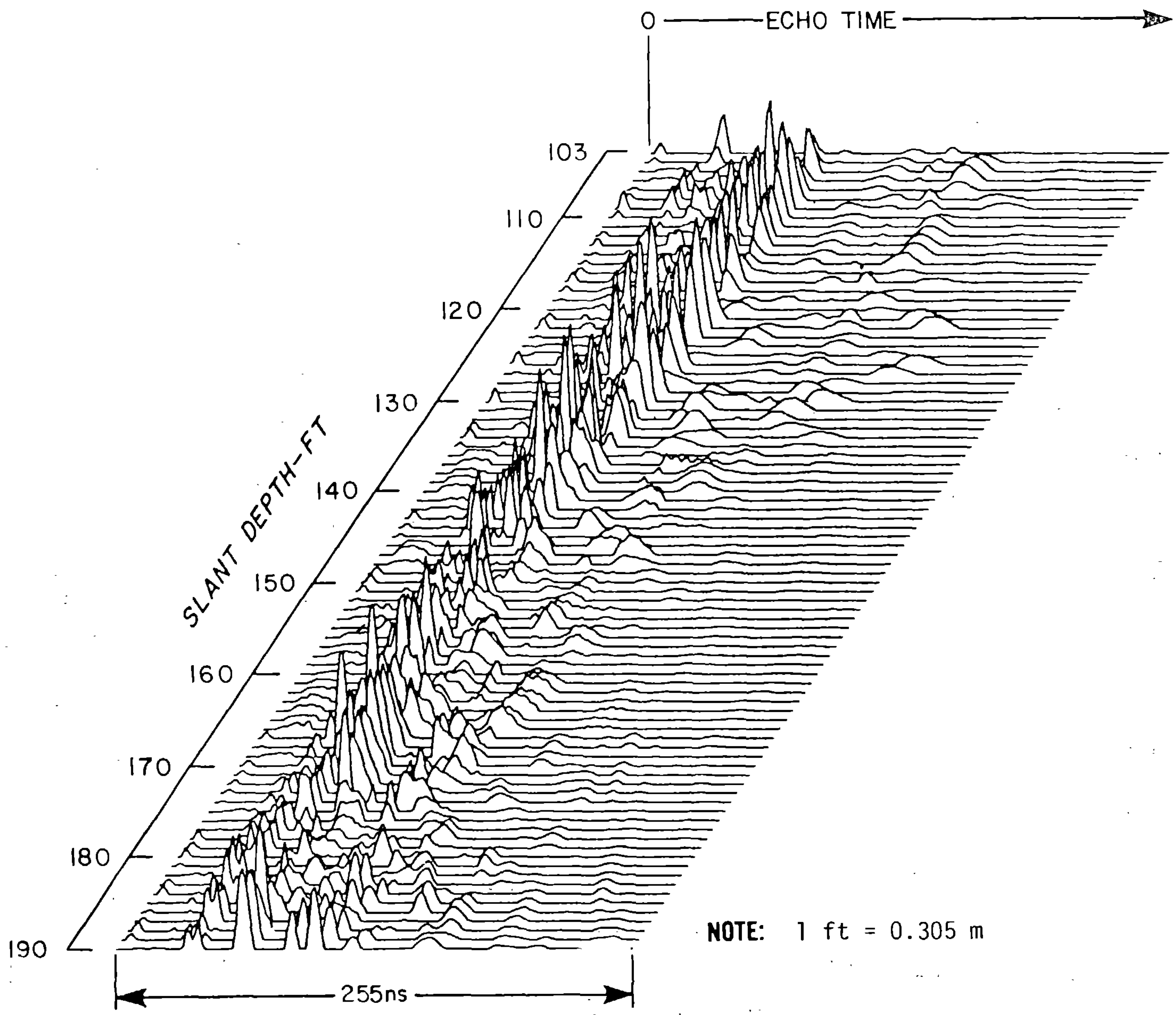


Figure E9. Electromagnetic pulse reflections observed in Borehole T1 processed to remove a 15-trace running average.

As a result of the indicated improvements gained from the 15-trace running average removal, additional processing of the data was considered desirable also to adjust the displayed trace times to correspond more accurately with propagation distance in the rock medium. This scale adjustment was based on propagation velocity data inferred from the hole-to-hole transmission measurements (described later) between Boreholes T2 and T3. Thus, by applying average velocity corrections versus slant depth to the time-base traces the adjusted traces may be redisplayed as approximate distance-base reflection waveforms.

Figure E10 shows the result of such velocity corrections applied to the same array of time-base waveform traces presented earlier in Figure E9. In this display the character of the reflection patterns appear to take on crude forms generally indicative of fractured rock structure, particularly at the deeper slant depths.

Hole-to-Hole Transmission Tests.--The primary purpose of the hole-to-hole electromagnetic transmission tests was to derive pulse travel times and amplitude decay rates along horizontal ray paths between the various test boreholes. Analysis of these data yielded average profiles of electromagnetic propagation velocity and attenuation rate for the rock zones between the holes.

The pulse travel times were determined by visual inspection of high-resolution strip chart records of pulse arrivals observed along horizontal paths between Borehole T1 and Boreholes T2 and T3. Travel times could not be determined for pulses received in Borehole BRP-27 because of an inaccurate transmitter synchronization condition in the recorded data. The long lengths of logging cable used with the downhole probes introduced a substantial amount of fixed time delay between the transmitter pulse trigger and the received electromagnetic pulse. This superfluous delay was eliminated by means of careful calibration of the field equipment system using pulse propagation measurements in air prior to operating the probe in the boreholes.

Table E3 lists the pulse travel times obtained from the measurements and the associated average propagation velocity profiles obtained by dividing the borehole separation distance by the measured pulse travel times.

Figure E11 presents the experimentally measured average pulse propagation velocity profiles for the rock materials intervening between Boreholes T1 and T2 and Boreholes T2 and T3. These velocity profiles show that the average relative dielectric constant in the rock zone between Boreholes T1 and T2 is anomalously high (relative dielectric constant approximately 16) and fairly uniform versus slant depth. This condition is strongly indicative of a water-saturated rock structure which, for the geologic structure prevalent at the Forest Glen test site, implies a highly fractured or porous rock formation.

The pulse propagation velocity profile shown for the rock materials intervening between Boreholes T2 and T3 indicate a substantially lower but varying relative dielectric constant (relative dielectric constant ranging from approximately 16 to approximately 4 over the depth profile shown). Because of the larger and probably more representative volume of rock material between Boreholes T2 and T3, this profile was used in making the velocity corrections described in the pulse reflections illustrated earlier in Figure E10.

Pulse attenuation rate profiles were determined from the signal amplitudes observed in the various receiving boreholes. The method employed in this analysis utilized the peak-to-peak pulse amplitudes measured in Borehole T2 as the reference level for

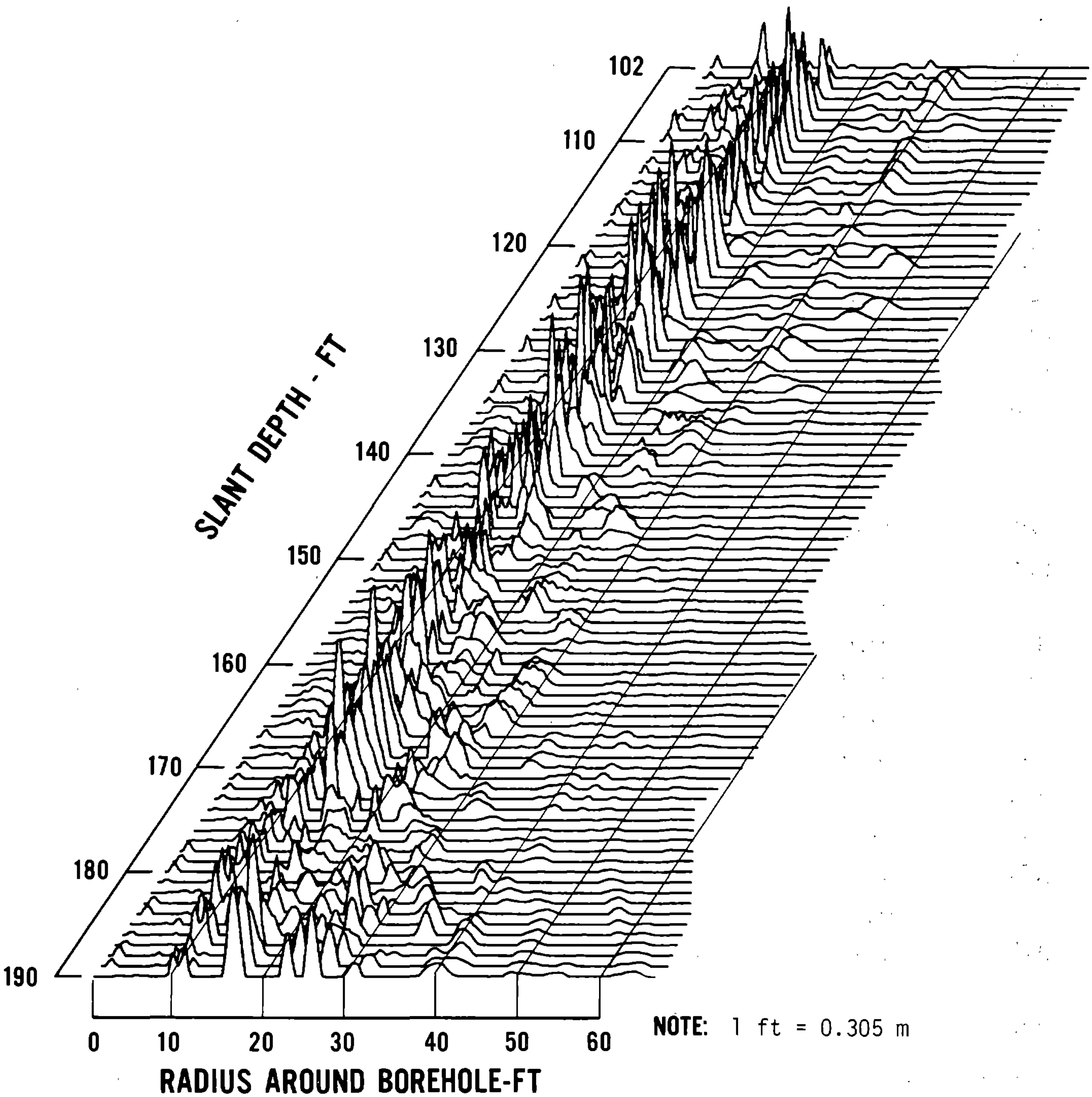
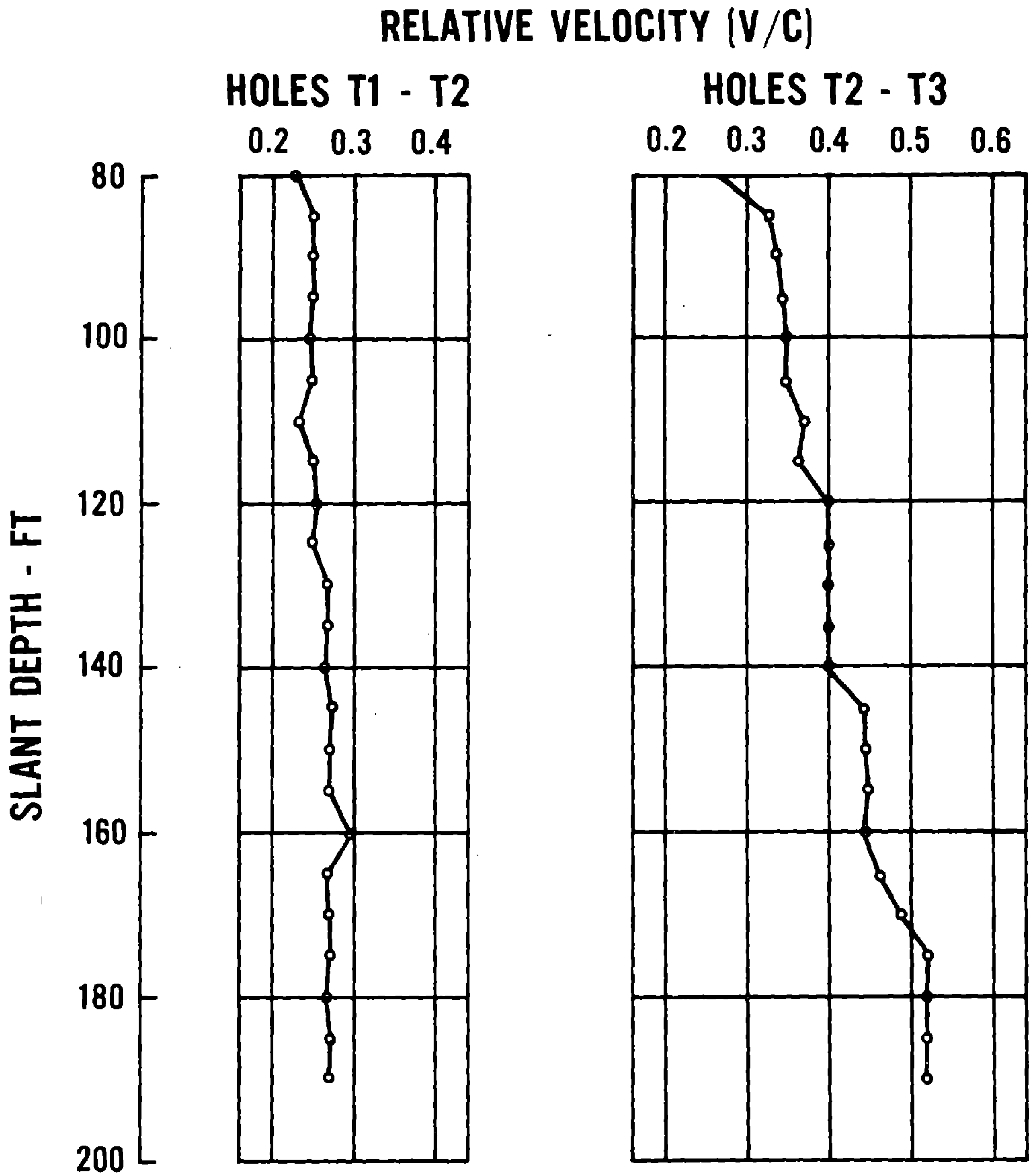


Figure E10. Electromagnetic pulse reflections observed in Borehole T1--15-trace running average removed and corrected for velocity variations with slant depth.

Table E3. Summary of electromagnetic pulse travel time data and average pulse propagation velocity profiles.

Slant Depth (ft)	Travel Time T1-T2(ns)	Travel Time T1-T3(ns)	Travel Time T2-T3(ns)	Pulse Propagation Velocity (Ft/ns) T1-T2	Pulse Propagation Velocity (Ft/ns) T2-T3
80	42.85	144.99	102.14	0.236	0.261
85	41.71	124.87	83.16	0.243	0.321
90	41.71	120.57	78.86	0.243	0.339
95	41.14	119.13	77.99	0.246	0.342
100	41.71	116.18	74.47	0.243	0.359
105	41.14	116.18	75.04	0.246	0.356
110	42.85	113.40	70.55	0.236	0.378
115	40.57	113.75	73.18	0.250	0.365
120	40.00	106.68	66.68	0.253	0.400
125	40.00	106.68	66.68	0.253	0.400
130	37.70	104.33	66.63	0.268	0.400
135	37.70	104.33	66.63	0.268	0.400
140	37.70	104.33	66.63	0.268	0.400
145	37.14	97.28	60.14	0.272	0.444
150	37.14	97.28	60.14	0.272	0.444
155	37.14	96.08	58.94	0.272	0.453
160	34.28	96.08	61.80	0.295	0.432
165	37.08	94.92	57.84	0.272	0.462
170	37.08	91.38	54.30	0.272	0.492
175	37.08	90.18	53.10	0.272	0.503
180	37.08	90.18	53.10	0.272	0.503
185	37.08	90.18	53.10	0.272	0.503
190	37.14	90.18	53.04	0.272	0.503

Note: 1 ft = 0.305 m



NOTE: 1 ft = 0.305 m

Figure E11. Average pulse propagation velocity profiles between Boreholes T1-T2 and Boreholes T2-T3.

evaluating corresponding pulse amplitudes observed in Borehole T3. Similarly, pulse amplitudes observed in Borehole BRP-27 were compared with a reference amplitude measured in Borehole T3. In all of these analyses, the propagation paths were horizontally oriented between the boreholes. Corrections were also made for an assumed spherical wave geometric spreading loss for the particular separation distances between the test boreholes. The average amplitude attenuation rates were determined by first expressing the interpreted net amplitude decay values observed between the test boreholes in decibels and then dividing these values by the borehole spacings at each slant depth measurement location. Table E4 summarizes the derived attenuation rates between Boreholes T2 and T3 and between Boreholes T3 and BRP-27.

Figure E12 illustrates the derived electromagnetic pulse attenuation rate profiles measured between Boreholes T2 and T3 and Boreholes T3 and BRP-27. As noted from these curves the average pulse attenuation rate in the more competent deeper rock materials at the Forest Glen Station excavation level are relatively low (0.5 dB/ft (1.64 dB/m) or less) whereas the shallower rock structure above a slant depth of about 120 feet (36 m) appears to exhibit significantly higher pulse attenuation effects representative of a weaker and more porous rock structure capable of holding a larger moisture content.

Interpretation of Results

The information contained in the measured and processed electromagnetic reflection signals and the hole-to-hole transmission signals can be interpreted from several viewpoints: (1) general implications of potential feasibility and usefulness of the instrumentation; (2) specific observations relevant to ground conditions at the Forest Glen Field Test Site; and (3) performance of the experimental instrumentation and data processing techniques employed in the field demonstration tests. Comments in each of these categories are presented below.

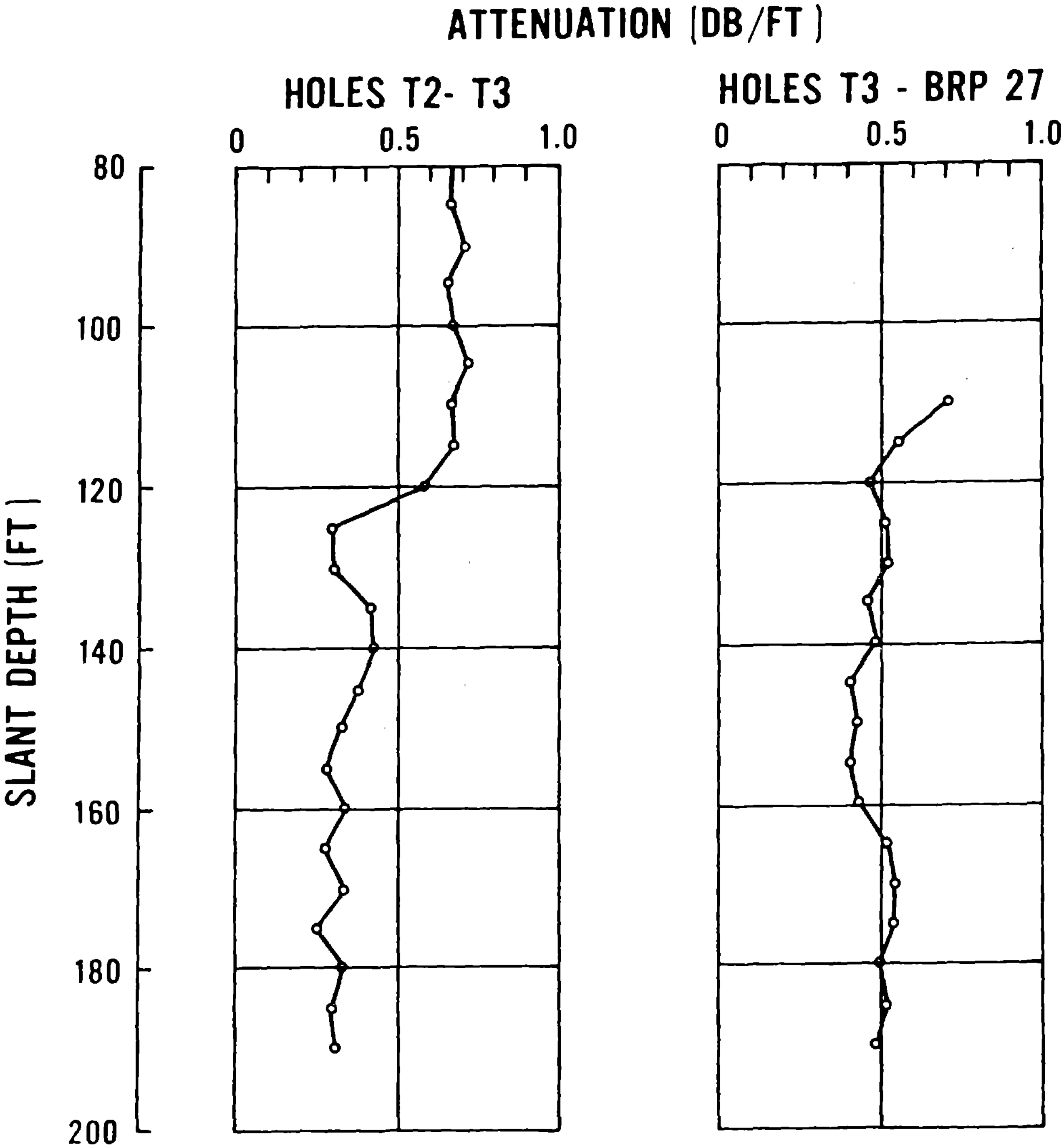
Pulse Reflection Tests.--In regard to the electromagnetic pulse reflection measurements, the processed data revealed convincing evidence of various rock-structure-related reflections at distances up to about 60 feet (18 m) away from the test borehole. This result is best illustrated in Figure E13 which shows apparent structural reflections possibly caused by contrasting gouge material located in the joints and shear zones of the rock. The improved resolution detail (i.e., higher frequency content), the faster propagation velocity (i.e., lower relative dielectric constant), and greater pulse reflection range (i.e., lower attenuation) are also noticeable in the deeper and relatively sound bedrock material below a slant depth of about 170 feet (52 m). The apparent rock structure reflection features are highlighted in Figure E13 to better reveal the continuity of the jointing and shear interfaces in the 20-60 foot (6-18 m) radial range around Borehole T1.

The apparent rock structure details indicated in Figure E13 do not necessarily represent the true rock structure because of the compositing effect of the omnidirectional borehole antenna which allows superposition of simultaneous responses from all directions around the borehole. Further, the analysis methods used to process and enhance the signals were relatively simple and incomplete. Other more advanced analysis procedures designed to provide a more narrow antenna field of view in the vertical plane and to account for the observed vertical velocity gradients in the medium as well as to better equalize pulse attenuation effects versus range could further enhance the clarity and accuracy of the display.

Table E4. Summary of electromagnetic pulse attenuation rate profiles.

Slant Depth (ft)	Total Attenuation Between T2-T3 dB	Attenuation Rate Between T2-T3 dB/ft	Total Attenuation Between T3&BRP-27 dB	Attenuation Rate Between T5&BRP-27 dB/ft
80	18	0.67	No Data	No Data
85	18.6	0.69	No Data	No Data
90	18.97	0.706	No Data	No Data
95	17.6	0.659	No Data	No Data
100	18.06	0.676	No Data	No Data
105	19.08	0.714	No Data	No Data
110	15.56	0.582	27.95	0.71
115	20.8	0.779	21.93	0.558
120	15.56	0.582	18.4	0.468
125	7.6	0.284	20.0	0.508
130	7.6	0.284	20.59	0.524
135	10.88	0.407	18.06	0.459
140	11.12	0.416	19.17	0.487
145	10.1	0.378	16.4	0.419
150	8.35	0.312	16.9	0.43
155	7.7	0.288	16.47	0.419
160	9.01	0.37	17.0	0.432
165	7.96	0.298	20	0.508
170	8.64	0.325	20.35	0.517
175	6.57	0.246	20.5	0.522
180	8.35	0.312	19.05	0.484
185	7.6	0.284	20.0	0.508
190	8.2	0.307	18.84	0.479

Note: 1 ft = 0.305 m



NOTE: 1 ft = 0.305 m

Figure E12. Average pulse attenuation rate profiles between Boreholes T2-T3 and Boreholes T3 and BRP-27.

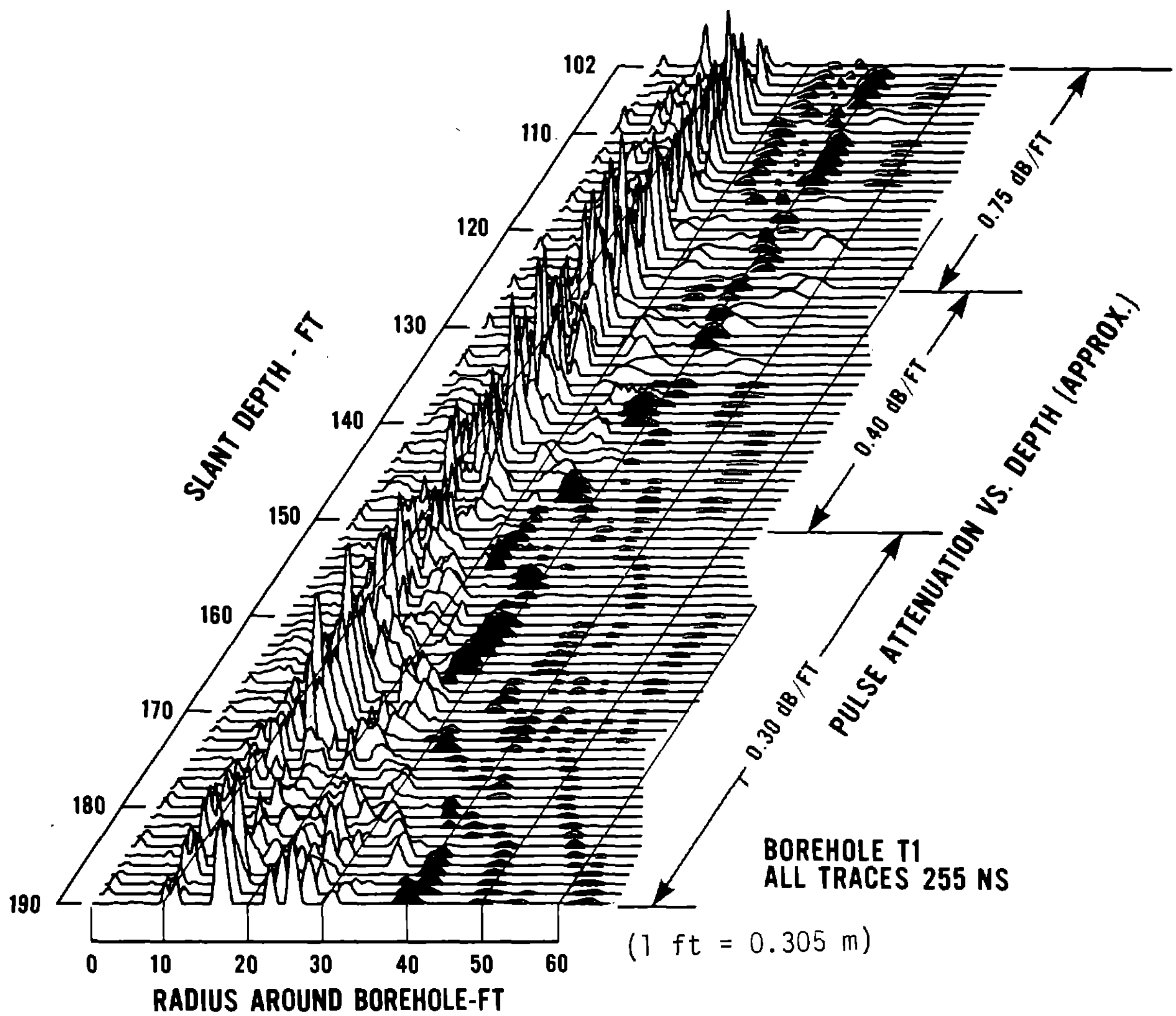


Figure E13. Electromagnetic pulse reflections observed in Borehole T1--highlighted returns in the 20-60 foot (6-18 m) range.

Hole-to-Hole Transmission Tests.—The hole-to-hole electromagnetic pulse transmission tests revealed useful information on the rock electromagnetic parameters of the medium scanned by the reflection probe. Additionally, however, these data also show a general correlation with the conventional core logs and wireline electrical resistivity logs obtained from the test boreholes. Figure E14 summarizes the hole-to-hole test data derived from the electromagnetic measurements and shows the interpreted core logs and electric logs for comparison. The primary differences in these data result largely from the fact that the conventional logs pertain to localized rock conditions along each borehole whereas the electromagnetic profiles pertain to the average conditions in the bulk rock volume between the test boreholes. Nevertheless, the major disturbance trends in pulse attenuation follow the major variations in the electrical resistivity and both of these parameters tend to correspond reasonably well with the implications of fracture jointing and relative moisture containing capabilities of the rock volume.

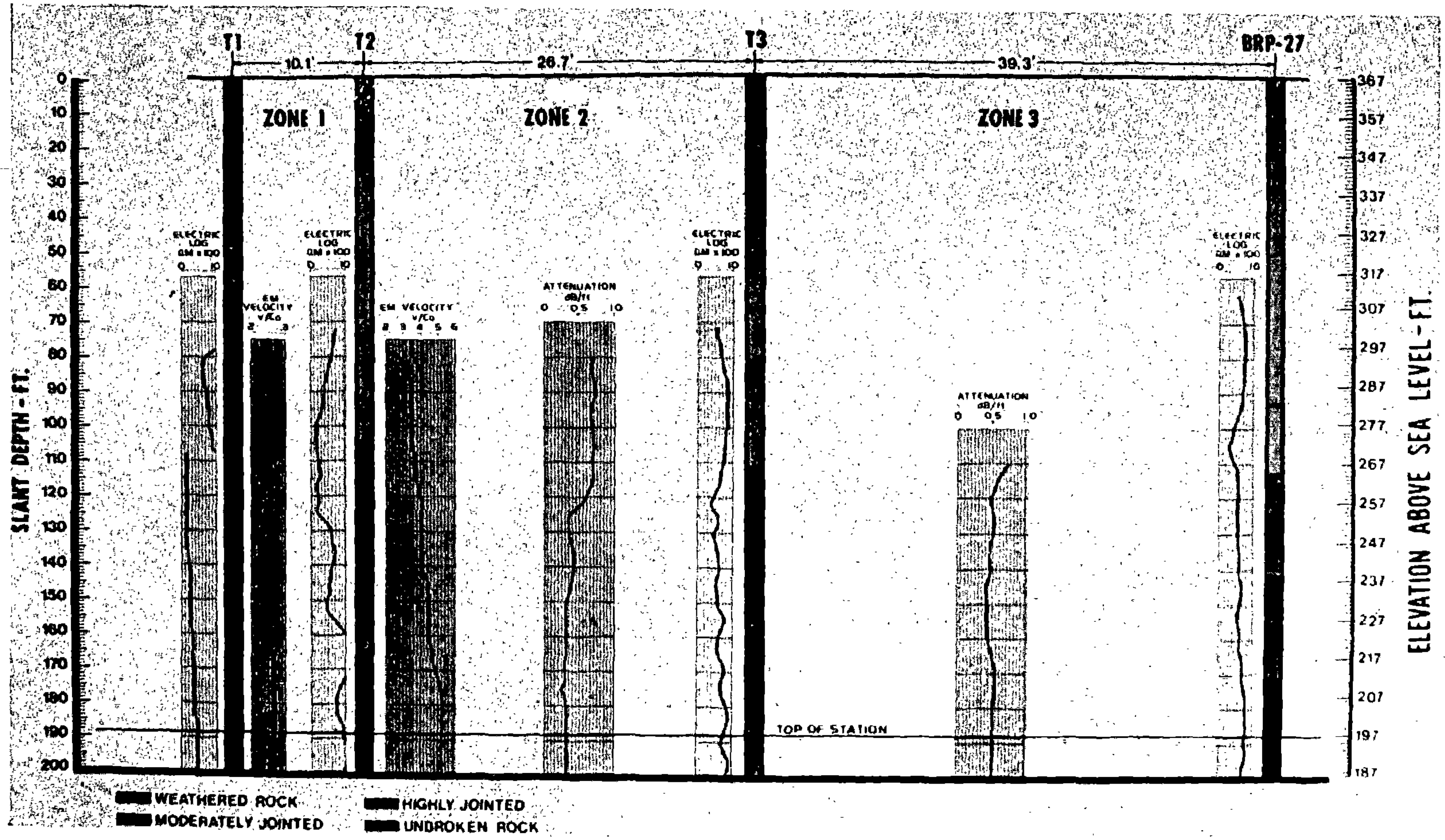
The electromagnetic propagation velocity profiles also correlate well with the indicated fracture conditions in the rock where the lower velocities correspond with the more highly fractured and, hence, greater moisture holding capabilities of the rock. This relationship implies an increased relative dielectric constant and electrical conductivity resulting from the increased moisture content of the jointed rock structure.

CONCLUSIONS AND RECOMMENDATIONS

The primary conclusion to be drawn from the brief electromagnetic pulse reflection tests performed at the Forest Glen Field Test Site is the fact that several apparently meaningful rock structure echos were observed at probing distances up to about 60 feet (18 m) around the test borehole. Verification of the specific geologic anomalies and structural details causing these reflections was not possible during the project and, hence, the exact validation of the electromagnetically-implied rock character remains uncertain. However, based upon the general fracture and jointing conditions inferred from drill cores and other geologic reconnaissance obtained from the test boreholes, the observed electromagnetic reflection data is technically plausible as a possible physical representation of the rock conditions.

Detailed and accurately revealing rock structure was not obtained in the reflection data but probably could be improved with the availability of test data containing a wider dynamic range than that afforded by the analog magnetic tape records. In this regard, the borehole electromagnetic reflection probe can provide a signal dynamic range in excess of 90 dB whereas the analog field data recordings obtained for analysis had an effective dynamic range in excess of 90 dB, including the time varying gain adjustments provided by the electromagnetic probe receiver. Therefore, the 30 dB difference (a numerical factor of about 30) in signal recording capability resulted in either over-ranging and saturation of the strong reflection signals or masking of the weak reflection signals by system noise from the recorder. The principal solution to this problem is to employ a digital data recording technique directly in the field to provide inherently wider dynamic range data acquisition. Improvements in the time varying gain capabilities of the probe receiver will also aid in compressing the dynamic range of the data recording requirements.

The technical results obtained in the Forest Glen field tests are encouraging enough to suggest that improvements in the borehole electromagnetic probe equipment be considered. In particular, the most significant improvement would be provisions for azimuthal directivity around the borehole to avoid the superposition of all reflections from the 360-degree omnidirectional field of view. This equipment improvement is



(1 ft = 0.305 m)

Figure E14. Summary of hole-to-hole electromagnetic transmission test data and related core logs and electrical resistivity logs.

technically feasible and, with proper developmental effort, could possibly provide an angular resolution in the range of about 90 degrees around the borehole. This antenna improvement together with the digital field data acquisition capability mentioned above represent solutions to the two greatest limitations of the present borehole electromagnetic probe.

Finally, a considerable amount of experience is needed in the field to establish the necessary correlations between the observable electromagnetic reflections and the geotechnical ground conditions of importance in the design and construction of tunnels. Specifically, this information must be gained from accurately controlled field tests where the geologic and geotechnical anomalies giving rise to the observed electromagnetic reflections can be physically verified and defined as a positive basis for evaluating the probe system performance. The overall technical results from the Forest Glen field tests are sufficiently promising to justify recommendations for the further development and controlled testing of the borehole electromagnetic reflection technique as initially explored in these state-of-the-art evaluation studies.

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APPENDIX F

BOREHOLE JACKING TESTS AT THE FOREST GLEN STATION SITE

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INTRODUCTION

The studies presented herein were made to increase preliminary knowledge of the engineering properties of the rock material at the Forest Glen Station site.

Divided into two main sections, the work included:

1. Downhole loading tests using the Goodman jack to measure the static deformation properties of the rock, and

2. Laboratory tests of selected rock cores at or near the locations of the downhole tests to determine the deformation constants and compare them with in situ results.

During the examination or utilization of these test results, the following points must be remembered and the data utilized accordingly.

Nondistribution

The field testing was conducted in one borehole, and laboratory samples were taken in two borings. The actual volume of material tested is only a minute fraction of the total cavern volume; the small number of tests does not permit the application of statistical methods to the resultant data. Conditions away from the borings could be different, but this report cannot reflect any such variations.

Absence of Joints

The effects of joints, faults, and fractures on the material cannot be assessed by laboratory tests. Generally the values of the physical properties are lowered by the presence of joints.

The rock affected by the Goodman jack is a cylinder some 12 inches long with a diameter of approximately three feet. The amount of joints, cracks, and weak areas contained in this volume is minimal, and so the results of the test generally show values for in-place intact rock. If an abnormality does pass under the plate, the relatively large area allotted to the abnormality compared with that allotted to the normal rock tends to overwhelm the results and produce a very low value of the modulus; the end result then being that the upper and lower bounds are obtained rather than the deformation modulus of the material mass.

Changed Conditions

The laboratory samples have been removed from their normal environment and subjected to surface conditions. The resulting change in physical characteristics due to this exposure is difficult to ascertain; it is expected, however, that the physical properties measured on in-place rock would be somewhat higher.

Optimization by Selection

The weaker rock in the mass is subject to breakage during drilling and recovery because this rock generally contains more natural joints and other weak structures. In badly broken or jointed rock, it is difficult to find a piece of core large enough to obtain a sample for testing in the laboratory. In the field, care must be taken to prevent broken rock from falling out of the sides of the hole and wedging the instrument into the hole. As a result, the field technician tends to select test areas in sound rock. Both of these selection processes tend to favor testing the better material in any given situation and could produce material properties for the stronger material.

STATIC DEFORMATION CHARACTERISTICS

The Borehole Jack

The borehole jack is a borehole probe with movable rigid bearing plates for measuring wall deformation as a function of applied load. Calculation of directional deformation in the rock is determined through load-deformation measurements using an assumed Poisson's ratio. The probe is designed to operate in a three inch, NX diameter borehole; the pressure plates can span diameters ranging between 2.75 and 3.25 inches, creating an effective working borehole size of approximately 2.9 to 3.1 inches to allow for average rock through 17-square-inch movable plates, transmitting a maximum bearing plate pressure of 9300 psi to the rock surface. Two LVDT displacement transducers are mounted within the jack at each end of the movable plates allowing precision measurements of deformation to be made. The system also includes a portable solid-state indicator for measuring displacement, hydraulic pump, pressure gauges, two hydraulic hoses, and electrical cable.

The advantages of this test are its relatively low cost in comparison with other in situ tests, its ability to measure properties at depth, and minimal disturbance of the in situ conditions. The disadvantages are the relatively small bearing surfaces, which sample material properties at selected points along the borehole, and poor mating of bearing plates to the rock surface. The U.S. Corps of Engineers, Missouri River Division Laboratory (Omnishi, 1971), and the U. S. Bureau of Mines, Spokane Mining Research Center (1969) have tested the Goodman jack and report low results relative to other methods of modulus measurement.

Field Testing

The borehole jack was used to obtain the static material properties of the rock in situ at Forest Glen. Three borings of sufficient length to intersect the cavern were available at the site. These borings were made on a small angle of the vertically grouted areas to prevent failure of the borehole walls, and redrilled to three inches with a rotary bit. This method of drilling produces an oblong hole with the short axis parallel to the strike of the hole. This elliptical nature of the resulting hole was not disclosed by the caliper log because it measures the average diameter, which was shown to be slightly under three and one-half inches. While lowering the probe into hole T-2, an obstruction was encountered at approximately 113 feet (inclined distance) which prevented the probe from going any deeper. Similar obstructions were encountered in boring T-3 and RP-27 just below the casing. The borehole jack is, of course, designed to operate in a circular hole with a nominal diameter of three inches. By expanding the jack parallel and perpendicular to the strike, the diameters were measured at less than two and seven-eighths and greater than three and one-half, respectively. The lack of time and funds available to redrill the holes to three inches in diameter prevented the test from being performed, except in the top 25 feet of T-2, where two tests were performed at 109.6 feet. Of these two, test number 1 was conducted with the applied stress perpendicular to the direction of Georgia Avenue at the site, and test number 2 was performed with the stress parallel to Georgia Avenue. The tests were conducted using the equipment described below, and according to the procedure outlined below:

Equipment.--

a. Model 52102 Goodman jack.

b. Schaevitz TR 100 LVDT (linear variable displacement transducer) readout box.

c. 600 feet of hydraulic line.

d. 300 feet of electric cable.

e. 300 feet of BX casing.

f. Hydraulic pump and pressure gauge.

Procedure.--

a. Low pressure and high pressure hydraulic lines and electric readout cable were threaded through the first section of BX casing.

b. The hydraulic lines and cable were attached to the Goodman jack which was threaded onto the cable by twisting it to prevent fouling of lines and cable.

c. The jack and casing were placed in the borehole, and additional casing and lengths of cable and lines were added as necessary to position the jack at the desired depth.

d. The test surfaces were oriented and the bearing was recorded.

e. The hydraulic lines were attached to the pump and the electric cable to the readout box.

f. Pressure was applied until the jack contacted the sides of the drill hole. The LVDT readings were recorded as the zero readings.

g. The load was applied in 10 equally spaced increments.

h. The load was held 15 minutes at the peak of each cycle to determine if the material exhibited time-dependent strain characteristics.

i. The load was removed in 10 equal decrements to obtain an unloading curve, and the minimum load was held for 15 minutes to allow the rock to rebound.

j. Two additional and similar cycles of loading were performed to successively higher loads.

k. The jack was collapsed and rotated 90 degrees, and steps 6 through 10 were repeated.

l. Upon completion of the second test, the jack was collapsed and moved to the next test position.

Data Reduction.--The equation used to obtain the modulus values was derived by assuming the actual pressure to be a constant radial boundary pressure plus shear and radial pressures distributed sinusoidally over the width of the plate. If the angle subtended by the width of the plate is about 45 degrees, little effect on the results occurs from the finite plate width. The results of a finite element program (Hall, 1972) show that a reduction of 14 percent in the value of the modulus is necessary to adjust to the actual length of the jack. The modulus was obtained by the use of the following equation:

$$E = 0.86 \frac{Ph}{w_h}$$

where

P = applied load

h = diameter of borehole

w_h = diametrical deformation

Results.--The results of the borehole jacking tests are summarized in Table F1 and displayed as stress-strain curves in Figures F1 and F2. The values obtained from each orientation are essentially the same, considering the small number of tests and the statistical scatter of results typical of all rock mechanics testing. The modulus values are relatively low; inspection of the stress-strain curves reveals crack-closing at the start of each cycle, and a moderate amount of permanent deformation. In addition, a significant amount of time-dependent strain occurred at the top of each cycle; this behavior has been plotted as strain vs. time in Figure F3. During test number 1, similar creep rates took place at all stresses, while the total time-dependent strain increased in proportion to the applied stress. Total time-dependent strains in test number 2 were less than in test number 1, indicating that working of the material had taken place during the first test.

Table F1. Borehole jacking test results.

	Test No. 1	Test No. 2
Depth, ft	109.6	109.6
Orientation, degrees relative to Ga. Ave.	90	0
Tangent Modulus x 10^6 psi	0.24	0.18
Secant Modulus x 10^6 psi	0.08	0.09
Recovery Modulus x 10^6 psi	1.4	1.9

Note: 1 psi = 6.9 kN/m^2

The borehole jacking test results compare well with the laboratory test results. The jacking measurements were made in situ and will, of course, reflect the effects of confining pressure, cracks, joints, and moisture. The confining pressure would tend to increase the moduli, while the macro-rock quality would tend to decrease them. In addition, strongly foliated materials such as these will sometimes show a modulus dependent upon the orientation of the applied stress. When the stress is applied normal to alternating low and high modulus layers, the low modulus material compresses and controls the bulk modulus of the rock. When the stress is applied parallel to such layers, the high modulus material controls the amount of strain and thus, the modulus. While this effect was not observed in the unweathered sample, it could well exist in the weathered rock because of the different weathering characteristics of quartz, feldspar, and the micas. The jacking test was conducted with the stress basically parallel to the foliation, which dipped 23° to the axis of the core. Thus, the values are similar, rather than the jacking test results being lower, as might be expected. Vertical in situ modulus values may prove to be lower than the figures presented here.

Laboratory Tests

A total of 11 unconfined uniaxial compression tests were performed on air-dried rock core specimens to determine their deformation constants. Ten tests were performed on unweathered material; five from boring T-2, five from boring RP-27, and

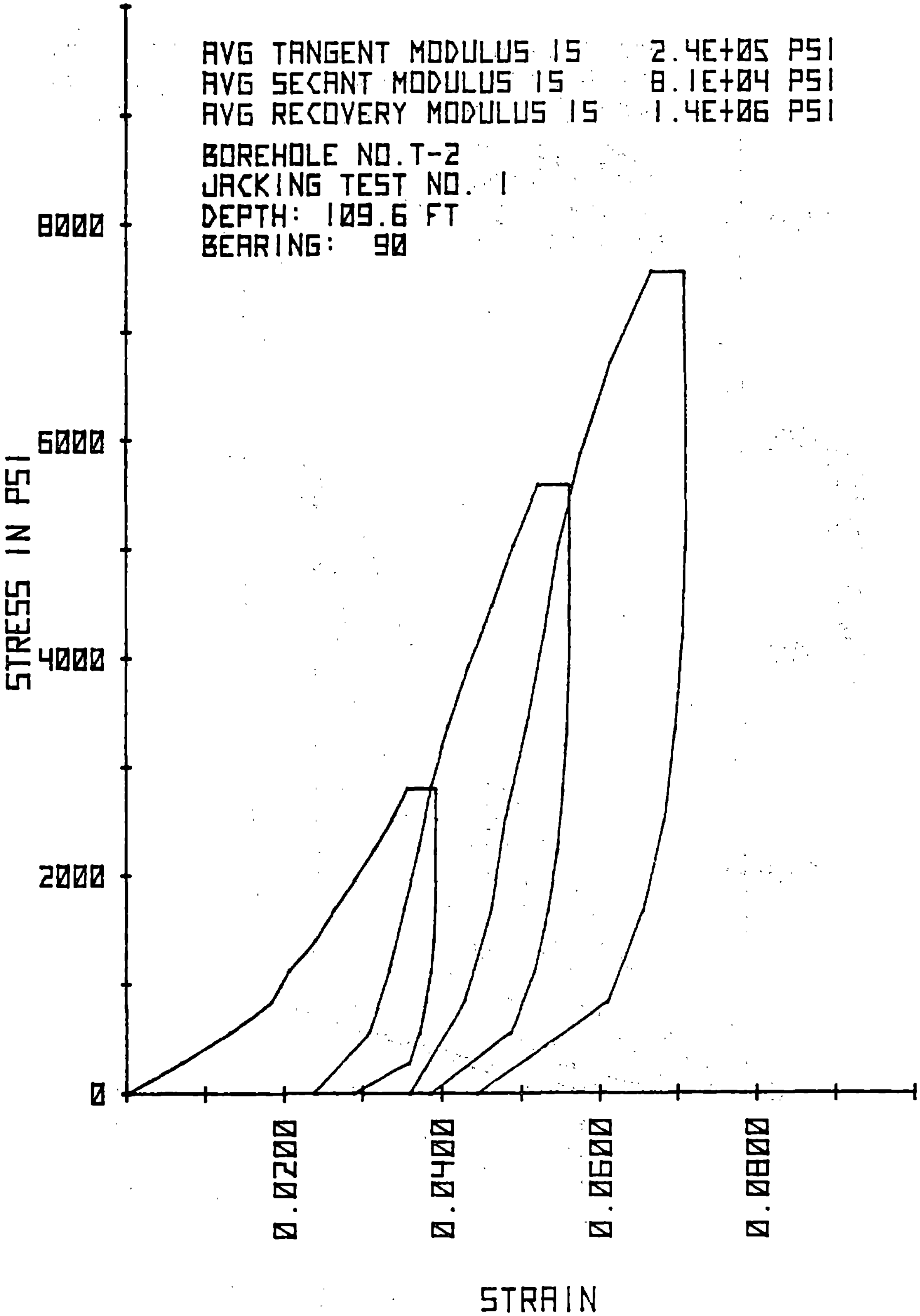


Figure F1. Borehole T-2, Jacking Test No. 1.

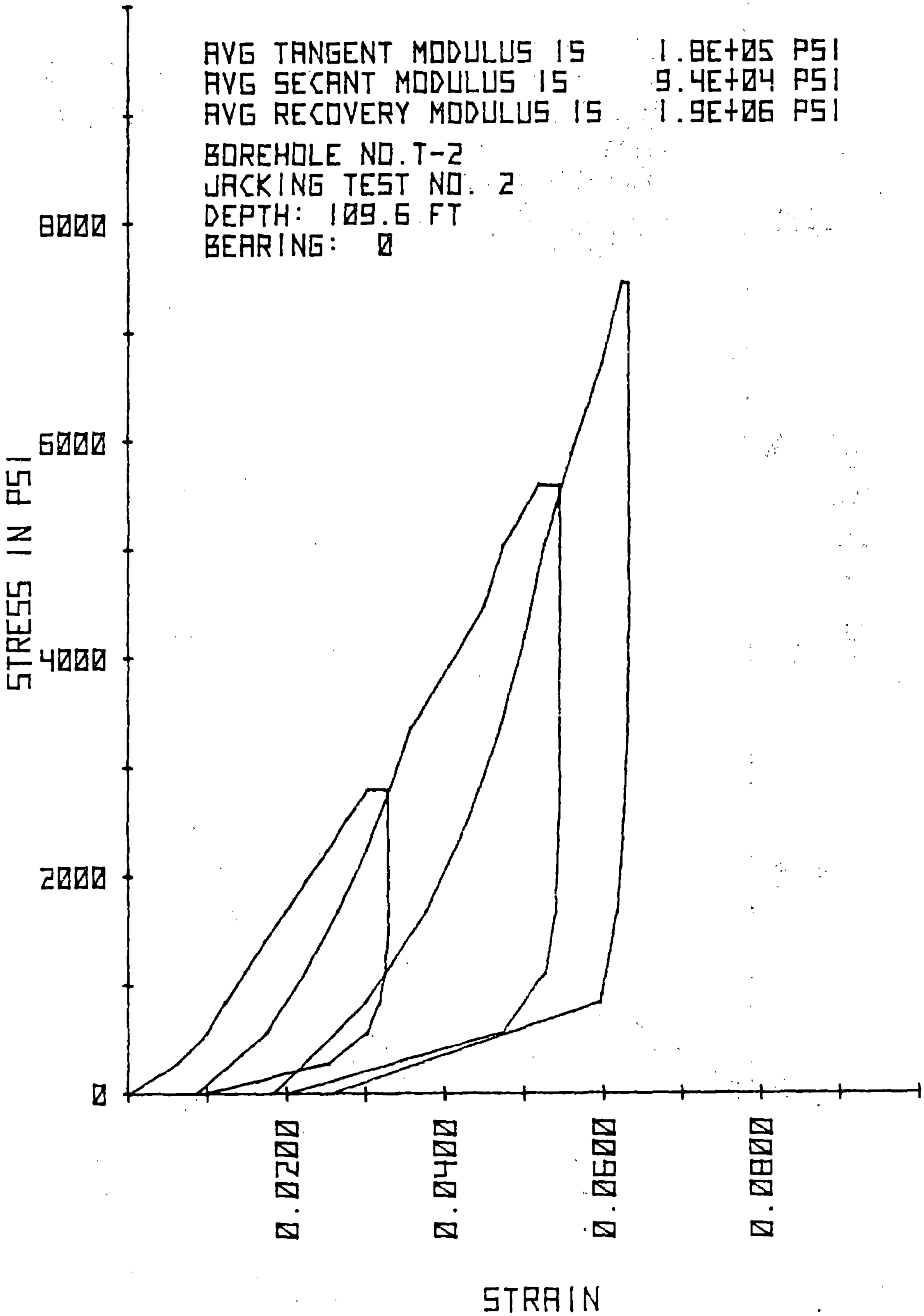
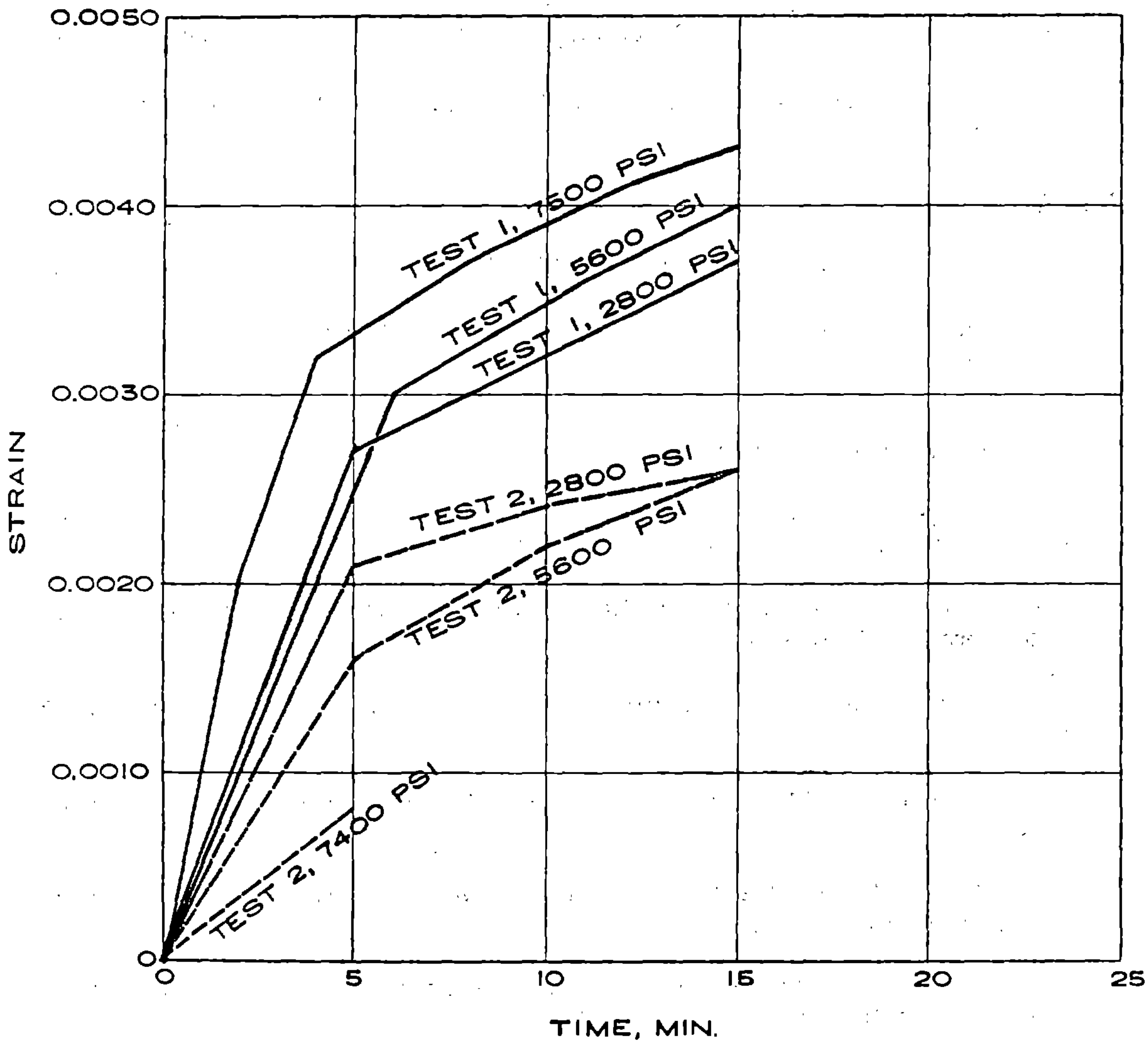


Figure F2. Borehole T-2, Jacking Test No. 2.



Note: 1 psi = 6.9 kN/m^2

Figure F3. Creep during borehole jacking tests.

one on slightly weathered material from boring T-2. Eleven core samples were returned to Portland and tested for modulus of deformation values and Poisson's Ratio using the equipment and procedures as follows:

Equipment.--

a. A 250,000 pound compression tester with a 2.25 inch ram operated by a hand pump.

b. Four SR-4 type strain gauges mounted on opposite sides of the core in two T-shaped rosettes.

c. A 6.5 volt solid state DC power source, a 10 channel switch and balance unit, and a high impedance digital voltmeter in a Wheatstone bridge circuit.

d. A Hewlett-Packard 9830 computer in direct hookup with the voltmeter for data acquisition and calculations.

Procedure.--

a. The samples were cut and their ends ground in accordance with ASTM D2938.

b. Strain gauges were applied according to the gauge manufacturer's recommendations.

c. A spherical seat and hardened steel platens were cleaned and inspected to see that they would perform properly.

d. The test specimen bearing surfaces were cleaned, and the specimen was placed on the bearing platens.

e. The axis of the specimen and the center of thrust of the spherical seat block were carefully aligned.

f. The load was applied in 10 equally spaced increments at a constant ratewithout shock.

g. Readings were taken of axial and radial strain after each increment of loading.

h. The peak load was maintained for several minutes to observe time-dependent strain behavior, if any.

i. The sample was unloaded in 10 equally spaced increments with strain readings at each step.

j. Two additional and similar cycles of loading were performed to loads of twice and three times the first cycle's peak load.

Results.--Because rock is not actually an elastic material, its behavior may be described by the use of the three deformation moduli shown on Figure F4.

a. The tangent modulus of deformation is the slope of the stress-strain curve obtained between two adjacent sets of data points. It neglects the end effects of the curve and is better suited to small stress changes.

b. The secant modulus of deformation is the slope of the line between zero stress and the stress in question. This modulus should be used for complete load steps from zero to the desired load. Sometimes the initial portion of a curve is concave upwards. This is often attributed to closing of microcracks caused by stress release, blasting, etc., and lowers the value of the secant modulus. The ratio between the secant modulus and tangent modulus, then, can be used as a means of measuring the micro-damage of the material. A ratio of one indicates no damage.

c. The recovery modulus of deformation is a tangent modulus on the stress-releasing portion of the stress-strain curve. This modulus is generally higher than the other two moduli and is used in calculations where unloading conditions are present. The difference between the tangent and recovery moduli indicates the material's capacity for hysteresis or energy storing. In a linearly elastic material all three moduli would be identical.

The results of the unconfined uniaxial deformation tests are presented in Table F2. Stress-strain curves for each sample are shown in Figures F5 through F14.

The modulus values for unweathered material generally range between 7 and 12 x 10^6 psi with relatively little spread in the data. Poisson's Ratio averages 0.187. These figures are representative of relatively high modulus material. The stress-strain curves are fairly linear, with unloading cycles similar to loading cycles. Very little permanent deformation (plastic deformation) was observed, and almost no time-dependent strain (creep) at peak stress levels. This material is highly elastic in its behavior.

This slightly weathered rock, on the other hand, exhibits modulus values ranging from 0.2 to 0.4 x 10^6 psi and a Poisson's Ratio of 0.037. Inspection of the stress-strain curve for this material (Figure F15) reveals unloading curves which are substantially different from loading curves, indicating that much of the energy is stored until low stress levels are reached. In addition, there is significant creep exhibited at the peak of each cycle and a large amount of permanent deformation at the bottom. This material shows a combination of elastic, plastic, and viscoelastic behavior, and the deformation values are in the low range of rock values. The behavior of this rock reflects the weathering it has undergone and may indicate the presence of a significant amount of clay minerals.

RESULTS AND CONCLUSIONS

The following are the major results and conclusions of this report:

a. For unweathered rock, the average material properties from laboratory samples are as follows:

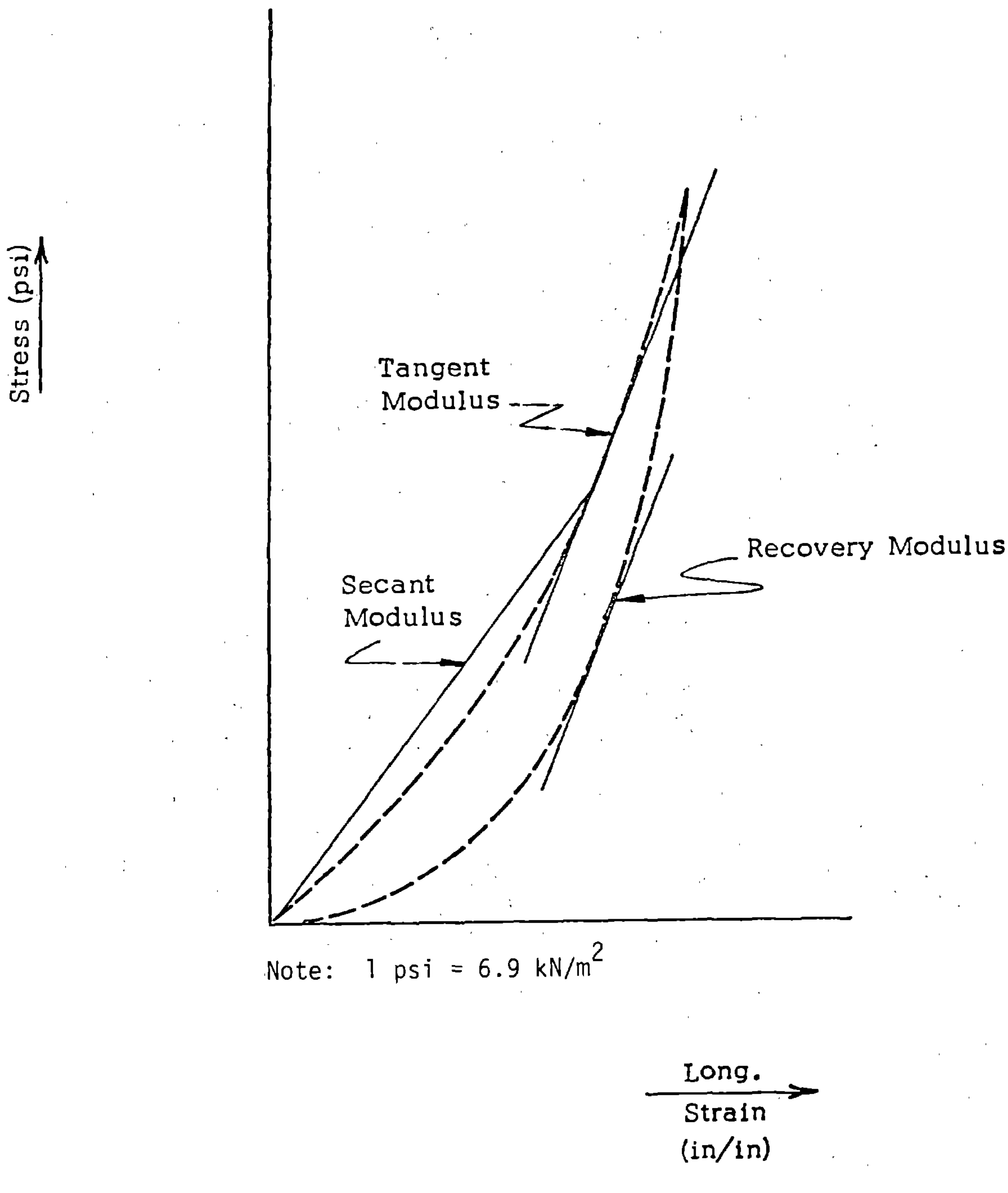


Figure F4. Relationship between tangent, secant, and recovery moduli.

tangent modulus x 10^6 psi:	9.1
secant modulus x 10^6 psi:	9.2
recovery modulus x 10^6 psi:	9.2
Poisson's ratio:	.187

This material exhibits predominantly elastic behavior with only a small degree of viscoelastic tendency and permanent set. No time-dependent strain was observed.

Table F2. Modulus of deformation results.

Sample No.	Depth, ft	Tangent x 10^6 psi	Secant x 10^6 psi	Recovery x 10^6 psi	Poisson's Ratio
Weathered Material:					
T-2-1	113.6-114.3	0.24	0.20	0.40	.037
Unweathered Material:					
T-2-2	190.8-192.3	12.4	14.2	12.0	.179
T-2-3	198.0-198.7	8.2	8.0	8.4	.167
T-2-4	208.0-208.7	7.2	6.9	7.5	.111
T-2-5	218.4-219.0	10.3	10.4	10.3	.187
T-2-6	226.9-227.5	10.2	10.7	10.1	.268
RP-27-1	193.4-194.3	9.4	9.6	9.7	.198
RP-27-2	201.5-202.3	10.0	10.2	10.1	.175
RP-27-3	213.0-214.1	7.1	6.7	7.6	.179
RP-27-4	223.0-223.9	7.7	7.8	7.9	.198
RP-27-5	233.0-234.2	8.1	8.0	8.4	.205
Avg. Unweathered Material:		9.1	9.2	9.2	.187
	Range:	7.1-12.4	6.7-14.2	7.5-12.0	.111-.268

Note: 1 ft = 0.305 m
1 psi = 6.9 kN/m^2

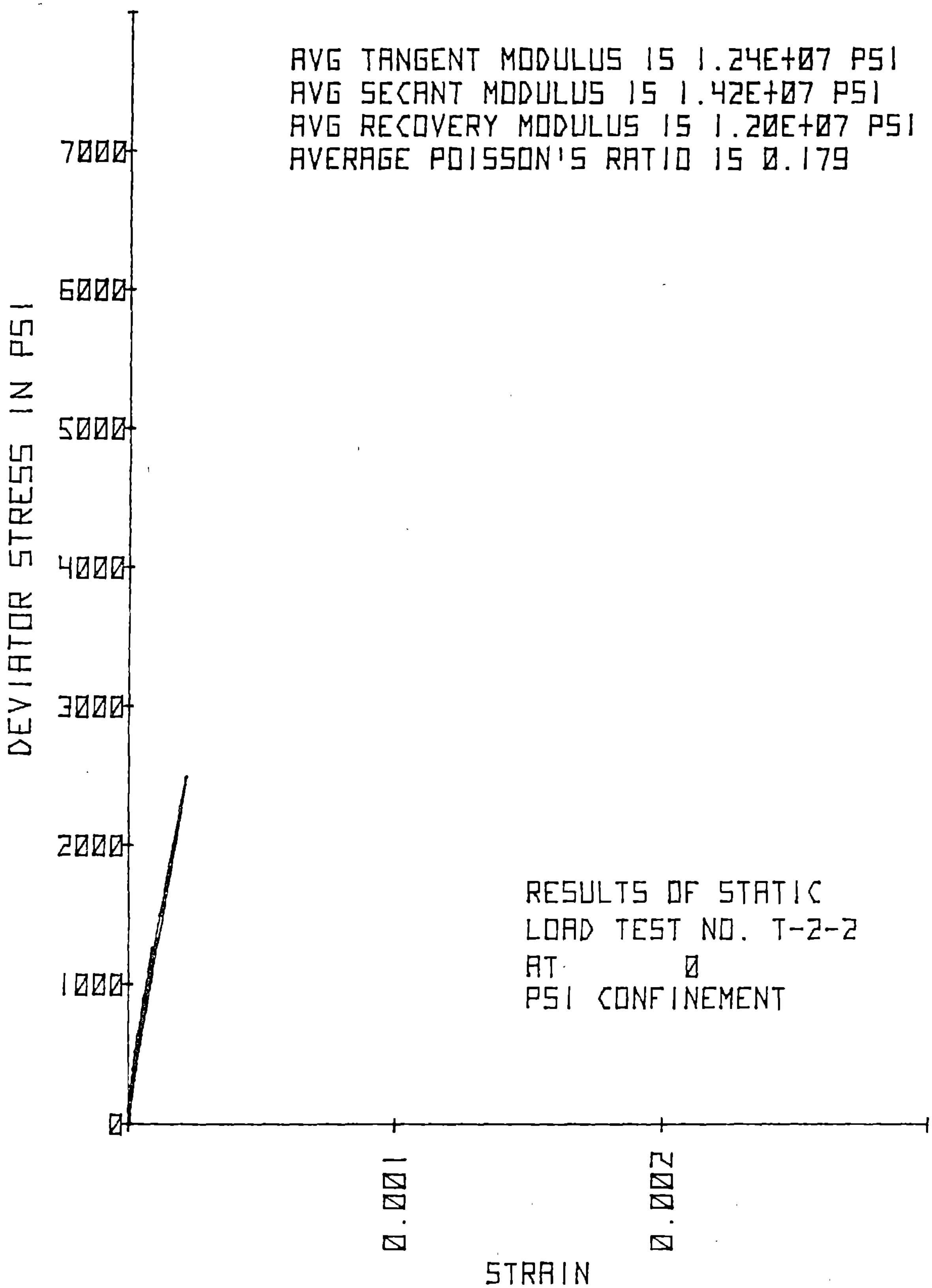


Figure F5. Results of static load test T-2-2 at 0 psi confinement.

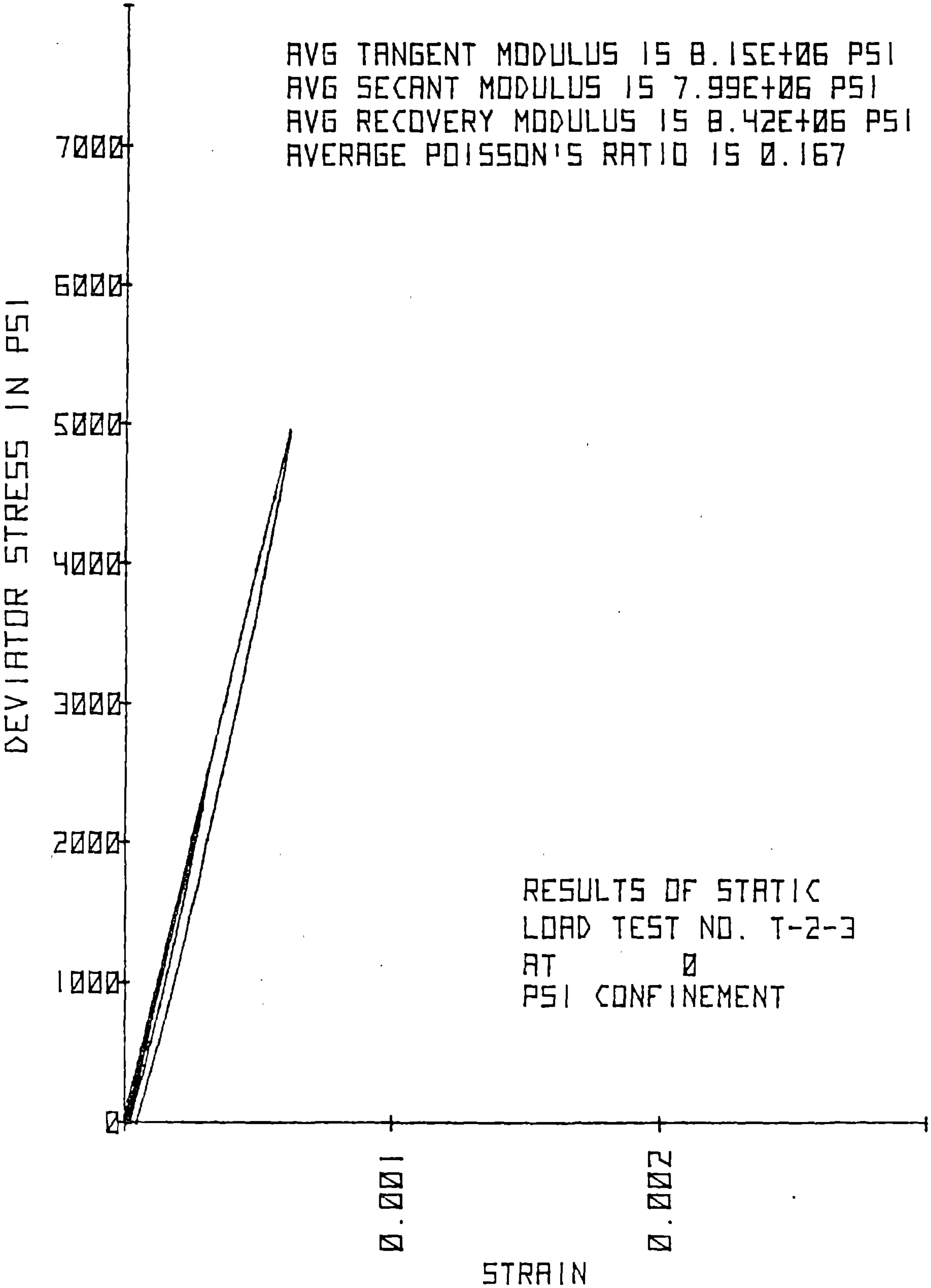


Figure F6. Results of static load test T-2-3 at 0 psi confinement.

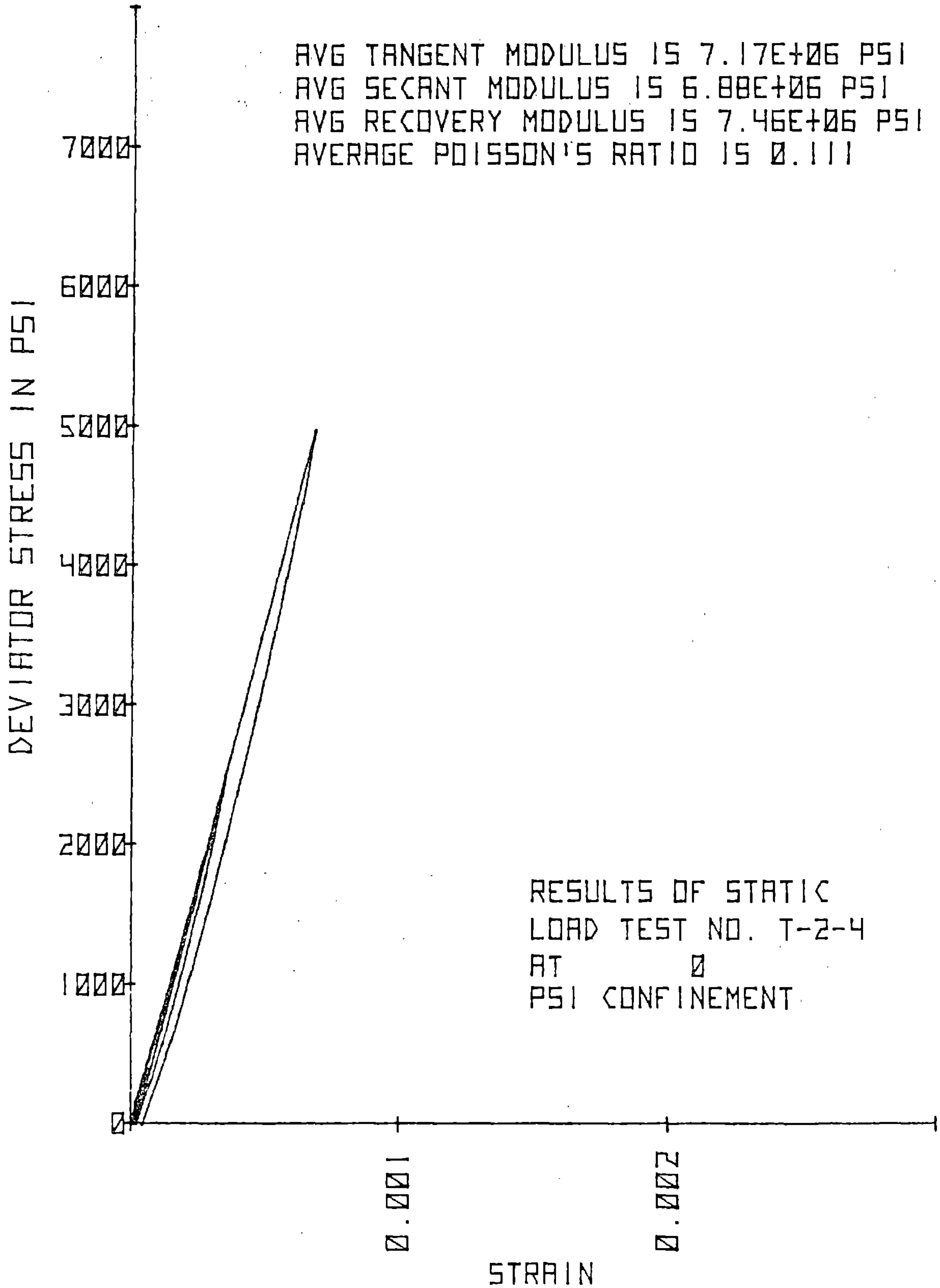


Figure F7. Results of static load test T-2-4 at 0 psi confinement.

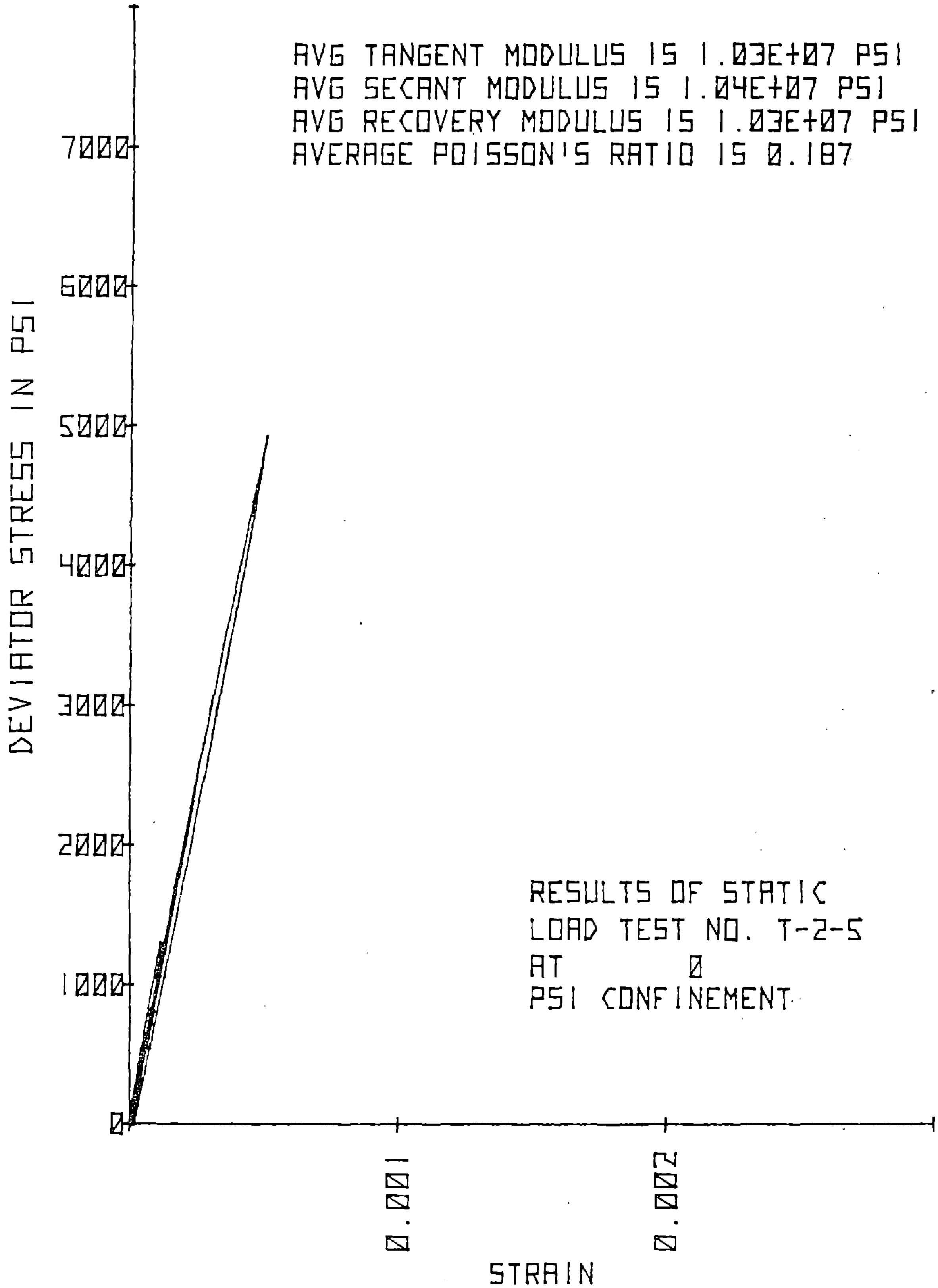


Figure F8. Results of static load test T-2-5 at 0 psi confinement.

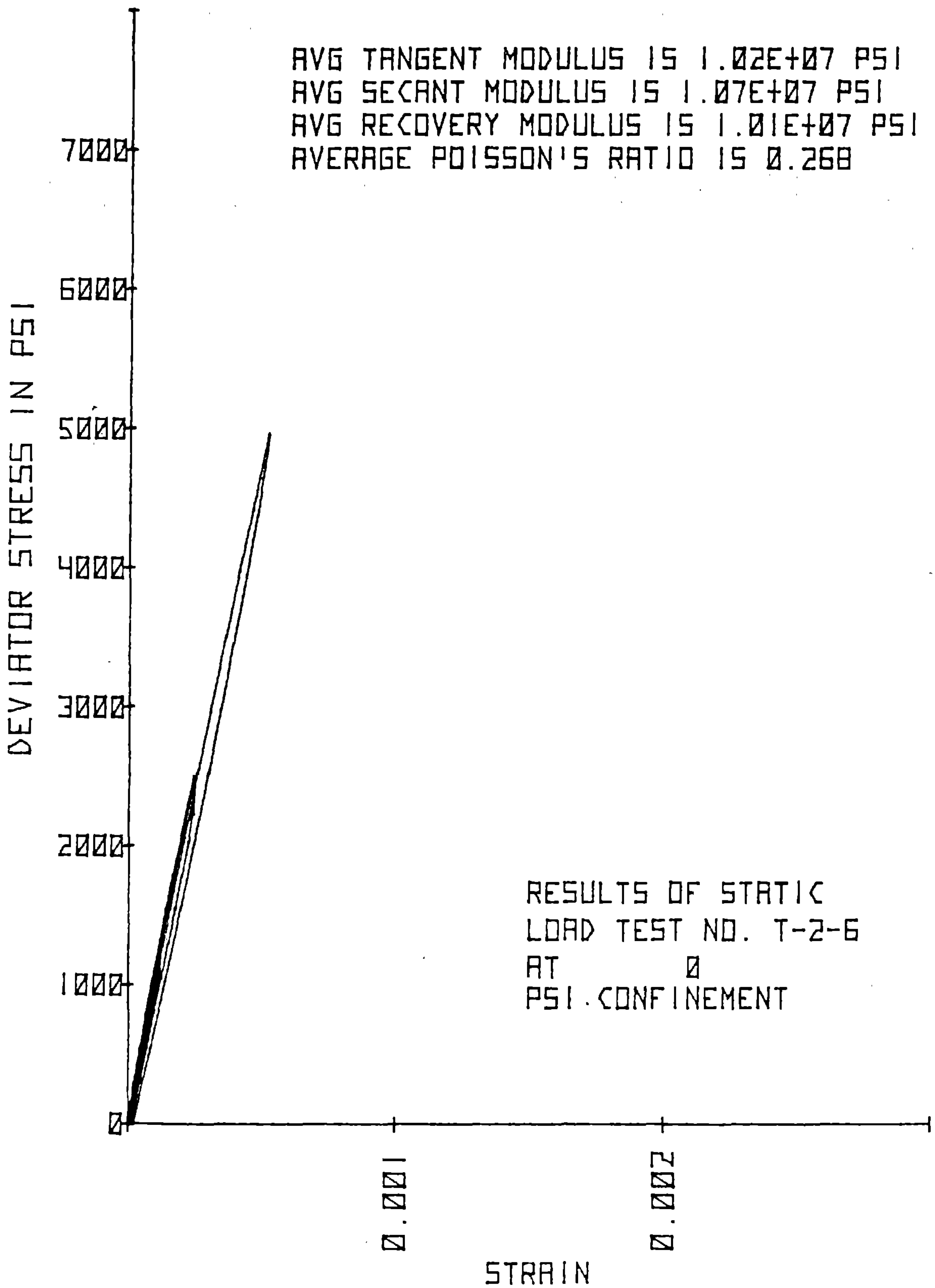


Figure F9. Results of static load test T-2-6 at 0 psi confinement.

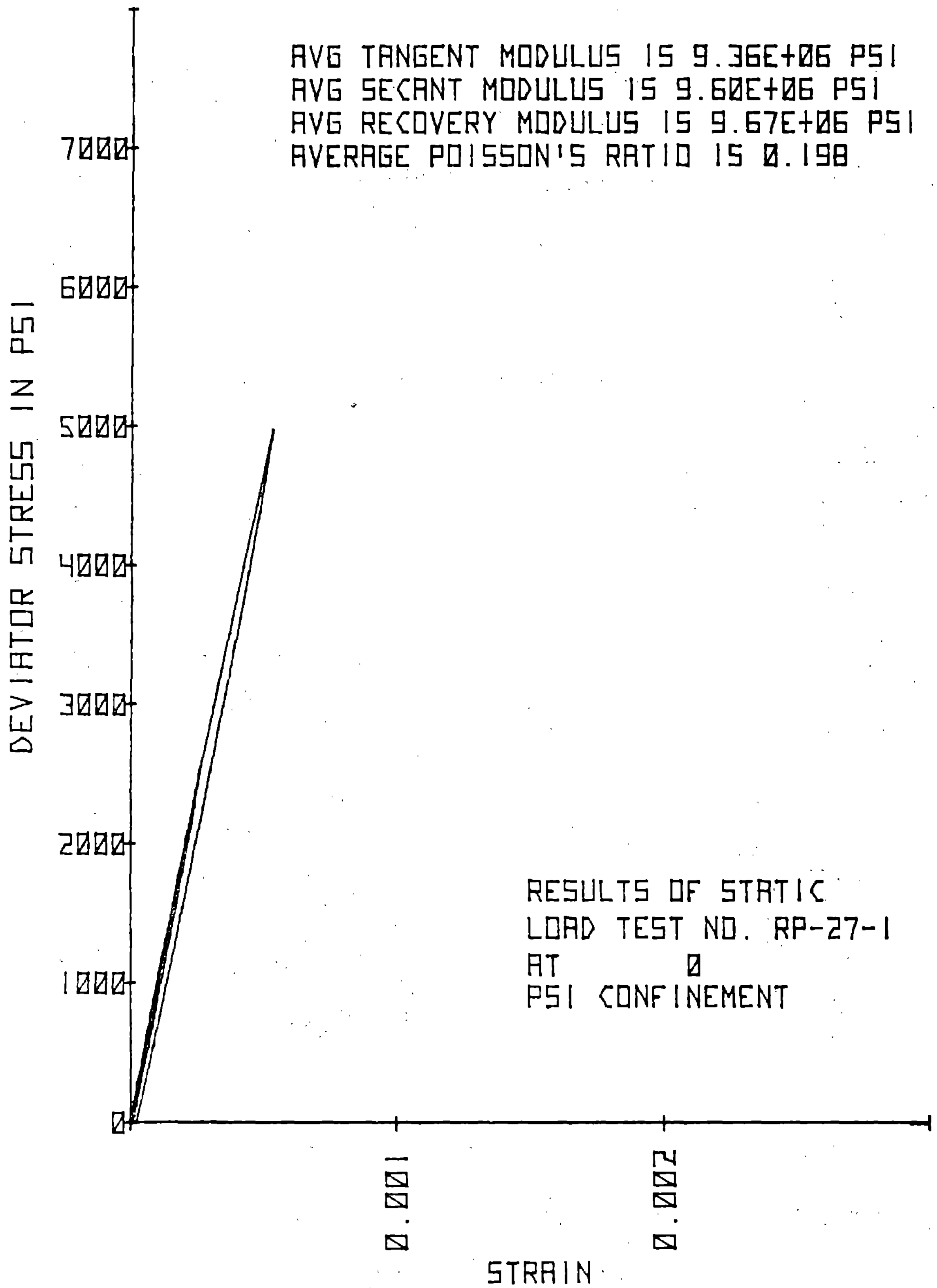


Figure F10. Results of static load test RP-27-1 at 0 psi confinement.

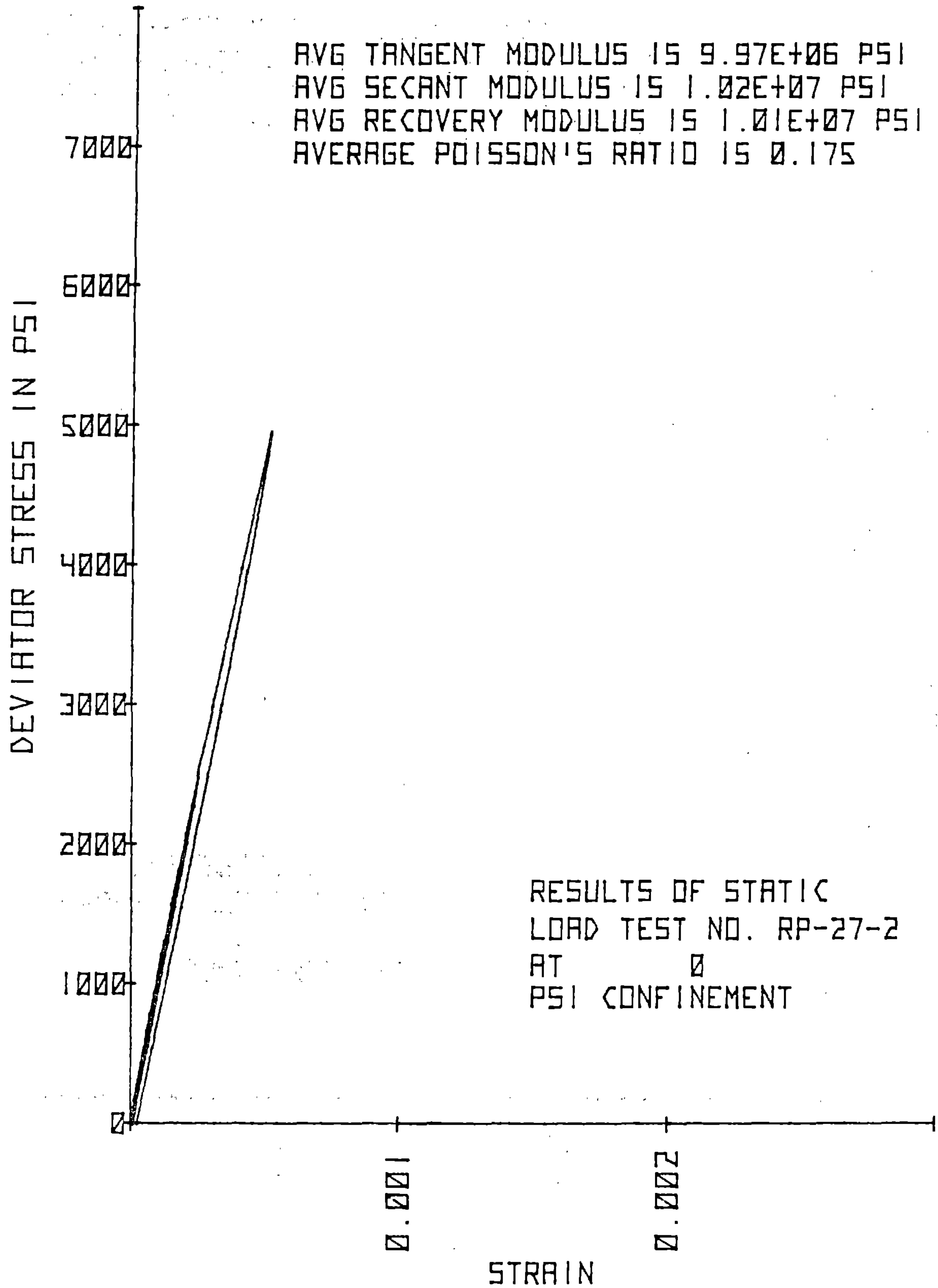


Figure F11. Results of static load test RP-27-2 at 0 psi confinement.

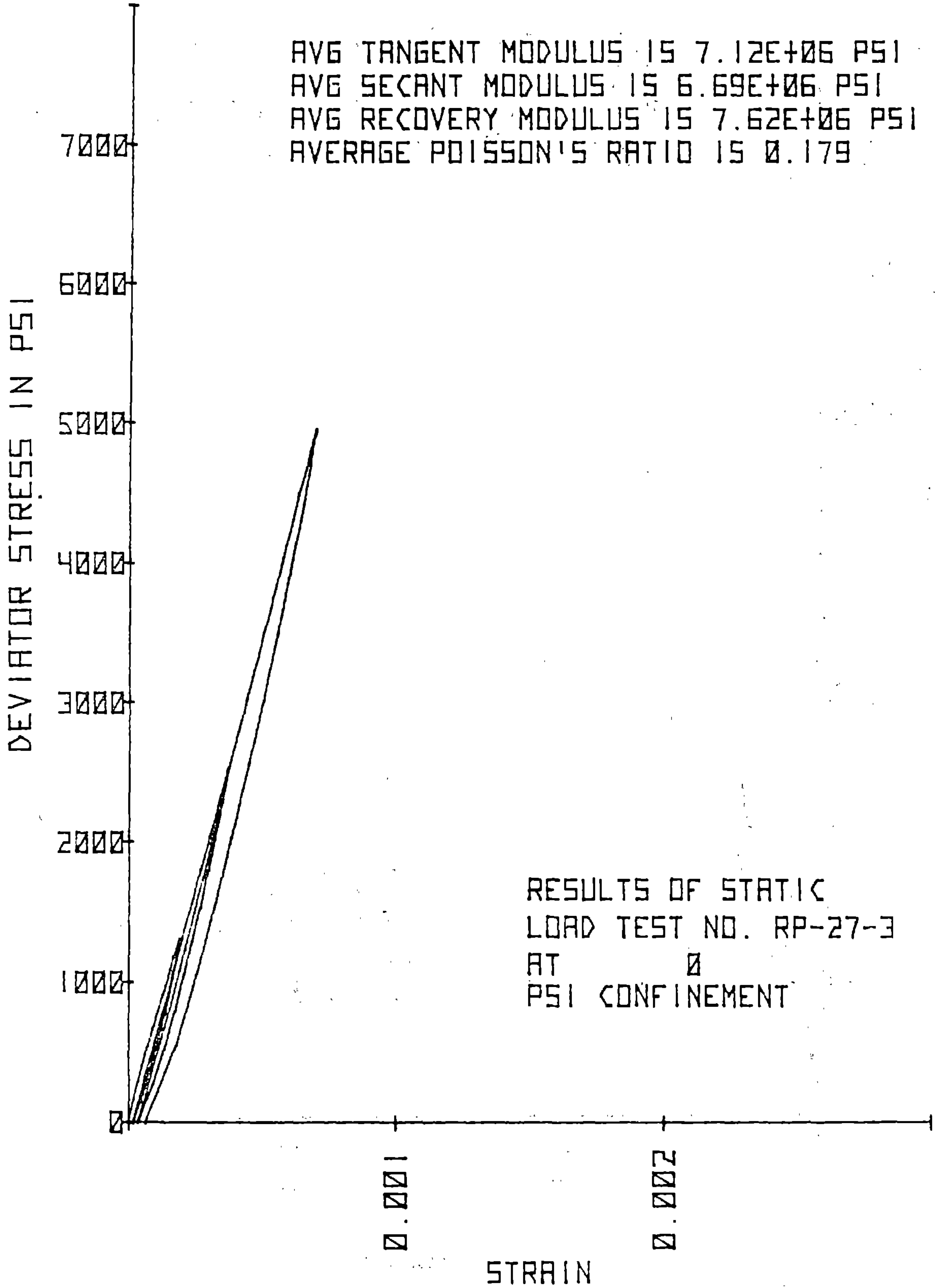


Figure F12. Results of static load test RP-27-3 at 0 psi confinement.

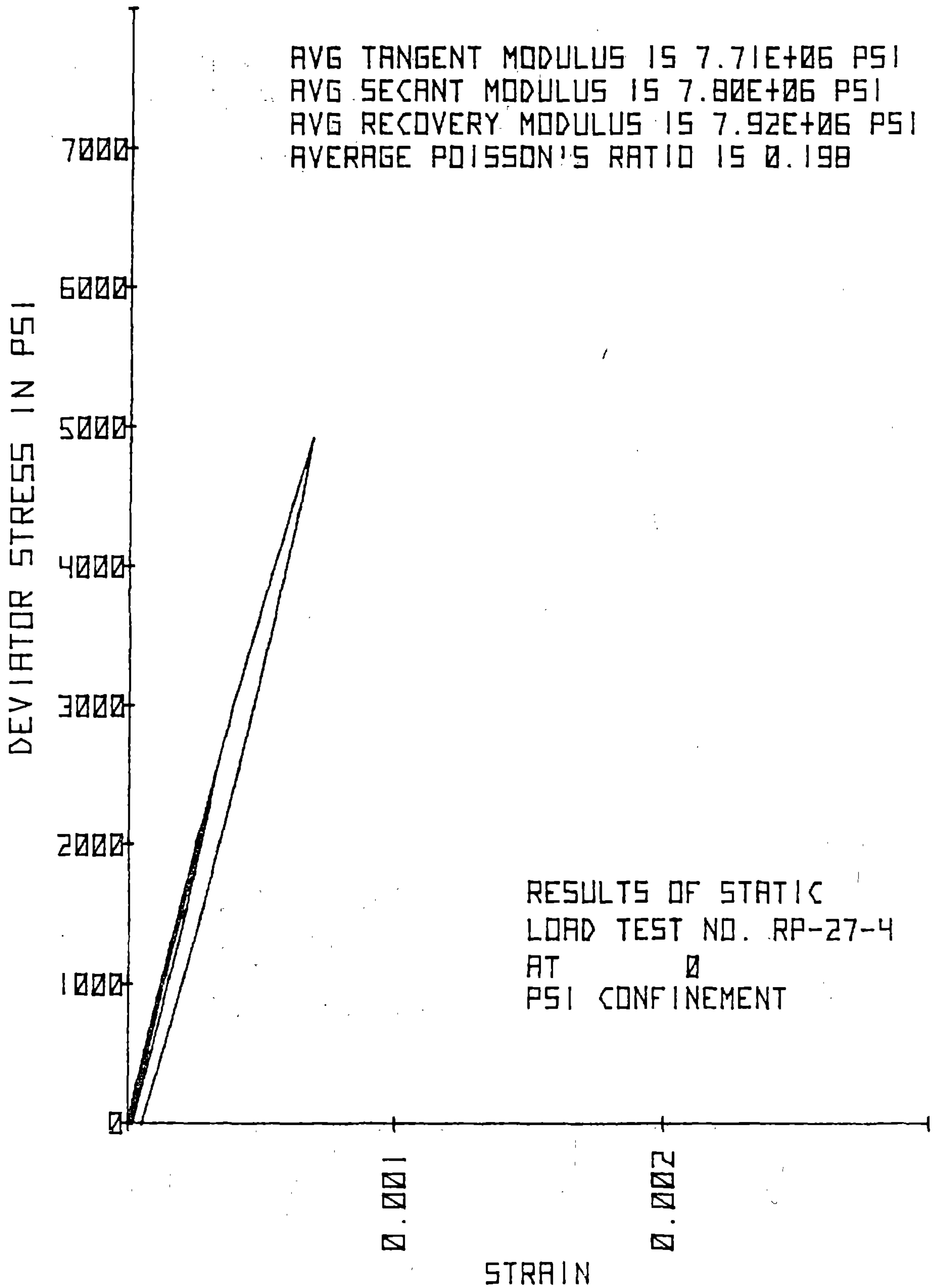


Figure F13. Results of static load test RP-27-4 at 0 psi confinement.

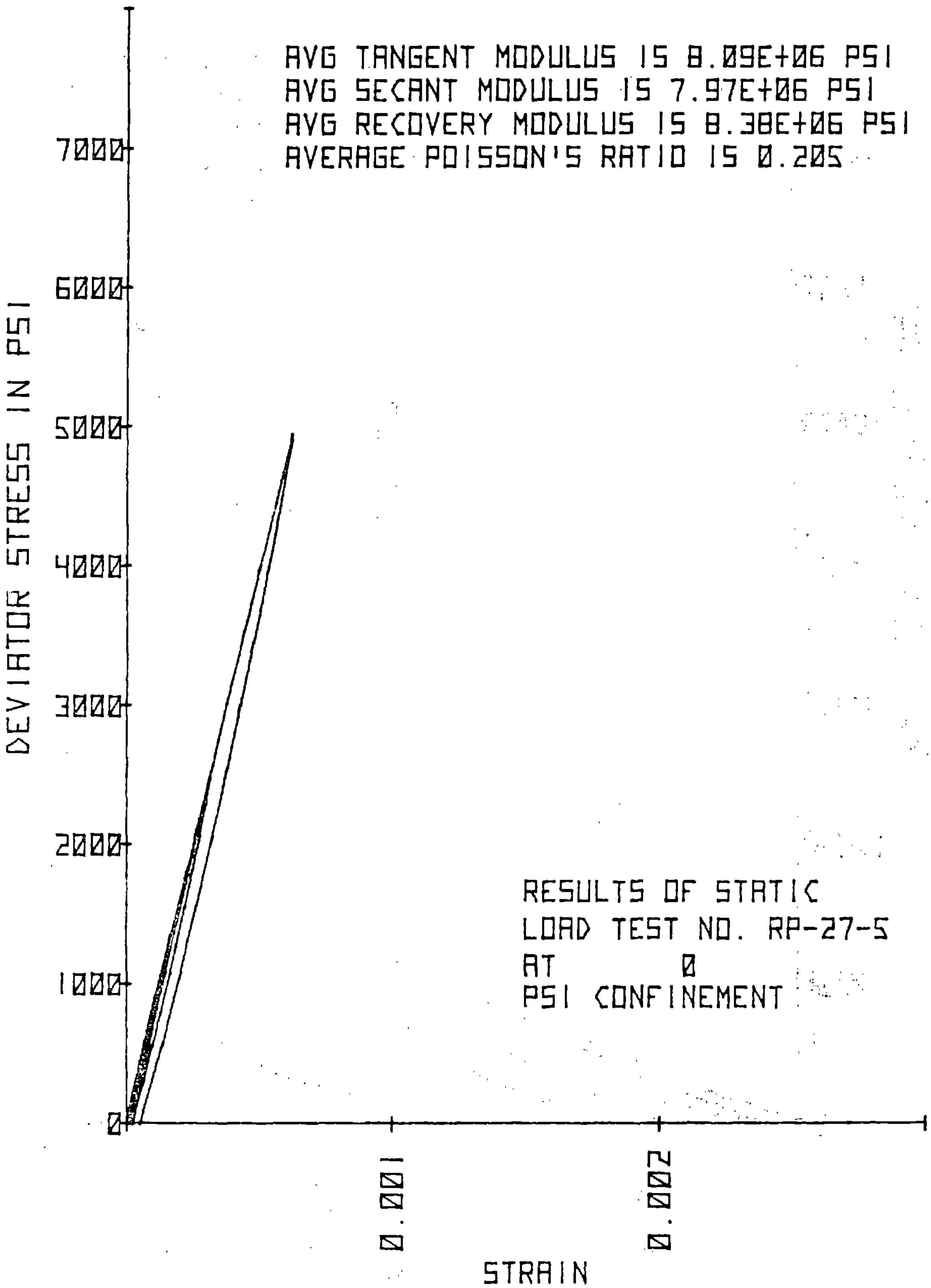


Figure F14. Results of static load test RP-27-5 at 0 psi confinement.

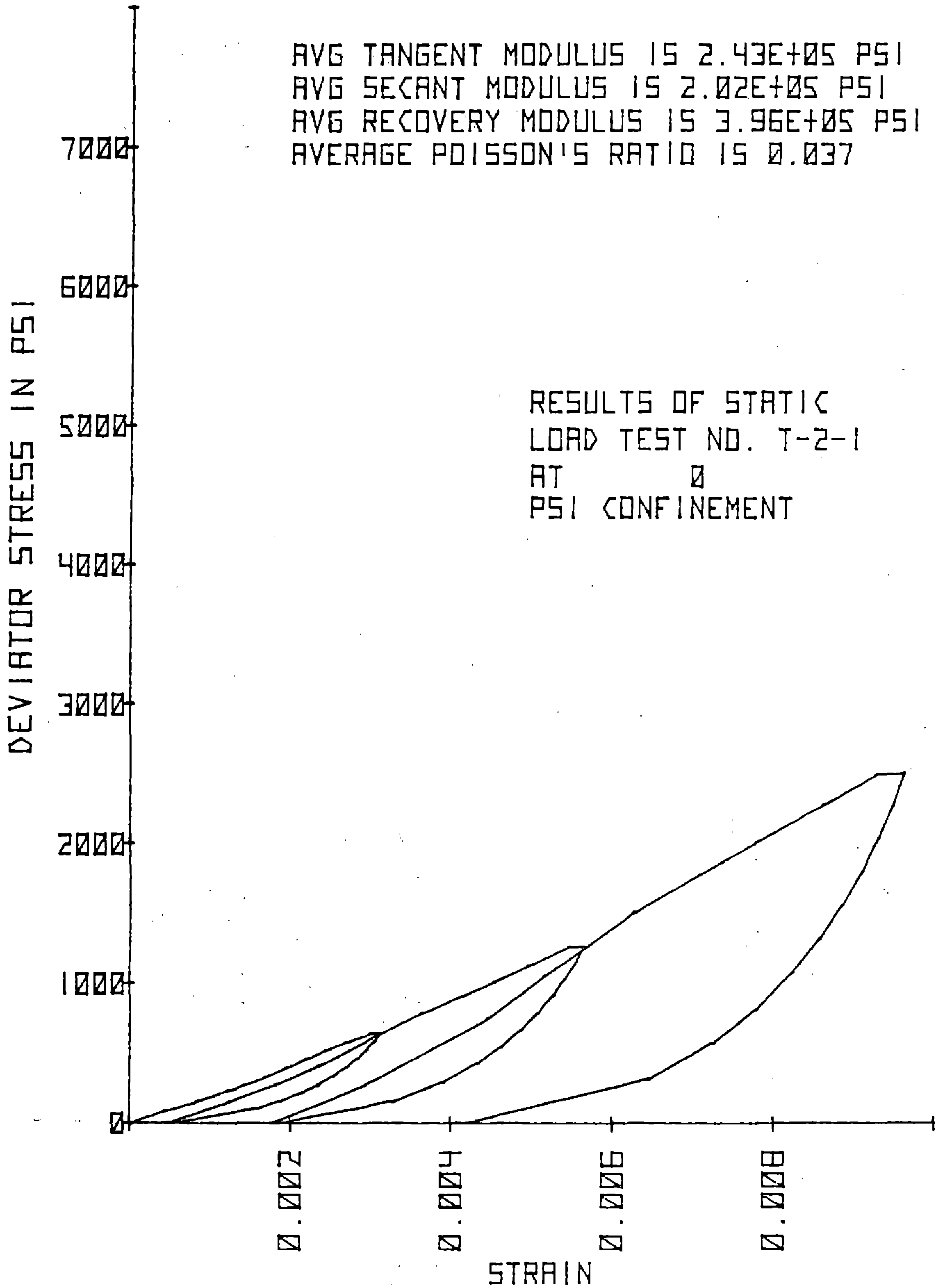


Figure F15. Results of static load test T-2-1 at 0 psi confinement.

b. For slightly weathered rock, average material properties may be summarized as follows:

	Laboratory	In Situ: Parallel to Ga. Ave.	In Situ: 90° to Ga. Ave.
Tangent modulus x 10^6 psi:	.24	.24	.18
Secant modulus x 10^6 psi:	.20	.08	.09
Recovery modulus x 10^6 psi:	.40	1.4	1.9
Poisson's ratio:	.037	--	--

Field and laboratory results are basically in good agreement.

This material exhibits a high degree of viscoelastic behavior and permanent deformation. A moderate amount of time-dependent strain was observed also.

c. The apparent closure of the three boreholes between 107 and 117 feet (inclined depth) indicates a relatively weak zone of rock subject to ravelling or some other form of failure or severe deformation.

d. The bearing capacity of the borehole wall was not exceeded by stresses up to 7500 psi. The stress levels on laboratory samples were 3000 and 5000 psi for weathered and unweathered rock, respectively, and no failure occurred in either case.

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2. "Goodman Jacking Tests," Spokane Mining Research Center. Internal Report for the U.S. Department of the Interior, Bureau of Mines, 1969.

APPENDIX G

ACOUSTIC PULSE-ECHO AND THROUGH-TRANSMISSION SURVEYS

Ted Price
Holosonics, Inc.

TECHNIQUES AND EQUIPMENT

Propagation of seismic and acoustic energy through solids has been studied for many years and is a reasonably well understood process. The use of explosive charges and mechanical-type impactors as seismic sources are the generally accepted techniques for most seismic studies carried out in the world today. Major advances in electro-mechanical sources and other systems, principally in offshore oil exploration, have occurred in recent years which have greatly increased the value of standard seismic data.

Standard seismic systems, however, are limited in attainable resolution by the long wavelength of low frequency energy. By increasing the acoustic frequency from the typical seismic range of 10-100 hertz to the kilohertz range, the wavelength, λ , is smaller, thereby increasing resolution which allows a better definition of observed targets. Applications of high frequency acoustic signals to geologic prediction and evaluation has been slow in coming since by changing the frequency parameters, one is also changing the type of information returned to the receiving transducers. Increasing the signal frequency greatly increases the complexity of the returned signals reflected from faults, cracks, and other acoustical discontinuities in the investigated environment.

Experience has shown that energy from a reasonable acoustical source propagates in the earth to a distance which is typically 30 to 60 wavelengths. This empirical relationship results from a combination of the theoretical attenuation of acoustic energy in solids due to frequency-dependent exponential terms, square law losses, and other scattering processes.

Using an empirical velocity of say, 16,000 feet/second (4878 m/sec) and assuming a maximum required range of sensitivity of 30 feet, the upper frequency limit becomes about 25 kilohertz depending upon the type of structure to be detected. For example, at 25 kilohertz and a rock velocity of 16,000 feet/second (4878 m/sec), the wavelength (λ) of the signal will be about 8 inches. Since the resolution is roughly $\lambda/2$, then in the above case the optimum resolution is about four inches. Lower frequencies, e.g., 8 kilohertz, may be used to increase the sensitive range to nearly 100 feet (30.5 meters), but with a corresponding decrease in resolution.

Holosonics' most advanced Minerals Acoustical Prospecting (MAP) system is an offspring of the original system developed by the company for use in vertical or horizontal drill holes. Designed initially for use in the Coeur d'Alene silver mines, the early probes were compact enough to fit an AX drill hole, and were well suited for BX and NX holes. However, the present system now incorporates an active downhole probe which is limited to NX holes or larger. Probe design and diameters are only limited by frequency which is an inherent characteristic of the ceramic transducer's physical size. Therefore, the lower frequency limits of the MAP system are set primarily by the size of the hole to be probed.

There are two basic modes of operation of the MAP system, the pulse-echo mode and the through-transmission (cross-hole) mode. In the pulse-echo operation, where the survey is done from a single borehole with one probe, essentially the system transmits a pulse of acoustic energy and then receives reflections from veins, faults, or other geological discontinuities within the "scanning window."

The MAP system incorporates a probe unit which is inserted into the drill holes. The probe is specifically designed to give maximum directionality consistent with the desired pressure output (see Figures G1, G2, G3, and G4).

In the through-transmission mode two probes are used, a transmitter in one hole and a receiver in another hole. In both modes of operation, the transmission pulse is controlled so as to establish an initial time (t_0). The initial time, t_0, then becomes the time from which echoes, reflected, or through-transmission energy are referenced thus establishing time-of-flight information for returning signals. The distance which is a function of time and velocity of the structure from the probe and the measured received amplitudes are the types of information obtained by the MAP system. These data are then used for a computer program which provides an accurate reconstruction of the detected anomaly and provides three-dimensional information about the structure.

Acoustical interfaces or reflectors are defined as occurring where a change in the density or elasticity of adjacent media caused a significant change in the acoustic impedance across the boundary. The change in impedance is accompanied by a change in the velocity of acoustical energy. It can be seen that in the geologic environment, a change in rock or mineral types which is accompanied by a change in acoustic velocity will cause reflectance of some of the energy reaching it.

The percentage of the incident energy reflected will be determined by the degree of the impedance mismatch and the angle of incidence. An interface transecting the wave path at any other than a right angle caused mode conversion of the incident energy into reflected and through-transmitted compressional waves as well as reflected and refracted waves which may be shear and/or compressional waves.

However, the geometry of the MAP system is such that given a simple reflecting surface, the reflected energy received must have been radiated from the point on the surface where the wave path was incidental to the surface at a right angle.

In this case there is no loss of incident energy through refraction, and the percentage of incident energy reflected (R) is a function of the change in impedance (Q) calculated as (simplified):

$$Q = pC$$

where p = density

C = acoustic velocity

and,

$$R = [(Q_1 - Q_2)/(Q_1 + Q_2)]^2$$

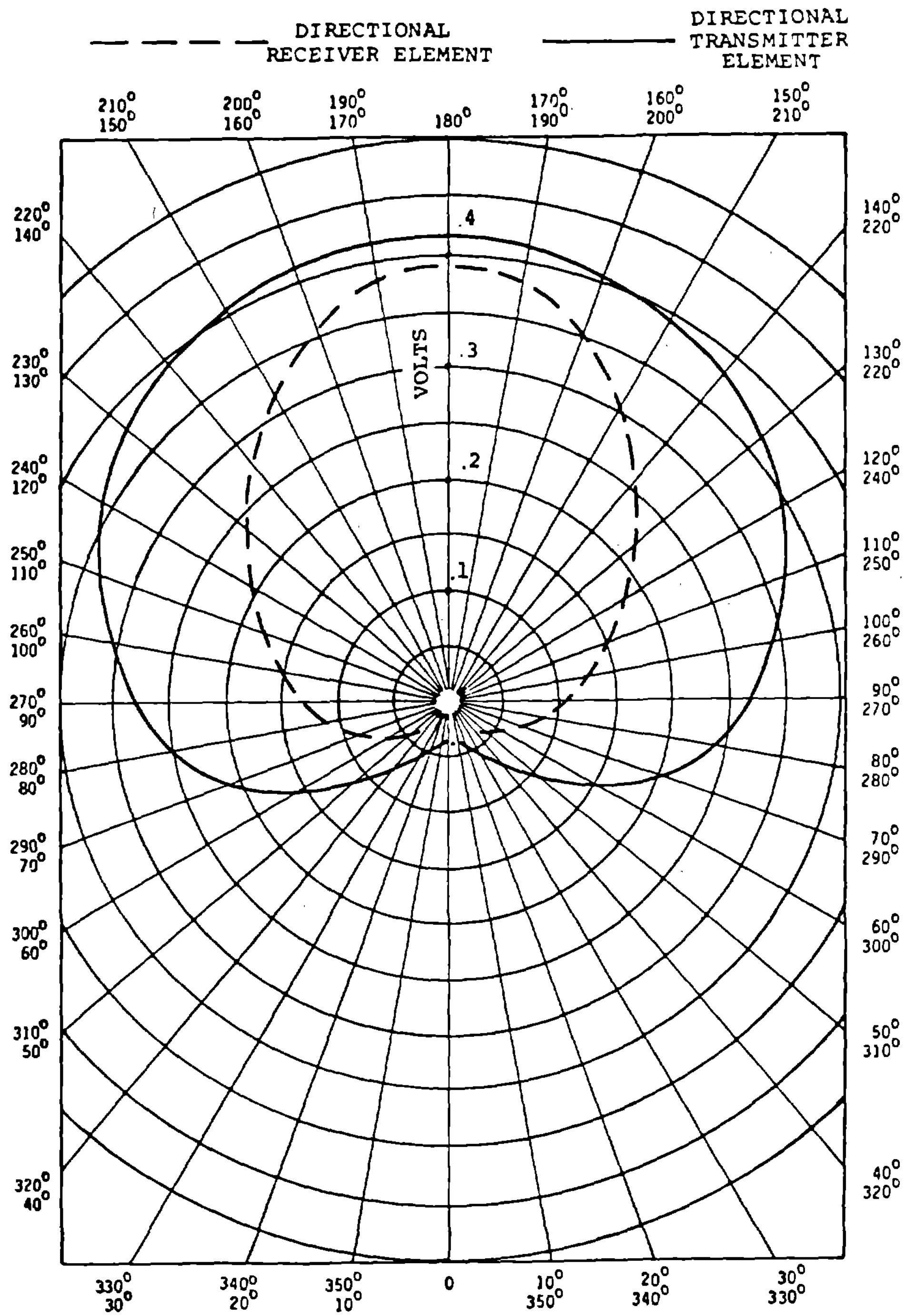


Figure G1. Horizontal beam plot. Directional 25 kHz PZT transducer in a water medium. Horizontal separation between the two elements is 48 inches.

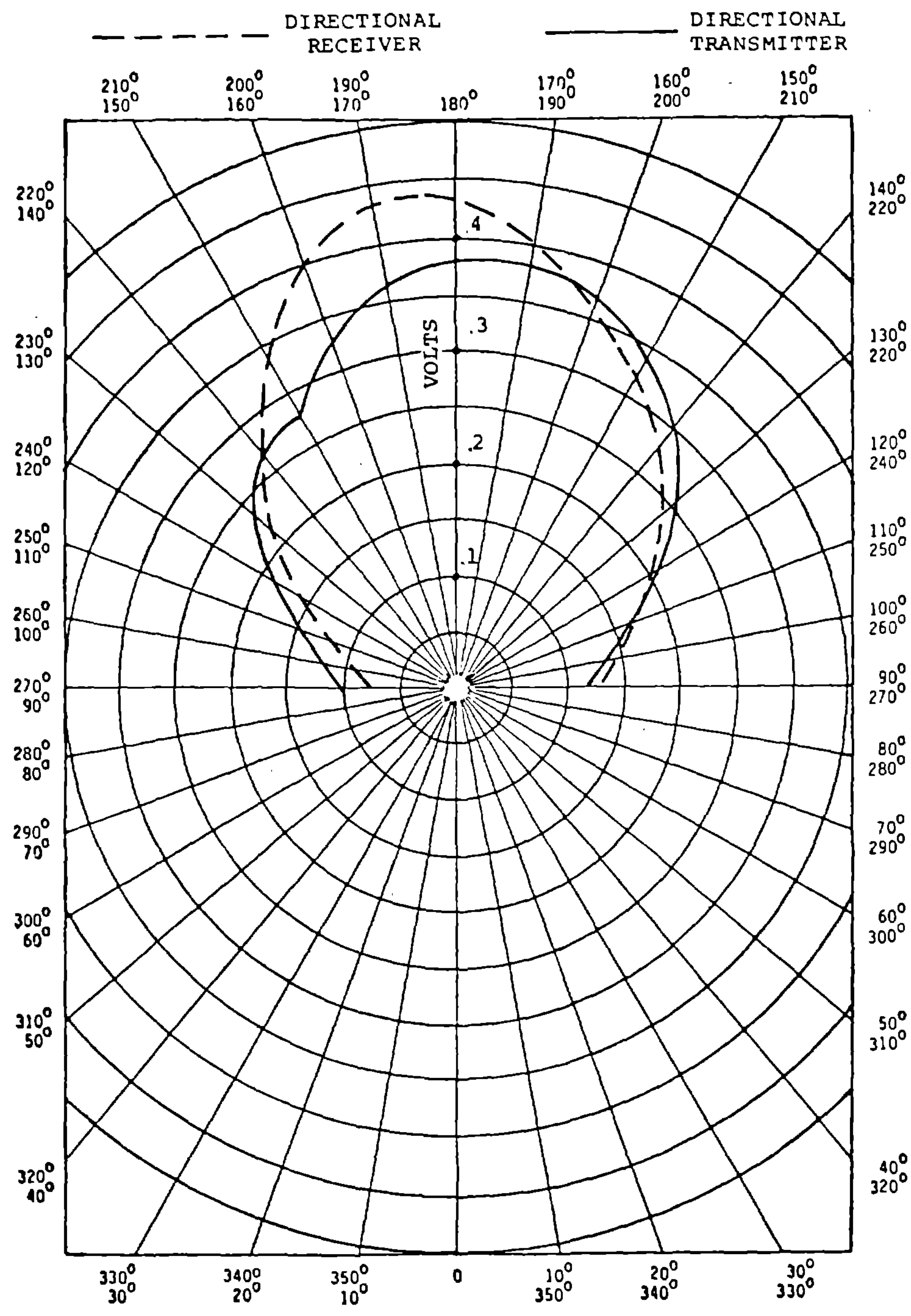


Figure G2. Horizontal beam plot. Directional 25 kHz PZT transducer in a concrete medium. Horizontal separation between the two elements is 120 inches.

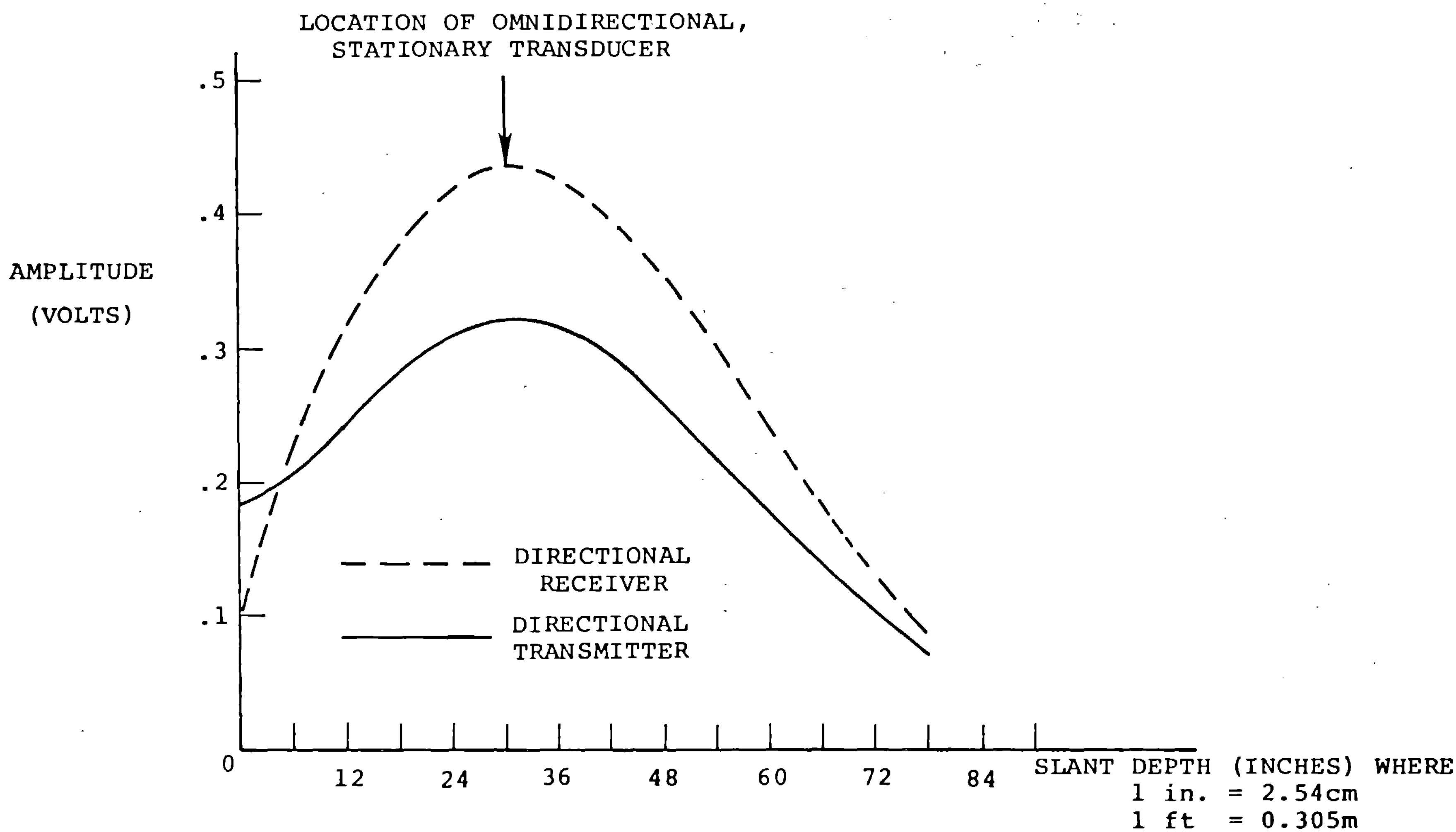


Figure G3. Vertical beam plot. Directional 25 kHz PZT transducer in a water medium. The horizontal separation between the elements is 48 inches.

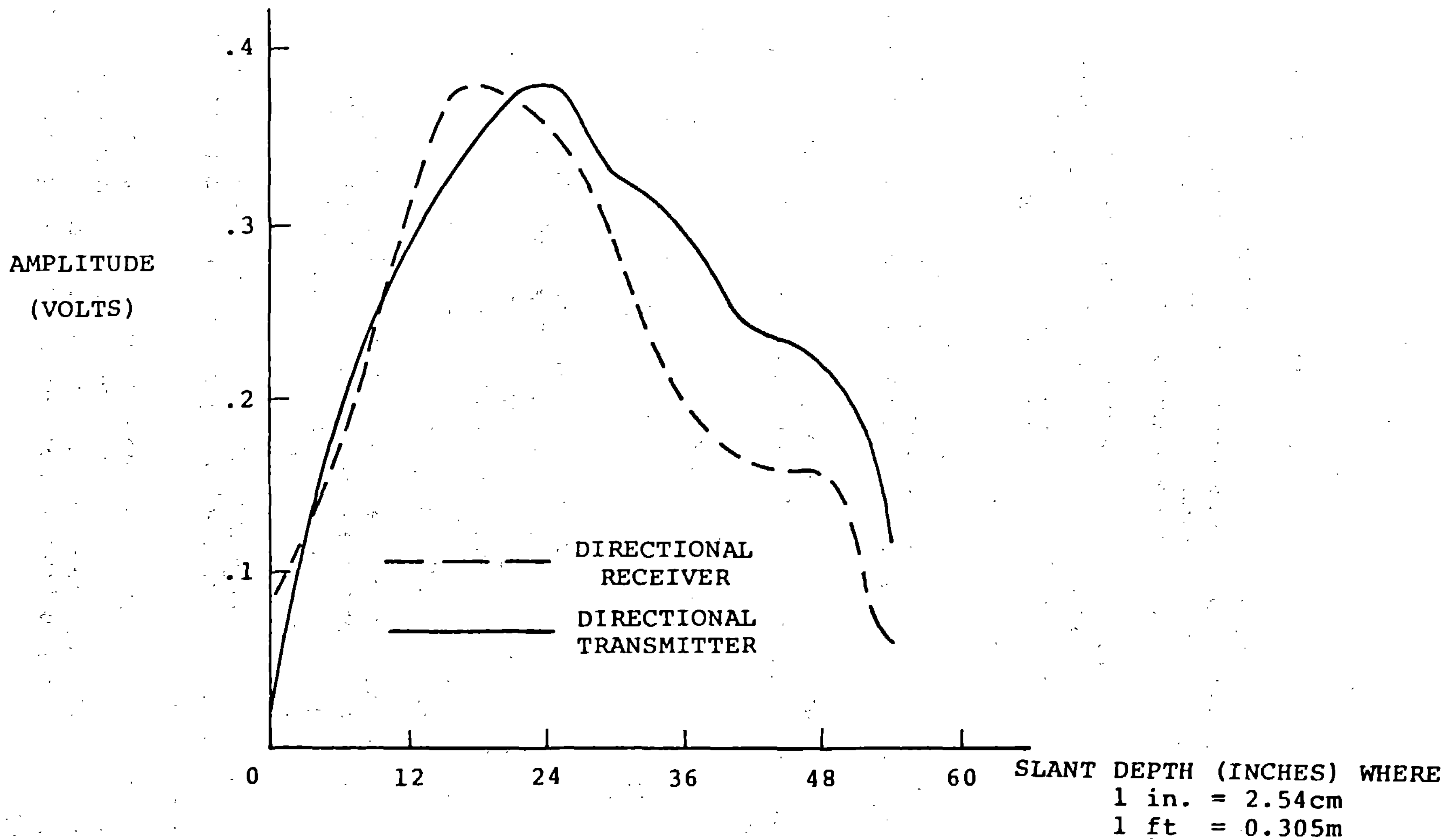


Figure G4. Vertical beam plot. Directional 25 kHz PZT transducer in a concrete medium. The horizontal separation between elements is 56 inches.

Since the incident and reflected wave paths are the same in this case, it is easy to determine distance (d) as:

$$d = 0.5tC_1$$

where t = elapsed time

C_1 = acoustic velocity on the near side of the boundary

Thus, the two recorded parameters are calculated as follows: 1) Distance to the reflecting surface is the elapsed time for the signal's arrival multiplied by the average acoustic velocity, and 2) amplitude of the reflected signal indicates the degree of impedance mismatch across the acoustical boundary.

A probe usually consists of one transmitting and one receiving element. These are both operated on a narrow bandwidth at 8 to 25 kilohertz. In normal operation of the MAP system, the initiation of the transmit signal triggers a trace on system monitors. This trace has a preset time duration corresponding to the maximum anticipated range of the survey under the given set of conditions.

The transmitted signal is fluid coupled or direct-coupled to the rock media. Reflected signals from interfaces within range of the system are picked up by a receiver element, filtered, amplified and displayed at the appropriate time position on the system visual monitors.

Normally, from 10 to 30 discrete signals are recognized depending on the complexity of the structure, the range achieved, and the frequency of the signal (see Figure G5).

The elapsed time for each signal arrival and the signal amplitude are determined. For each survey, these data constitute thousands of bits of information which are provided as input for the computer program to analyze and reconstruct the observed structures.

As a function of the probe design, the acoustical signal intensity is broadly collimated, defining the "acoustic window" extending perpendicularly in only one direction from the axis of the probe (note again the beam plots in Figures G1, G2, G3, and G4). It was noted earlier that the physics of the acoustical wavefront are such that reflected signals will only be received from planes or structures that have a surface roughly perpendicular to the output acoustic signal.

Thus, data are collected in a series of vertical survey points rotated around the drill hole. The computer analysis of the data is normally presented as two opposing survey quadrants such as 0° and 180° orientations, 90° and 270° orientations, giving a volume of data around the drill hole.

The effective range of the MAP system operating at 265 kilohertz varies from 15 feet to 50 feet depending largely on the attenuation characteristics of the rock in which measurements are being taken.

Since the energy density and complexity from near and far reflectors vary over several orders of magnitude (due to the effects of attenuation), specially designed amplifiers and filters are employed. Time variable gain amplifiers such as logarithmic, expontential, or step function types are used depending upon the particular geologic application.

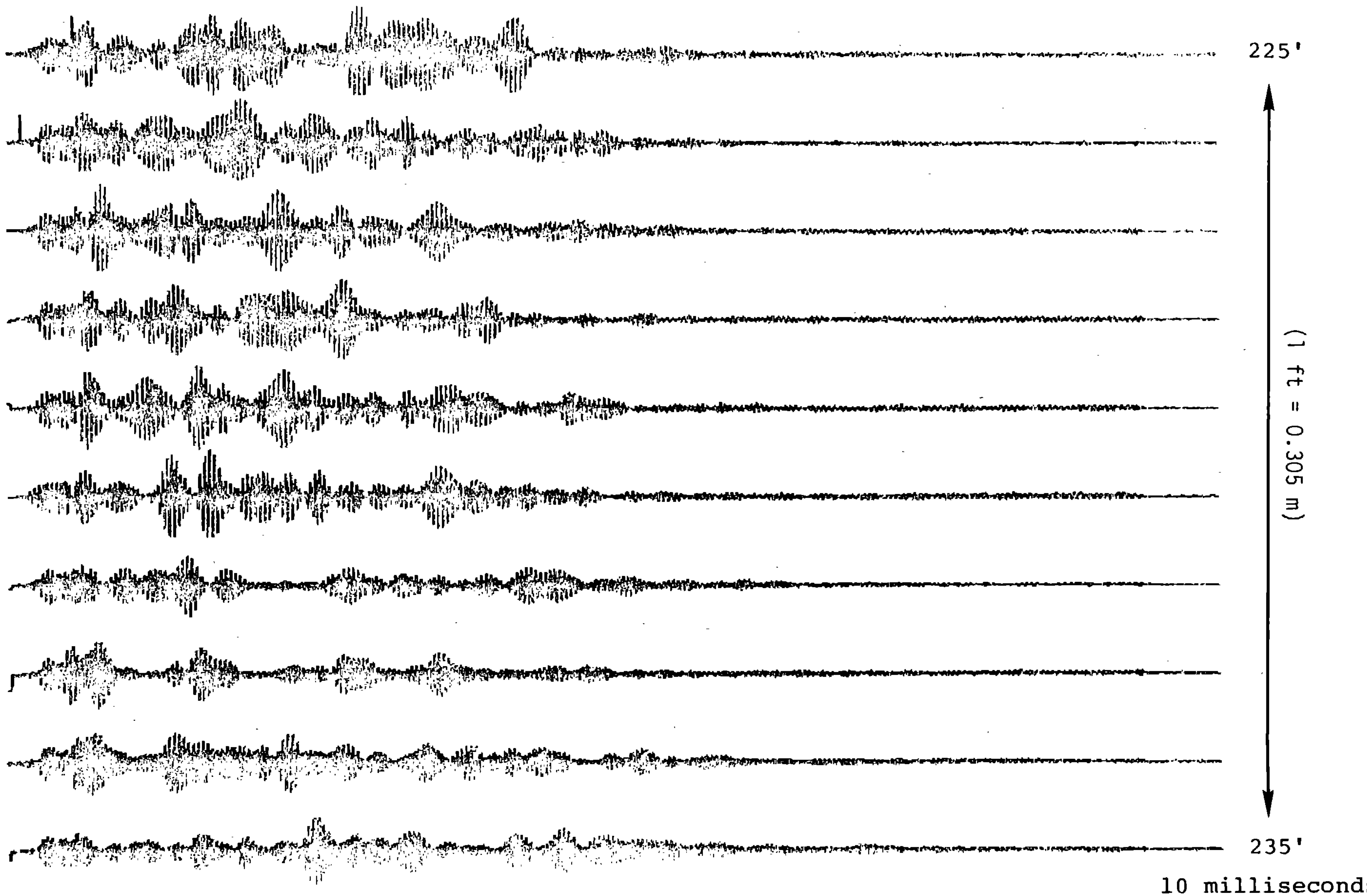


Figure G5. Computer printed pulse-echo signals from Boring T3, Direction #3.
Each trace represents one foot of averaged signals.

Recent incorporation of a microprocessor into the MAP system has significantly simplified field operations as well as subsequent computer analysis. The microprocessor coordinates system triggers, signal averaging routines, probe depth and orientation recording, and digital data storage onto magnetic tape (see Figure G6). The number of transmitted pulses per foot as well as the number of received signal records may be field adjusted to enhance the data and optimize signal-to-noise ratios. The digitized data accompanied with identifying information such as hole number, probe depth and orientation, etc., are automatically stored on magnetic tape.

FIELD PROGRAM

After several drilling delays, notice was received that the site would be ready on August 15, 1977. Our field crew and equipment were mobilized and arrived in Washington, D.C. on August 16. The field equipment was set up and operation checks made. In attempting to take data in the first pair of borings (T-1 and T-2), obstructions were found in both borings preventing a complete survey of the test holes. At this time, the decision was made by the FHWA to discontinue our surveys until the borings could be grouted and redrilled.

When notification was received that the grouting program was complete at the research site, Holosonics' crews were remobilized to the site for survey commencement on September 14 (see Table G1, Field Activity Summary). The surveys proceeded in essentially three phases: 25 kHz pulse-echo, 18 kHz through-transmission, and through-transmission utilizing our high energy sparker probe system.

The logging procedure in the pulse-echo series of surveys consisted of taking data readings at one-foot intervals generally from the bottom of the hole up to the bottom of the casing. Since the acoustical probe in this case is directional, four signal ensembles were derived from each station to cover the four radial quadrants: 0^{o}, 90^{o}, 180^{o}, and 270^{o}. The 0^{o} quadrant by convention is "up" for a horizontal hole and north for a vertical hole. The other quadrants are counted off clockwise looking down the hole.

In the Forest Glen experiment, we designated the northerly probe window orientation as direction N', with directions E', S', and W' corresponding to the 90^{o} clockwise rotations. This orientation scheme centered the acoustic window of the probe at about N12^{o}W for direction N', which is the same orientation as the line of boreholes.

The basic procedure adopted at this site was to log the hole from the bottom up, keeping the probe oriented in only one direction, but firing the probe four times per foot. The microprocessor would average the four signals obtained per foot and then write the digitized averaged data for that particular directional orientation and depth onto magnetic tape. This procedure was duplicated in all four directional orientations and in each of the borings.

Since the microprocessor is linked to the depth measuring servo system, all the data labeling on tape is accomplished by the microprocessor. The operator need only to define the initial parameters, such as hole number, directional orientation, depth increments, pulses per foot, pulses per average value, logging direction, and starting depth for the microprocessor to automatically run the system. Because the data on the magnetic tape is labeled and digitized, it is directly compatible with computer input.

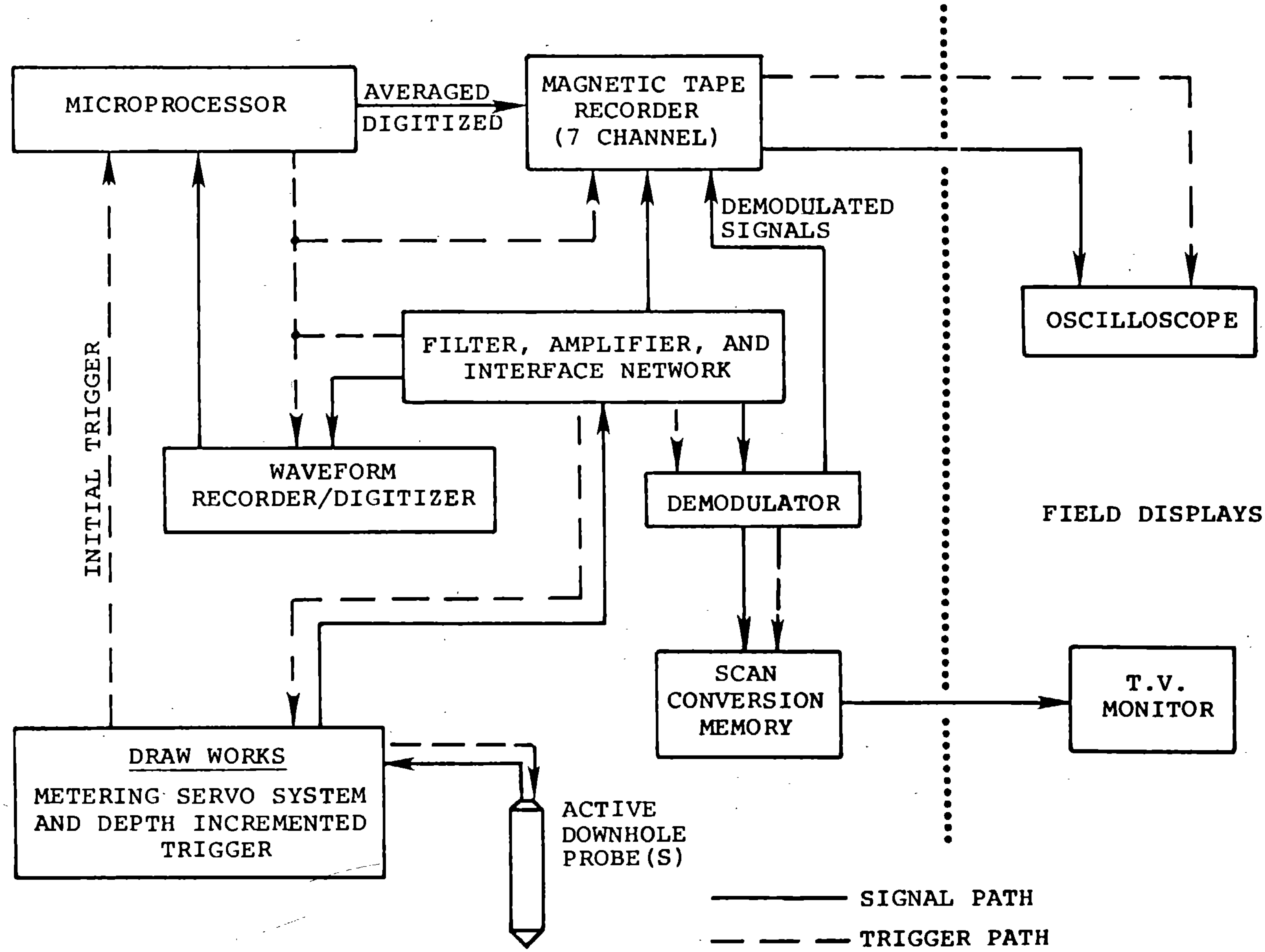


Figure G6. Block diagram of the acoustical survey data acquisition system.

Table G1. Field activity summary.

Date	Activity
9/12/77	Mobilization of the crew from Richland, WA to Washington, D.C.
9/13/77	Equipment set-up and operational check at the field sites.
9/14/77	Pulse-Echo surveys in Boring T-1, all four quadrants, in one foot increments, from 80 to 235 feet inclined depth.
	Pulse-Echo surveys in Boring T-2, all four quadrants, in one foot increments, from 80 to 260 feet inclined depth.
9/15/77	Pulse-Echo surveys in Boring T-3, all four quadrants, in one foot increments, from 80 to 260 feet inclined depth.
	Briefing and equipment demonstration on site.
9/16/77	Equipment modifications were made so that data gathering would be compatible with a high intensity 20 kHz electromagnetic noise problem created by the Navy at Annapolis during the weekend.
9/17/77	Pulse-Echo surveys in Boring BRP-27, all four quadrants, in one foot increments, from 100 to 260 feet inclined depth.
9/18/77	Through-Transmission (cross-hole) set-up for 18 kHz crystal probes.
	Surveys:
	T-2 T-1 from 235' to 45' T-2 T-3 from 260' to 100' T-3 T-1 from 235' to 120' T-3 BRP-27 from 260' to 140' T-2 BRP-27 from 260' to 150' T-1 BRP-27 from 235' to 200'
9/19/77	Through-Transmission surveys using the high energy sparker probe.
	Surveys:
	T-1 BRP-27 from 235' to 180' T-3 BRP-27 from 160' to 140' T-3 T-1 from 160' to 70'
	Equipment dismantled and packed.

Note: 1 ft = 0.305 m

Borings T-1, T-2, and T-3 were all logged without incident in two days, but as BRP-27 was being logged initially, a significant 20 kHz noise problem developed. After some investigation, it was determined that the probable source of the 20 kHz electromagnetic noise was the U.S. Navy undersea communications center at Annapolis. Because the frequency of the noise was so near our operating acoustical frequency, electronic filtering techniques were not satisfactory. However, with some minor downhole preamplifier modifications along with the installation of a grounded wire mesh around the transducers, the noise level was reduced to an acceptable level. The remaining pulse-echo surveys in Boring BRP-27 then proceeded smoothly without further incident.

The first through-transmission surveys were done utilizing an 18 kHz PZT transmitter. At this frequency, greater rock penetration may be achieved than in the 25 kHz pulse-echo surveys. A corresponding loss in resolution will occur. However, the primary purpose of the through-transmission surveys is to establish the first arrival time of the compressional and shear waves; therefore, the decrease in resolution is not detrimental.

Two probes are utilized in the through-transmission mode, each being in a different borehole, but maintained at the same depths. As in the pulse-echo surveys, it was decided to fire the transmitter probe four times per foot and average four signals at a time. To accomplish this, the microprocessor was set up with control parameters similar to those used in the pulse-echo surveys. This averaging technique which resulted in one averaged and digitized signal per foot enhances the signal-to-noise ratio substantially (see Figure G7).

All the possible through-transmission hole combinations were logged (see Table G1, 9/18/77). The shallowest depth able to be logged with the PZT probes is dependent on the rock quality and hole separation distance. That is, as the probes come up hole, rock quality typically decreases and signal attenuation increases, therefore establishing an upper depth limit for detectable signal transmission.

In the upper portions of the holes, especially over the greatest horizontal distances, it was necessary to use Holosonics' downhole sparker probe as a high energy transmitter. Examples of the type of signals derived from the sparker surveys may be seen in Figure G16. Table G1 lists the holes and depths surveyed with the sparker system.

Field displays for on-site analysis include a scan conversion memory where filtered and conditioned records may be stacked and displayed. Signal arrival times versus depth relationships may therefore be observed in "real time." Conventional oscilloscope displays of raw data are also monitored. Figure G8, for example, is the scan converter display of the pulse-echo survey in Boring BRP-27, directional orientation N' (north). Note the structural features dipping away from the borehole in the upper portion of the displays. The vertical scale is 60 feet and the horizontal scale is operator adjustable, and in this case was set at six milliseconds. Six milliseconds are quickly converted to about 55 feet assuming a velocity of 18,000 feet per second (5487.8 m/sec) and a two-way signal path as in the pulse-echo surveys. Therefore, taking into account the exaggerated horizontal scale, the structural features agree well with mapped joint trends in the area.

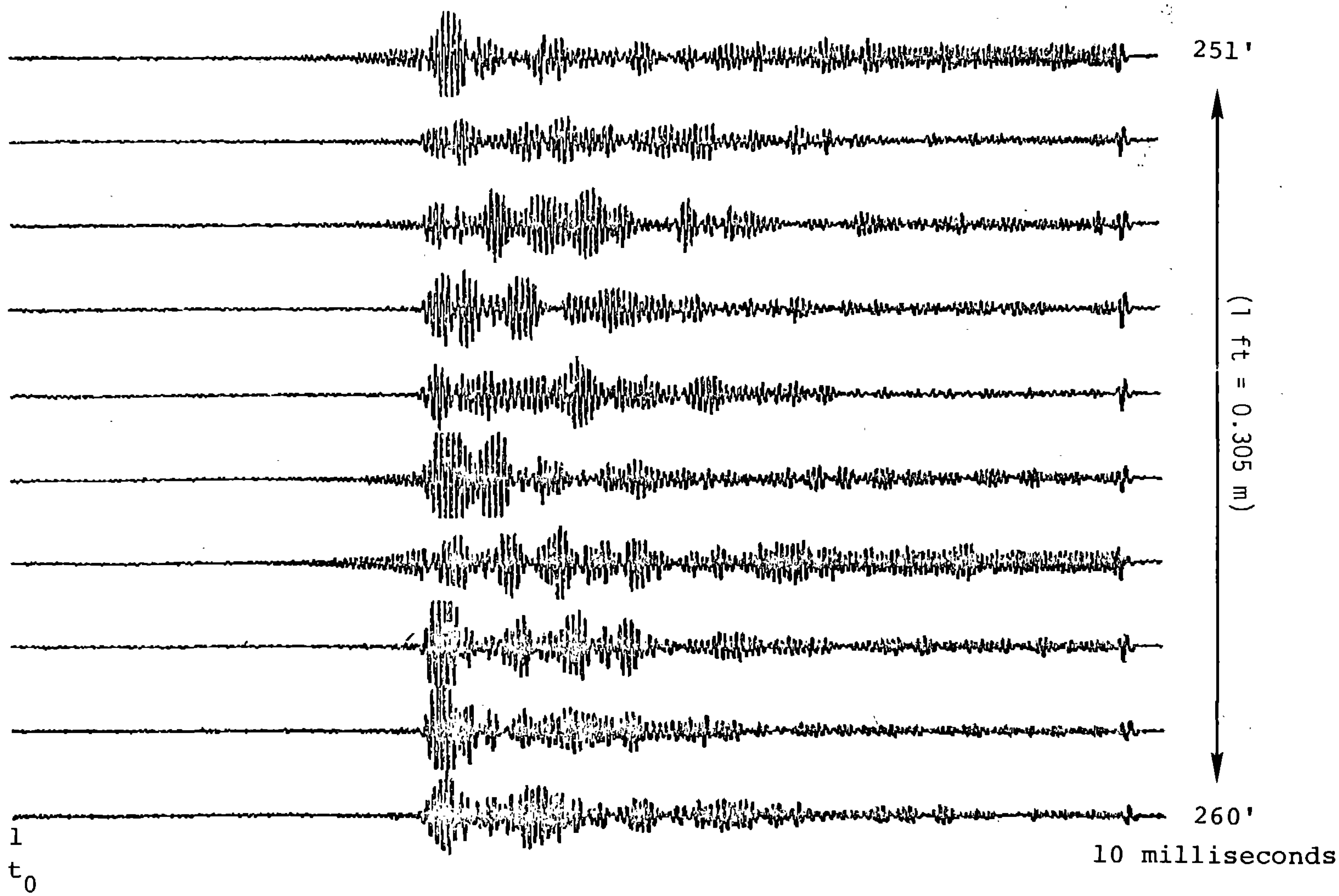


Figure G7. Computer printed through-transmission signals from survey T2 → T4. Each trace represents one foot of four averaged signals.

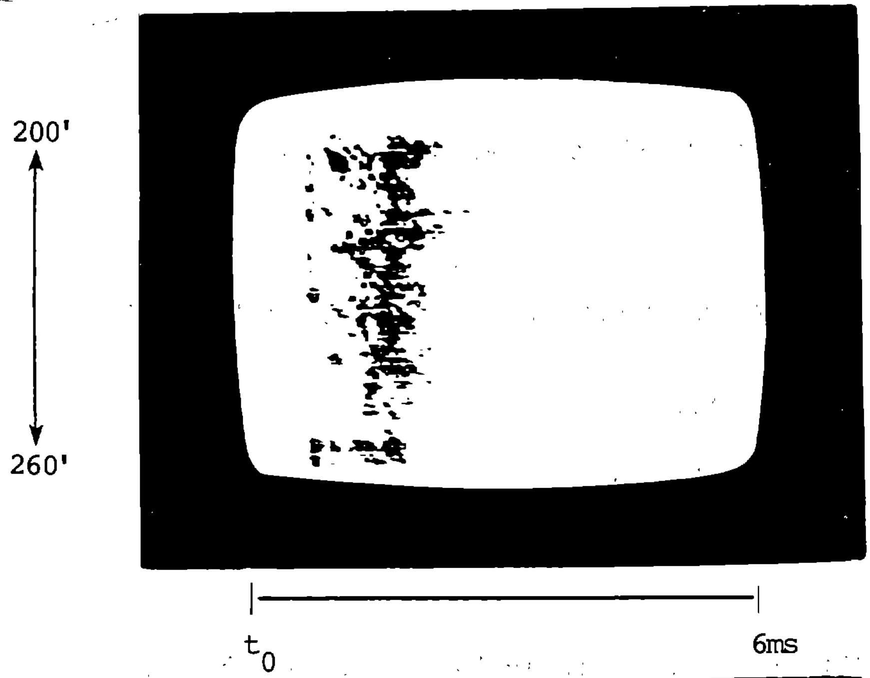


Figure G8. Scan converter field display of the pulse-echo survey, direction N', Boring BRP-27.

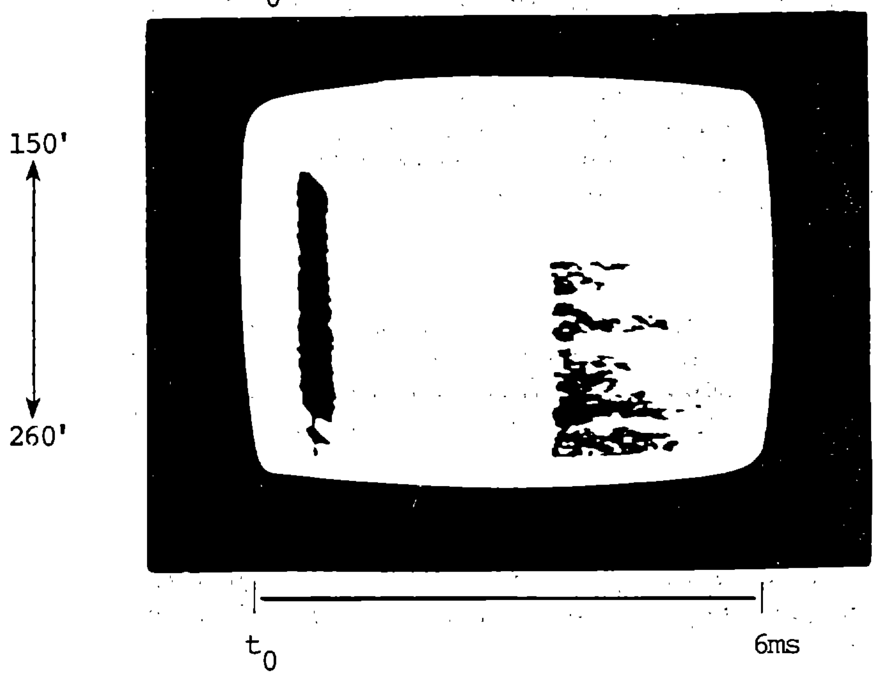


Figure G9. Scan converter field display of the through-transmission survey, T2 → T4.

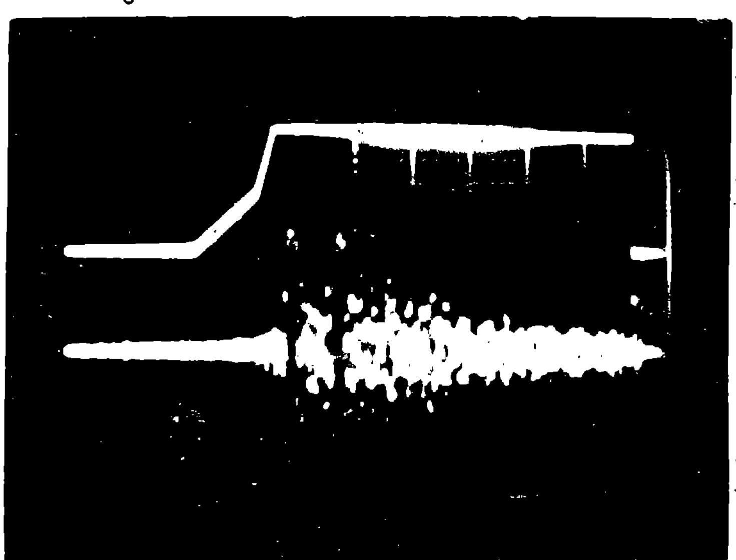


Figure G10. Oscilloscope field display of the 260-foot depth, through-transmission survey T2 → T4. The scale is one millisecond/division and two volts/division.

(1 ft = 0.305 m)

Figures G9 and G10 represent through-transmission data as seen on the scan converter display and on the oscilloscope.

DATA PROCESSING METHODS

Processing of the raw field data to derive final acoustical survey logs consists of four major steps:

1. Computer input and data record editing.

2. Signal range and amplitude determination.

3. Correlation of meaningful reflection sets.

4. Data plotting.

The general methods used to accomplish these steps are discussed below. Each of the major steps consists of one or more individual programs which are run sequentially by the data analyst. Provisions are made for the analyst to vary the programming parameters by use of keyboard entry. Parameters may be varied to take into account changing physical conditions such as velocity or time scale settings, or to affect the final data analysis by being more or less restrictive on the amount of data accepted as valid or the number of aligned signals necessary to represent a true reflecting surface.

Computer Input and Data Record Editing

The first step in analysis is to read the digital data into the computer. The second step involves only minor editing in which the analyst verifies the data headings and organization as printed on a line printer. Any points where data are redundant, missing, or otherwise unsatisfactory, are corrected at this time by using an editing program to correct the data file.

Signal Range and Amplitude Determination

This program assumes that the arrival of energy will always result in an increase in the rate of energy arrival. Therefore, the slope of the raw data curve will increase each time energy arrives at the receiver.

The data are smoothed by taking a running average over the data record. The program then computes the first and second derivatives of the resulting data. At each point where the first derivative is significantly greater than that of surrounding values, the range of an energy reflection is noted. The amplitude of the energy reflection is chosen as the amplitude at which the slope of the raw data curve next becomes minimal (except in cases where the slope is negative). When the slope is negative, the amplitude is taken as the amplitude of the raw data curve at the time of maximum (least negative) slope. The program then writes an output record consisting of depth, probe orientation, and a list of the ranges and amplitudes of each reflection.

Correlation of Meaningful Reflection Sets

This program assumes that noise and energy arriving from scattering will arrive at (more or less) random time intervals, whereas energy arriving from a fixed target will arrive at range intervals consistent with changes in probe position.

The program first reconstructs data records from the range information obtained from the above described program. Next the program in effect computes cross correlation functions between a record consisting of all zeros except the single data point being evaluated, and the records above and below it. The resulting cross correlations are evaluated for consistent values by means of a voting system. Those data points which do not meet minimum standards of consistent position are discarded. The reflections which are retained are then stored on output records consisting of depth, probe orientation, range of reflection, amplitude of reflection, lag value at which the best "line up" with other reflections occurred, and the number of "votes" the reflection received. The number of votes is a relative measure of how well each reflection lines up with reflections above and below.

Data Plotting

Looking at the computer outputs, it can be seen that there are many short line segments plotted (see Figure G11, for example). Under the controls set in the voting program, each line segment represents a match-up of five signals in a line. The length of each line is a function of the "votes" the reflection received. This is a very restrictive constraint. A large percentage of the signals received and detected by the peak detection algorithm is rejected because of insufficient votes in the voting algorithm. The longer the line segment, the greater the degree of reliance placed on it. The orientation of the line represents the angle at which they best line up with reflections above and below. The center of the line is at the depth and range at which reflection was received.

From this it should be recognized that each line segment plotted is a significant acoustic signal, having been seen from five consecutive survey depths along the hole. When several of these line segments can be matched up to form a continuous line, or a broken line with a strong directional trend, this is truly valid and significant information.

Figures G11 and G12 show the change in the amount of data plotted caused by a one-step reduction in the voting restraint. The factor used to compute and plot in Figure G12 was .7 (on a scale of 0.0 to 1.0). Figure G11 was computed with a voting restraint of .6. Note the increase in data plotted. Note also that the data have not been changed by reduction in the vote factor, but additional data have been added. Every line segment plotted in Figure G12 is also plotted in Figure G11.

The decision to use one or the other of the vote restraints is a subjective decision. A geologist familiar with the use of acoustical survey data might desire the extra information provided by a smaller vote factor to assist his interpretation of the geology. Another person might wish to have the less detailed presentation. In fact, this could be carried to extremes by increasing the restraints so that only three or four lines appear on the plot, but this extreme is usually counter-productive.

Since many reflections come from energy which is traveling along the wall of the hole instead of through the formation, these reflections have a strong tendency to obscure the reflections of interest. These reflections are distinguished by the fact that they move approximately the same distance in range that the probe is moved along the borehole. The plotting routine discards information which indicate a target that makes a true angle with the borehole greater than fifty degrees.

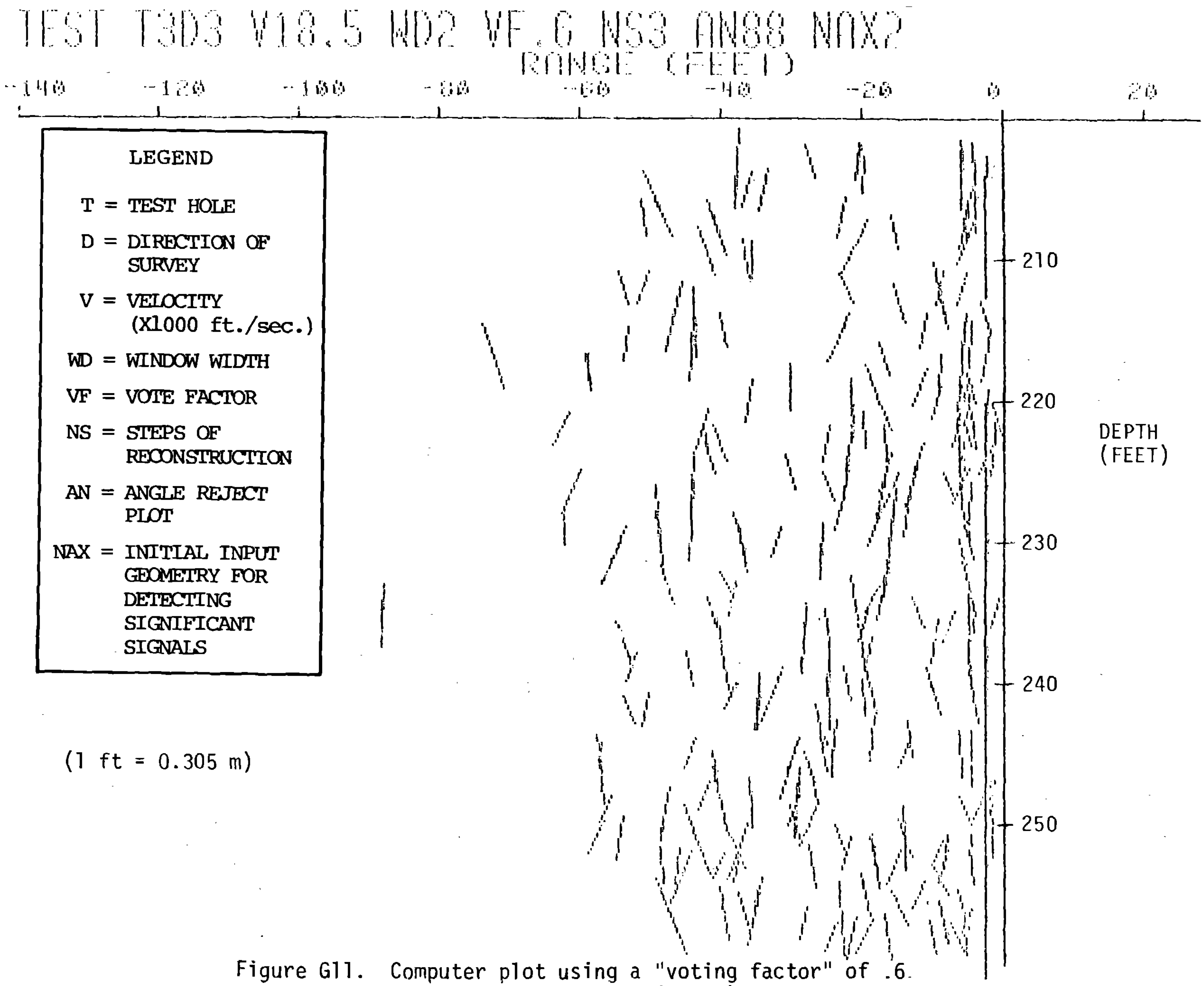


Figure G11. Computer plot using a "voting factor" of .6. Boring T3 direction 3 (south).

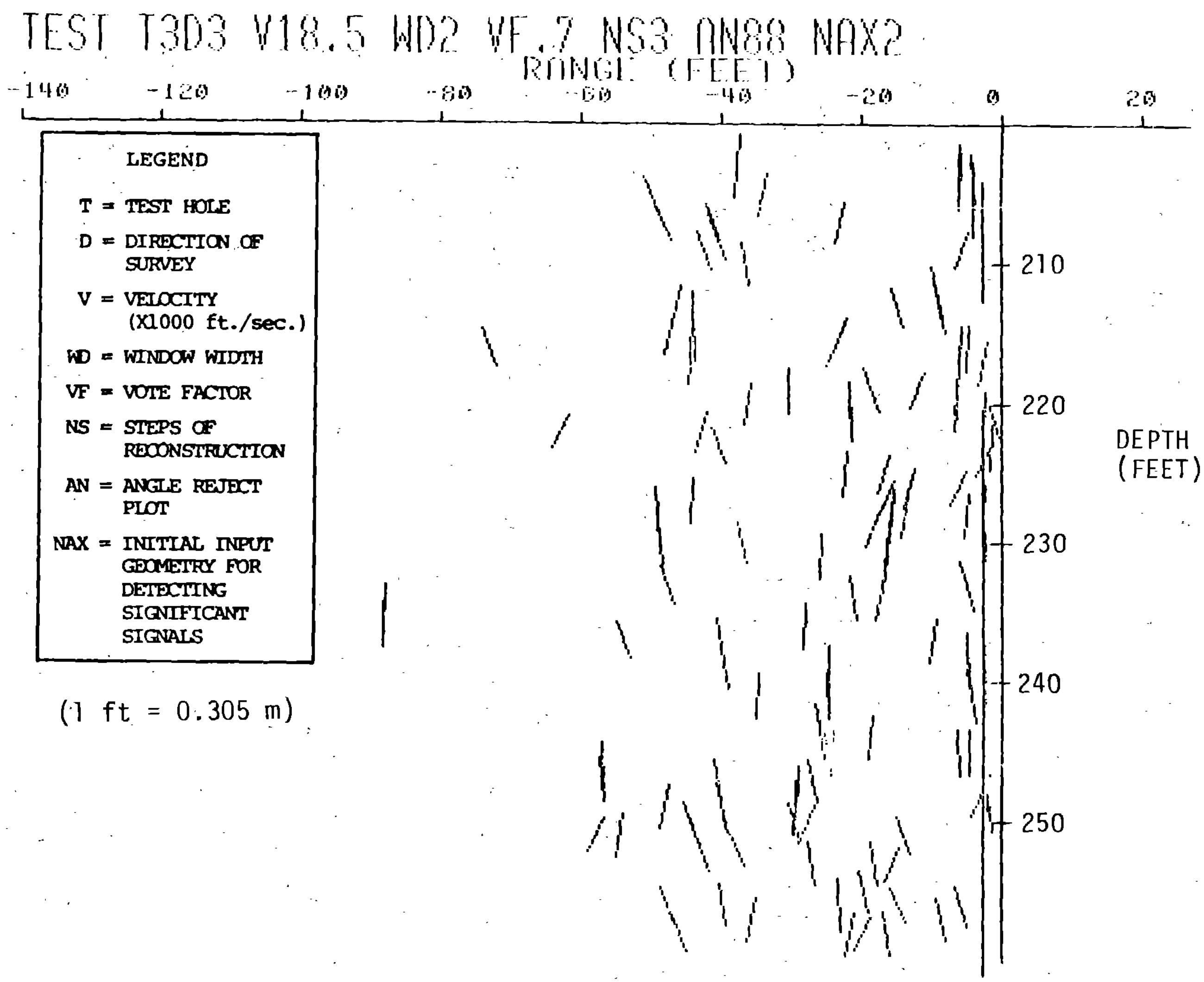


Figure G12. Computer plot using a "voting factor" of .7
Boring T3 direction 3 (south).

Capability also exists to plot the output records of each major step of the data processing system. This enables the analyst to go back through any set of data if the final output is not as expected, and to check the handling of the data for computer read errors or other malfunctions.

These data processing procedures are used for both pulse-echo and through-transmission surveying. The through-transmission analyses differ in that a subroutine can stack data before the correlation program is available for use, and the final data plotting presents the data in terms of velocity versus boring depth as opposed to range versus reflection horizon.

SURVEY RESULTS

Through-Transmission

As described, a total of nine through-transmission surveys were conducted on September 18 and 19, 1977. Six of the surveys used a matched pair of 18 kHz phased array probes, and the remaining three utilized our high energy sparker probe system. The six 18 kHz surveys were conducted to collect data between each of the 4 borings (3 surveys T-2 → T-1, T-2 → T-3, T-3 → BRP-27) and to collect data which overlapped the borings (3 surveys T-3 → T-1, T-2 → BRP-27, T-1 → BRP-27). The overlapping surveys provide an excellent check for determining an average velocity across the entire survey area and in describing any lateral variations in acoustic velocity.

The high energy sparker system was utilized for resurveying the "long distance" data (T-1 → BRP-27) and to determine acoustic wave velocity at shallow depths where the standard 18 kHz cannot penetrate between borings.

Standard through-transmission surveys produce three basic types of data. One, if a constant velocity is assumed for a given zone of interest (based on rock core examinations or other input) relatively detailed data can be obtained on borehole deviation; second, if boring survey data are available, detailed plots of acoustic wave velocity can be made; and thirdly, by examination of received signal strength, inferences on rock quality and/or location of crushed or broken rock zones can be produced.

Under this program, the through-transmission survey was utilized to produce acoustic wave velocities needed for analysis of pulse-echo surveys. Having quality data on the subsurface acoustic velocity eliminates an important variable in the solution of the pulse-echo equation, thereby increasing the validity of interpreted results.

A secondary purpose for these tests was for deriving data on the nature of the rock between the borings. The data produced from these surveys have proven to be of limited value for this purpose due to the highly complex and layered nature of the subsurface. That is, the borings were drilled perpendicular to the general foliation which creates a layered appearing medium to the high frequency acoustic waves. Because the layering is parallel to the acoustic wave propagation direction, the potential for wave guides exists. Further, the different rock fabric associated with the layering will cause changes in the acoustic propagation properties when different fabrics are encountered. The net result is that a piece-wise continuous arrival time curve is created. Compressional wave velocity (first arrivals) can be obtained from the records, but arrivals of the shear waves can become masked because of the multitude of other signals after the first arrival (reflections, etc.).

Figure G13 shows the results of one of the through-transmission surveys conducted. Interpreted P and S wave velocities are shown on the record. These values were determined based on the velocity profile and an artificial pulse-echo record created from the through-transmission data (Figure G14). Notice the scattering of data after the p-wave arrival showing reflections and other complicating data. Data from other through-transmission surveys are contained in Appendix A.

Figure G15 shows some raw data plots from the sparker through-transmission surveys. Notice that a strong first arrival can be seen above the background noise. This represents a p-wave velocity of approximately 16,000 feet/sec (4878 m/sec). Figure G16 shows the computer output after velocity analysis. It can be seen that the analysis is ineffective. This is due to the low frequency of the sparker data as compared to our 18 kHz data. The present computer analysis is based on high frequency reduction methods and is presently ineffective on low frequency data.

The resultant through-transmission analysis from all surveys is contained in Appendix A as noted. In general, these surveys indicate a lateral increase in p-wave velocity from approximately 16,000 feet/second (4878 m/sec) at Boring 1 to above 18,000 feet/second (5487.8 m/sec) at Boring BRP-27. Generally, the borings have a constant velocity from the bottom of the hole to around 160 feet depth (borehole depth) where the velocity begins to decrease. This suggests that the north end of the survey area has lower quality rock than the southern end and that the penetration of weathering and rock deterioration is to a depth of approximately 160 feet (borehole depth).

Pulse-Echo

Four complete surveys were conducted in each of the four boreholes resulting in a total of sixteen pulse-echo surveys during the three days of September 14, 15, and 17, 1977. In all of the surveys, a directional 25 kHz PZT transducer assembly was used. Each of the four quadrants around the boreholes are represented by one of the four survey orientations. The four quadrants, designated by directions N', E', S', and W' are aligned with the orientation N12°W, N78°E, S12°E, and S78°W, respectively. As can be seen on the transducer beam plots defining the "acoustic window," each quadrant is reasonably well represented.

The survey orientations were chosen so that directions N' and S' would overlap between different borings since these two directions correspond to the line of boreholes. The overlap of data provides a means of verifying detected structures between borings. The survey orientations also place the "acoustic window" nearly normal to the strike of the major joints as depicted by Mueser, Rutledge, Wentworth and Johnston's Joint Diagram of the Forest Glen Station.

Figures G17 and G18 are reproductions in reduced scale of typical computer output with the best signal parameters for interpretation. Additional computer outputs, using different plotting parameters in conjunction with these, enhance the final interpretation. Figure G17 is a pieced together composite of a portion of Boring T-3 representing directions N' and S', and Figure G18 is a composite of a portion of Boring T-3, directions E' and W'. The center line represents the borehole (equivalent to the initial transmit time t_0) and the range of the reflectors to the left and right of the borehole is defined by the acoustic velocity determined in the through-transmission surveys.

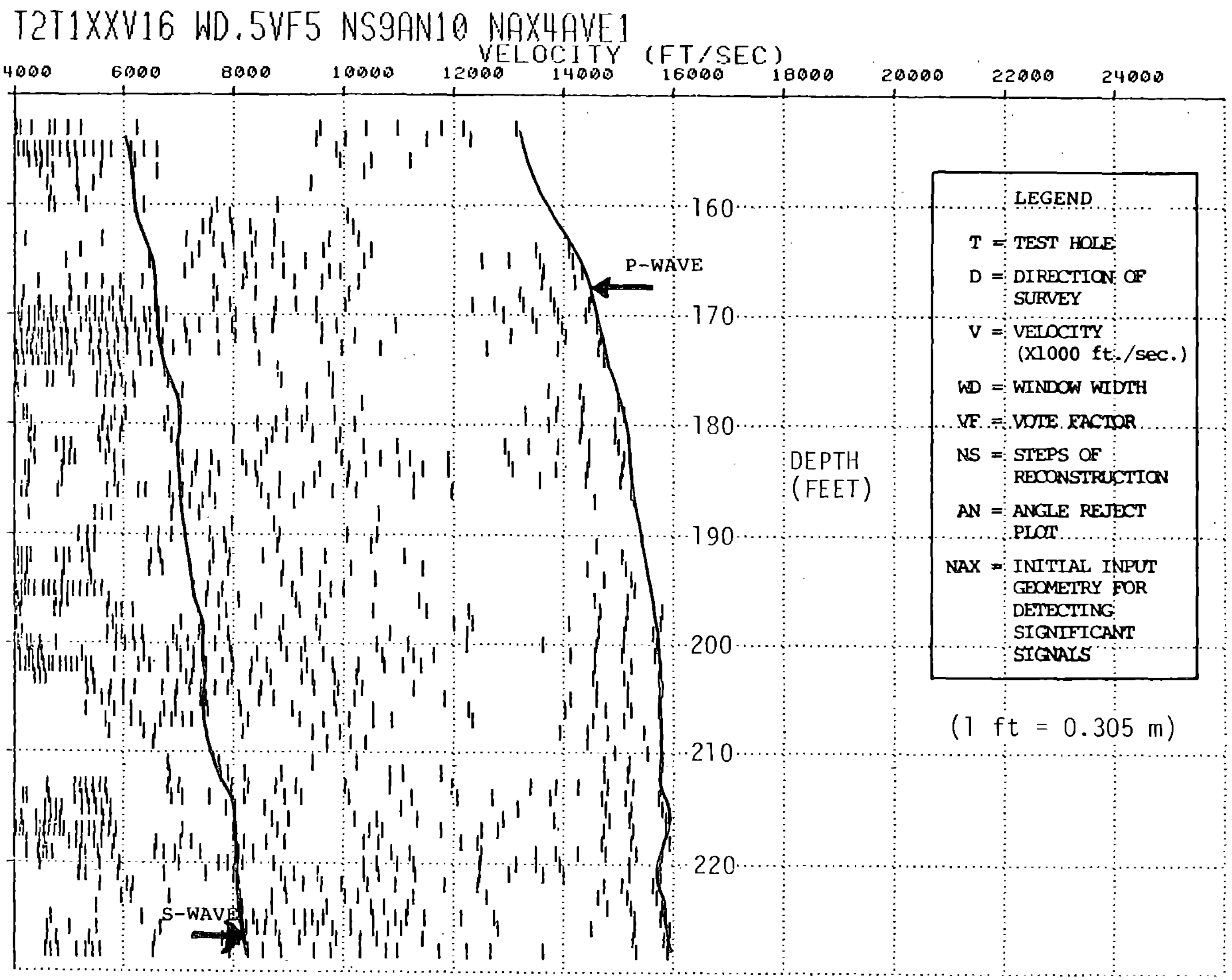


Figure G13. 18 kHz through-transmission computer velocity plot from Boring T2 to T1.

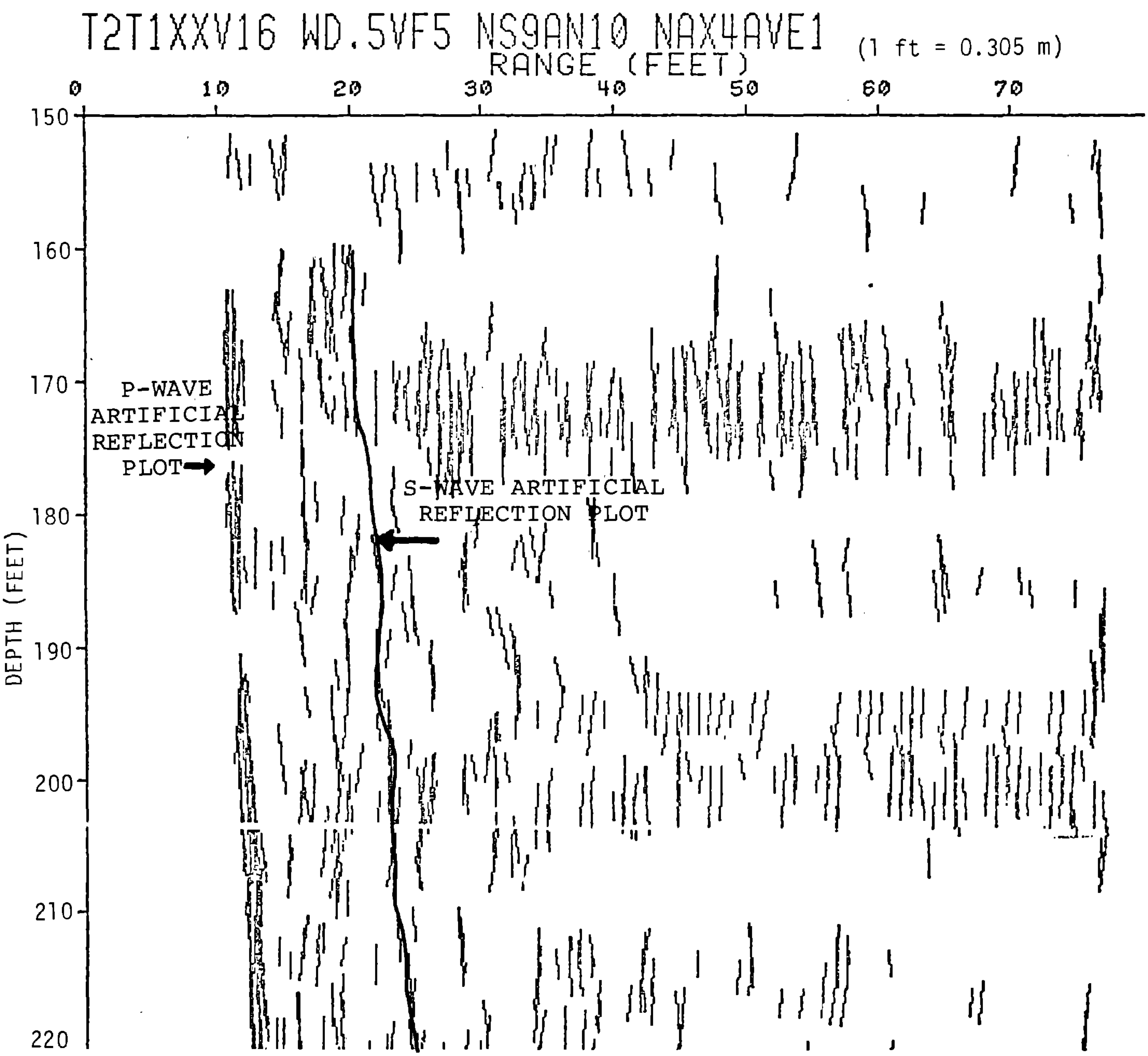


Figure G14. Artificial pulse-echo record created with through-transmission data from Boring T2 to T1.

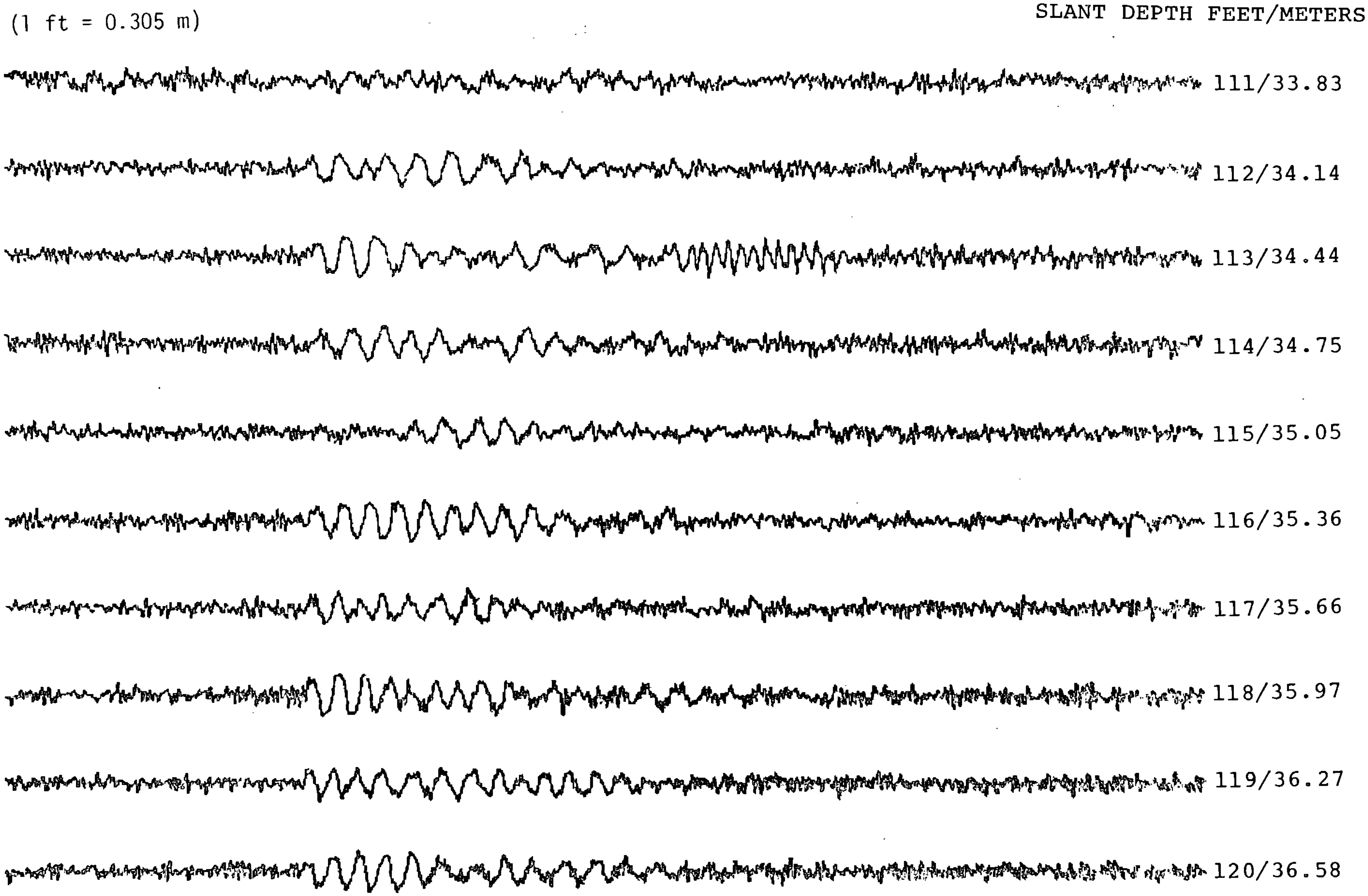


Figure G15. Sparker through-transmission raw data plots for Borings T3 → T1.

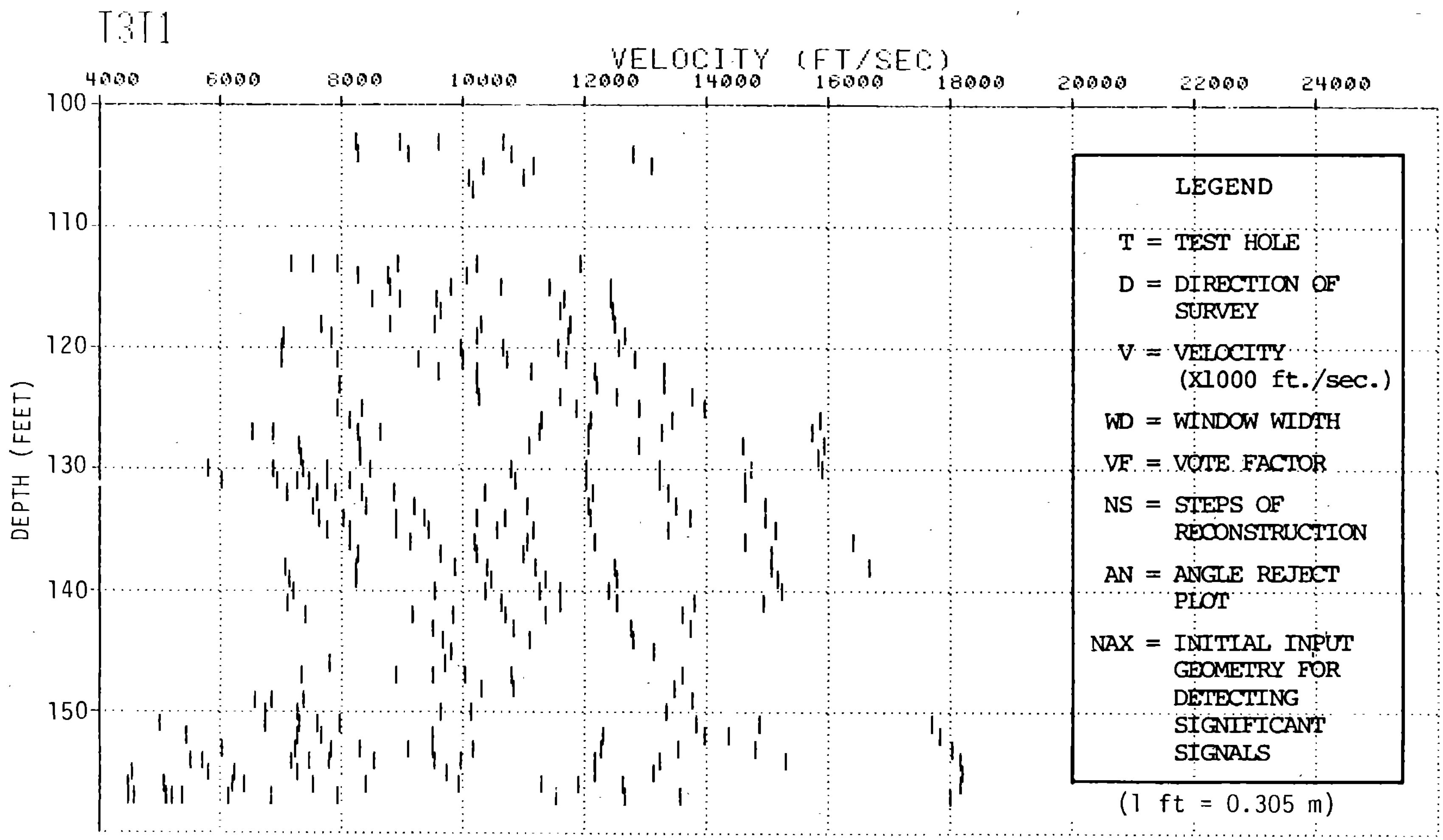


Figure G16. Sparker through-transmission computer velocity plot from Boring T3 → T1.

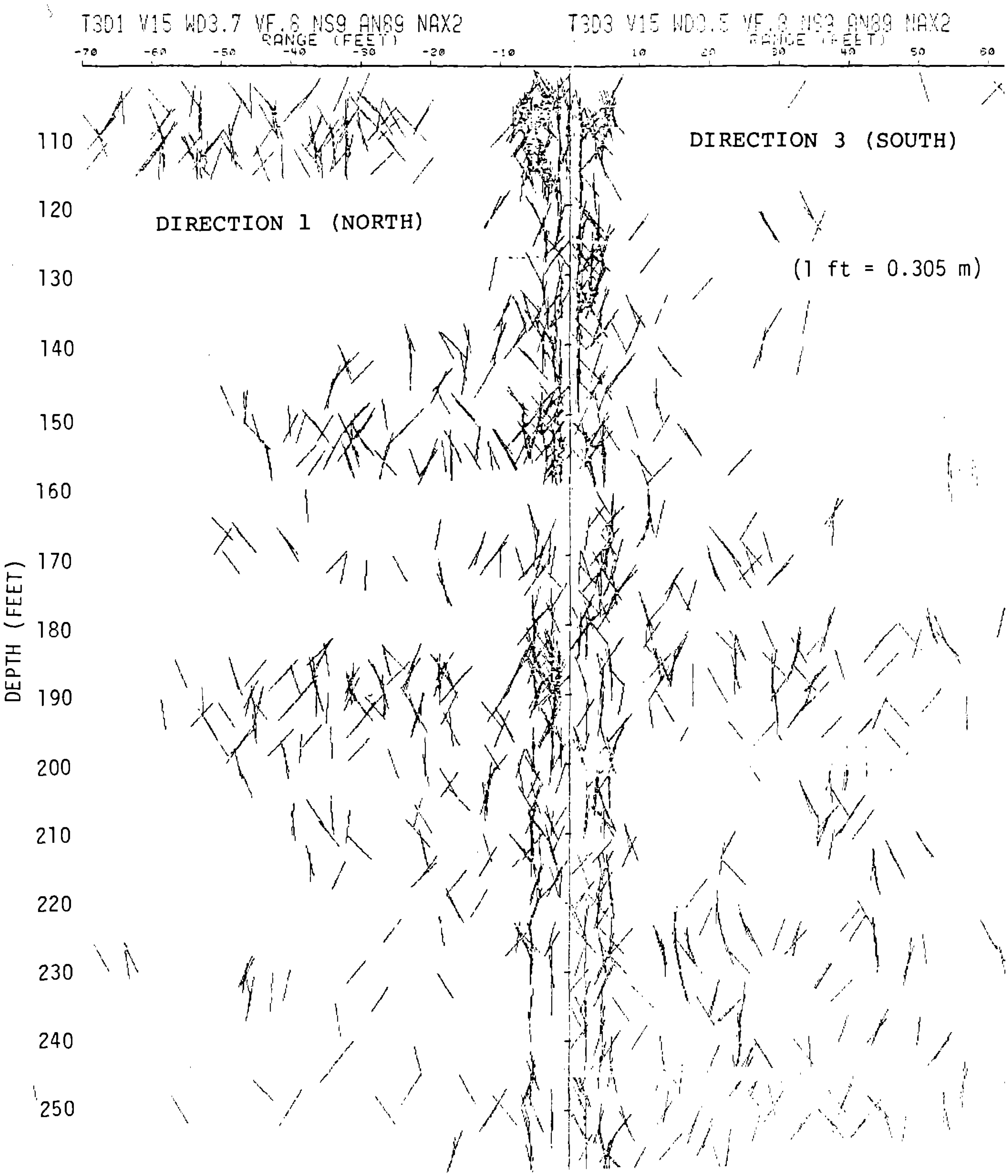


Figure G17. Composite computer plots for pulse-echo surveys in Hole T3, directions N' and S'.

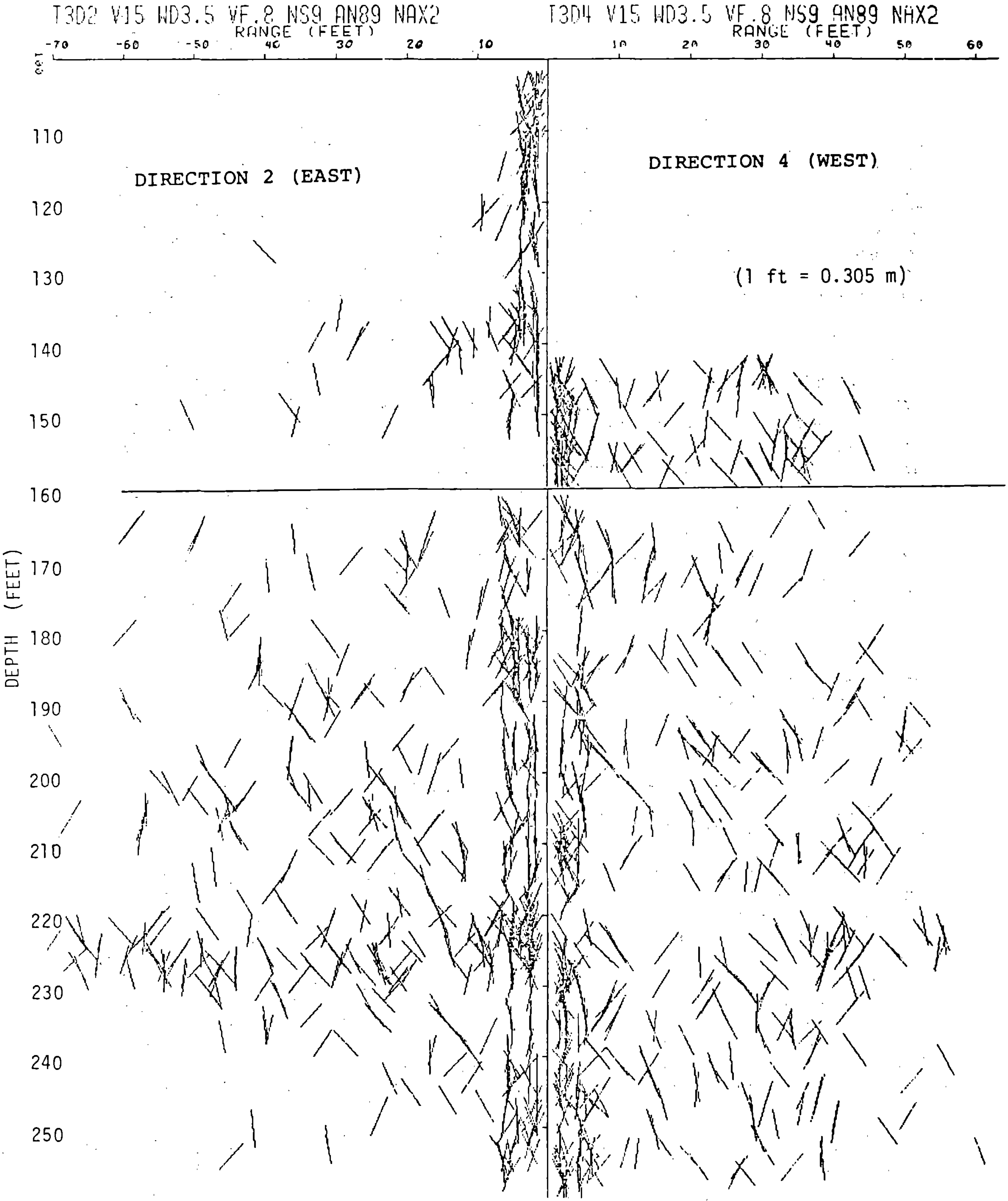


Figure G18. Composite computer plots for pulse-echo surveys in Hole T3, directions E' and W'.

Figures G19 and G20 are interpretations of the computer output for Boring T-3, showing the more significant information. Bear in mind that the boreholes are inclined about 30° and are roughly normal to the foliation, mapped as striking N16E and dipping 20°-60°W by the local consulting engineers. Therefore, due to the geometry of our system, we cannot detect the foliation, but most of the prominent joints are detectable. In Figure G19, two prominent joint trends are defined which correlate well with published geology. These include the 70°-80° southerly dipping joint patterns which strike west and southwest, and the less prominent north dipping structures as evidenced by the shorter length plotted lines dipping steeply to the north and striking west-northwest.

The inclination of the boreholes create a geometry where one of the structural joint planes is nearly parallel to the borehole. The vertically trending reflections in the E' and W' direction in Figure G20 represent this structure. Correcting for the borehole inclination, these reflections indicate steep east dipping, northerly striking jointing structure which correspond extremely well with primary jointing mapped by local geologists as 70° east dipping. The E', W' direction interpretation of Boring T-3 also indicated high angle structural jointing dipping about 60°-80° to the west.

Figure G21 is a composite of the interpreted data in the N' and S' directions. The effect is a north-south (approximate) cross-section along the borehole line depicting the major structural trends. From this cross-section, it is concluded that the jointing is consistent across the surveyed area. The plotting of less data above about 140 to 160 feet also indicates a significant rock quality change probably depicting the depth of weathering penetration.

No significant faults or other extensive single features such as long continuous veins were detected by our surveys. Although small scale veins and fracturing certainly exist, they are difficult to differentiate from the prominent joints.

CONCLUSION

Acoustical surveys conducted at the Forest Glen research site have shown that acoustical surveying is a viable method for geologic structure prediction for the rock conditions at the research site.

Four boreholes were surveyed using our pulse-echo system which showed the existence of reflecting horizons that can be directly attributed to prominent joint patterns in the rock. Because of the geometry of our technique, the foliation (normal to boring) and its major joint pattern (parallel to the boring) were not detected. However, the data produced by the system do support interpreted geology.

The nine through-transmission surveys produce very controlled primary wave velocities and some shear wave velocity data. These surveys indicate that the rock at the northern end of the site is more fractured than the southern end. It is further felt that the weathering has penetrated to an elevation of 210 feet (160-foot borehole depth) [48.78 meters borehole depth, elevation 64 m] and does not extend significantly below this level.

The scan conversion memory system has shown that it is an effective display technique and can be used to obtain real time quick-look data for field interpretation.

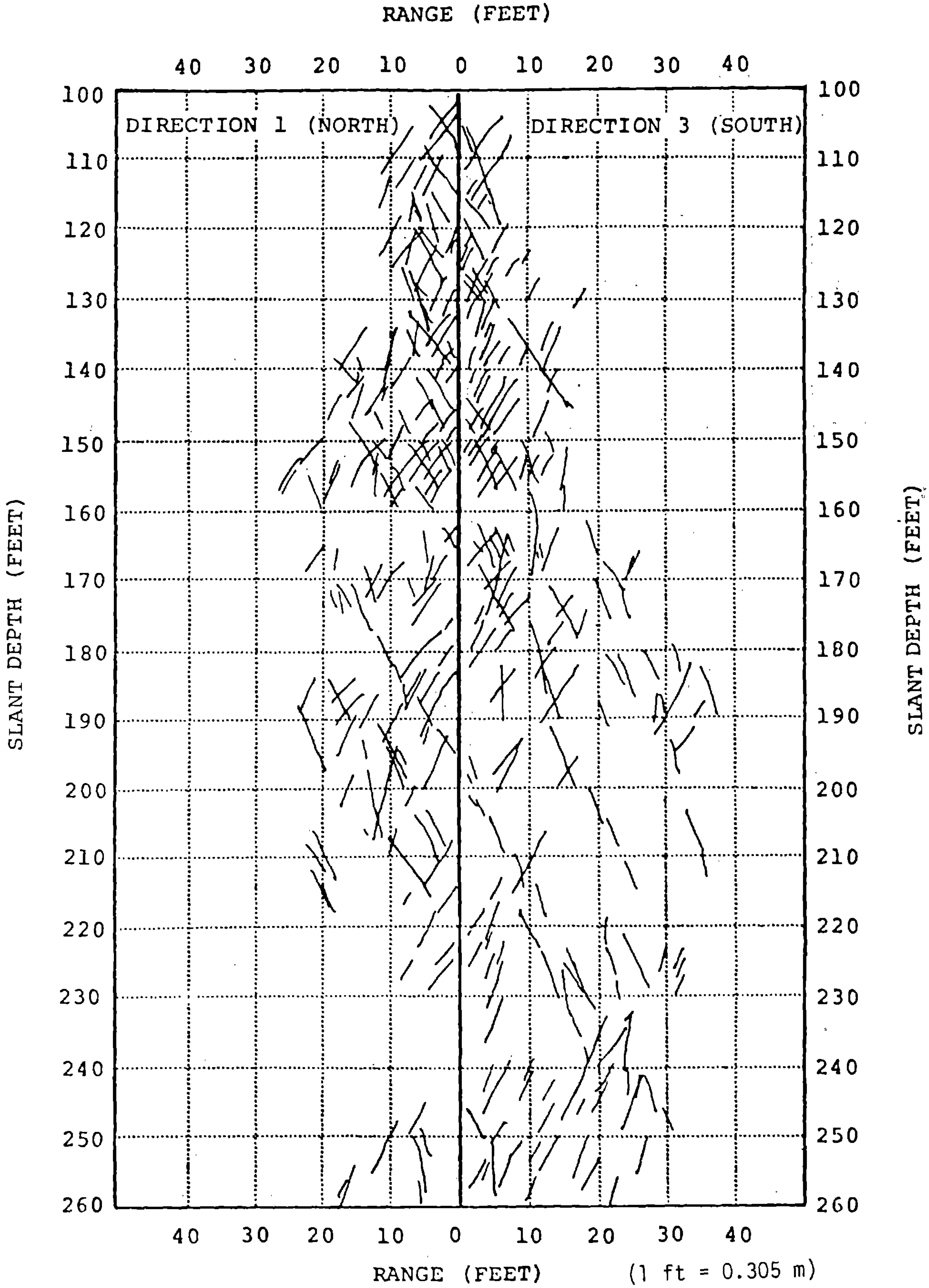


Figure G19. Interpretation of potential structural features at Boring T3.

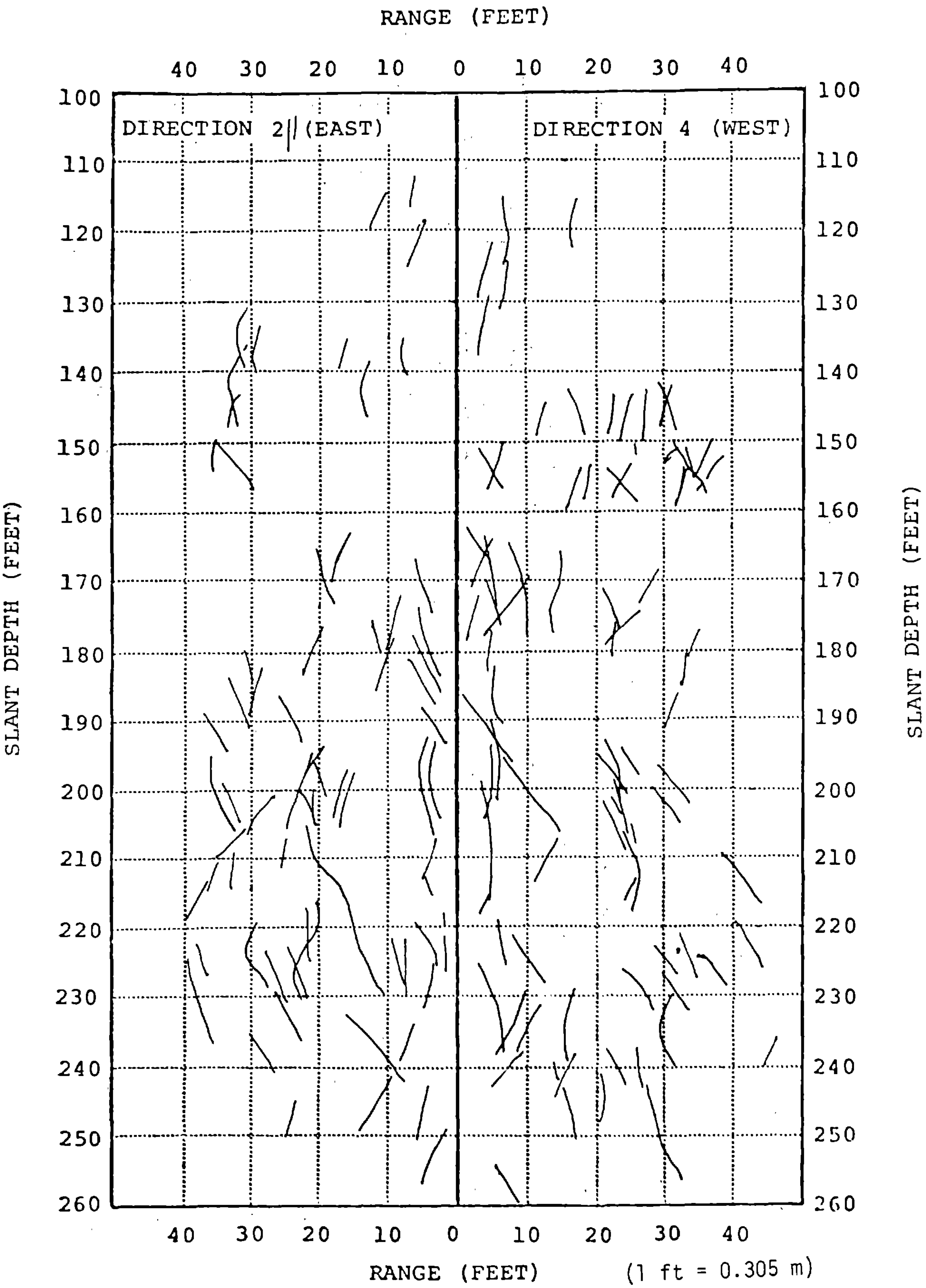


Figure G20. Interpretation of potential structural features at Boring T3.

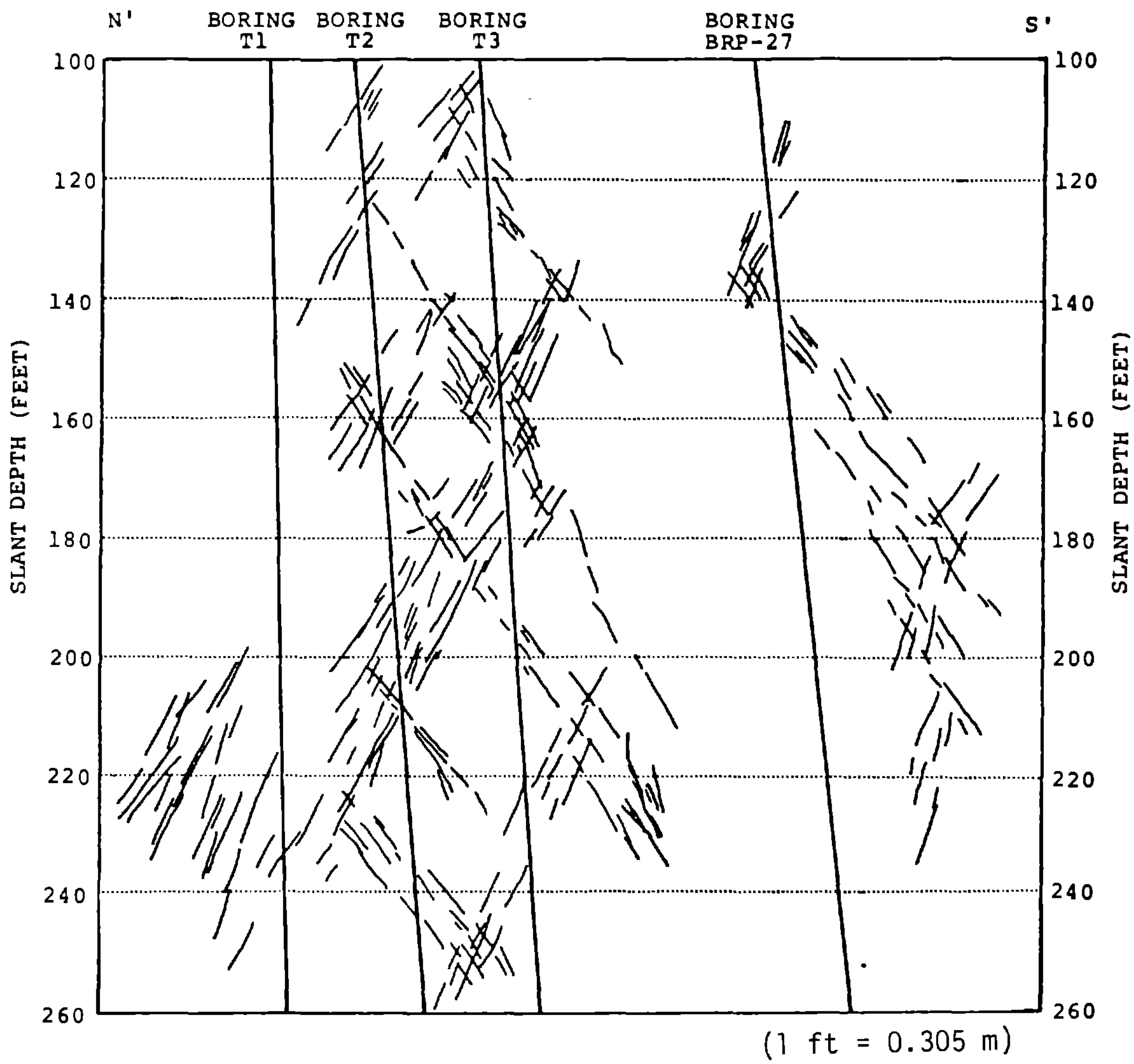


Figure G21. Interpreted structural cross-section showing major jointing.

The data, as presented in the text of this report using the acoustic technique, could have significant positive effects on understanding the local geology. The data produced by the system will be of particular benefit when used by local engineering geologists familiar with local structure and construction requirements.

APPENDIX H

ELECTROMAGNETIC PULSE-ECHO AND CROSS-HOLE SURVEY SYSTEM

L.A. Rubin, J. C. Fowler, and G.G. Marino
ENSCO, Inc.

INTRODUCTION

General

ENSCO, Inc., as part of NSF/RANN (Excavation Technology) Grant APR-76-03300, participated in the Forest Glen Research Experiments. Our experiment consisted of using the existing NX-borehole ground-probing radar developed with FHWA funding under the NSF grant. The balance of the radar and supporting equipment was ENSCO-owned commercial radar gear.

The radar was used in two modes; borehole-to-borehole (transillumination) and T-R (transmit-receive) from a single borehole. All four holes in pars and singles were probed and data was recorded. This site provided a difficult challenge for the borehole radar. It was designed primarily for use in multiple, closed-space NX horizontal boreholes. At Forest Glen, the boreholes were drilled subperpendicular to principal foliation and hence to most interesting features.

Presented Results

The transillumination (borehole-to-borehole) tests conducted between boreholes T-1 and T-2, and between BRP-27 and T-3, provided average velocity data from which we computed the dielectric constants as a function of slant depth. These data and the attenuation data are highly correlated to other available data sets.

The T-R (transmit-receive) tests provided adequate reflection data. The radar behaved mostly like a logging tool in that most of the interfaces were subperpendicular to the boreholes. We delineated many of the high-angle joints. Our penetration range, when looking into the edge of a broken zone interface, was about five feet. Otherwise, we were able to detect features out to ranges of 20 or more feet (6.1 m).

Subsequent Discussion

In the "Description of the System" section, we explain both the radar system that was used and its evolution. The section on "Field Measurements" discusses measurement techniques and presents the acquired data. Some data reduction exercises are attempted in order to relate the geophysical measurements to site characteristics. This is followed by conclusionary remarks and recommendations in specific areas for future application of this exploration technique to the design and construction of underground structures.

DESCRIPTION OF THE SYSTEM

Background

In an effort to comply with the NSF Technical Evaluation Group (TEG) recommendations, two antennas were built for use in a limited NX-size borehole. The initial work with the antennas was marked by a number of persistent problems, including the propensity of the units to leak whenever placed in over 50 feet (15.25 m) of water. At the time of the Forest Glen experiments (mid-November 1977), the system was a brassboard prototype without optimization and unfortunately of dubious operational status. As a result of these and earlier experiments (at Chantilly Quarry), ENSCO has been able to improve the system.

Description

The radar system that was used for these tests was a commercial prototype two-octave bandwidth ground-probing radar system built by Geophysical Survey Systems, Inc. (GSSI), per ENSCO's specifications. As shown in Figure H1, it consists of two antennas, one of which can act as both a transmitter and receiver while the second is only a transmitter. These antennas are basically encased dipole or, more specifically, bow-tie configurations. The peak power out is 50 watts with a short pulse of 10 ns duration. The pulse center frequency is approximately 100 MHz. The system has a total dynamic range of 120 dB. The probes are operated in adjacent boreholes and are connected by cable umbilicals to the master control and recording unit (see Figure H2).

FIELD MEASUREMENTS

Introduction

In the transillumination mode (borehole-to-borehole), the two downhole probes include a T (transmit) only and the T-R (transmit-receive) unit. The results of the tests consisted of phase velocity characteristics and gross spectral damping values of the penetrated bulk material between the transmit and receive radar probes. These results are discussed under "Transillumination Tests."

In the T-R (transmit-receive) mode of operation, the borehole radar consists of a single downhole unit containing both functions (T-R) in the same package. The short repetitive pulse is transmitted out into the ground as shown in Figure H3 and at each geologic anomaly (fracture zone with water, for example) a certain percentage of each pulse is reflected back to the receiver. The two-way path requires a transmit time equal to twice the distance divided by the wave propagation velocity in the ground. The velocity of electromagnetic waves in the frequency range of radar is strongly dependent on the water content, since the velocity is inversely proportional to the square root of the dielectric constant. At very high frequencies, dry rock has a relative dielectric constant of about two to six, while water is approximately 81. We can determine the in situ velocity by performing borehole-to-borehole measurements (transillumination). These velocity determinations can then be used to convert our radar profiles from time to distance.

In the Section on "EM Properties of the Host Intact Rock," we review properties of solid rock so that we can interpret cross hole measurements and factor out those results which can be attributed to site conditions. In this case, it is helpful to understand the electrical response of the intact rock.

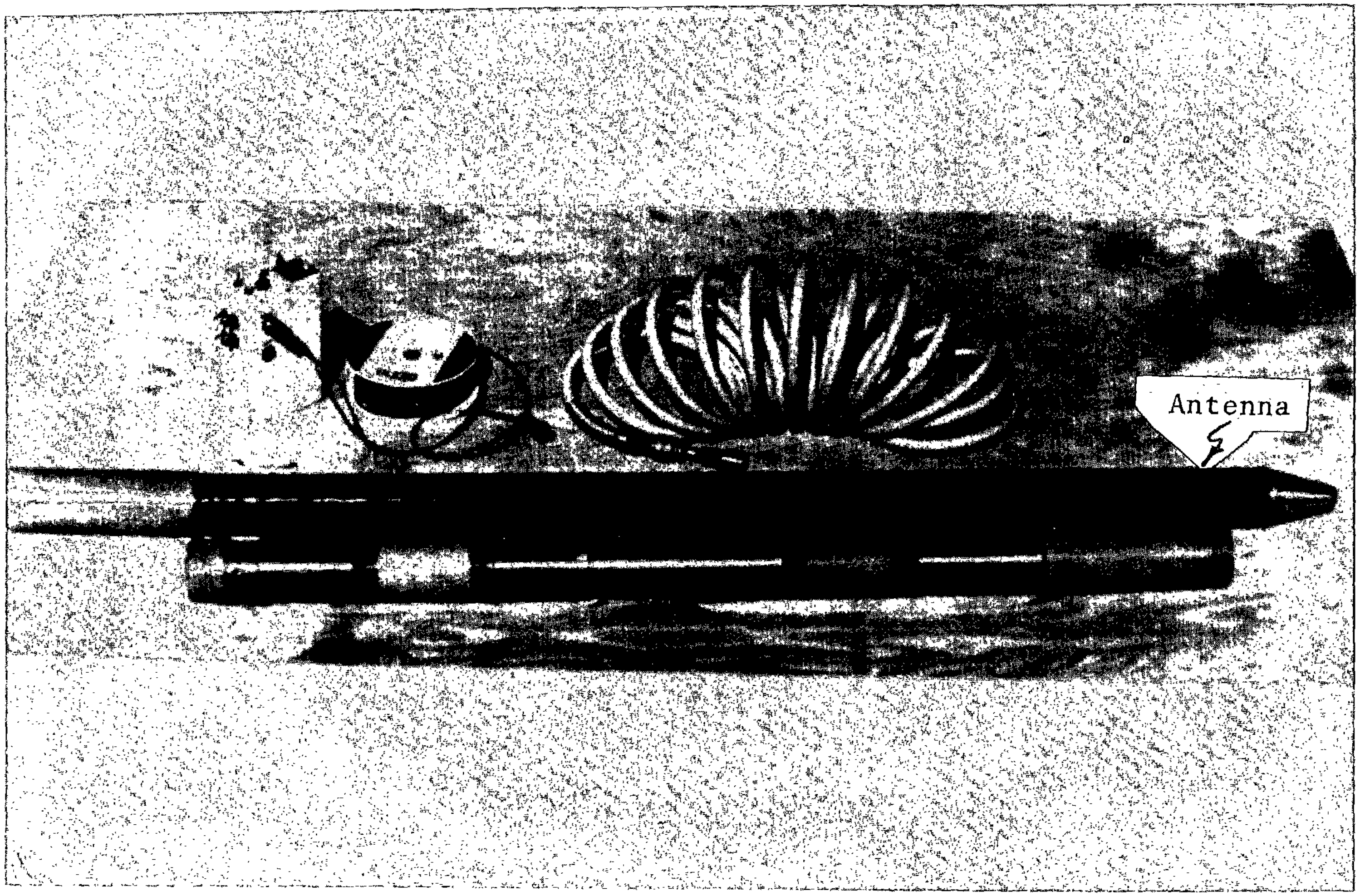


Figure H1. NX borehole radar antenna (plus worm components).

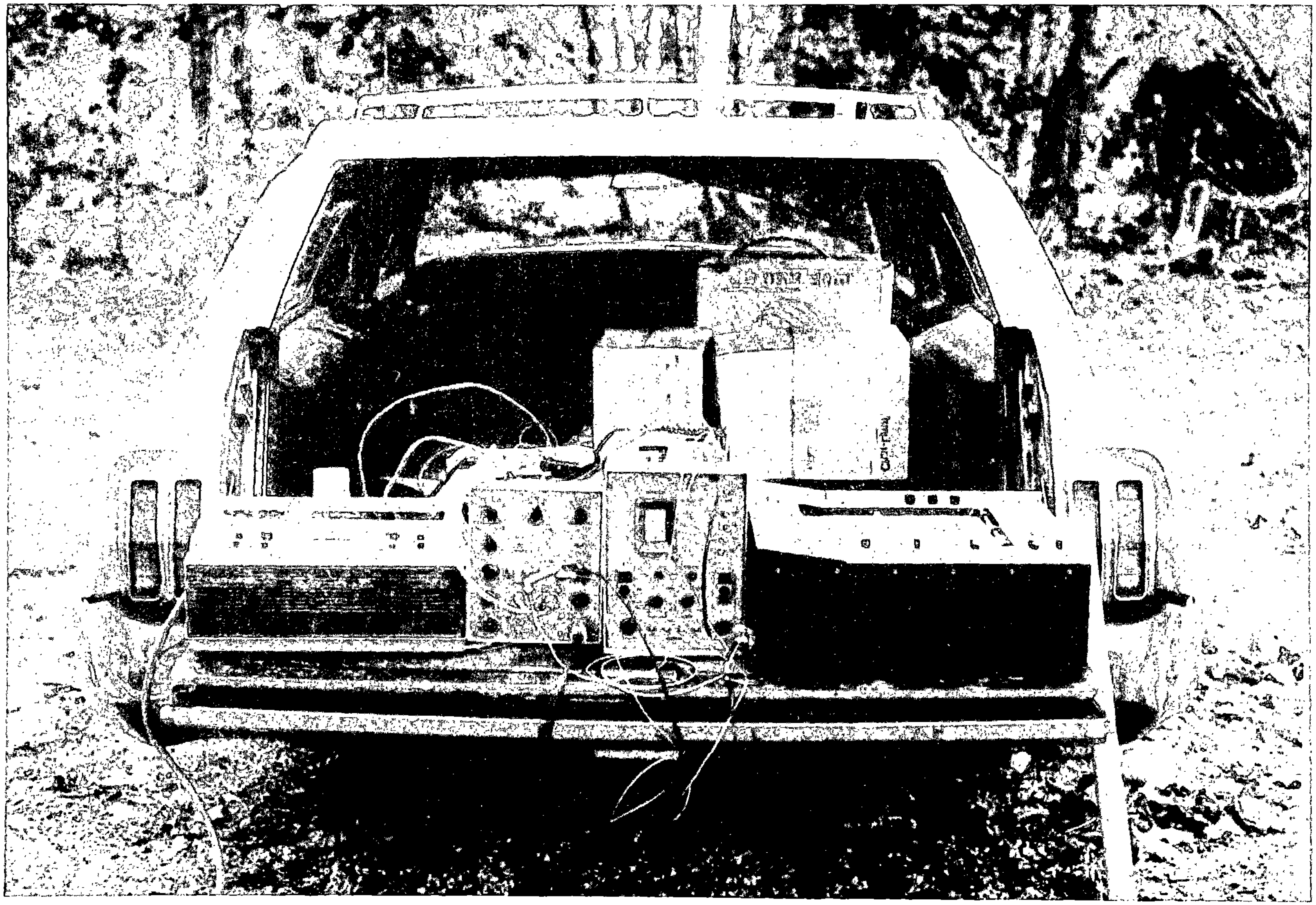


Figure H2. Master control and recording unit.

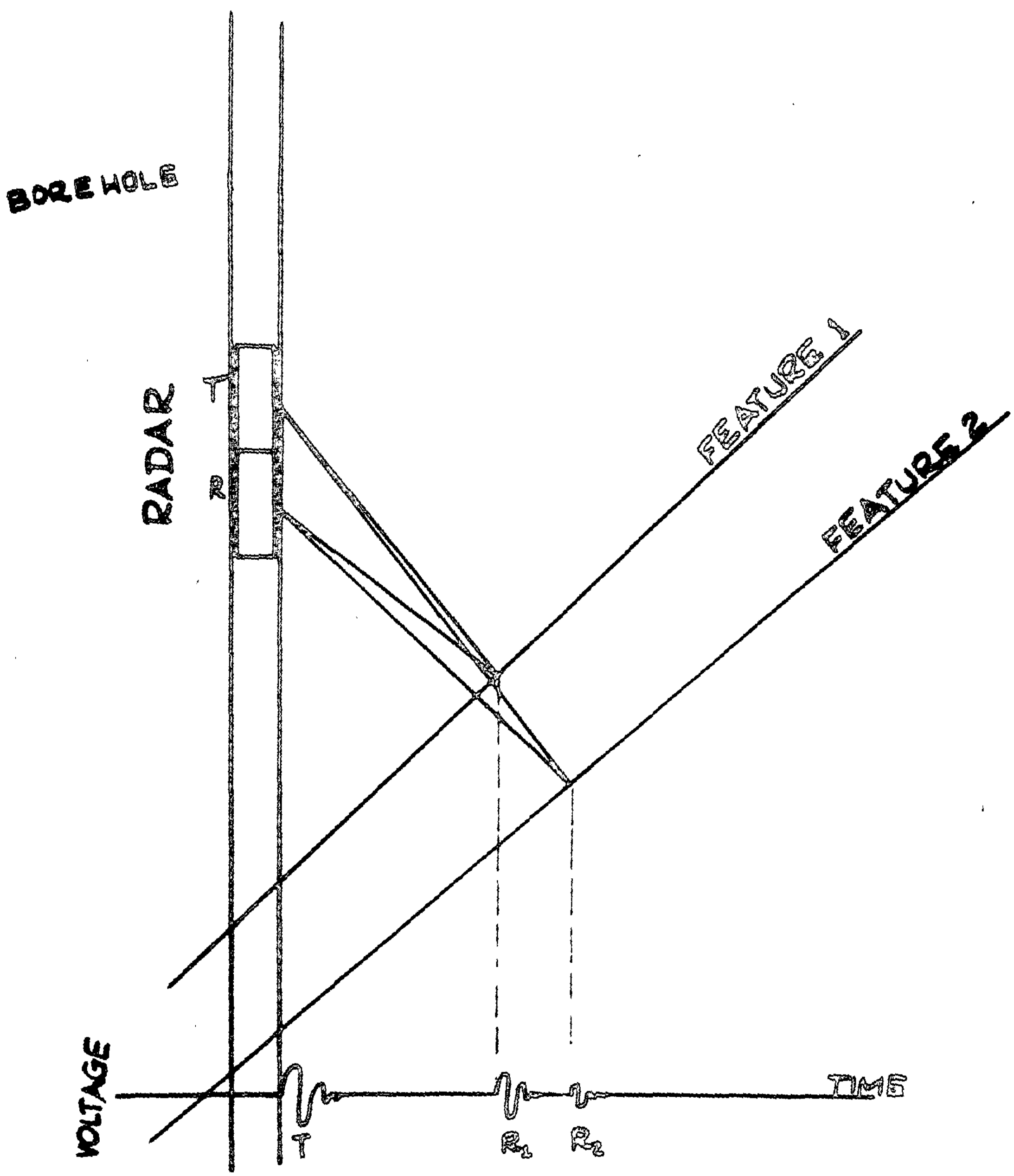


Figure H3. Typical borehole radar setup, transmit-receive (T-R) mode (schematic).

Electromagnetic Properties of the Host Intact Rock

Laboratory data of the intact Metro rock (of both the as-cut and soaked rock) by Cook (1) showed that the loss tangent was less than 6.5^{o} for frequencies above 50 MHz. A plot of his results is shown in Figure H4. It must be kept in mind that these VHF electromagnetic low-dispersion results are probably the lower limit of the in situ properties of the Forest Glen bedrock. Clearly, increased bulk moisture from the structural rock characteristics will have an effect on field results.

In Figure H5, Cook has calculated the attenuation properties from the same laboratory data. The intact rock indicates a relatively small change in the rate of attenuation between 50 to 100 MHz. This characteristic is also portrayed by the loss tangent results reported above.

The above figure also shows important range-resolution data based on a combination of laboratory and field measurements for a wide range of rock types. Here, the Washington, D.C. Metro rocks are classified as schist. The radar operated primarily between 50 and 150 MHz. As in our previous radar work in the geologically similar Zoo Park Station crown drift (2), the ranges at Forest Glen were in the 20- to 60-foot (6.1 to 18.3 m) category for transillumination and in the 5- to 25-foot (7.63 m) category for transmit-receive mode.

Transillumination Tests

The transillumination measurements are primarily used to determine the relative dielectric constants (wave velocities) of the various layers between the boreholes at different depths. The typical transillumination radar print-out is shown in Figures H6 and H7. Figure H6 shows the short distance between boreholes T-1 and T-2, a distance of only 20 feet (6.1 m). Figure H7 is the same basic data between BRP-27 and T-3, a distance of 51 feet (15.56 m). These were done at depths of 165 and 200 feet (50.33 and 61.0 m), respectively. Interpretation of these data was performed by an analysis of the assessed laboratory electrical properties, the material characteristics of the relative bulk dielectric constants, and the mean frequency of the received waveforms.

The most astounding result here is the consistent propagation of the high-frequency electromagnetic energy through the diverse geological settings over these distances. The dielectric values computed as a result of these cross-hole tests were superimposed on the geologic section of the borehole configuration. This is shown in Figure H8. While there is nothing surprising in this presentation, there is a high correlation with other known factors which relate to dielectric constant, such as water content and the degree of fracturing. The plotted relative dielectric constants, ϵ_r, with slant depth indicate a general decrease in dispersion. This can be attributed to the simpler geologic characteristics with depth.

In Figure H9, the mean frequency of the received pulse of these transmissions was plotted. The mean frequency is determined by averaging the spectral content of the trace. This mean spectral plot correlates with the corresponding ϵ_r values in that the lower frequency content waveforms (consequently more materially attenuated) are associated with relatively high dielectric values. As expected, the frequency content of the received pulse generally increases correspondingly with the increased integrity of the bedrock.

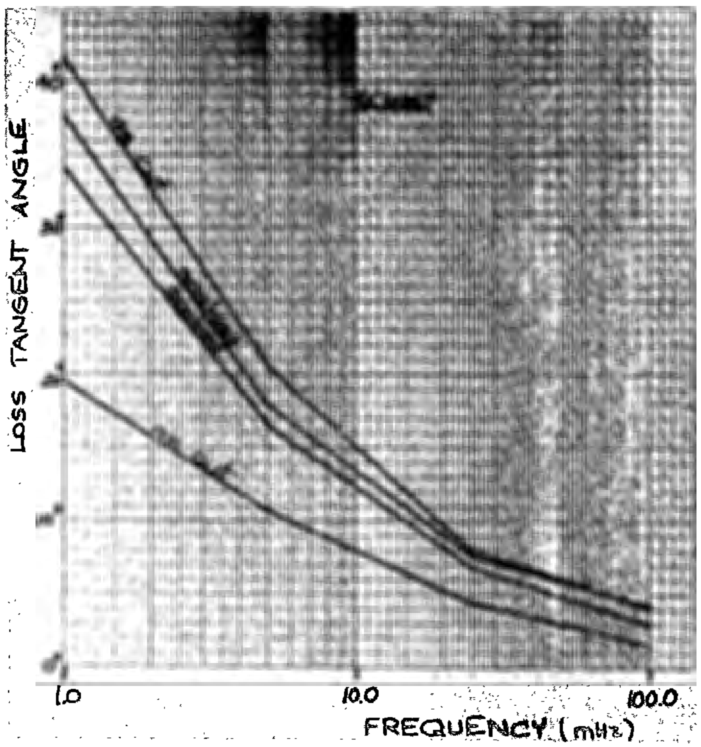


Figure H4. Loss tangent effects vs. frequency for laboratory tested intact samples. Specimens were classified as schist with moderate to indistinct foliation, from Washington, D.C. Metro (Cook [1]).

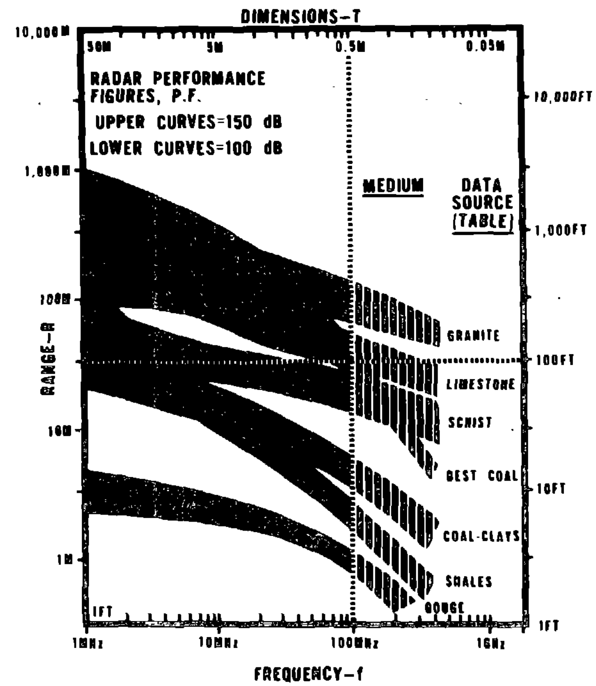
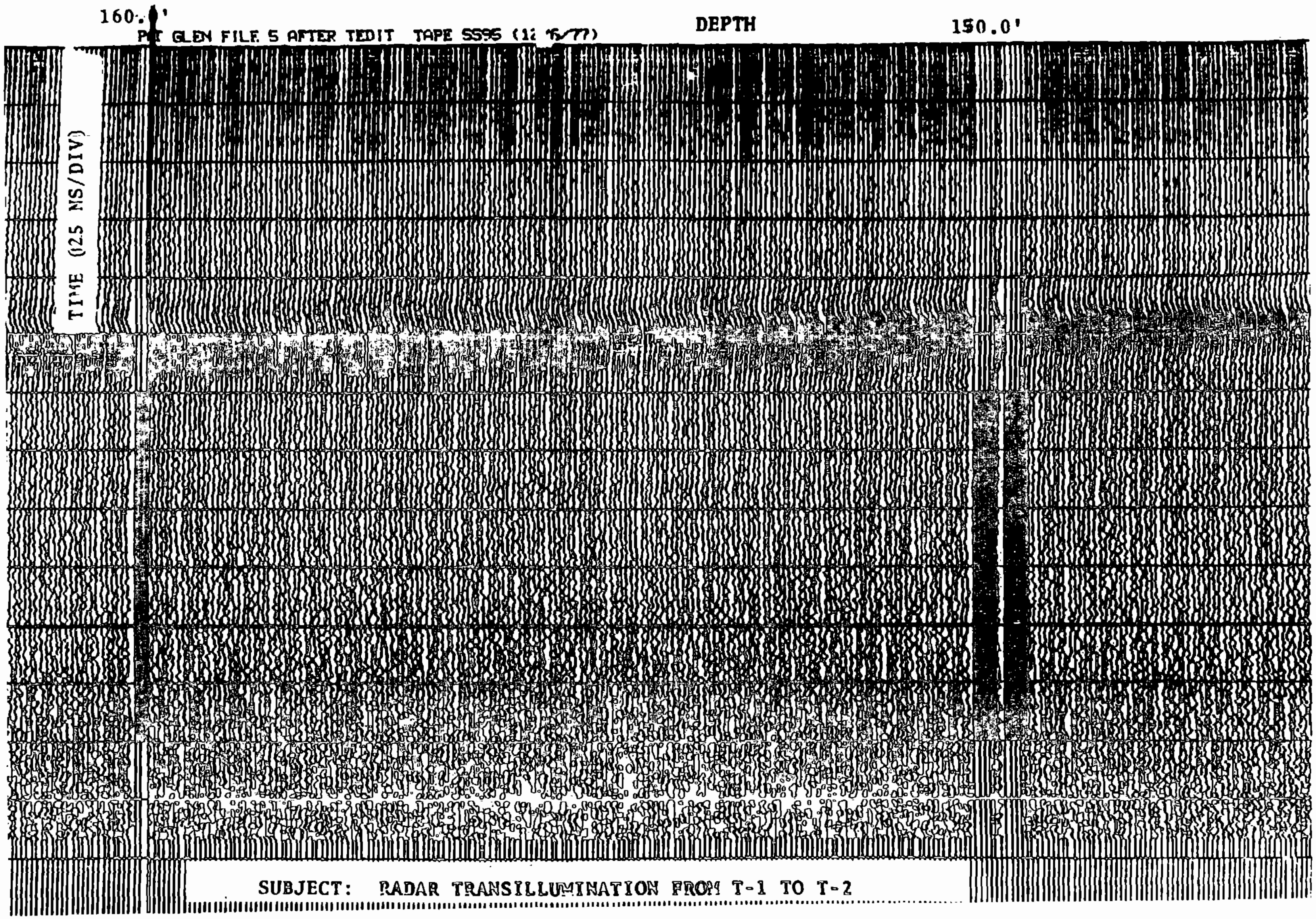


Figure H5. Radar probing distances through some typical "rocks".



(1 ft = 0.305 m)

Figure H6. Radar transillumination from Borehole T-1 to Borehole T-2.

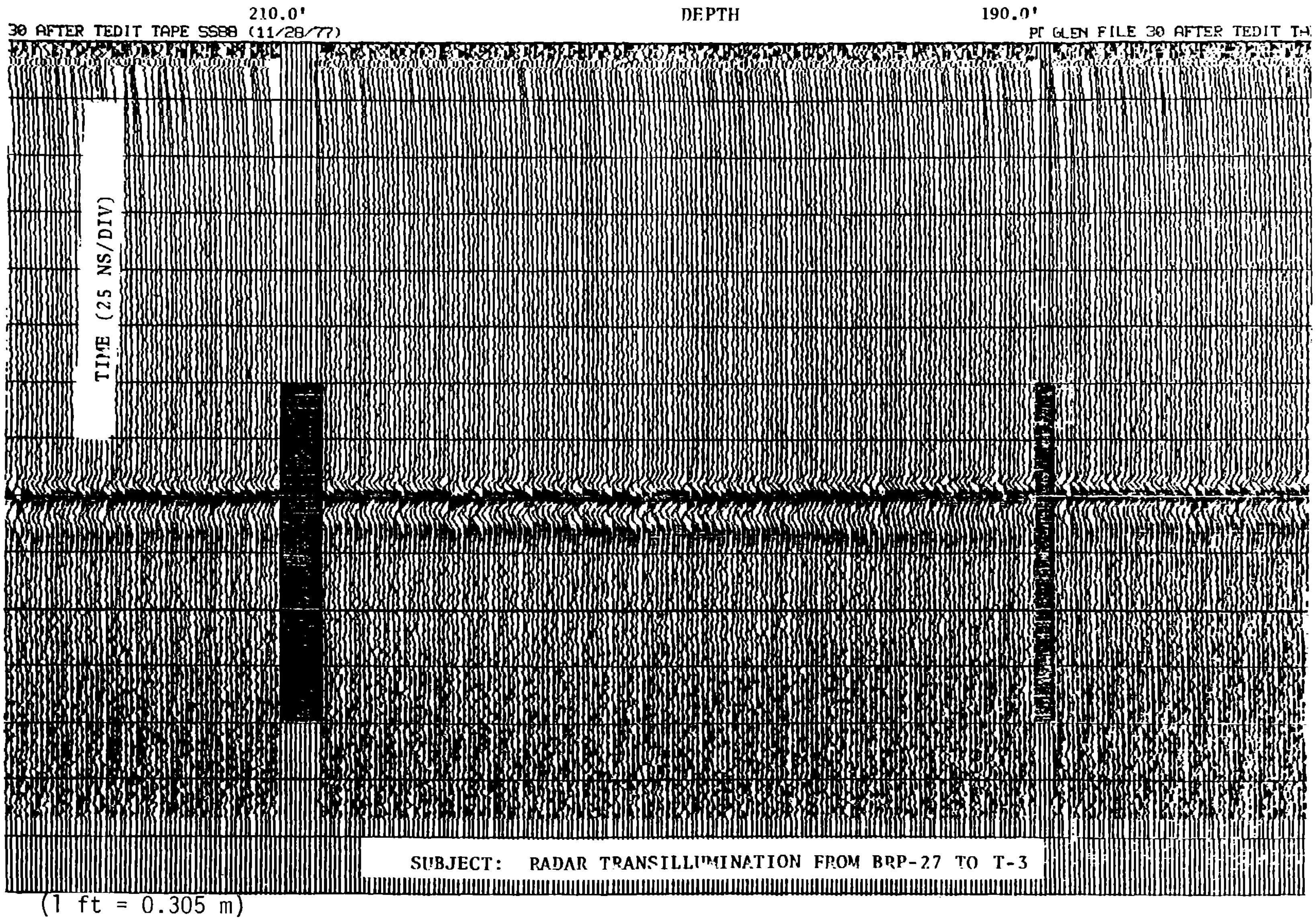
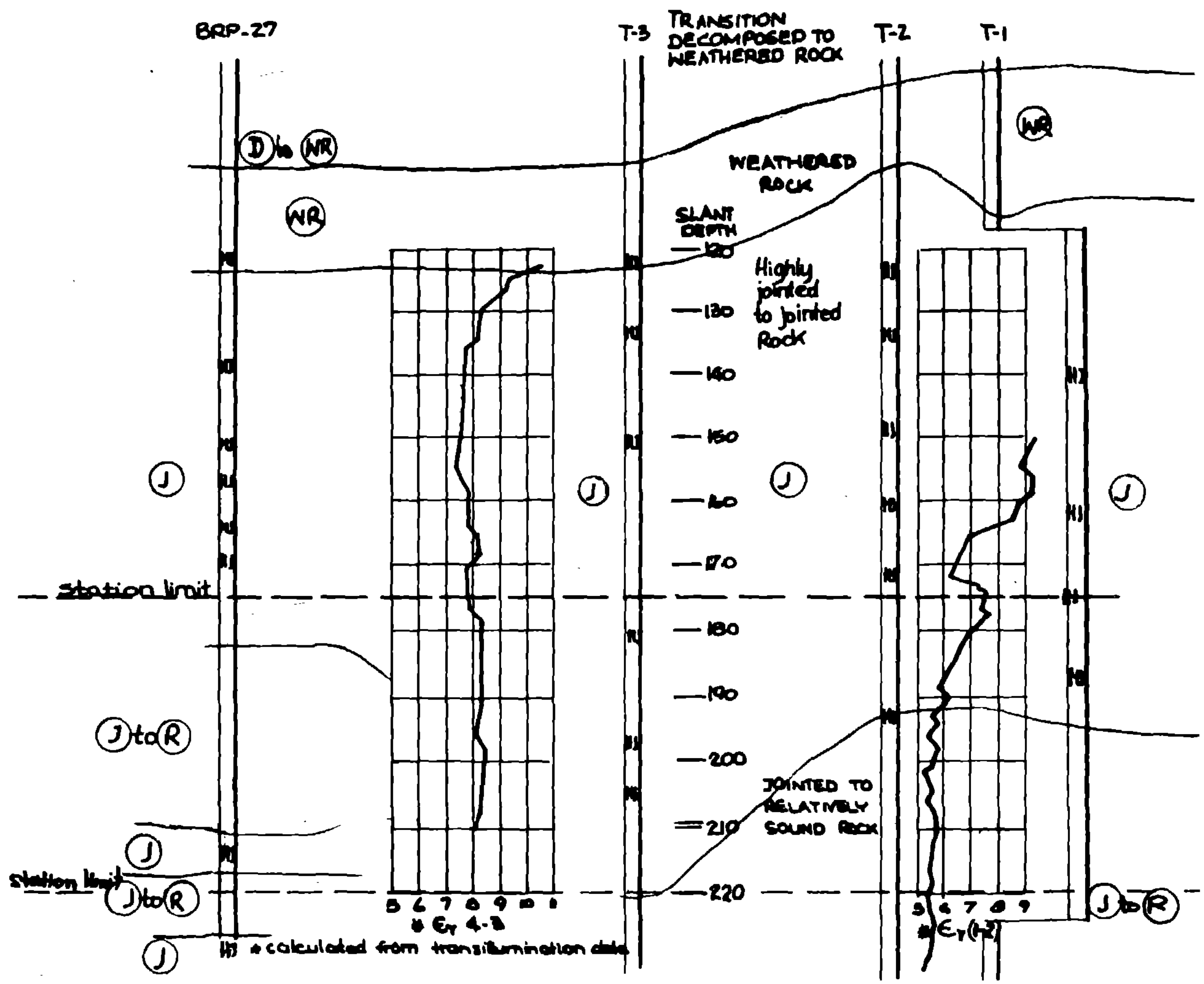


Figure H7. Radar transillumination from Borehole BRP-27 to Borehole T-3.



(1 ft = 0.305 m)

Figure H8. Dielectric values vs. rock profile characteristics.

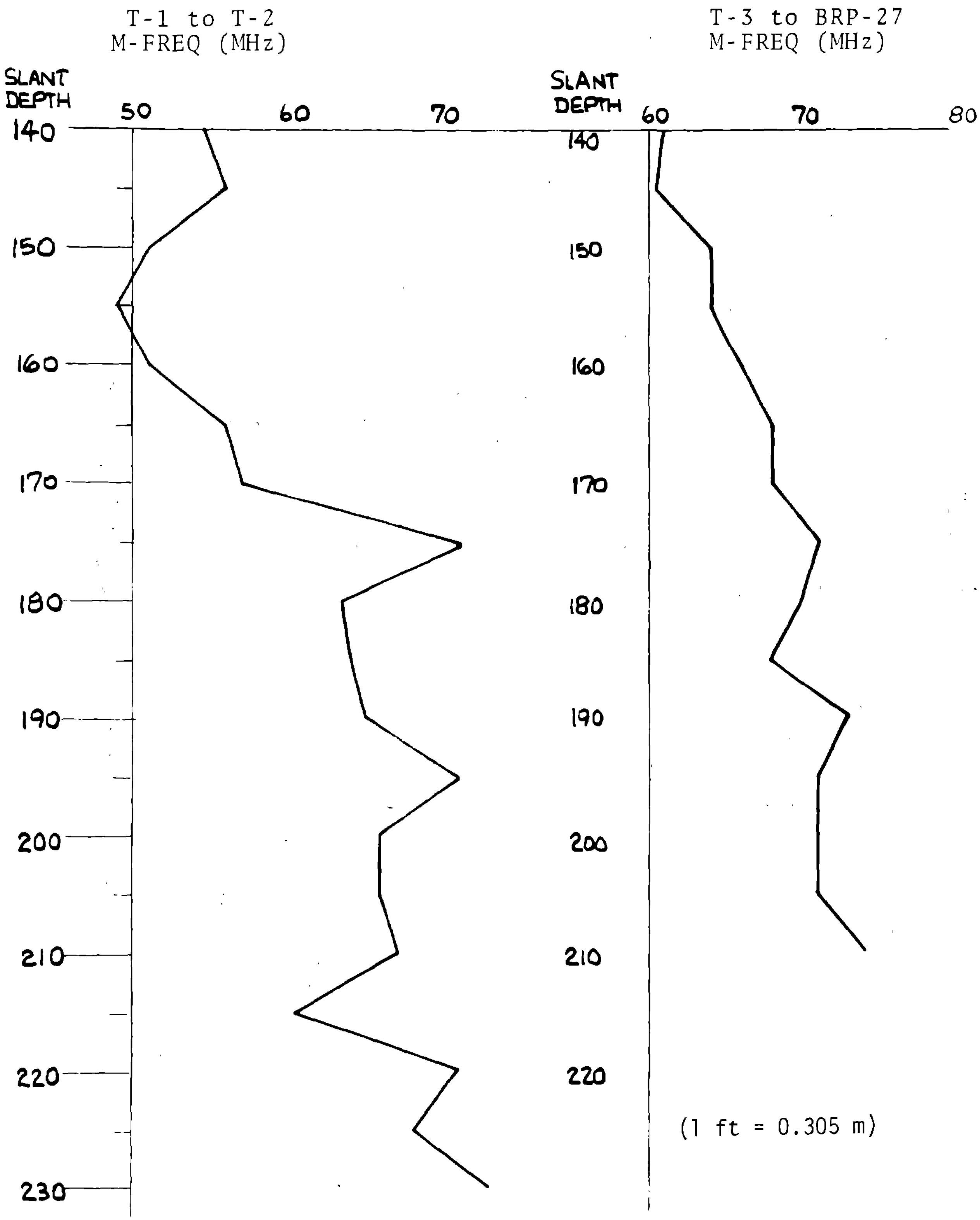


Figure H9. Mean frequency of received pulse from crosshole transmissions.

There is an apparent discrepancy in the mean spectral measurements between transmissions from T-1 to T-2 and those of BRP-27 to T-3. The values are generally higher in BRP-27 to T-3 even though the transmission distance is over twice that of T-1 to T-2. This can be attributed to one or more of the following: instrumentation variations, location of transmitter in a five-inch hole (T-1), and/or significant material attenuation differences.

T-R Results

System Considerations.--T-R (transmit-receiver) tests involve the use of a single borehole. The radar unit contains the transmitter and receiver in one package. The problem at Forest Glen insofar as radar is concerned is that the associated foliation structure is basically subperpendicular to the boreholes (3). Here, the radar is continually looking into the edges of zones rather than their sides. The clearest success of radar traverse is parallel to the zone rather than perpendicular to it. For example, in the Zoo Park Station work (2), which was conducted along a horizontal pilot drift, almost all of the features of interest were near horizontal foliation planes and schistose intrusive zones. At the same time, the weathered zone of the rock which was easily detected 40 feet (12.2 m) away from the pilot tunnel turned out to be almost perpendicular to the traverse point of the radar in the pilot drift.

The geometrical considerations for different features from a radar traverse of a borehole are shown in Figure H10. It is an inherent characteristic of dipole antennas (4) that moving off the center of the beam (along a perpendicular to the borehole axis) there is a significant power drop, the pattern of which is influenced by the nearfield effects. Thus, as the radar approaches a low angle (subperpendicular to the borehole) feature, very little energy is incident on the target. Ideally, the target line should be colinear with the traverse line so that the maximum coupling of the electrical field takes place at the interface.

High-angle features (subparallel to borehole) therefore show up best. The radar passes through low-angle features, which show up only as "clumps". Unfortunately, at Forest Glen the boreholes were drilled almost perfectly subperpendicular to the foliation. Most of the geological features of interest lie subparallel to the foliation.

Figure H11a helps to define the relationship between θ , D, and Time. θ is the complement of the acute angle formed by the fracture and the borehole. D is the distance from the radar to this intersection. The figure shows the time in nanoseconds that a feature "appears" as a function of both D and θ. This curve assumes a constant velocity of 0.36 feet/nanoseconds (0.11 m/nanosecond). While not exactly true, it is close enough for use within a range of about 20 feet (6.1 m). These features show clearly on typical T-R mode radar profiles. In Figure H11b, the profile of borehole T-3 between 177 and 195 feet (53.99 and 59.48 m) slant depth is shown. The features around 181-185 feet (55.21-56.43 m) are clearly high-angle.

T-R Reflections.--A composite profile of the time-domain traces from a depth of 80 to 210.0 feet (24.4 to 64.05 m) in T-3 is shown in Figure H12. Here each trace represents a stack of ten original ones and results in slightly more than one trace per half foot (0.15 m). At this scale, the visibility of reflections from minor structural features which typically are apparent for traversing distances of 5 to 10 feet (1.5 to 3.05 m) become "out of focus." A minor foliation shear zone which extends from about 160 to 163 feet (48.8 to 49.72 m) can be seen on this display. This feature is the most significant

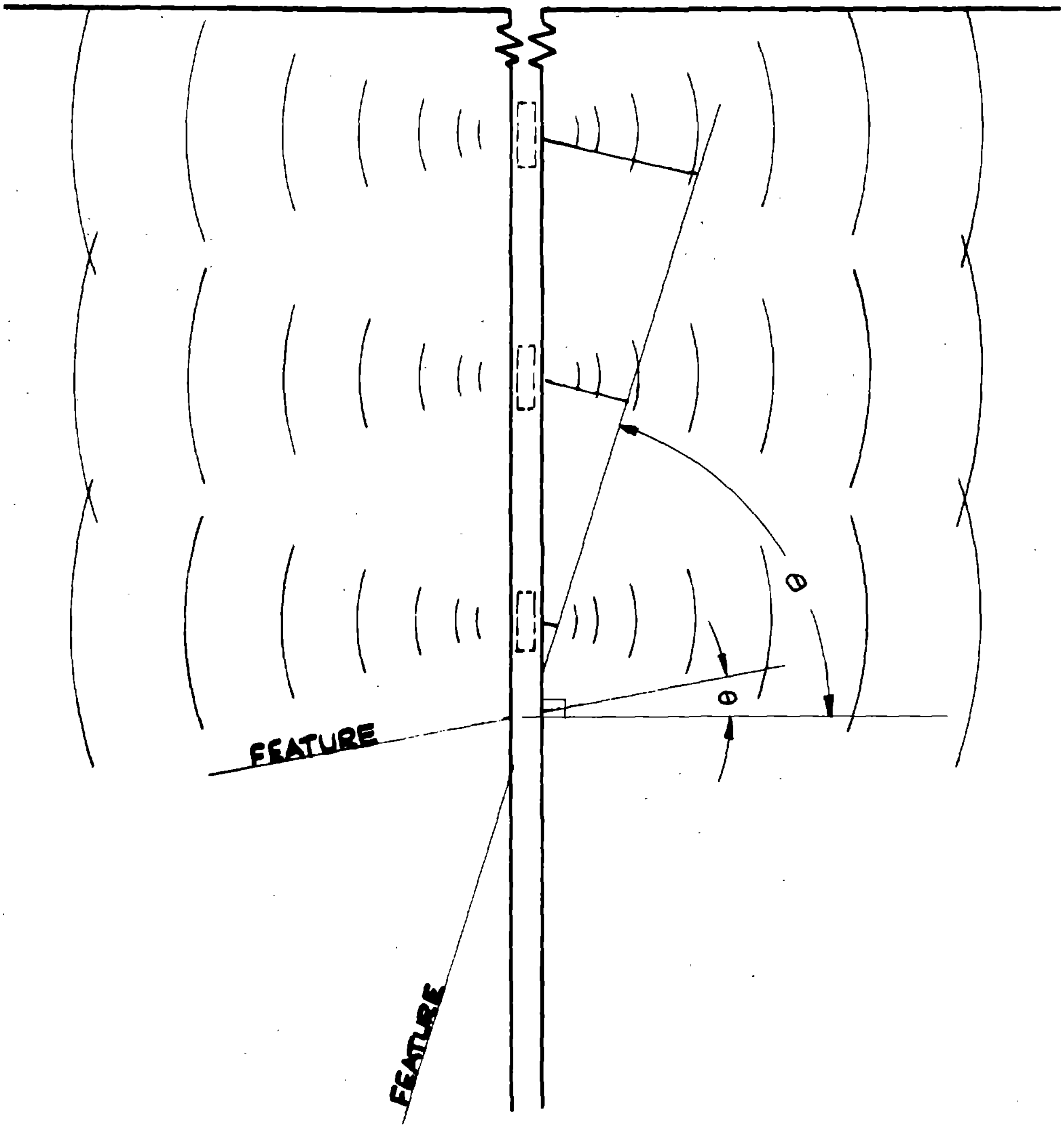
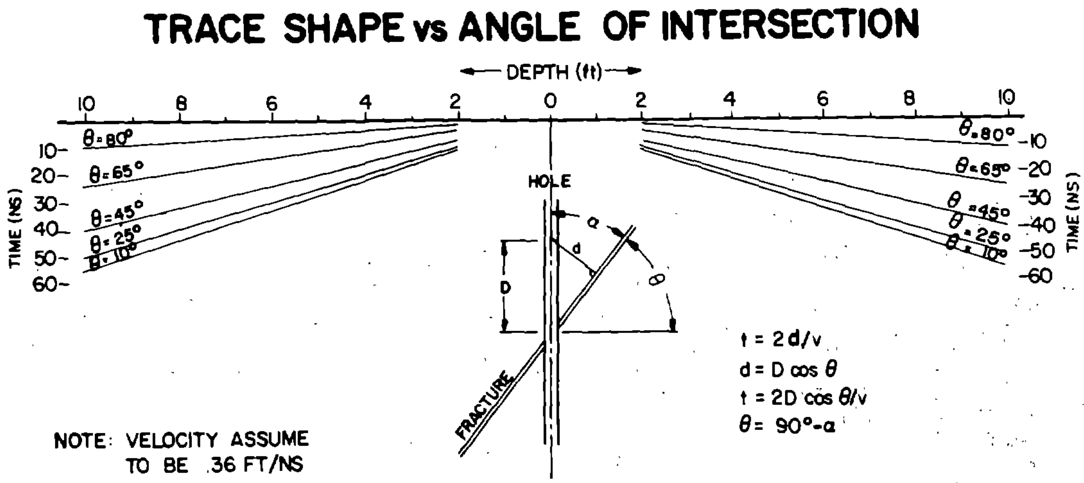
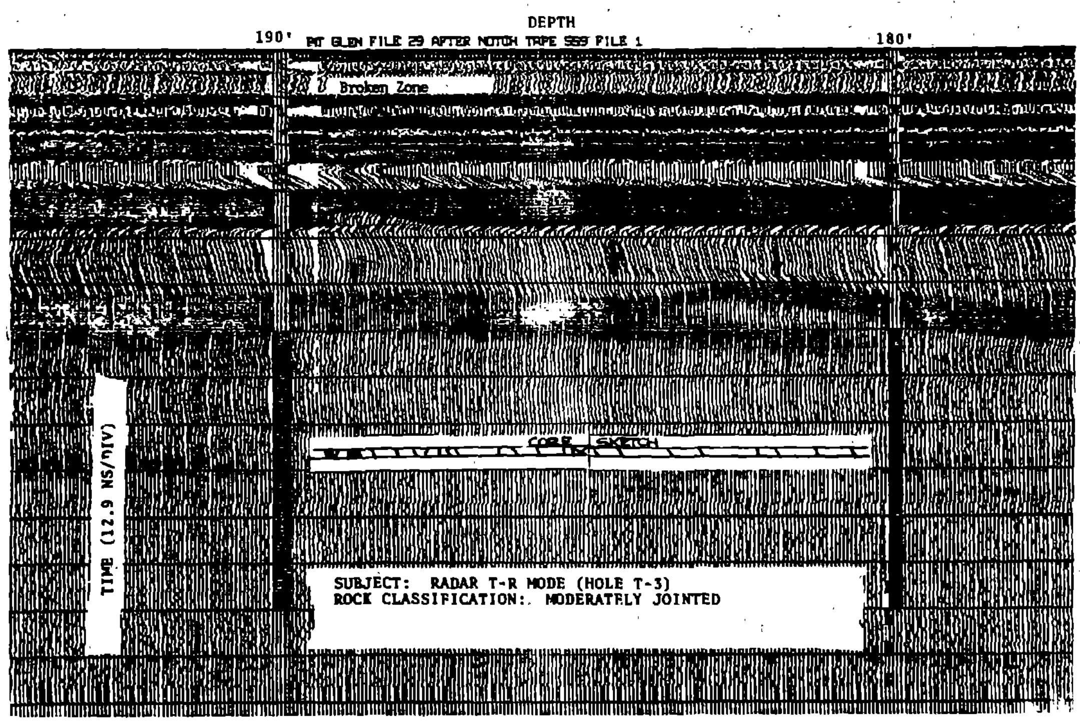


Figure H10. Geometrical considerations for high and low angle features for radar.



1 ft = 0.305 m

(a)



1 ft = 0.305 m

(b)

Figure H11. (a) Trace shape vs. angle of intersection; (b) Transmit-receive borehole radar mode for Hole T-3 in moderately jointed rock.

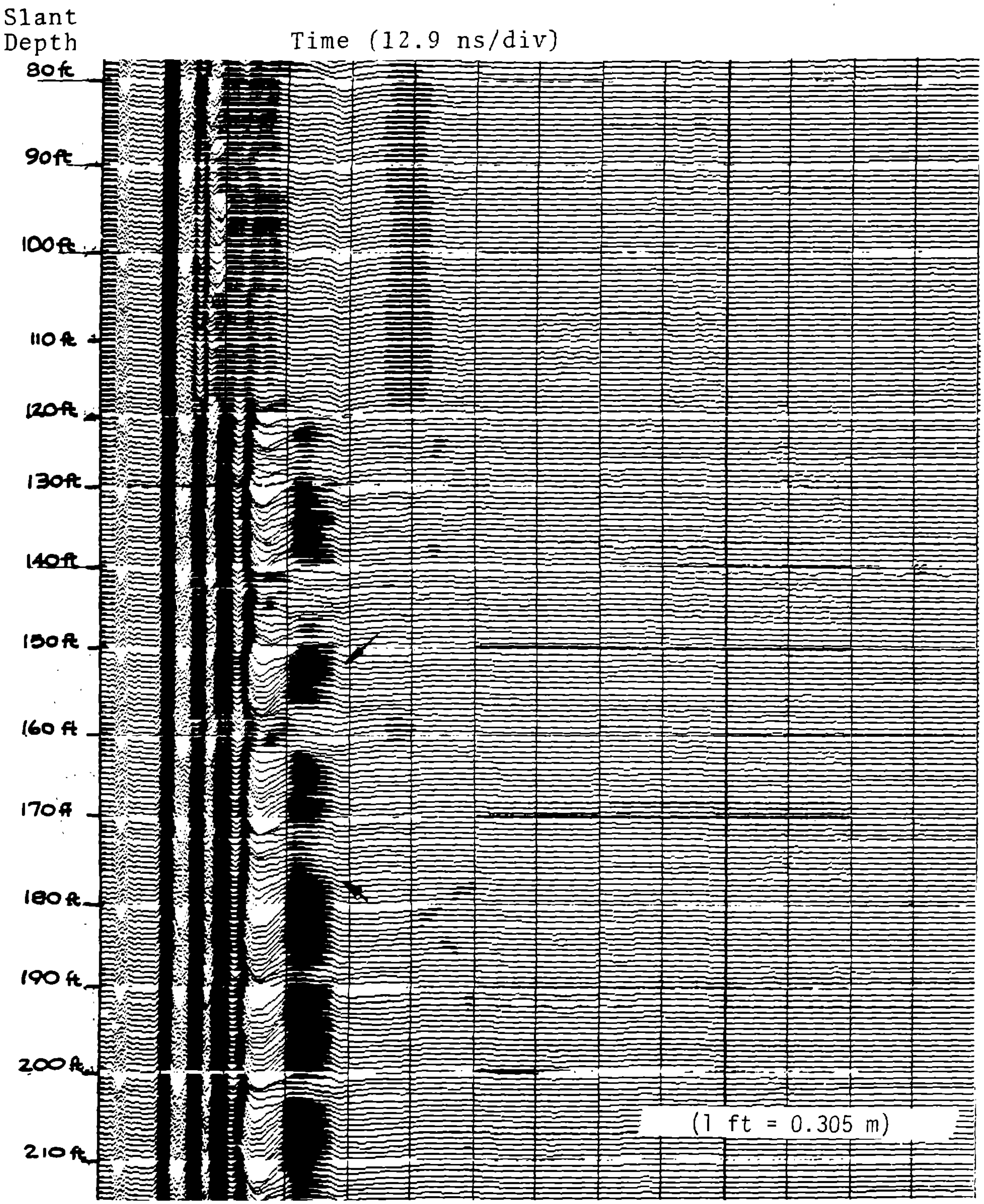


Figure H12. A composite section of T-R time domain traces T-3. Each trace represents a stack of 10 original traces. Arrows indicate composite reflections of a shear zone at 160 to 163 feet (48.8 to 49.72 m) in depth.

discontinuity observed in the borehole. Although other perturbations are shown, we were not able to make any other obvious structural correlations. Apparently, these other perturbations are an integration of events from the average dominant fracture characteristics at various depths.

Figure H13 shows a radar profile from BRP-27 between the slant depths of 160 and 170 feet (48.8 and 51.85 m) in an area containing a highly broken zone and a quartzite vein. Both of these features show up on the radar presentation and are correlated very well to the core data shown. The intensely broken area seems to be more toward 161 feet (49.11 m) than the area of no core recovery around 162.5 feet (49.56 m). Boundary planes of the broken zones seem to approximately parallel the foliation.

In Figure H14, we are in Borehole T-2 below 180 feet (54.9 m). This is an area containing a highly jointed section of broken material with some chlorite deposits. In this region the jointing appears to cross the foliation at around 60-70°. While there are intense radar returns close to the borehole, very little information comes from a few feet beyond. Borehole reflectivity of the broken material is obviously quite high.

Figure H15 shows a section from T-3 at a slant depth of from 120 to 130 feet (36.6 to 39.65 m). It is a highly jointed region which consists of a number of high-angle joints with respect to the foliation. Four areas have been delineated in this radar map as follows:

- At 120 feet (36.6 m), an apparent 70° joint x F.
- At 122 feet (37.21 m), there is a gouge-filled joint at 60°.
- At approximately 127 feet (38.74 m), another joint at about 65° x F.
- At approximately 128 feet (39.04 m), a significant broken zone which shows up as interference close to the borehole.

Figure H16 covers the slant depth from 140 to 150 feet (42.7 to 45.75 m). In this area, there are two features of interest. Between 140 and 142 feet (42.7 and 43.31 m), there is highly-weathered broken rock which shows up very clearly in the radar picture and at around 148 feet (45.14 m) a region of irregular jointing of about 70° typically.

In the area between 141 and 148 feet (43.01 and 45.14 m), the closely spaced foliation joints would indicate a high degree of weathering.

Figure H17 covers the area from 150 to 160 feet (45.75 to 48.8 m). Here there are two major features. At about 152 feet (46.36 m), there are a series of high-angle joints (between 45° and 60°). Some of these joints do not appear very strongly as radar returns. The 60° return is clear but the 45° joint is not. The other feature of the area is in the region from 158 to 162 feet (48.19 to 49.41 m), a highly jointed region which once again appears quite pronounced on the radar return. There are several high-angle joints but they are very tight and discontinuous.

Figure H18 includes the region from 190 to 200 feet (57.95 to 61.0 m). It is an area of very tight jointing in relatively sound rock and, as expected, almost devoid of any detail.

Examples of Traces in the Time and Frequency Domain.--In Figure H19, we see radar time traces from four specific areas of the T-3 profile. The 208-foot (63.44 m) slant

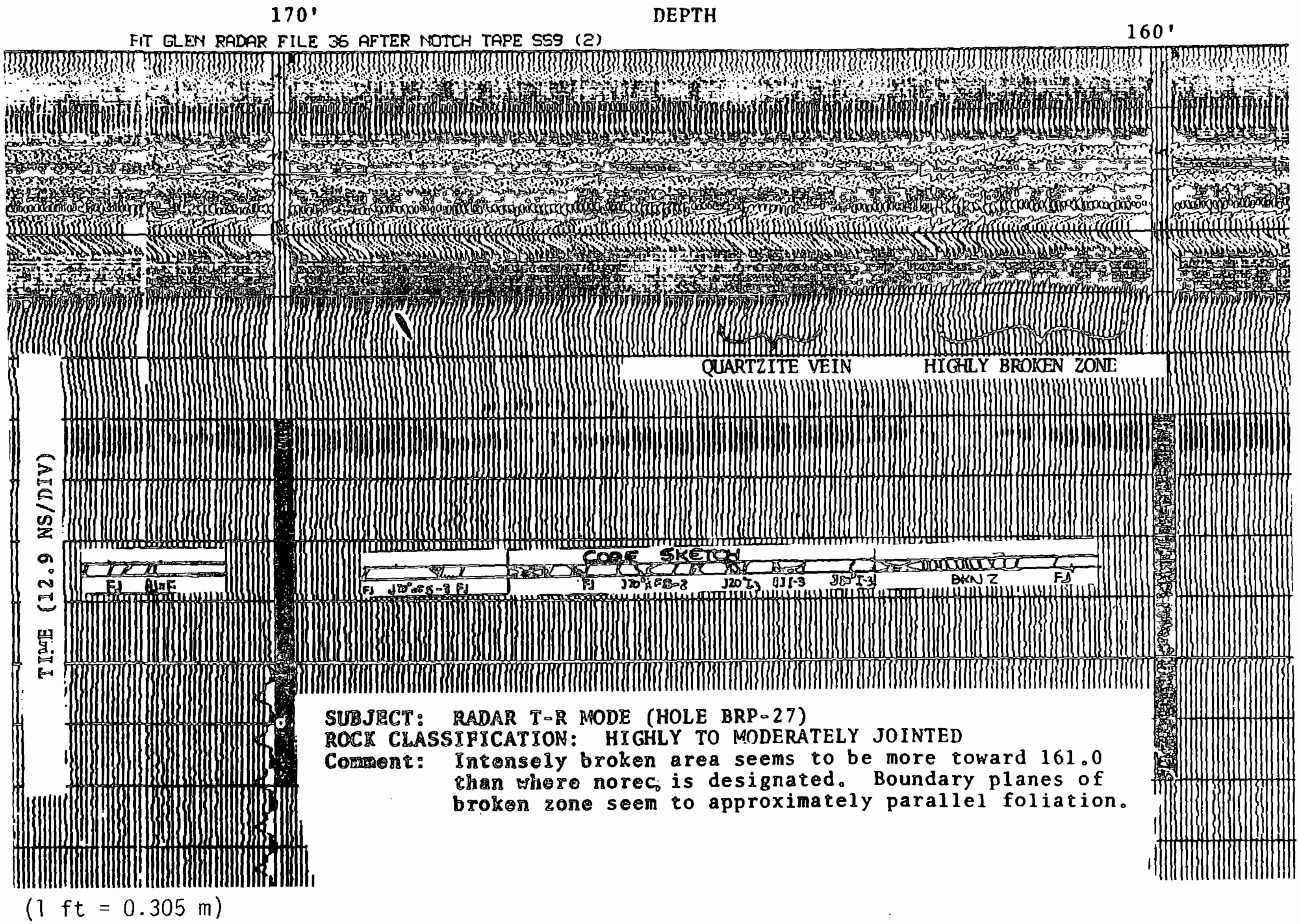
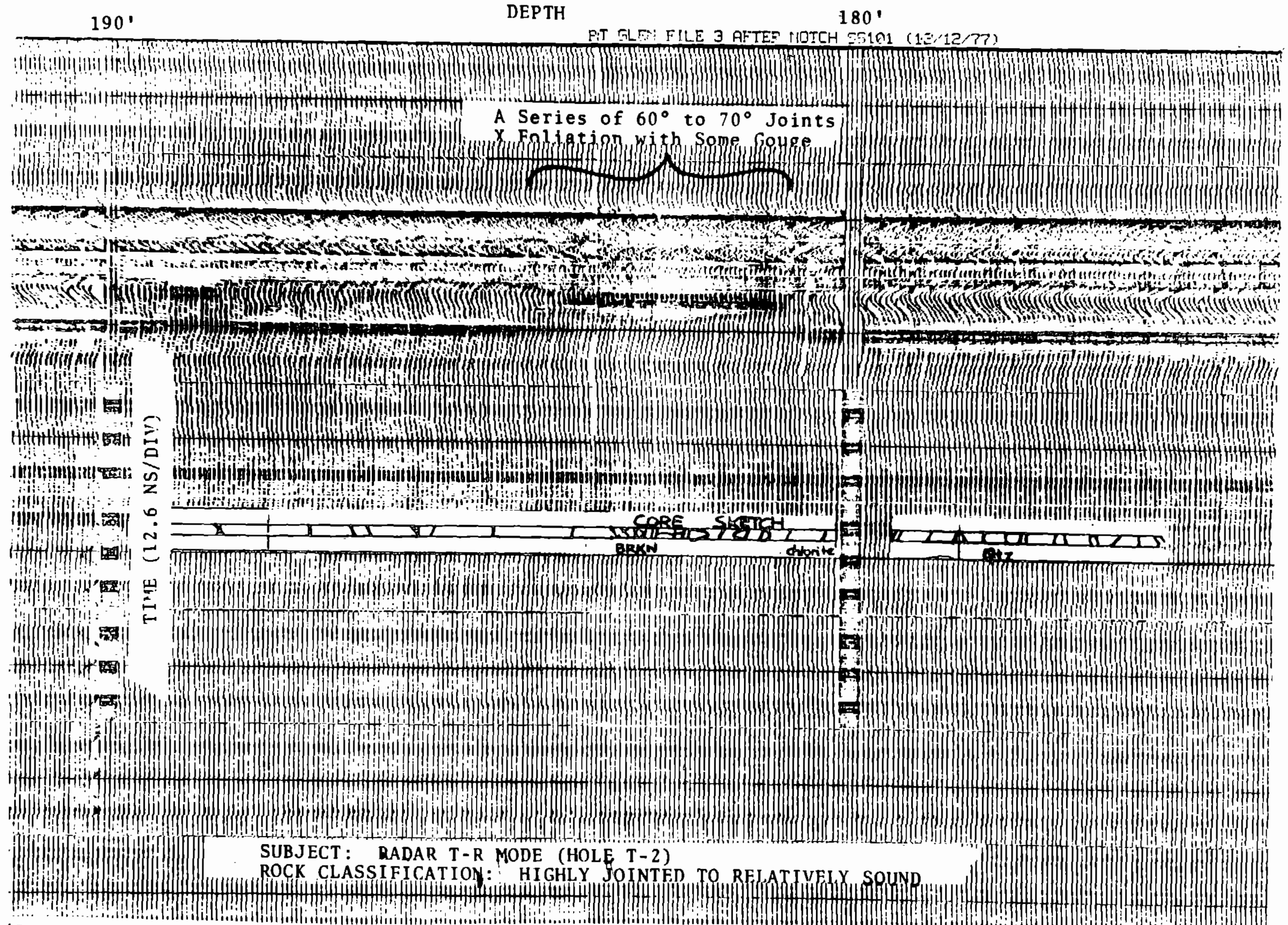
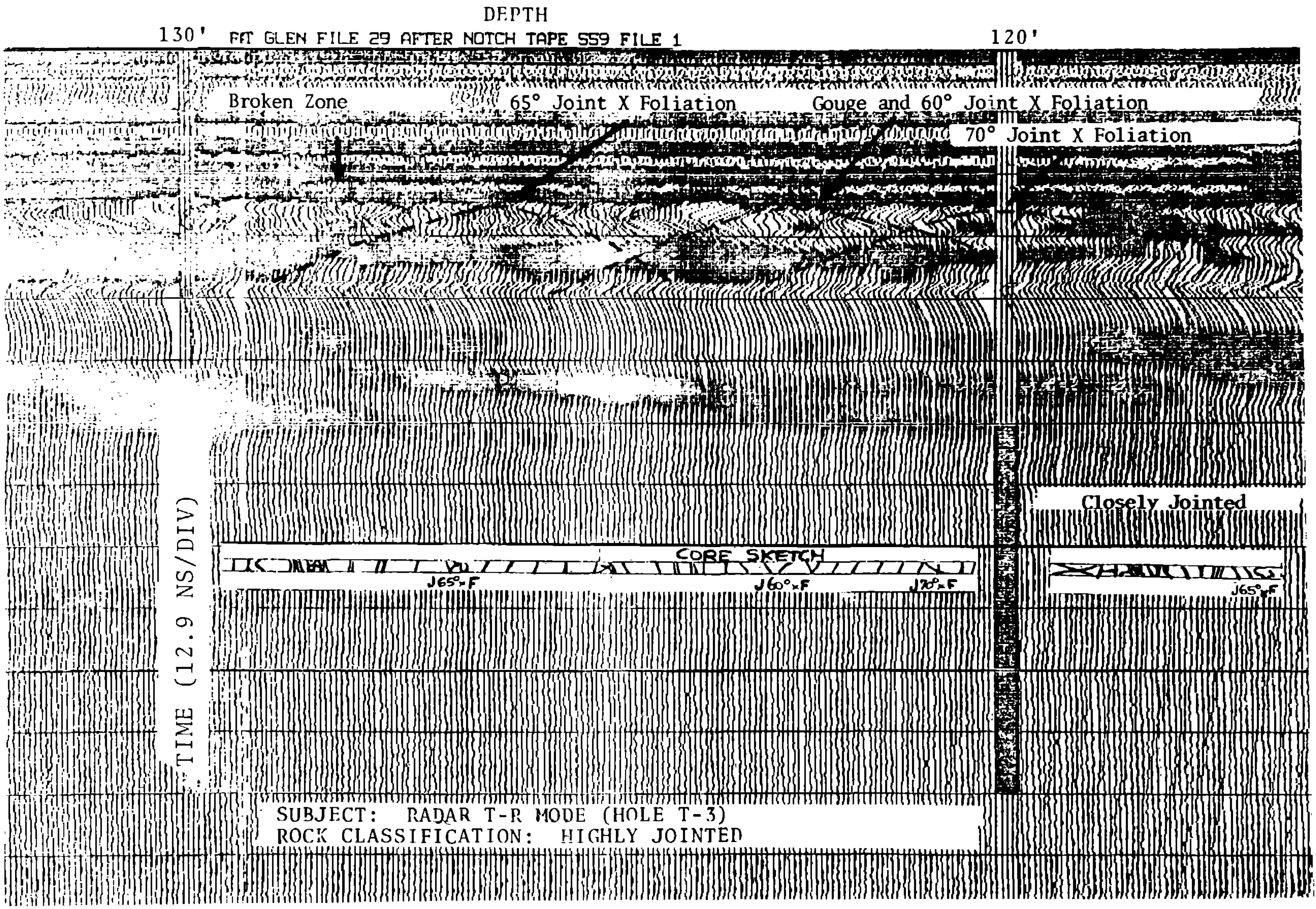


Figure H13. Radar profile from Hole BRP-27.



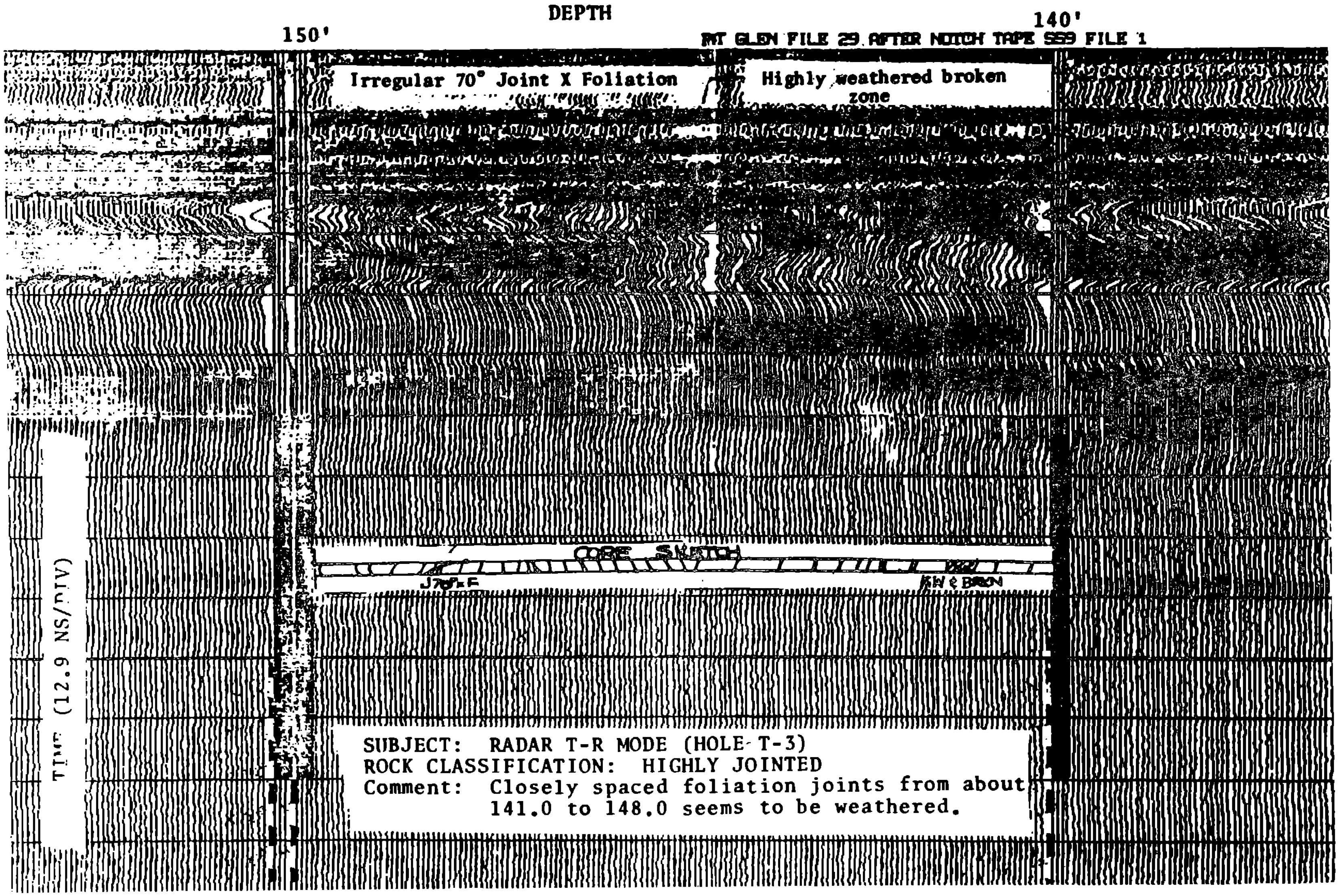
(1 ft = 0.305 m)

Figure H14. Radar profile from Hole T-2.



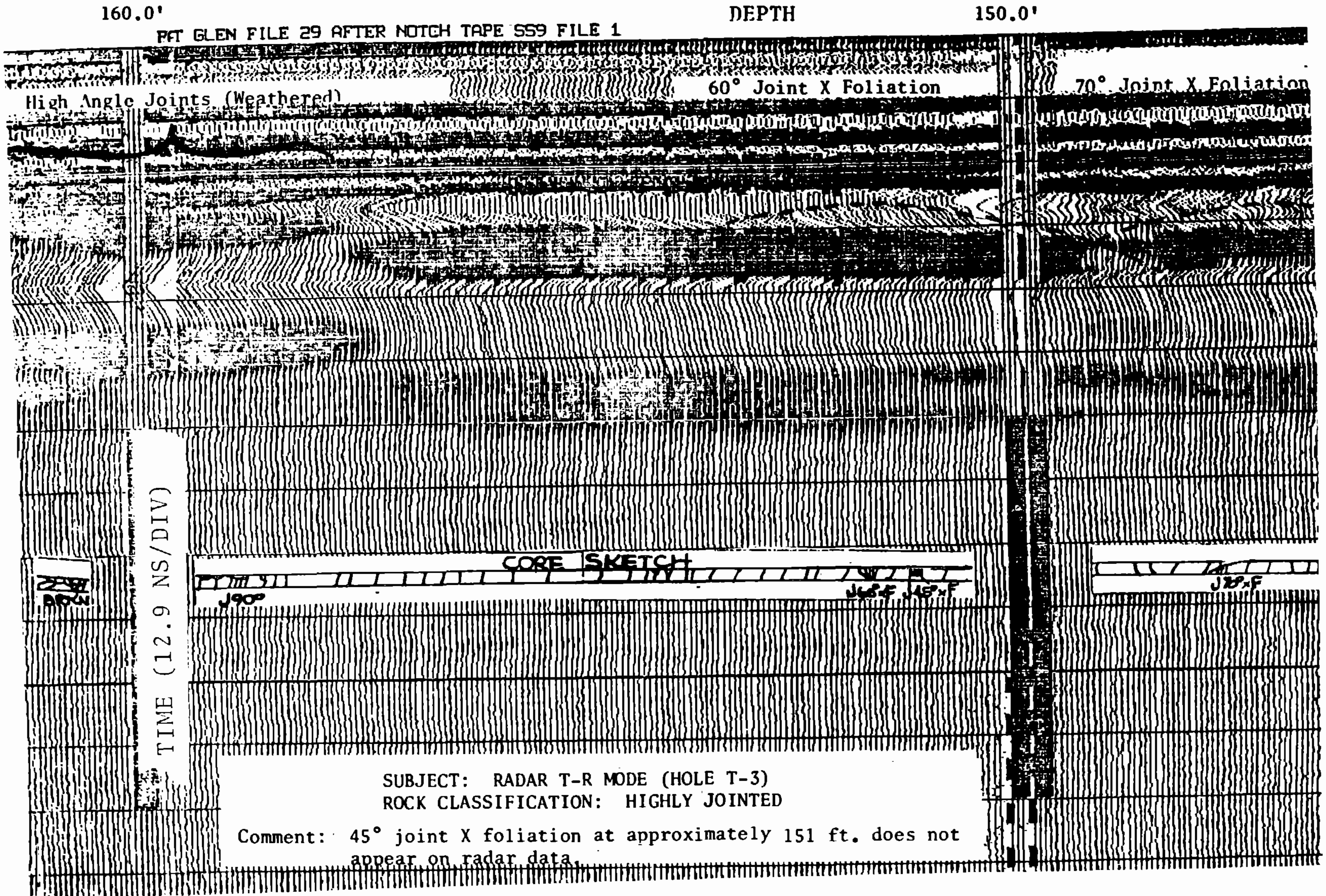
(1 ft = 0.305 m)

Figure H15. Radar profile from Hole T-3, slant depth from 120-130 feet.



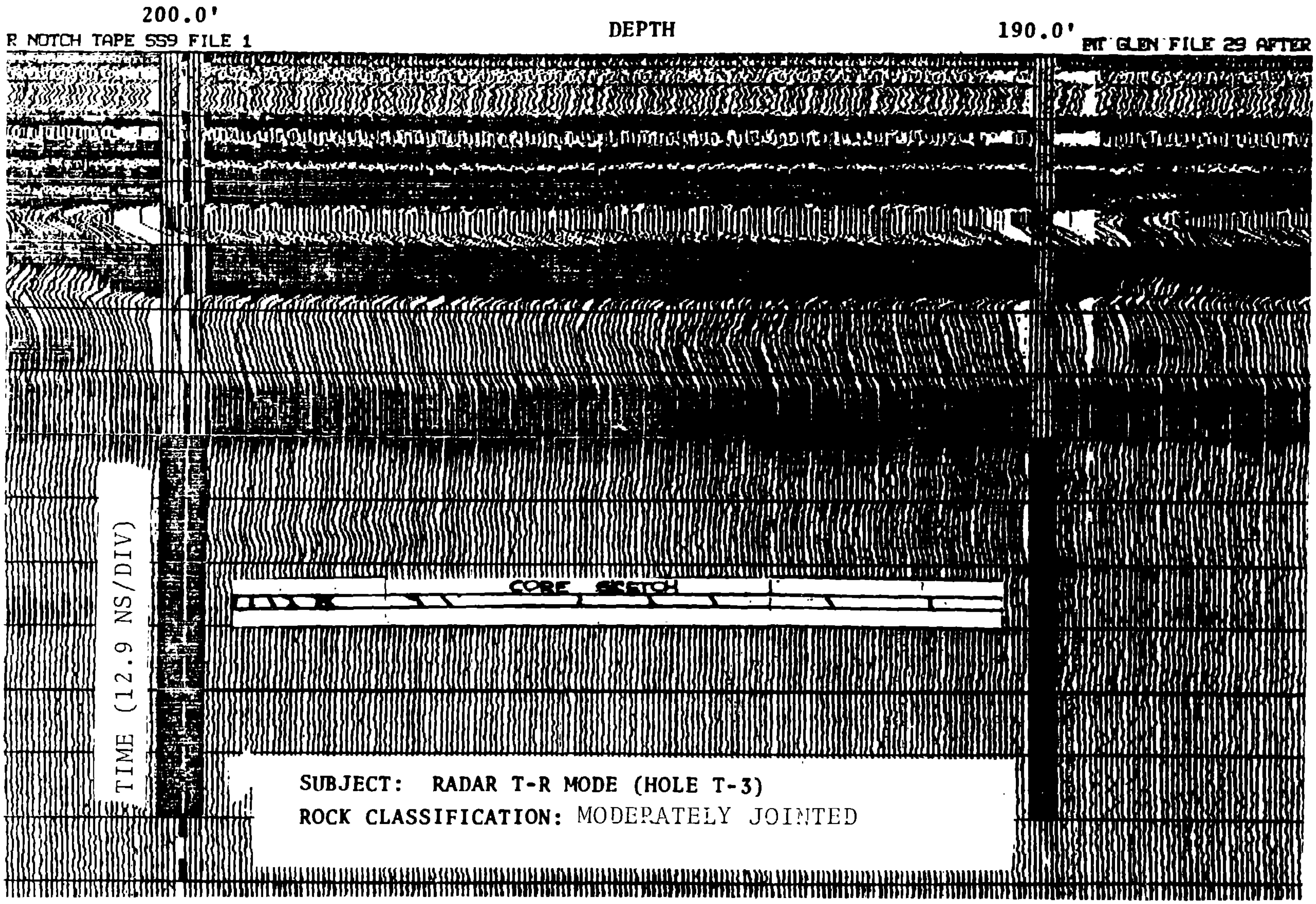
(1 ft = 0.305 m)

Figure H16. Radar profile from Hole T-3, slant depth from 140-150 feet.



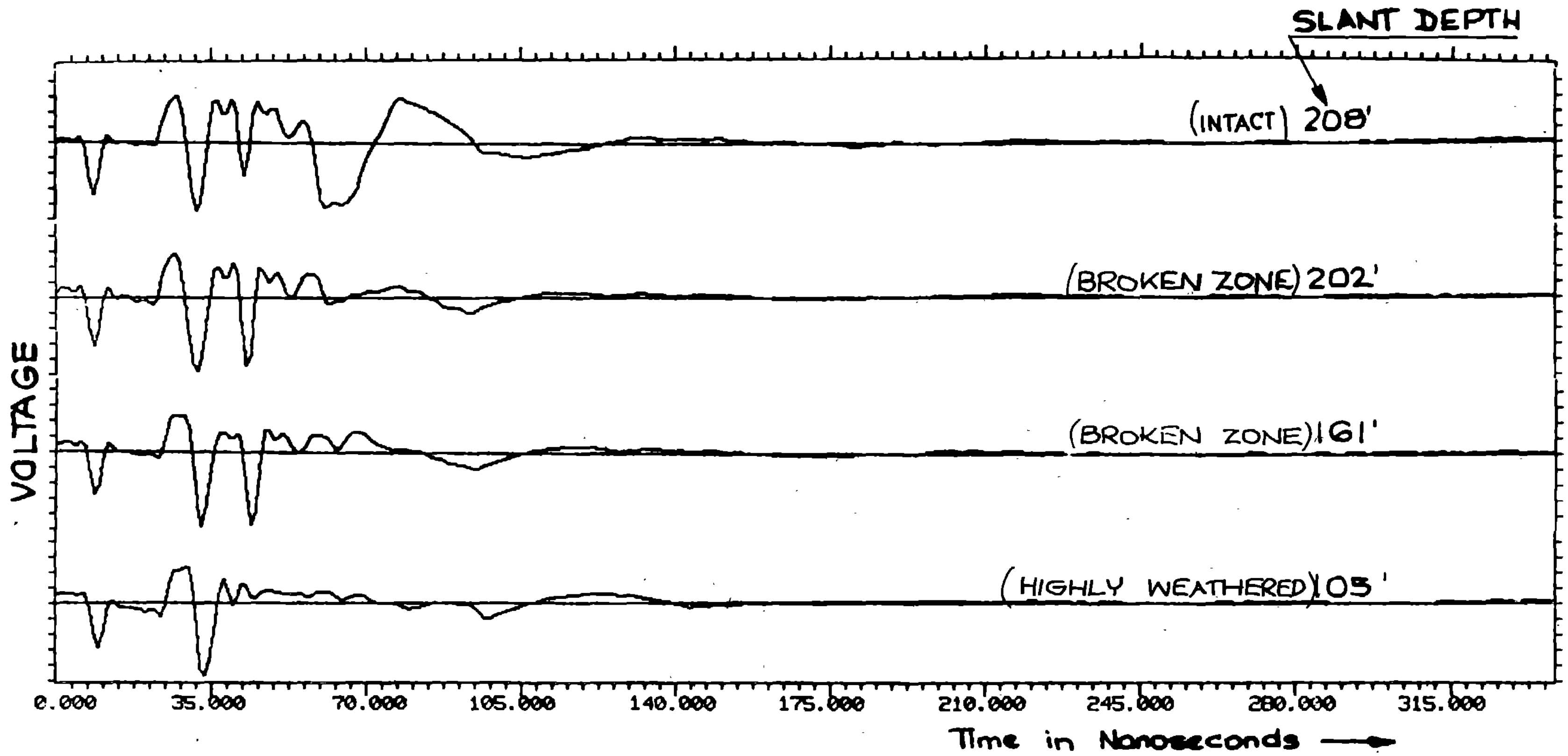
(1 ft = 0.305 m)

Figure H17. Radar profile from Hole T-3, slant depth from 150-160 feet.



(1 ft = 0.305 m)

Figure H18. Radar profile from Hole T-3, slant depth from 190-200 feet.



(1 ft = 0.305 m)

Figure H19. Time-domain radar traces for Hole T-3:T-R mode.

depth point is within an interval of a recovery rate and RQD* of 98/50, respectively. The five-foot interval which encompasses this area is classified as unweathered and moderately jointed. The 202-foot (61.61 m) point is within values of 98/50. It is unweathered, including joints, at 202 to 203 feet (61.61 to 61.92 m). However, there is a highly broken area consisting of three 65° XF joints, slickensided and smooth. The 161-foot (49.11 m) slant depth is an area having a recovery rate and RQD of 98/10, respectively. This section is unweathered except at the joints. The 161-foot (49.11 m) point consists of J 85° XF and J 90° XF and a broken zone much like the area around 203 feet (61.92 m). Note the similarity between the two traces. The 105-foot (32.03 m) area has values of 95/5. This is a moderately weathered area with jointing. Again, the radar trace is different from the preceding three.

The frequency-domain transforms of the time-domain traces of Figure H19 are shown in Figure H20. One sees trends and differences between the four areas here as with the time-domain. These elementary "signatures", when combined with the other available radar data such as velocity (relative dielectric constant), attenuation versus frequency, etc., can constitute part of a library of signatures which can be stored in a computer. Any subsequently acquired radar data can then be compared with the stored "labeled" signatures to help future site investigations.

Reduction of T-R Data.--In an effort to better understand the radar data, we have performed some additional signal processing and transformations from the time domain to the frequency domain. In the upper half of Figures H21 through H23 are radar time records. In the lower half of these records is a plot of the mean frequency in MHz for each radar return pulse. Five-foot average RQD values are plotted as dots in the same plot. These figures are data taken from hole T-3, ranging from 103 to 214 feet (31.42 to 65.27 m) in depth.

The above data was quantified in Figures H24 and H25. Here, we related the RQD values and fractures per foot with the radar return mean frequency, respectively. It should be noted that the mean frequency was averaged over two- and five-foot (0.61 and 1.53 m) intervals for the fractures per foot (m) and RQD correlations. In some areas of the geology (135 to 170 feet (41.18 to 51.85 m)), these relationships appear to be excellent. In the area of no weathering, there is apparent negative correlation. In the region of high weathering, it is risky to try correlations, since there is some question about what RQD means in such zones. We are not prepared to go further in our interpretation of these correlations at this time, but will continue our studies. It is interesting to note the correlation of the mean frequency with the borehole resistivity measurement shown in Figure H26.

GENERAL CONCLUSIONS

Remarks

The NX borehole radar was specifically built to be cost-effective for use in existing exploration boreholes. It is disappointing to operate the radar in a geologic environment which has nearly all of the interesting features in planes subperpendicular to the

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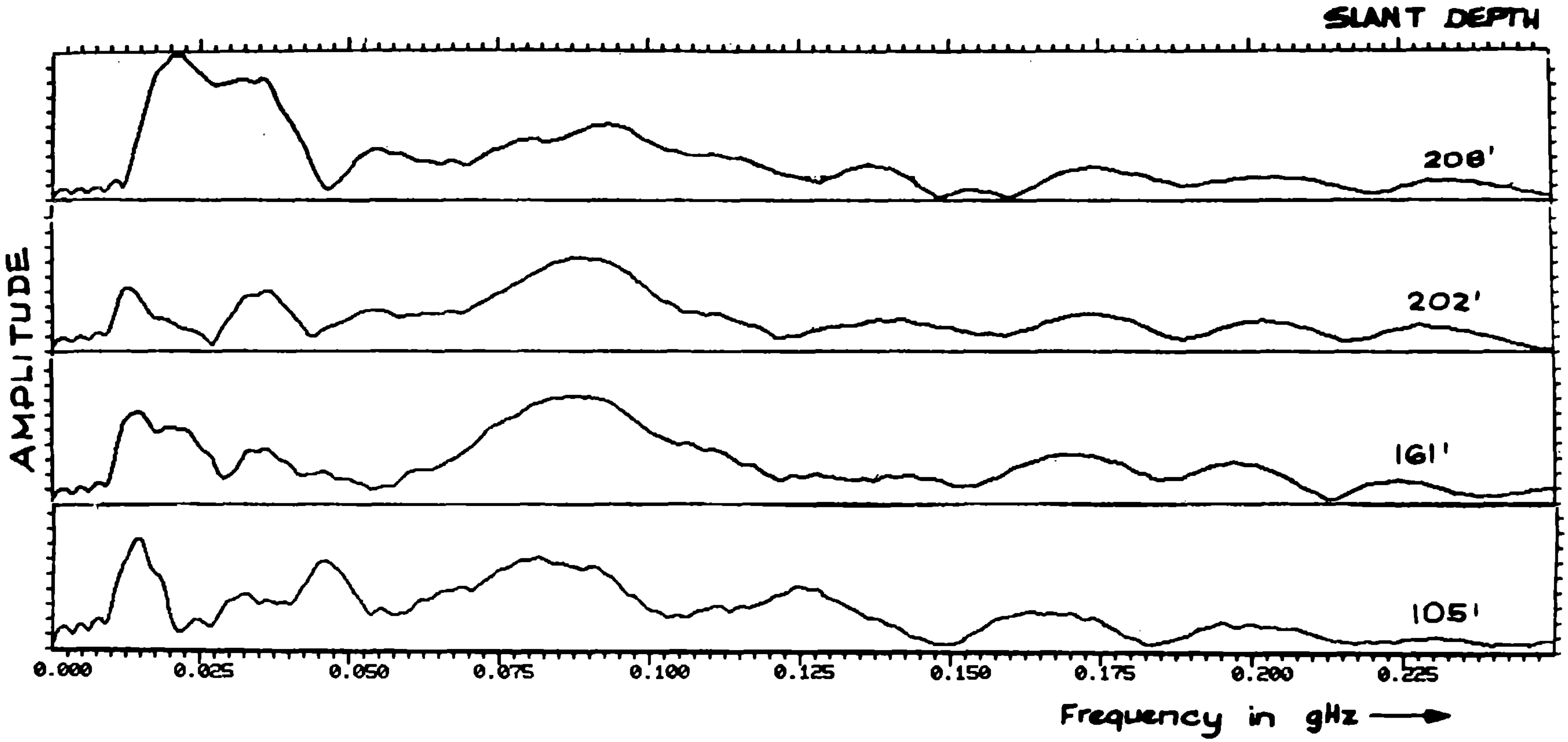
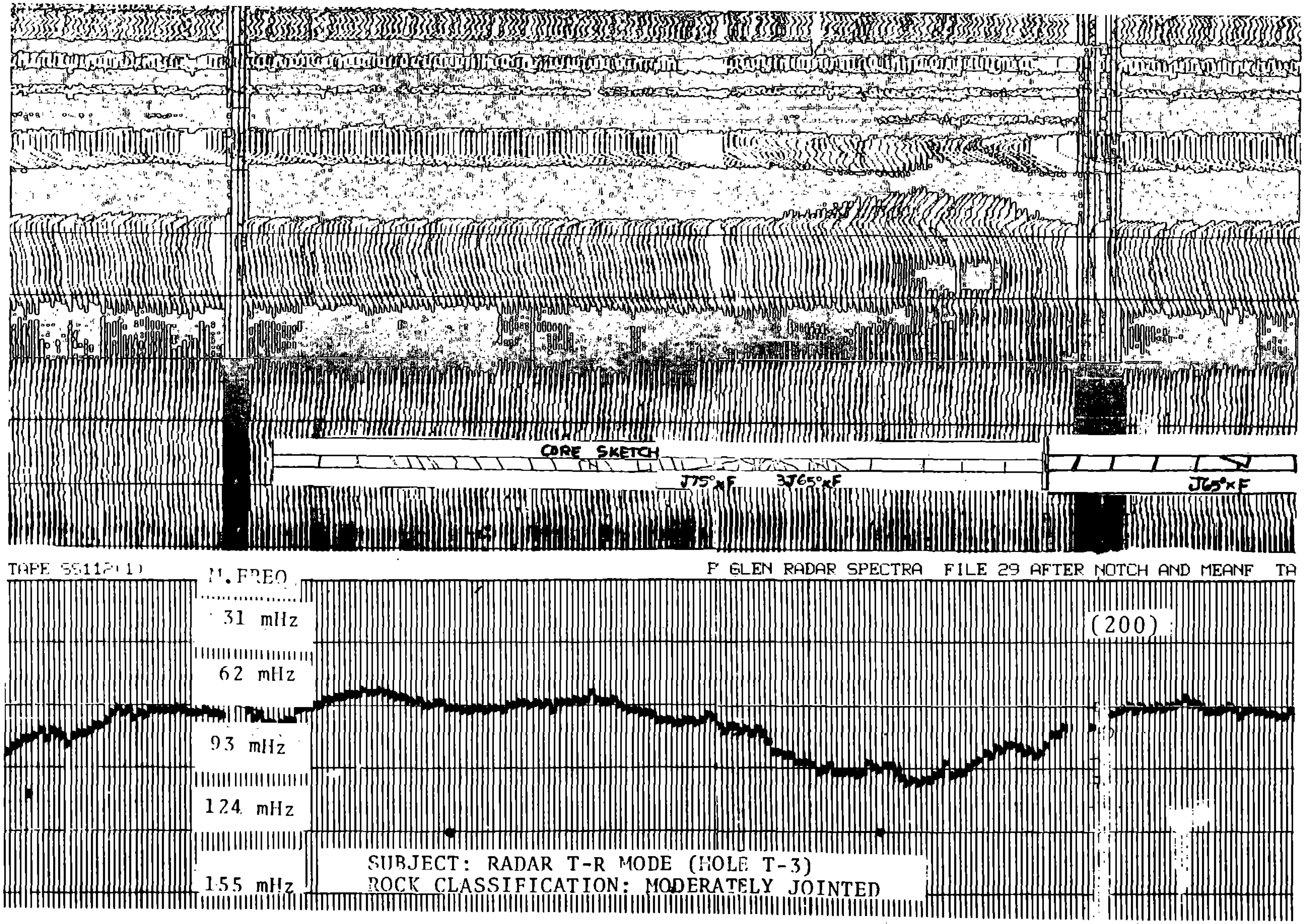
*Rock Quality Descriptor.



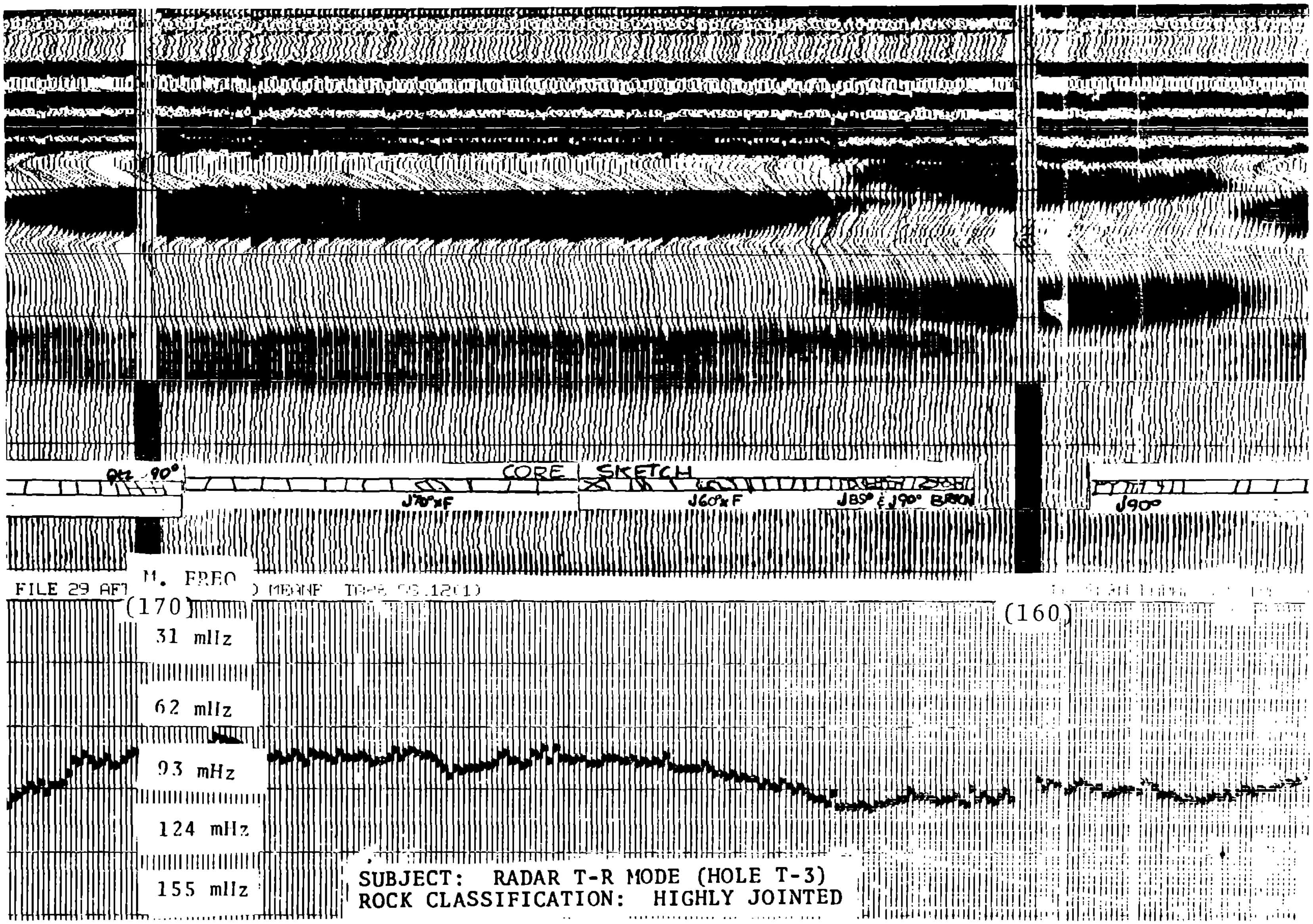
(1 ft = 0.305 m)

Figure H20. Frequency-domain amplitude spectra for Hole T-3:T-R mode.



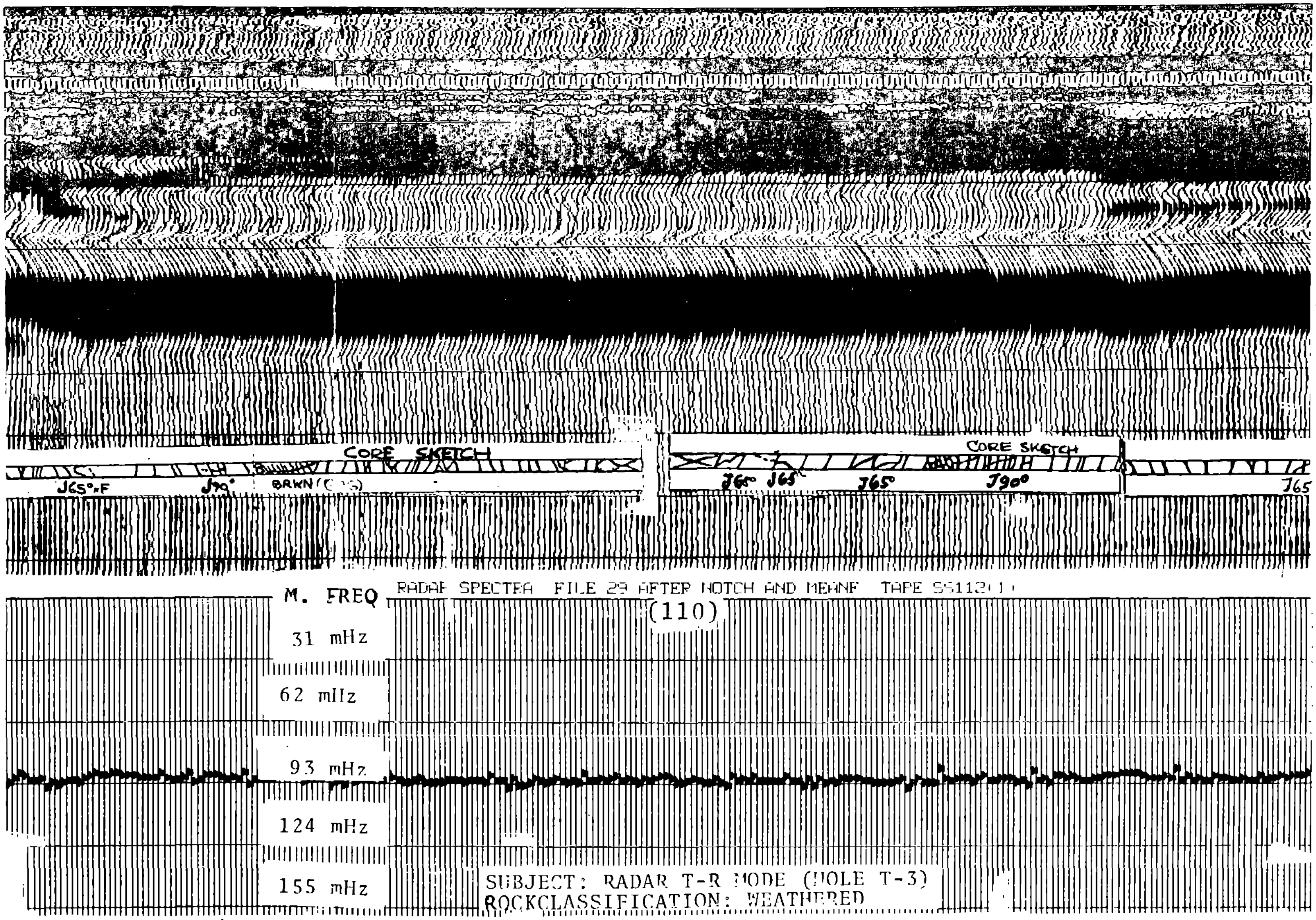
(1 ft = 0.305 m)

Figure H21. Transmit-receive borehole radar mode for Hole T-3 in moderately jointed rock.



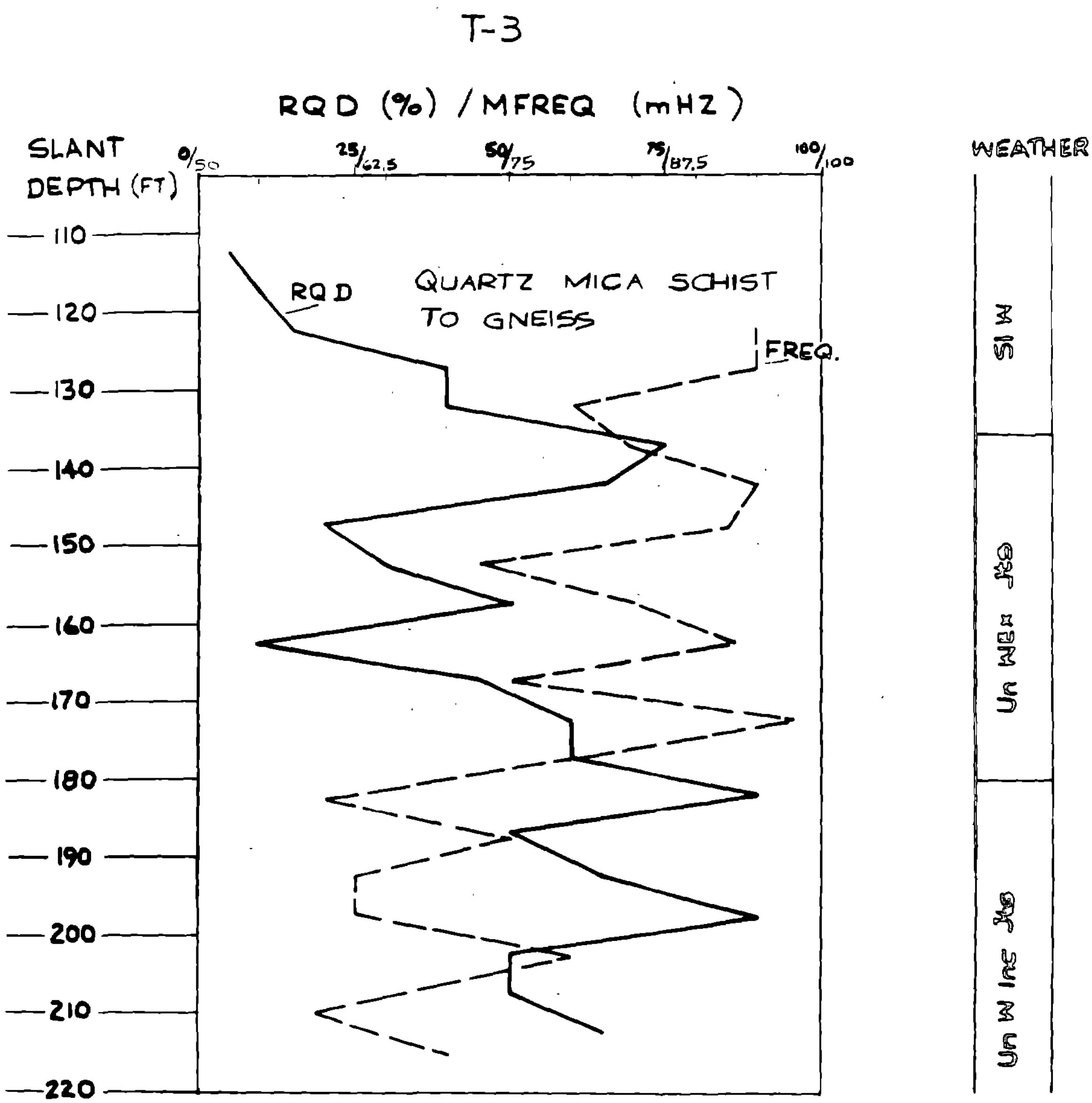
(1 ft = 0.305 m)

Figure H22. Transmit-receive borehole radar mode for Hole T-3 in highly jointed rock.



(1 ft = 0.305 m)

Figure H23. Transmit-receive borehole radar mode for Hole T-3 in weathered rock.

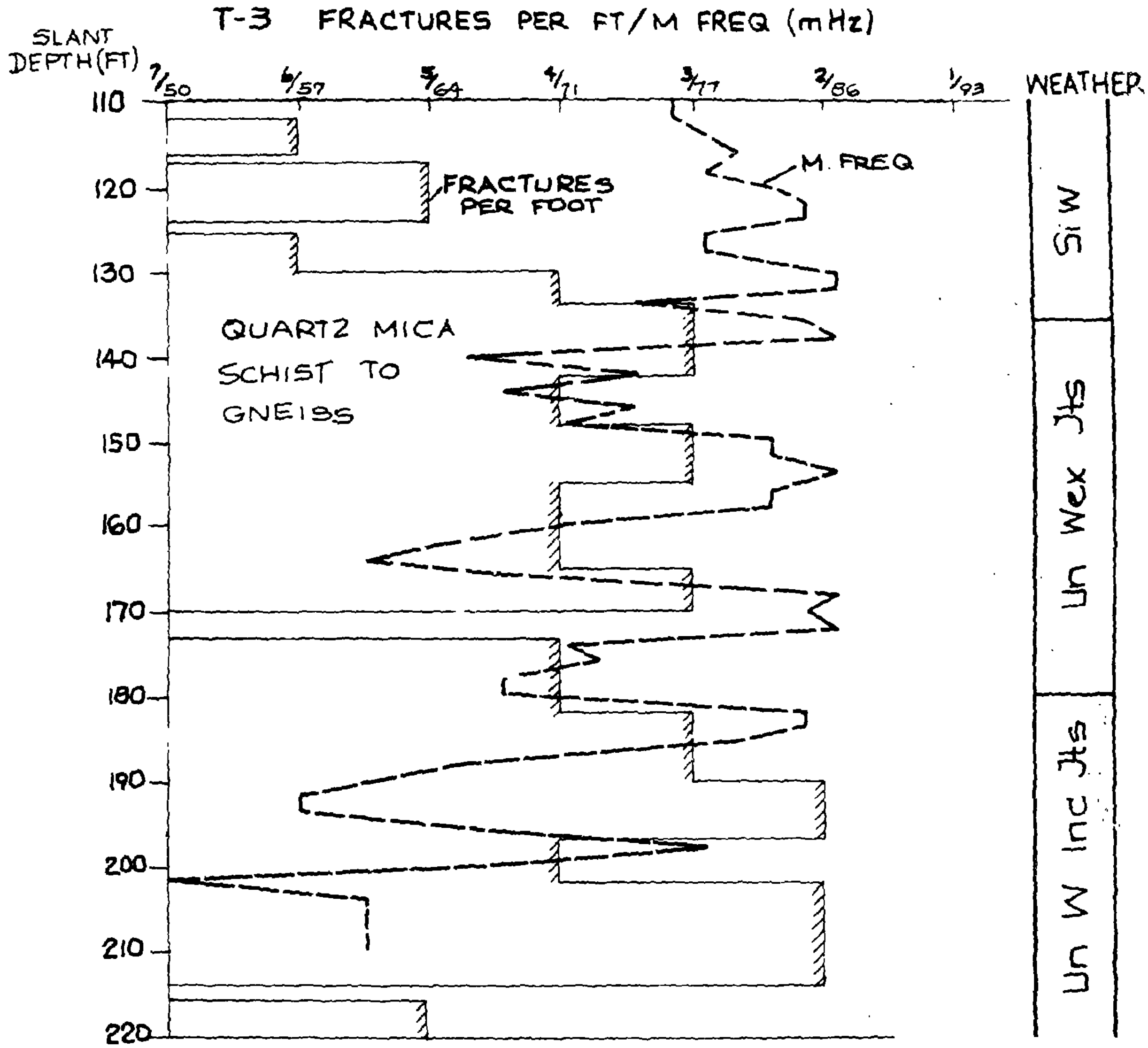


(1 ft = 0.305 m)

NOTES: RQD and rock weathering classification taken directly from MRJ & D geologic log.

Mean frequency was averaged over 5-foot RQD intervals.

Figure H24. Mean frequency related to RQD and weathering.

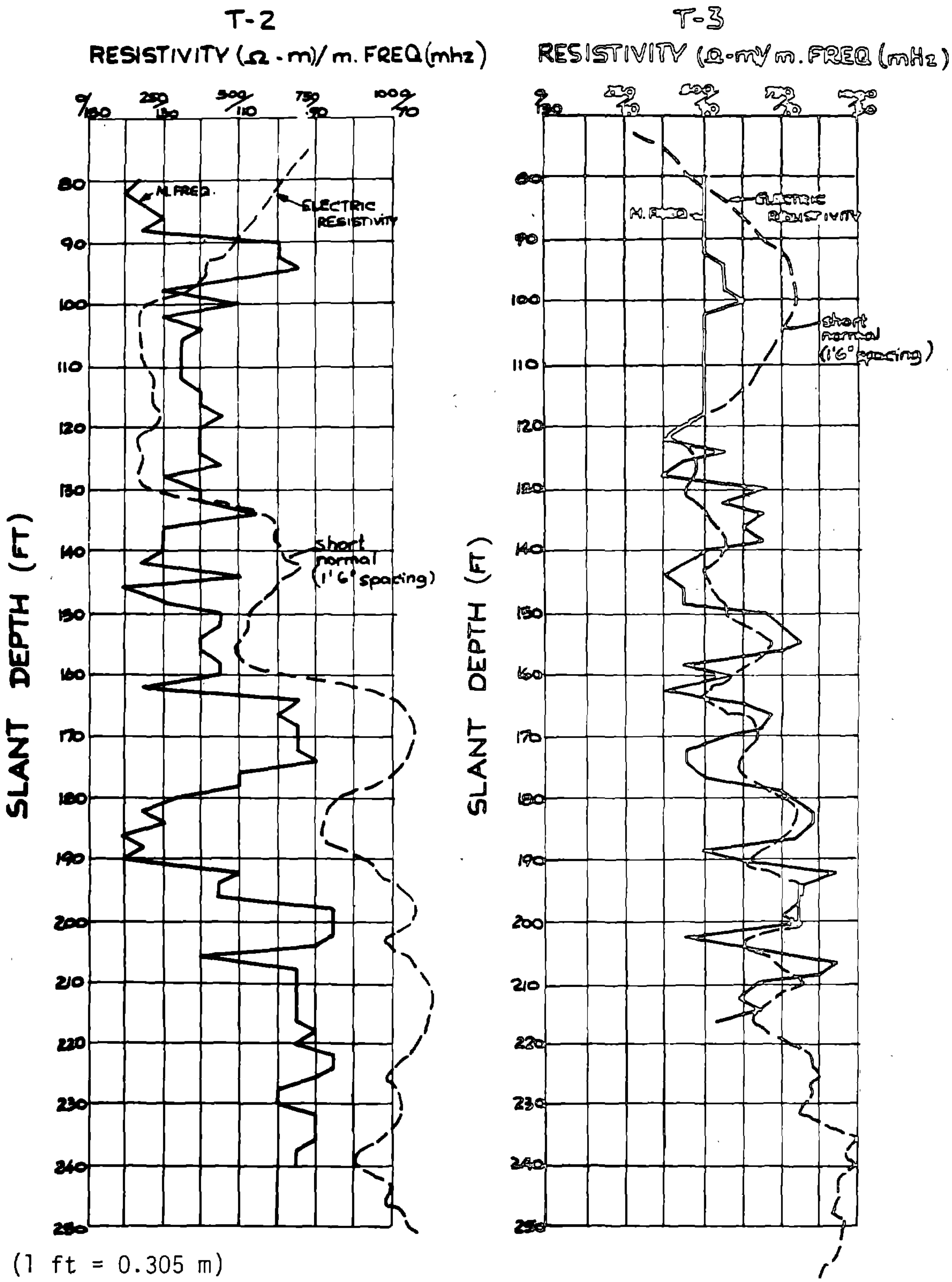


(1 ft = 0.305 m)

NOTES: Fracturing and rock weathering classification taken directly from MRJ & D geologic log.

Mean frequency was averaged over 2-foot intervals.

Figure H25. Mean frequency related to fractures per foot and weathering.



(1 ft = 0.305 m)

NOTE: Holes were grouted and then reamed.

Figure H26. Correlation of borehole electric resistivity with mean frequency.

boreholes. If, on the other hand, the exploration holes at Forest Glen had been drilled as slant horizontal boreholes, such that 100 feet (30.5 m) or more was colinear with the tunnel alignment, the story might be very much different. Interestingly enough, the 30 or so feet (9.15 m) in the proposed tunnel section appear to be reasonably free of features. The critical crown area above the tunnel alignment is quite rich in features and therefore horizontal holes would have made an excellent exploration base from which to investigate this zone.

It is not unexpected that the radar data turned out as it did. Previous experience indicates that features which are subparallel to planes through the borehole will give much better returns than features which are nearly perpendicular to the borehole. We did anticipate that had there been any major shear zones, faults, or intrusives other than sub parallel to the foliation, we would have found them easily with the radar.

The very good transillumination data, of course, gives average dielectric constant values and gross attenuation rates for the region between the two boreholes being used. While this information might be useful, it is also probable that it could be obtained by other techniques. On the other hand, if there had been any features as previously described, they would have shown up in the transillumination data. At least it is comforting to see that at these frequencies (50-150 MHz), we are experiencing excellent propagation ranges and thus we are led to the conclusion that the transillumination technique in the future will be most useful.

The T-R (transmit-receive) data covered in "Field Measurements" is difficult to assess. As noted, the difficulty of using geophysical penetrating probes from boreholes that are sub perpendicular to the features is the leading determinant here. The features that did show up are reasonably well correlated to the core data.

Correlation of radar time-domain and frequency-domain data with site conditions discussed in the above cited section is a new concept which is still mostly untried. The preliminary results cited here indicate the possibility of obtaining highly diagnostic signatures of geologic structure in the future. Looking one step beyond, it is our hope, and constant mission, to develop high-resolution geophysical sensing out to a point where it becomes an integral part of the geotechnical site investigation picture.

Our current work is directed at providing electromagnetic and acoustic models of real geologic scenarios so that we may develop better radars, acoustic probes, computer algorithms, and especially, better and more consistent interpretational techniques. We are simultaneously collecting field data, using hardware which we are interactively developing. The hardware capabilities must keep pace with our other developments in signal processing, algorithms, acquisition modes, and interpretational techniques.

Future Considerations

The future of borehole radar lies in several areas in which we recommend specific improvements:

- Provide the ability to drill slant/horizontal boreholes along controlled trajectories at reasonable cost.
- Develop a technique for separating transmitter and receiver in the same borehole to provide various offsets.

- Increase the resolution-range of the borehole radars by including more low-frequency energy and increasing signal-to-noise generally.
- Use closely-spaced (15 feet (4.58 m) or so) multiple NX, or single larger boreholes in order to attain larger apertures and thus some degree of directivity for sorting out features in terms of angular discrimination.
- Increase selection of computer algorithms useful in reducing borehole reverberations and other forms of interference clutter.
- Develop better computer processes. Combine the results of transillumination data and increase our correlations of both time-domain and frequency-domain signatures from specific interfaces related to specific radar geometries.
- Set up a central depository for high-resolution geophysical signatures such that all investigation can contribute to, and use, such a library freely.
- Repeat the Forest Glen experiment at other locations and include both vertical, near vertical, slant-horizontal, and horizontal boreholes.

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2. Rubin, L. A., Griffin, J. N., and Still, W.L., "Final Report Phase I--Feasibility of Subsurface Site Investigation by Electromagnetic Radar," NSF (RANN) Grant No. APR75-13414, Report No. NSF-RA-76-0187, NTIS PB259335/AS, March 31, 1976.

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APPENDIX H-1

ZONE DESCRIPTIONS

Stratum D: This layer is of soil consistency and basically contains no rock-like remnants. Its typical thickness ranges from 10 to 60 feet (3 to 18 m) with N blow ranging from 30 to 100 per foot (10 to 33 per meter). Basically, 100 blow material defines the lower limit of this stratum.

Stratum D to WR: D to WR denotes the transition zone in which the profile material transfers from residual soil or saprolite to a weathered rock. It consists of rock-like remnants surrounded and separated by material of the consistency of the residual soil. The percent of the amount of residual soil continuously decreases with depth within this zone or, conversely, the rock-like remnants becomes larger in proportion. The delineation of the WR interface is by no means abrupt boundary change.

Zone WR: This zone consists of weathered and jointed bed rock. The weathering is along joints and generally affects the mineral fabric. In fact, a most significant feature here is the continuous decrease in the degree of leaching of the mineral fabric. The zone is determined in the core generally by considering the following criteria:

- Relatively close joint spacing
- RQD ≈ 10 to 50% (although may be frequently 0)
- High rate of recovery
- Moderate foliation

Zone J: J represents highly jointed to jointed bedrock. Weathering is confined to alteration or talc deposits in joint planes. This zone has been found to be the most extensive from past Metro studies where similar deposits are encountered. The rock within this zone is broken down into subzones ranging from highly jointed, HJ , to moderately jointed, MJ , to jointed, J . This is determined from core data. The basic core criteria applied to J is:

- RQD ≈ 40 to 75%
- Rock mass weathering relatively rare
- Joint spacing greater than one per foot (0.3 per meter)
- Moderate to poor foliation.

Zone R: R consists of relatively sound bedrock, which is occasionally moderately jonted. Weathering is confined principally to joints. This zone is free of open and latent joints in situ. Basically, core classification criteria consists of RQD <75% and the foliation is indistinct. However, this zone is rarely encountered and the most intact material discerned is J to R which is of the same characteristics except that RQD ranges from 65 to 95%.

APPENDIX I

CROSS-HOLE SHEAR WAVE VELOCITY STUDY, FOREST GLEN STATION, WMATA

Ronald E. Smith
Woodward-Clyde Consultants

INTRODUCTION

The aim of a cross-hole survey is to determine the velocities of seismic waves along strata at various depths below the ground surface. Seismic energy, generated by a source lowered down one borehole, travels along a stratum and is detected by geophones located in other boreholes. All sources generate both compressional (P) waves and rotational, shear (S) waves, but each source is designed to emphasize one type. Similarly, geophones are designed to enhance the detection of one type of wave. Of the two wave types, a shear wave is the most difficult to generate and detect. Seismic velocities are determined by accurately measuring the instant the energy source is activated, the time of arrival of the seismic waves at the geophones, and the source-geophone distances.

The downhole shear wave source (a shear wave hammer) developed by Woodward-Clyde Consultants generates both the shear waves that are polarized in the axial direction of the borehole and maximum amplitude propagated in a direction perpendicular to the axis, that is, radially from the borehole. Detection of the shear waves is maximized by orienting a geophone along the direction of polarization of the waves and locating the geophone in the plane perpendicular to the borehole that contains the source. In horizontally bedded strata, therefore, the source should be placed in a vertical borehole so that the maximum amplitudes of the waves propagate horizontally along the strata. The shear wave detection is then maximized using vertical component geophones located in vertical boreholes at the same elevation as the source.

In order to achieve the same effects in dipping strata, the source and detector boreholes should be drilled perpendicular to the plane of the strata. Data analysis can be simplified if the geophones can be placed close enough to the source to ensure that the signals detected result from directly propagating waves rather than waves refracted along the interfaces with adjacent layers.

Contrary to the above, the test boring program at Forest Glen resulted in boreholes drilled approximately 25 degrees from the perpendicular, at a skew angle to the strata. This situation is far from ideal for a cross hole shear wave survey. If source and detectors are located at the same relative position in a layer, the detectors are not situated along the direction of maximum amplitude propagation. Conversely, if the geophones are situated along the direction of maximum amplitude propagation, it is probable that they will detect waves that have undergone complex refractions and reflections at layer interfaces. It is also possible that source and geophones would not even be situated in the same layer. Any of these situations causes a severe reduction in data quality.

For the Forest Glen survey, measurements were made with source and detectors located at the same depths within each borehole, after the determination that record quality was not improved at other elevations.

FIELD PROCEDURE

A typical field layout for a cross hole shear wave survey is shown schematically in Figure I1. In the Forest Glen project the shear wave hammer was lowered down borehole T1 (an end hole of the array), and the vertical component geophones were lowered down holes T2, T3 and RP27. The hammer and geophones were all lowered to the same slant depth.

Schematic diagrams of the shear wave hammer and geophone are shown in Figures I2 and I3, respectively. The hammer is coupled to the borehole wall by hydraulic jacks actuated at the ground surface (Figure I2). Similarly, geophones are coupled to the borehole by means of inflating heavy rubber balloons protruding from the sides of the geophone housing (Figure I3). Shear waves, polarized upward in the borehole axial direction, are produced by pulling the hammer sharply upward. The wave is detected on each of the three geophones and the received signals are recorded as the top three traces on the storage oscilloscope. The hammer is then released and generates a second wave, polarized in the downward axial direction and recorded as a second set of three traces (Figure I4). The origin time of the hammer blows are detected by trigger devices (Figure I2), the signals from which trigger the oscilloscope. Shear wave velocity determinations were made at 10-foot (3 m) intervals from a depth of 35 feet to 200 feet (10.7 to 61 m).

DATA ANALYSIS

Sample records from the Forest Glen site are shown in Figures I5 and I6. Each record contains six traces, and while the top three traces are for the upward blow of the shear impulse source, the bottom three traces are for the downward blow of the source. The first trace in each set is the signal as observed at the near geophone G_1 in hole T2; the second trace is the signal observed at the geophone G_2 in hole T3; and the third trace is the signal observed at the geophone G_3 in hole RP27.

The general characteristics of these records are as follows: 1) Shot time, or the triggering of the oscilloscope, is shown by the beginning of the trace at the left side of the figure; 2) the compressional (P) wave is observed as a small motion on the traces prior to the major excursions; and 3) shear (S) wave arrivals are observed as large upward or downward excursions of the signal and are noted on all figures by the label T_s. In general, the shear wave arrivals exhibit a distinctly lower frequency than shown by the compressional wave arrivals; the shear wave arrivals at the three geophones are noted by the second subscript, T_{s1} and T_{s2}, for the first and second geophones, respectively. Since traces 1 and 4 are both from the first geophone, and since all conditions are constant except for the polarity of the generating impulse, the S wave signal in the traces theoretically should be a mirror image of each other, as shown in Figure I4. This generally should be true in practice after random effects in transmission are considered. The same can be said for other pairs of traces from other geophones. This feature aids in identifying S wave arrivals.

The compressional (P) and shear (S) wave arrivals were interpreted on the records according to the criteria described above, and the onset of each arrival was accurately measured relative to the shot time. Radial source-geophone distances were determined from borehole deviation measurements. Travel time (arrival time minus shot time) versus source-geophone distance plots were then constructed for each phase from each shot depth. The slopes of these plots give the P and S wave velocities. Formation velocities at

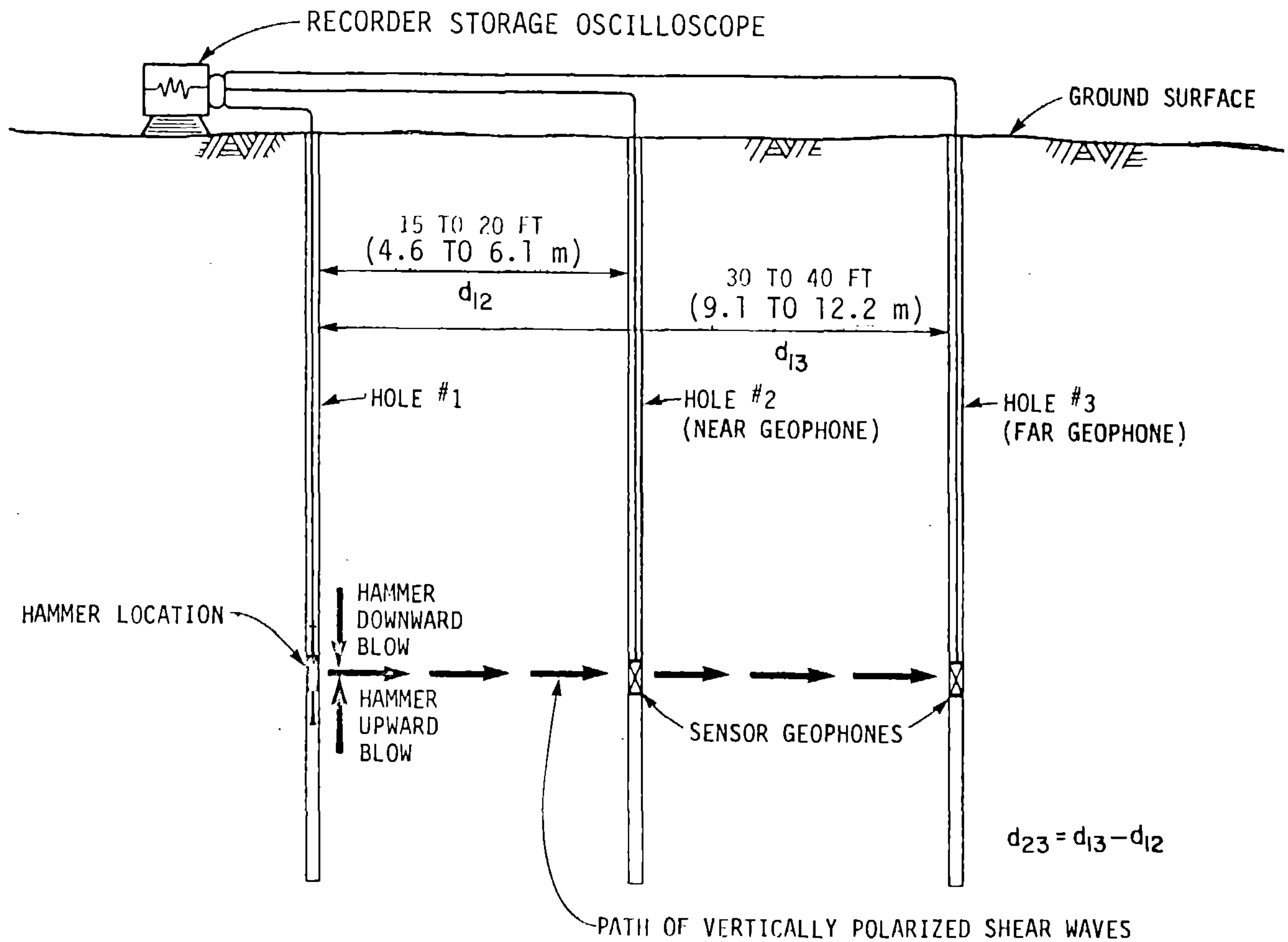


Figure 11. Schematic arrangement of crosshole shear wave measurements.

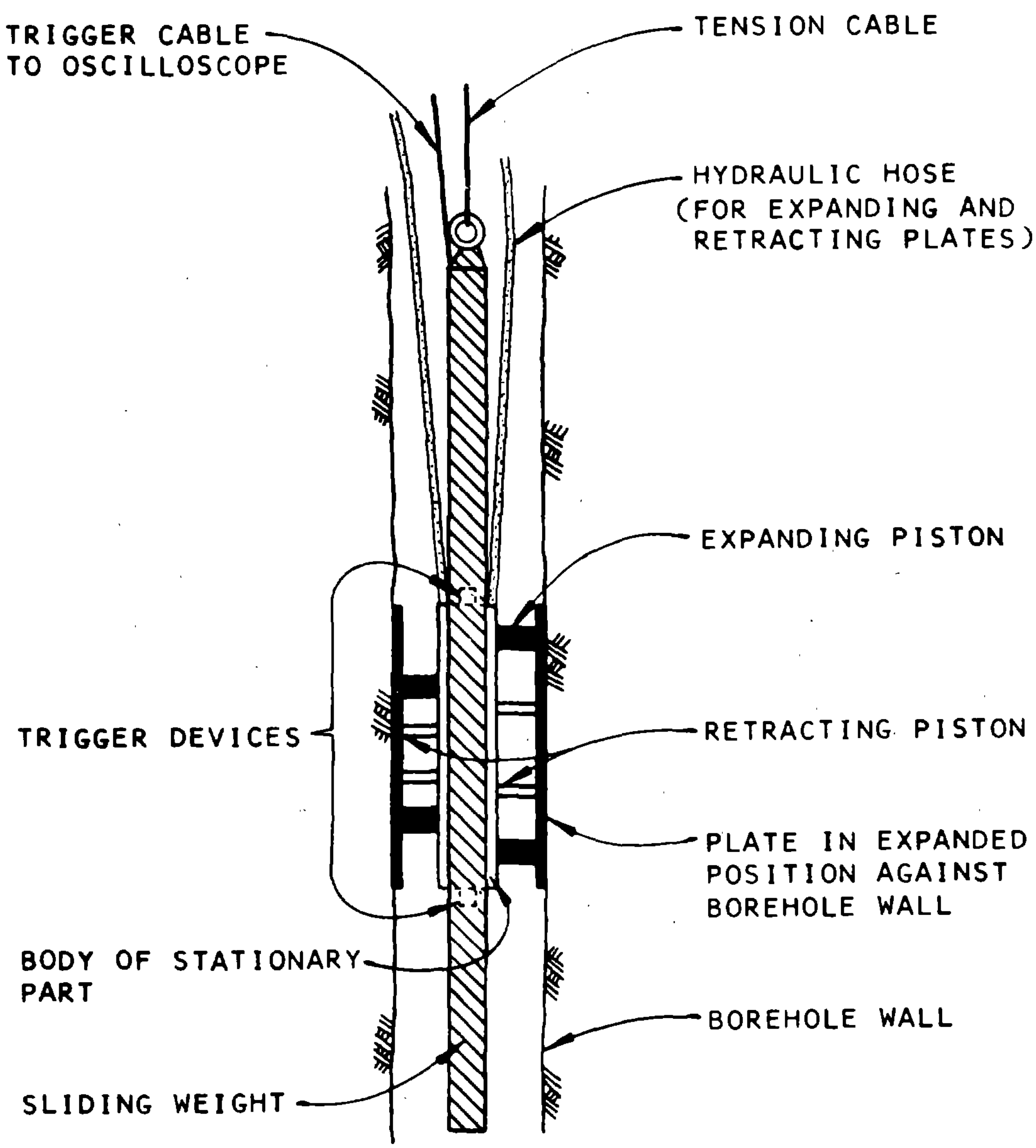


Figure I2. Details of shear wave hammer (schematic).

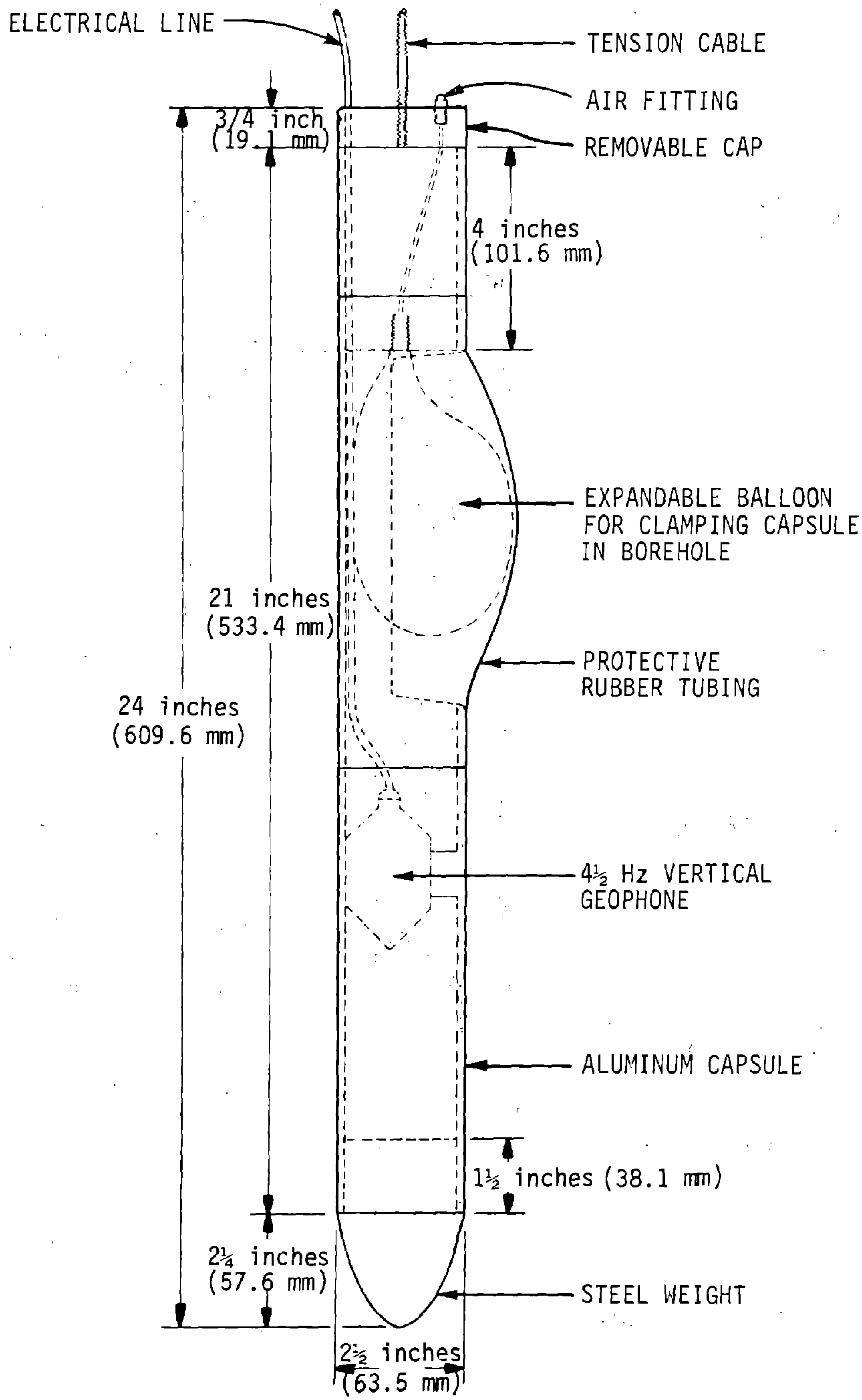
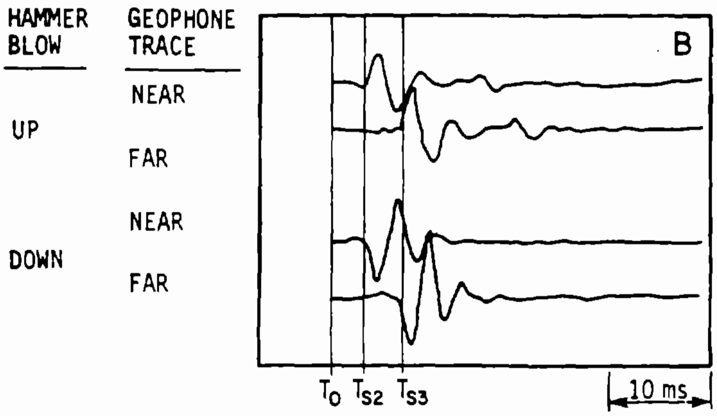


Figure I3. Borehole geophone capsule (schematic).

LARGE DAMPING: DEPTH = 175 Feet (53.3 m)

V_s = 3100 FPS



SLIGHT DAMPING: DEPTH = 45 Feet (13.7 m)

$$V_s = \frac{T_{S2} - T_{S3}}{d_{23}} = 1700 \text{ FPS}$$

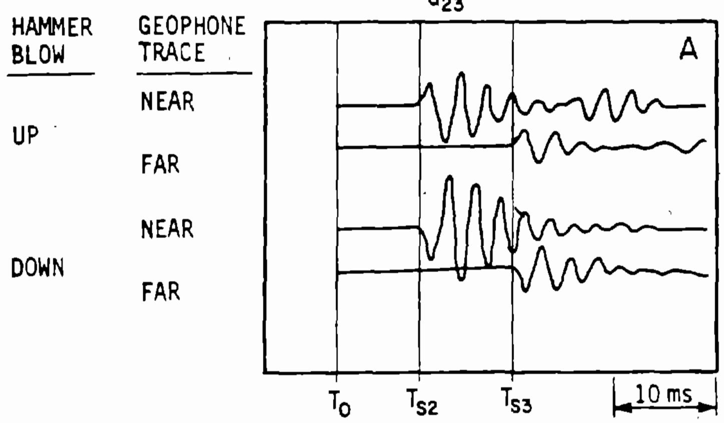


Figure I4. Sample records showing shear wave reversals and exponentially decaying signals.

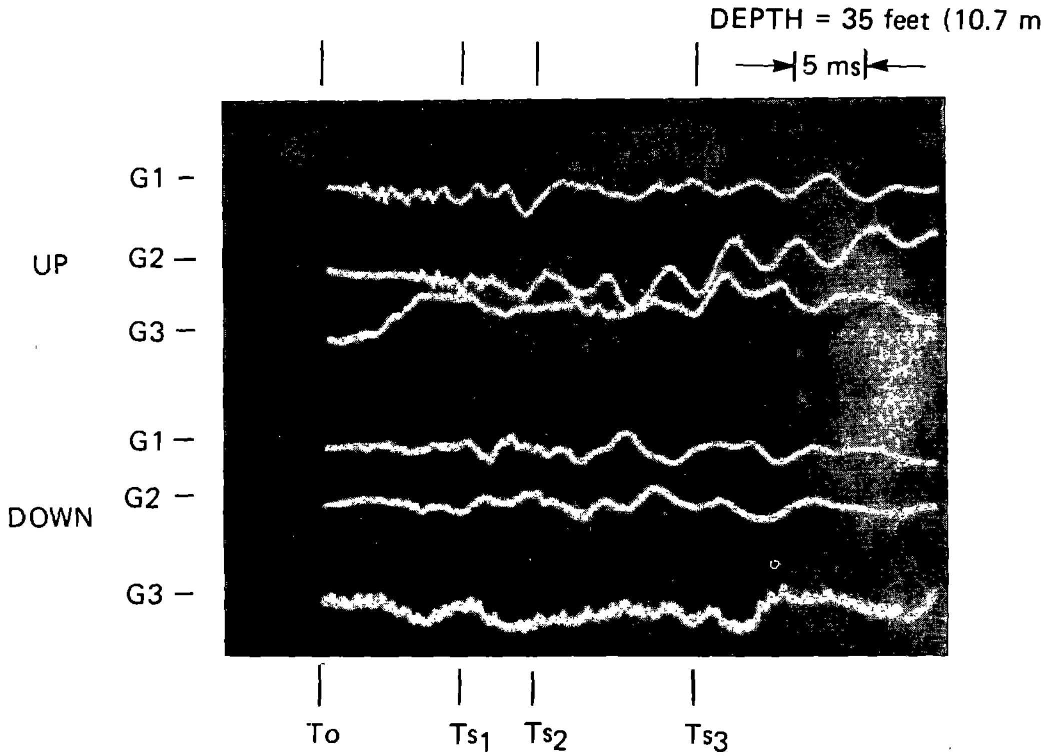


Figure I5. Sample record showing shear wave arrivals at three geophones.

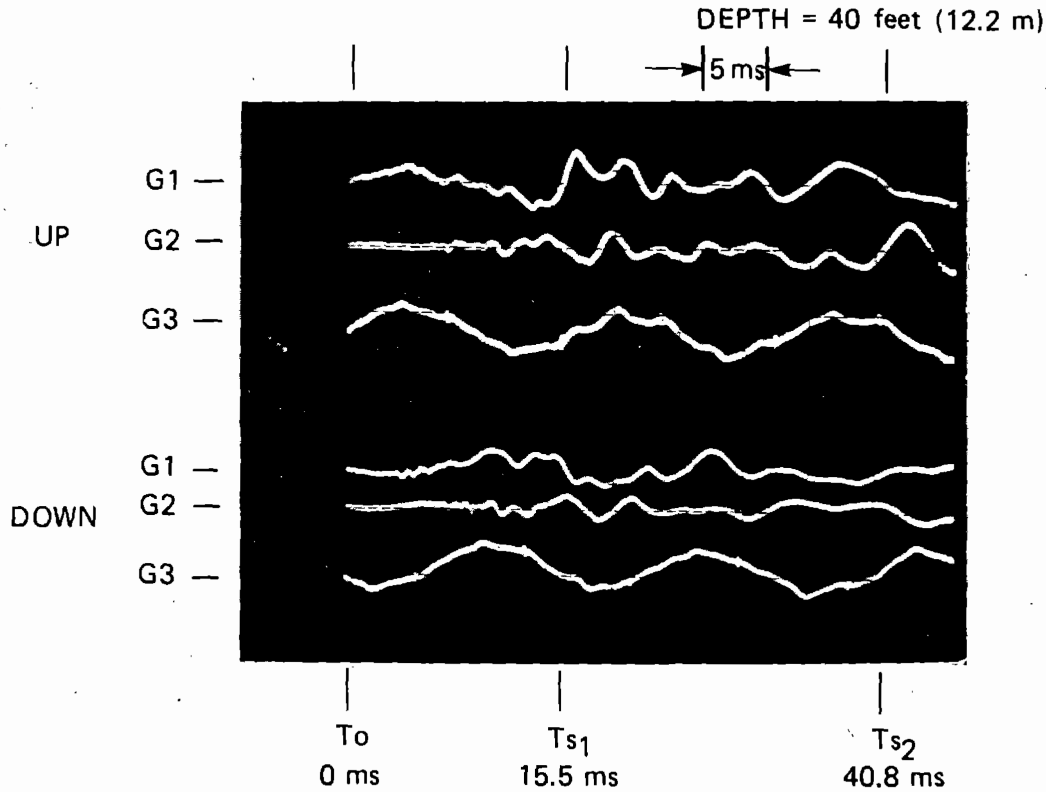


Figure I6. Sample record showing shear wave at G1 and G2.

each depth were, in general, computed as the average of the velocities for the two plots of each phase. This graphic method of analysis provides a check of the reliability of the data, since each plot should pass through the origin and since the data scatter can be seen easily.

RESULTS

The results of the survey are shown in Table II below, from which it can be seen that the technique was of only limited success. This can be ascribed, in part, to the non-ideal field set-up constrained by the layout and orientation of the boreholes, as discussed in the introduction.

Although P wave arrivals could be identified and read with a fair measure of precision, yielding good P wave velocities, it was very difficult to reliably identify S wave arrivals on all but a very few of the records. In addition, the energy of the source was not sufficient to provide consistently readable records from the most distant borehole, RP27, which was located approximately 80 feet (24.4 m) from the source. Therefore, some of the velocity determinations are based on only two data points. No S wave readings could be made of the records from depths greater than 110 feet (33.5 m).

Table II. Compressional and shear wave velocities at various depths.

Slant Depth (ft)	Slant Depth (m)	V_P (ft/sec)	V_P (m/sec)	V_s (ft/sec)	V_s (m/sec)
35	(10.7)	4,900	(1,494)	-----	-----
40	(12.2)	-----	-----	-----	-----
50	(15.2)	6,650	(2,027)	3,200	(975)
60	(18.3)	6,800	(2,083)	4,400	(1,341)
70	(21.3)	-----	-----	-----	-----
80	(24.4)	8,500	(2,591)	4,800	(1,463)
90	(27.4)	11,000	(3,353)	5,000	(1,524)
100	(30.5)	12,000	(3,658)	5,550	(1,676)
110	(33.5)	11,800	(3,597)	4,900	(1,494)

CONCLUSION

The cross-hole shear wave survey at Forest Glen yielded marginal results of limited usefulness. While the poor quality of the data obtained can, as described above, be ascribed in part to the constraints imposed on the field layout, it is not known how successful the technique would have been at the Forest Glen site if an ideal set-up could have been achieved. The P wave velocities shown in Table II are judged to be reliable. It is felt, however, that the S wave velocity results are poor and not of the standard we consider for engineering applications.

APPENDIX J

ACOUSTIC PULSE-ECHO AND CROSS-HOLE SURVEY

James C. Fowler
ENSCO, Inc.

INTRODUCTION

ENSCO, Inc. participated in the field testing portion of the Forest Glen research experiment with two different sets of equipment. The first series of tests, which are described in a separate report, utilized a short pulse ground probing radar. The tests discussed in this report involve the use of a prototype acoustic mapping system. This equipment is being developed for the Federal Highway Administration under Contract DOT-FH-11-9120, "Development of an Acoustic Sensing System."

The Forest Glen site provided a first test for the equipment. Therefore, as in any initial test, there were the inevitable problems with the equipment. Most of these were minor, and after some modifications it was possible to obtain the necessary data. The map produced from this data shows the major known changes in the rock. In addition, it was possible to map the fracture frequency in the rock by using the attenuation of the transmitted signal.

The system used in this test is a crosshole acoustic system. That is, the source and receiver are located in separate boreholes. The data obtained is dependent upon the bulk modulus and density of the material between the holes. Because the source and receiver are in separate holes, the signals are affected by the entire bulk of material between the holes. Thus it is very difficult to measure changes in small portions of the mass, but easier to detect small changes in the entire mass.

The actual techniques, equipment, and interpretations will be discussed in the following sections.

FIELD EQUIPMENT

The acoustic system was designed to operate in water saturated soils. Therefore, the coupling mechanism for both the source and receivers is the water in the borehole. To operate effectively in hard rock areas, other forms of coupling might be used.

Figure J1 shows a block diagram of the acoustic sensing system. The system consists of five major units. These are the source, receivers, tape recorder, hard copy device, and central control unit. The tape recorder is a Honeywell Model 5600 with 14 changes of record and playback electronics. This unit is used to record the data for computer processing at a later date. The hard copy device is a Honeywell Model 1858 oscillographic recorder, which is used for analyzing the data in the field before computer processing.

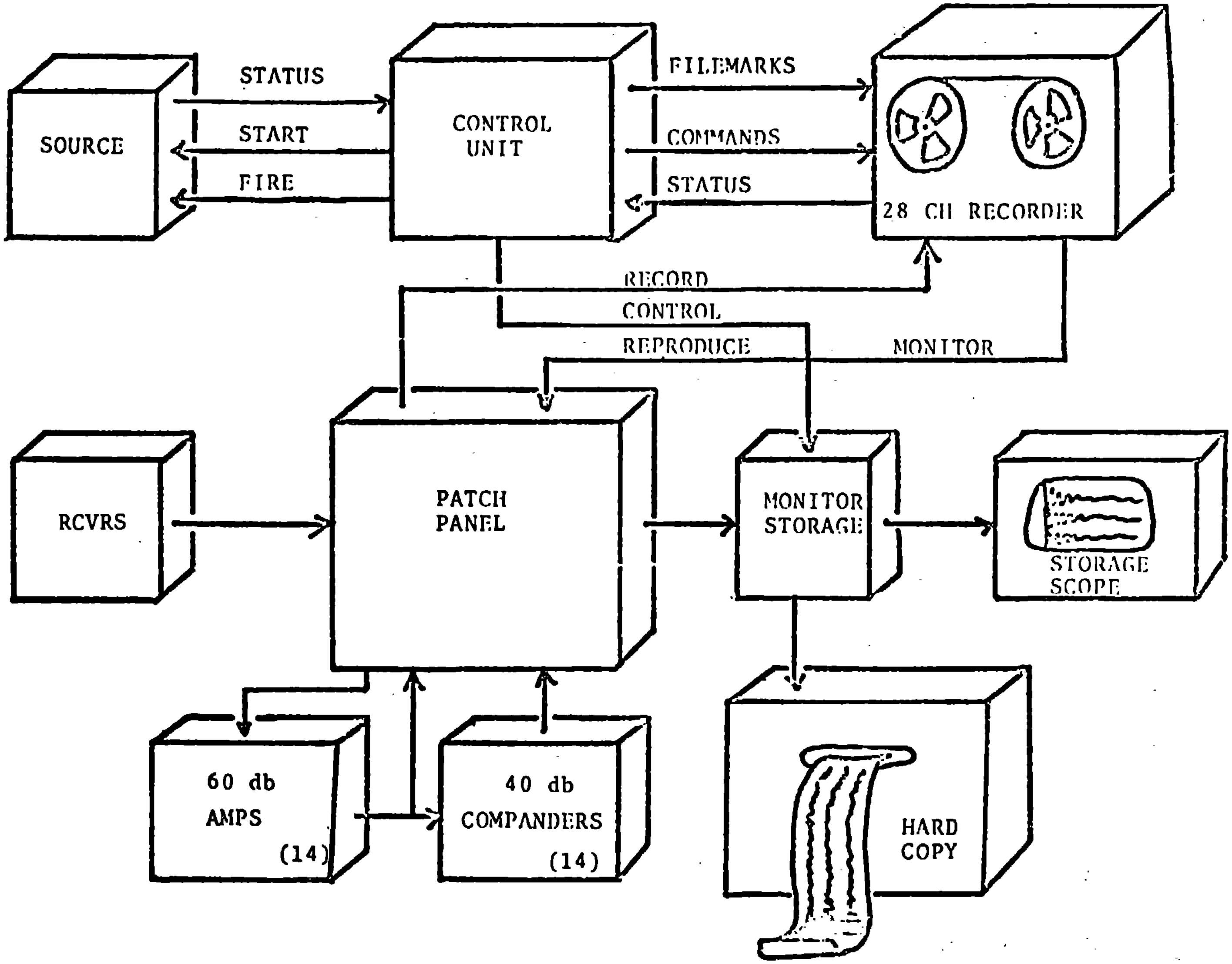


Figure J1. System block diagram.

The source for this system is a high energy sparker which was constructed by Simplec Manufacturing Company. The uphole unit is capable of delivering a maximum of 1250 Joules of energy to the downhole line. The downhole unit consists of a simple spark gap. The sparker is designed to operate in water filled holes and has a pulse with frequency content up to 5 kHz.

The receivers were also constructed by Simplec and they consist of strings of crystal accelerometers. The strings have either 12 receivers at one-foot intervals or six receivers at intervals of two feet. The receiver downhole unit also contains the preamplifiers for the crystal receivers. The response of the total system is constant from 200 Hz to 10 kHz.

The final system component is the central control unit. This unit contains the receiver input circuits, the amplifiers, and visual monitor. The controller performs the timing operations necessary to coordinate the action of the recorders and the source unit. The control unit also contains the filters and amplifiers necessary to make the receiver signals compatible with the recorder. Finally, the control unit contains a small storage scope where the received signals are displayed to the operator after each shot. This allows the operator to check the data for major problems before moving the source to the next position. The entire system is capable of being transported and operated from the back of a small panel truck.

FIELD TESTS

The Forest Glen site provided the first test for this equipment. Some minor problems delayed the test for a few days; however, after this initial delay it was possible to acquire the acoustic data in a relativley quick time. Because of the depth and spacing of the test holes, the receiver string with two feet between receivers was used. Table J1 shows the various source/receiver locations occupied during the tests. This test program produced over 10,000 individual record traces.

Table J1. Source/receiver layout

RECEIVER		SOURCE	
Hole	Interval (ft)*	Hole	Interval (ft)
1	2+	2	10
1	2	3	10
1	2	4	20
2	2	3	10
2	2	BRP-27	20
3	2	BRP-27	10

*Minimum depth 40 ft; maximum depth 220 ft

+1 ft = 0.305 m

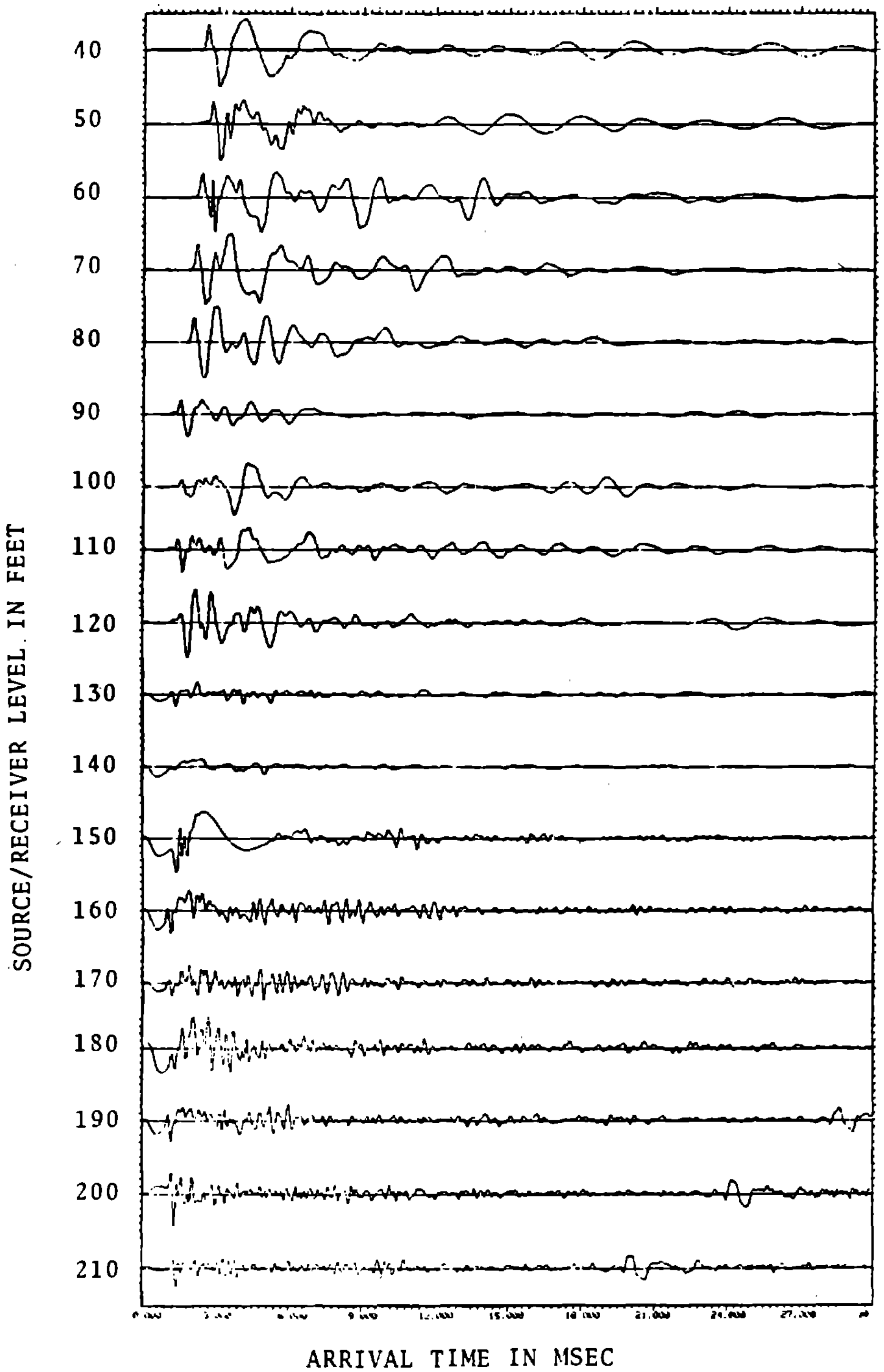
Figure J2 shows data taken between Holes 1 and 2. In this figure, the bottom trace represents the signal received at 210 feet (64.0 meters) in Hole 1 when the source is at 210 feet (64.0 meters) in Hole 2. The trace above this one represents the results when both the source and receiver are at 200 feet (61.0 meters). Each trace above these represents the raising of the source and receiver by 10 feet (3.05 meters). Two things are easily seen in this display. First, the frequency content of the pulse changes as the source and receiver are raised. Secondly, the velocity between the holes slows at the upper levels.

In a continuous rock mass the acoustic velocity is proportional to the bulk modulus divided by the mass density. The velocity also will be affected by the amount of rock fracturing or open discontinuities. The density log shows very little change in density, therefore the slowing in velocity represents either a reduction in the bulk modulus of the rock or an increase in the fracturing at the upper levels of the hole. Figure J3 shows the change in velocity with depth of the signals in Figure J2. The velocity profile also shows layering effects with the changes taking place at 50 feet (15.0 meters), 80 feet (24.4 meters), 135 feet (41.1 meters), and 175 feet (53.3 meters).

In addition to the velocity change, there is a noticeable change in the frequency content of the signal between the two holes. That is, the received signal at the top of the hole is lower in frequency than the signal received when the source and receiver are at the bottom. Figure J4 shows a graphical representation of this effect. Here the average frequency of the first ten milliseconds of the received signal (shown in Figure J2) are plotted as a function of depth. Since the source is relatively consistent, these changes in frequency represent a change in the attenuation of the various frequencies by the rock. At this site the increased attenuation is probably due to an increase in the amount of fractures in the rock. Figure J5 shows the fracturing in the rock as determined by the boring log for Borehole T1 compared with the mean frequency of the received signal. Note that the areas of high fracturing also correspond to the areas of low mean frequency. There will be an inherent difference inasmuch as the mean frequency is measured between the two holes and averages a large mass of rock while the borehole fracture logging measures the fractured rock in a single hole by means of the amount of rock core retrieved by the drilling process.

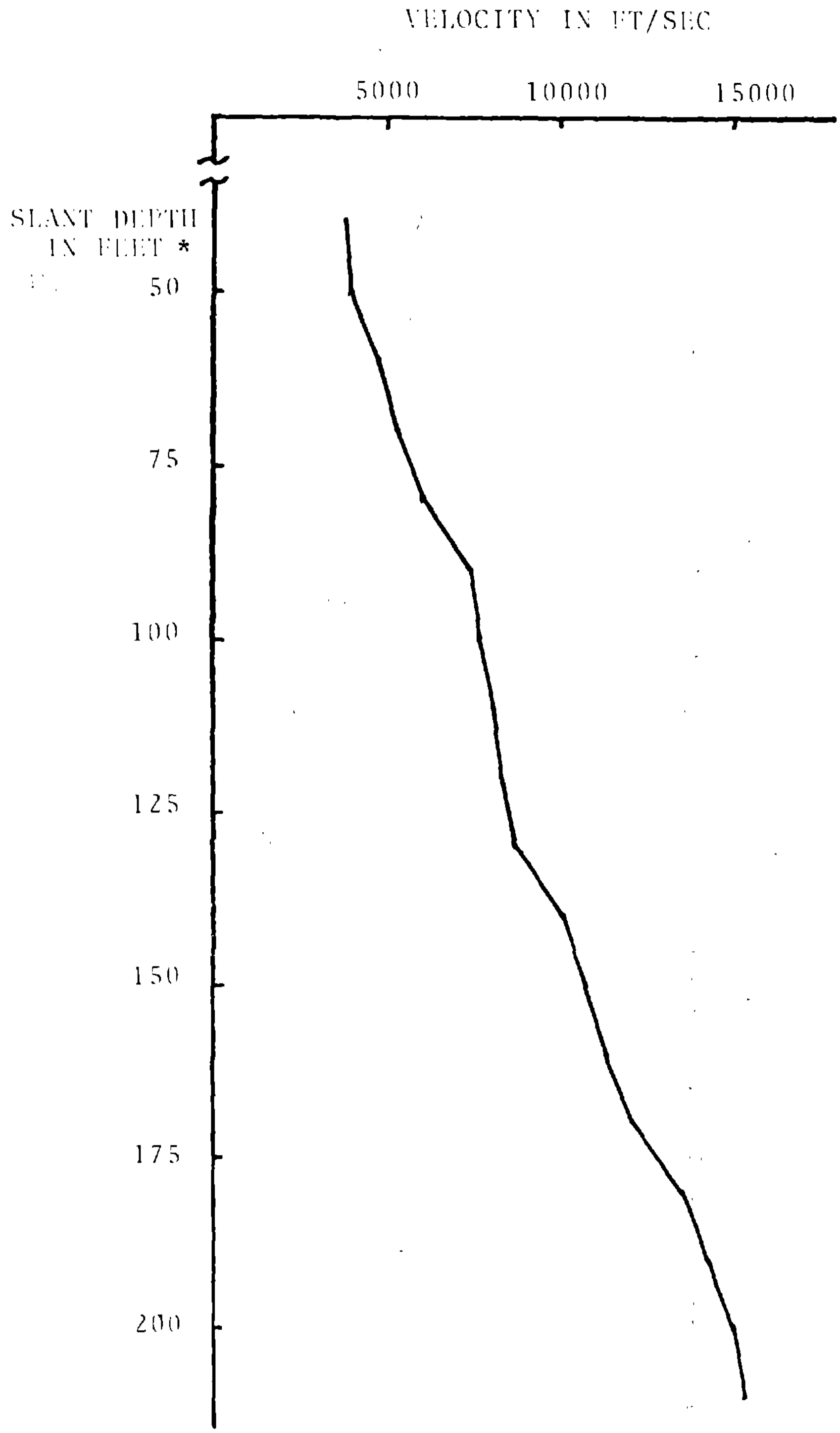
Figures J6 through J11 show the results of recording the signals at regular increments in Holes T1, T2, and T3 with the source located at 210 feet (64.0 meters) in Holes T2, T3, and BRP-27. From these plots it is possible to see the arrival of compressional waves (P waves), shear waves (S waves), and fluid waves (F waves).

Figure J6 shows the arrivals in Hole 1 when the source is at the bottom of Hole 2. Each trace represents the signal received at a given level. The first arrival is the one which has followed the minimum travel time path. Other arrivals have followed various other paths. The arrival marked P1 represents the first arrival and it is traveling with a P wave velocity. Arrival P2 parallels P1 and is therefore a second P wave arrival which looks as if it comes from a reflection of the source. The distance to the reflector is one-half the time difference between the two signals (about 6 msec). Arrival F1 is a fluid wave up the hole in that it is traveling at about 5000 ft/sec (164.0 msec) or the velocity of sound in water. The velocity of the fluid or tube wave is dependent upon the compressional velocity of the fluid and the shear velocity of the rock. Thus in areas where the shear velocity changes or where the hole size changes, reflections are obtained. Note that at about 115 feet (35.1 meters) a reflection can be seen at 80 feet (24.4 meters) where the hole changes, a major reflection is seen on F1.



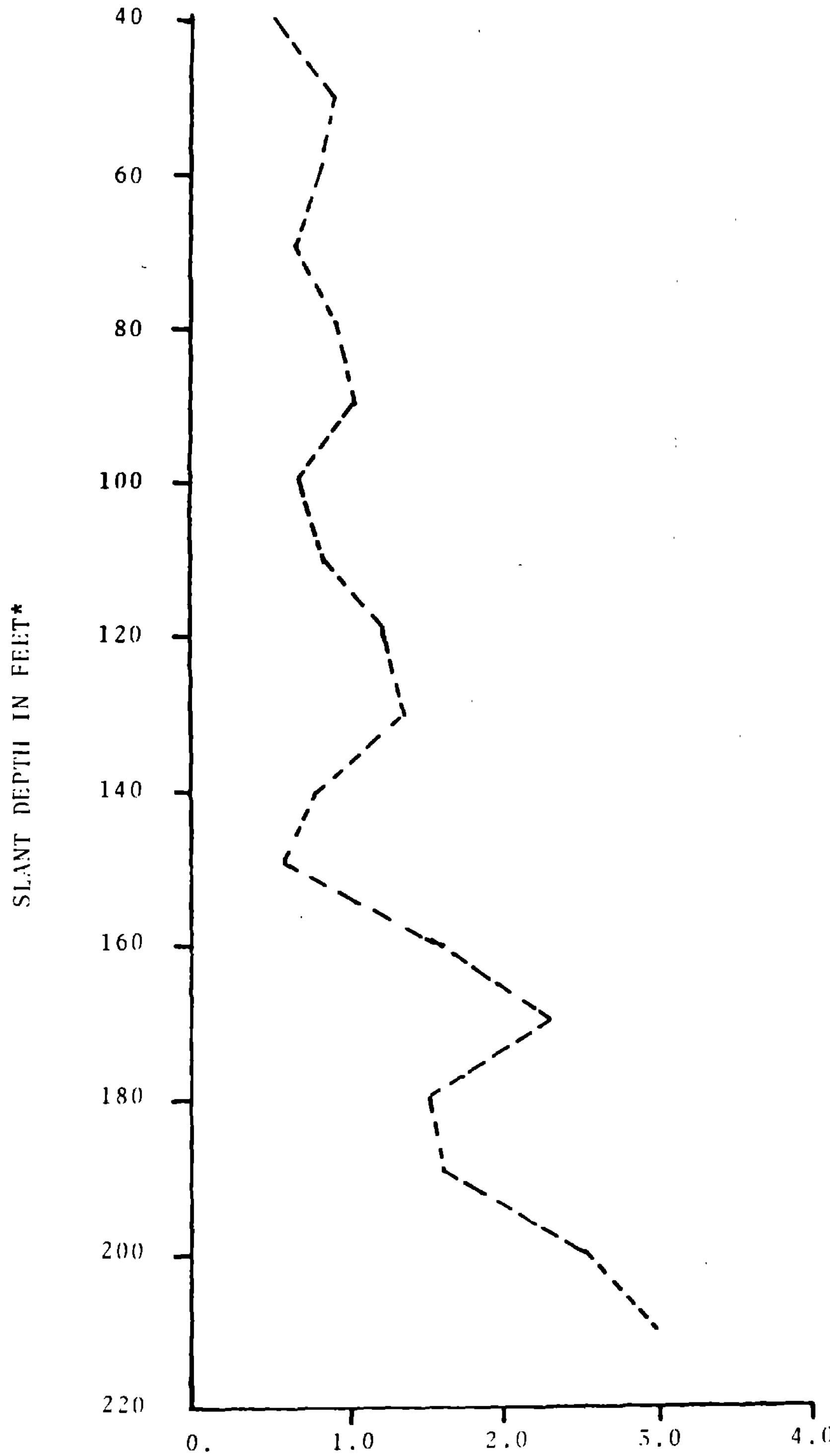
(1 ft = 0.305 m)

Figure J2. Crosshole signal from Holes 1 to 2 source located in Hole 2 receiver located in Hole 1.



*(1 ft = 0.305 m)

Figure J3. P-wave velocity profile between Holes 1 and 2.



*(1 ft = 0.305 m)

Figure J4. Mean frequency in kHz of received signal.

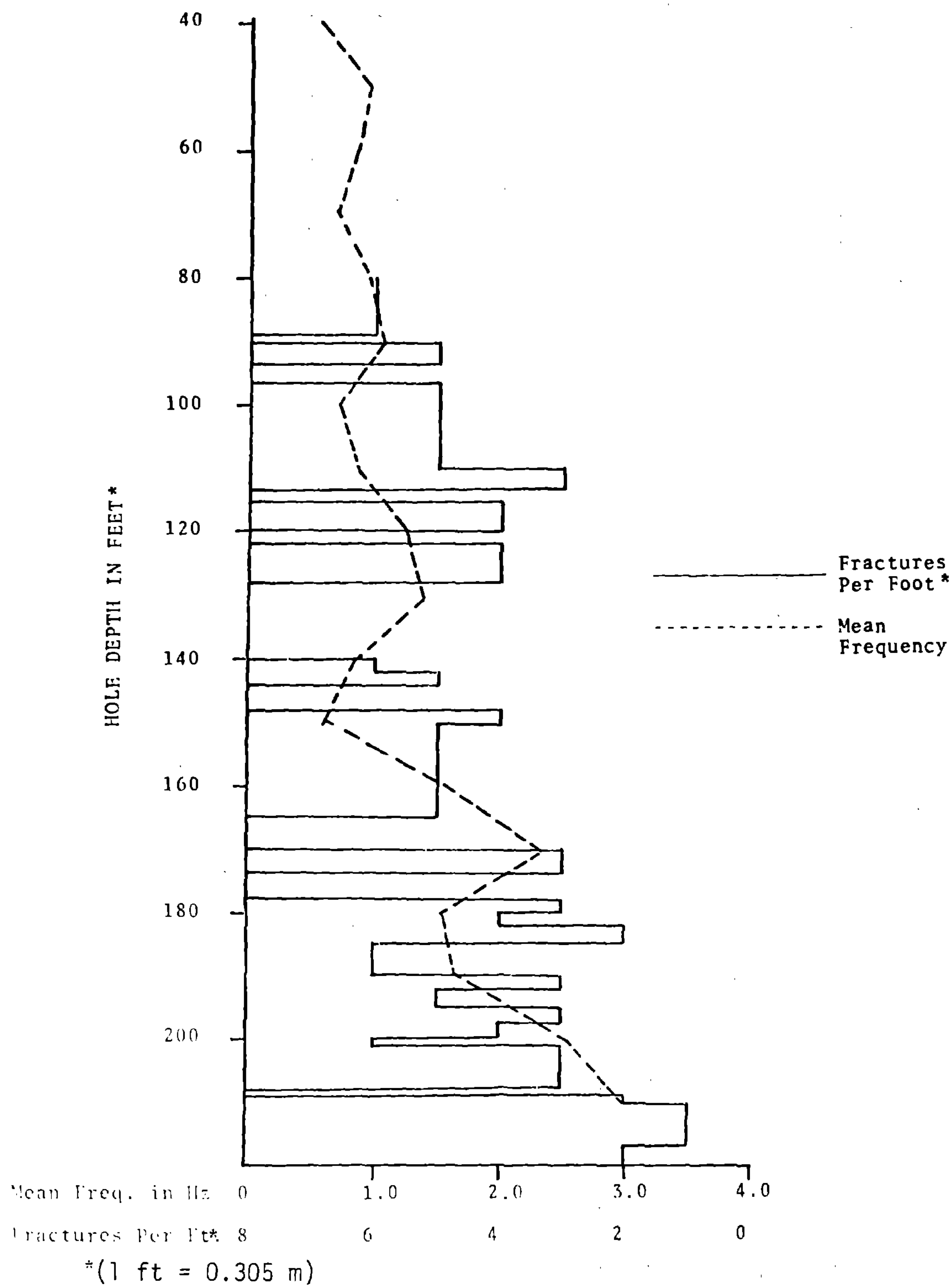
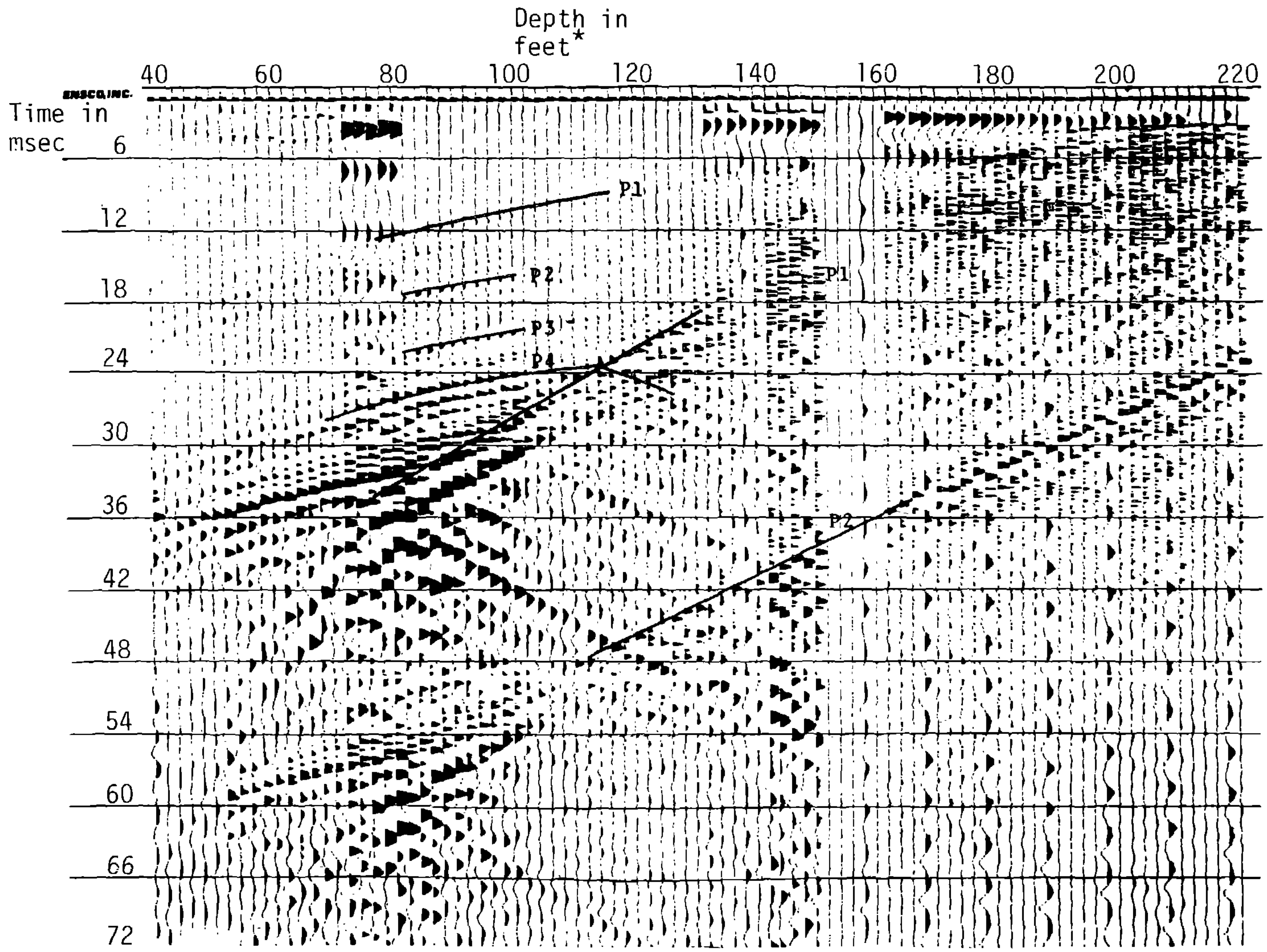


Figure J5. Pulse frequency and fractures per foot for Hole T2.



*(1 ft = 0.305 m)

Figure J6. Acoustic signals received in Hole T1 with source at 210 feet in Hole T2.

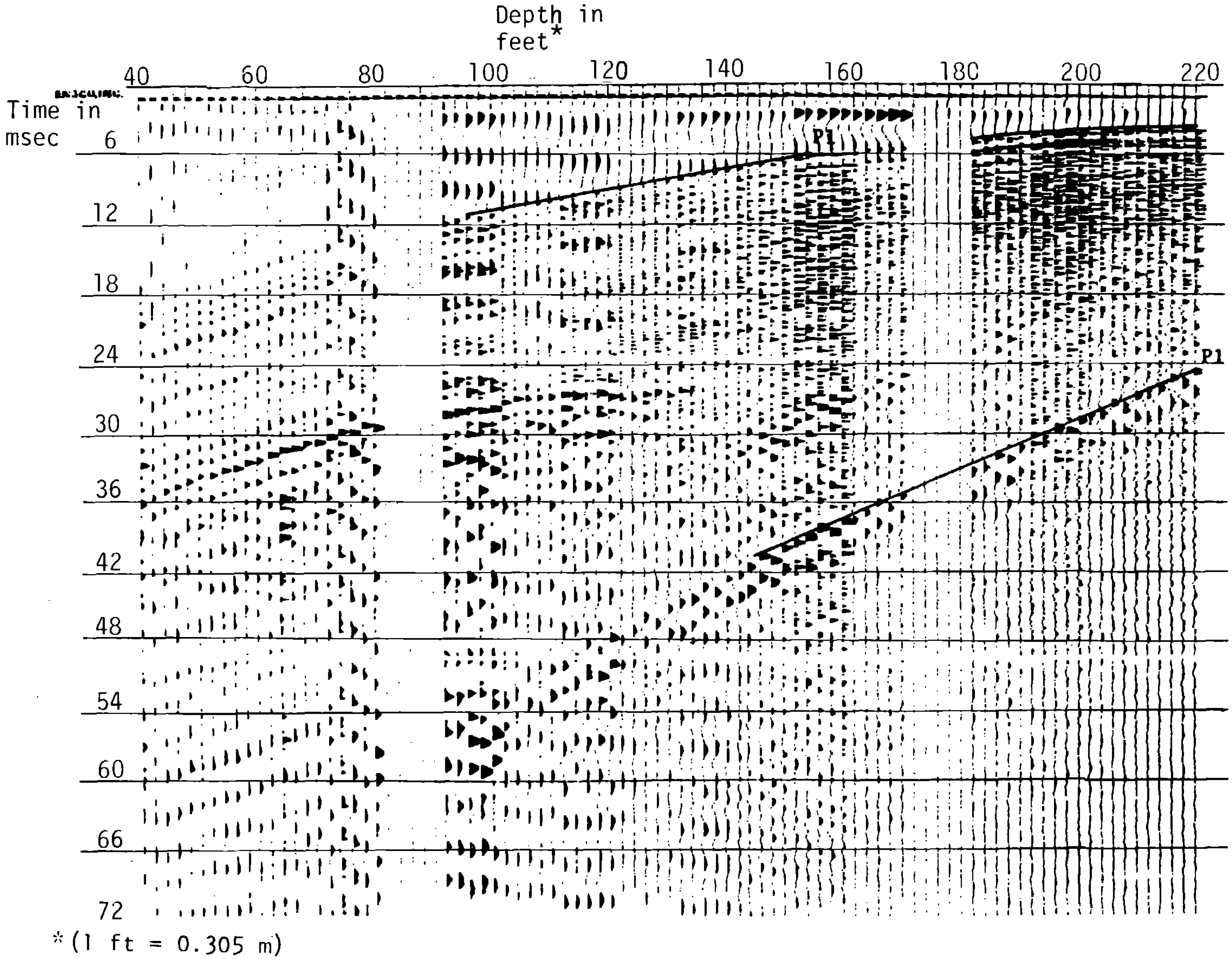
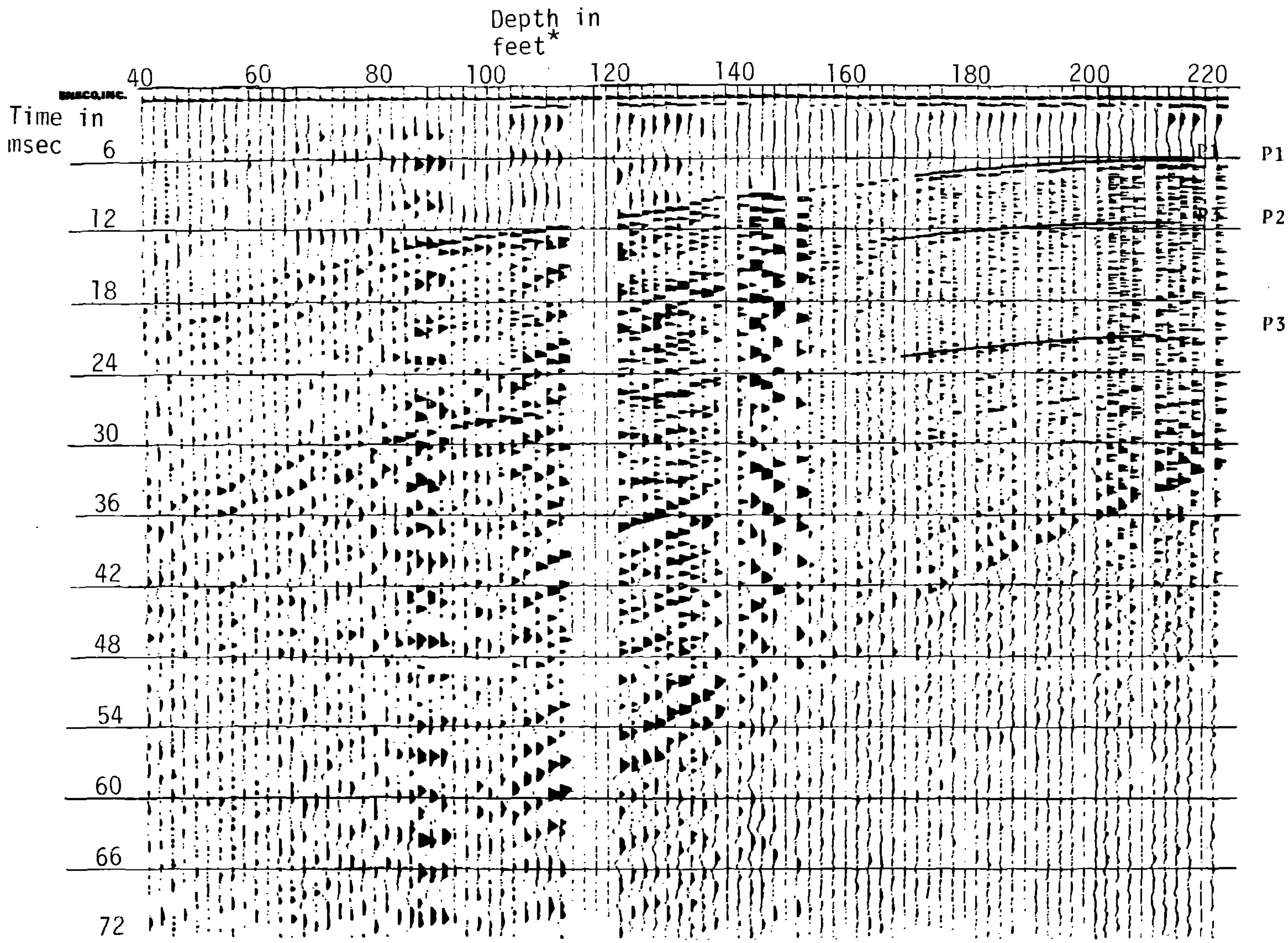
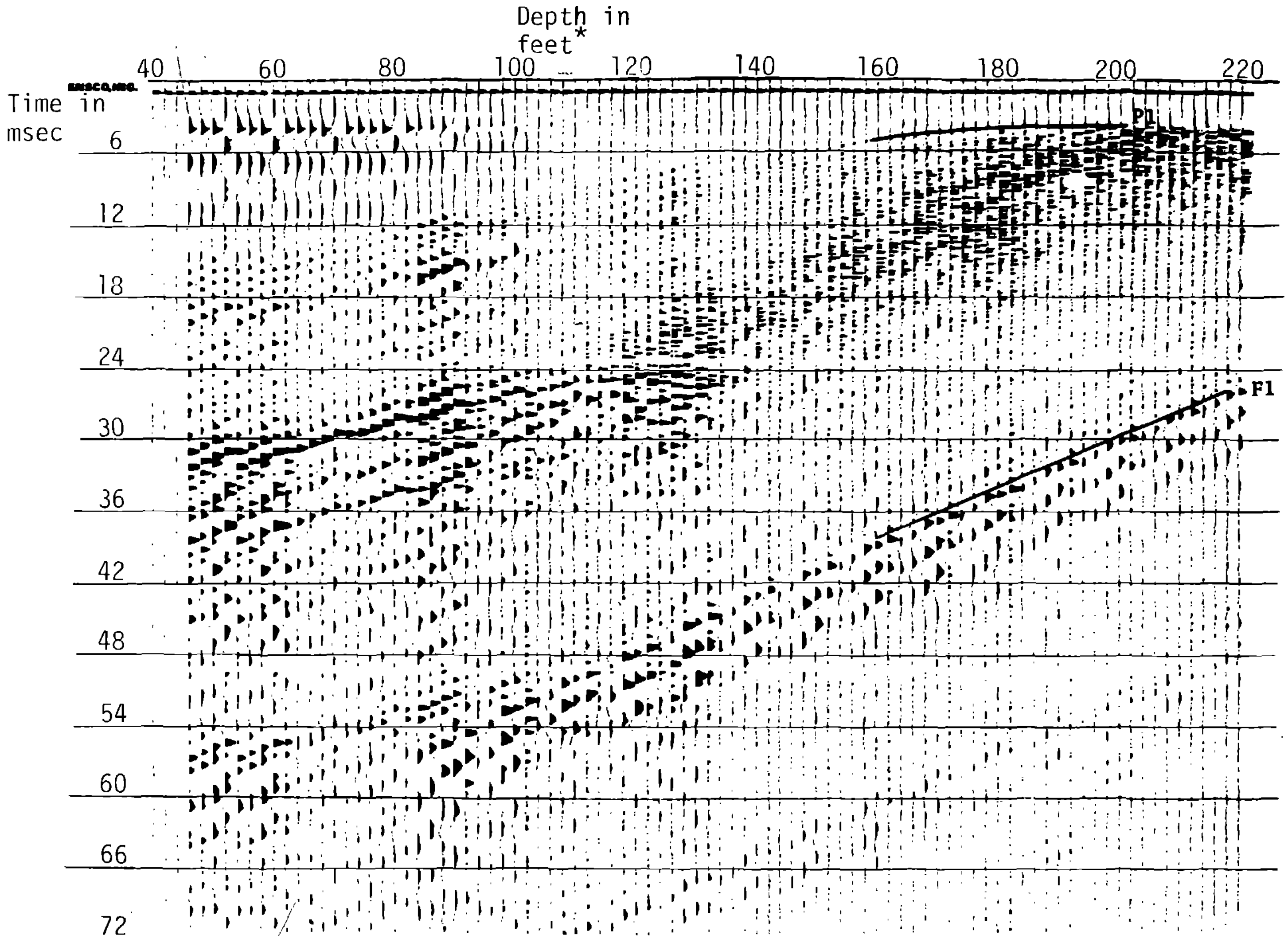


Figure J7. Acoustic signals received in Hole 1 with source at 210 feet in Hole 3.



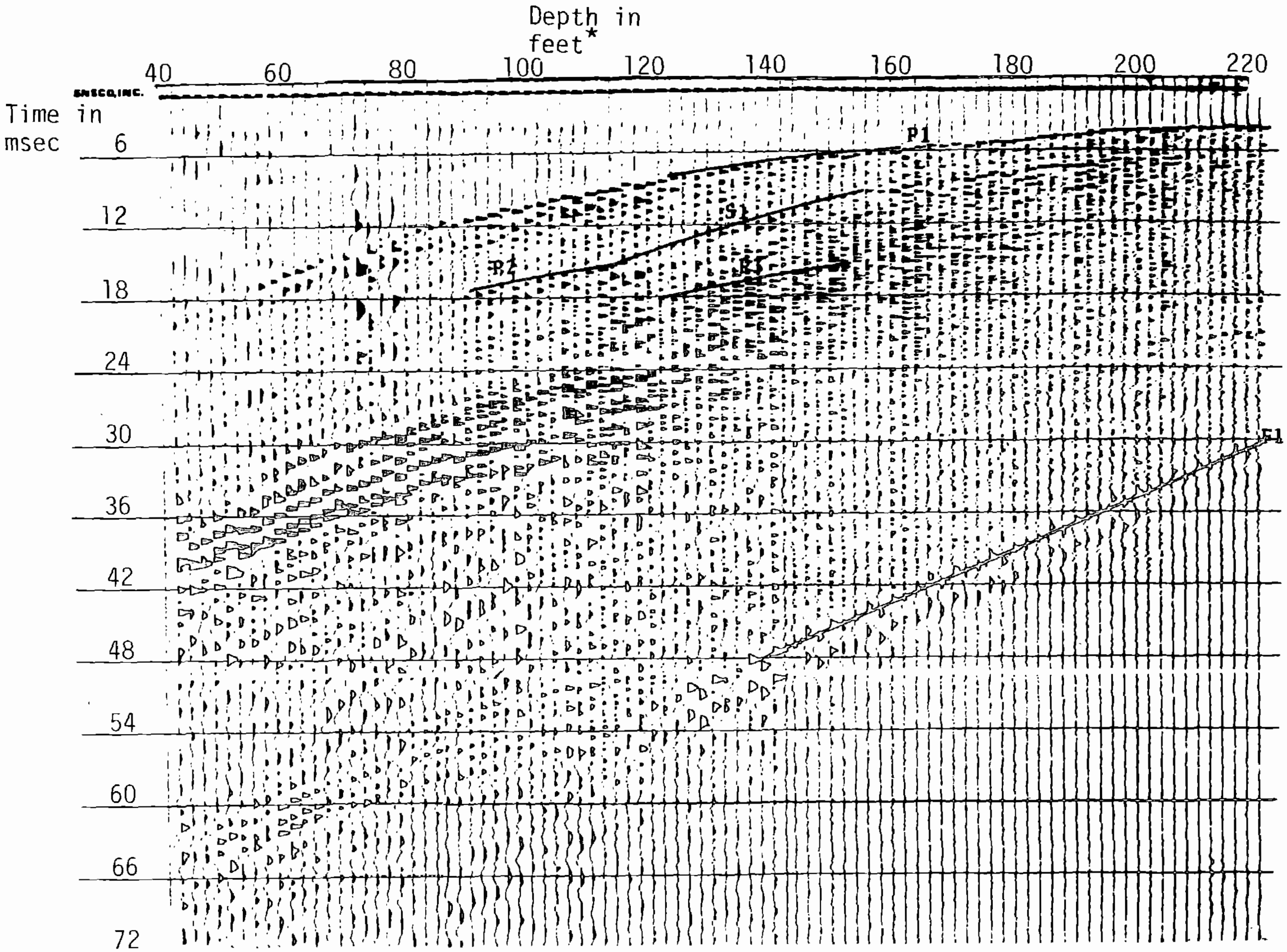
*(1 ft = 0.305 m)

Figure J8. Acoustic signals received in Hole 1 with source at 210 feet in Hole BRP-27.



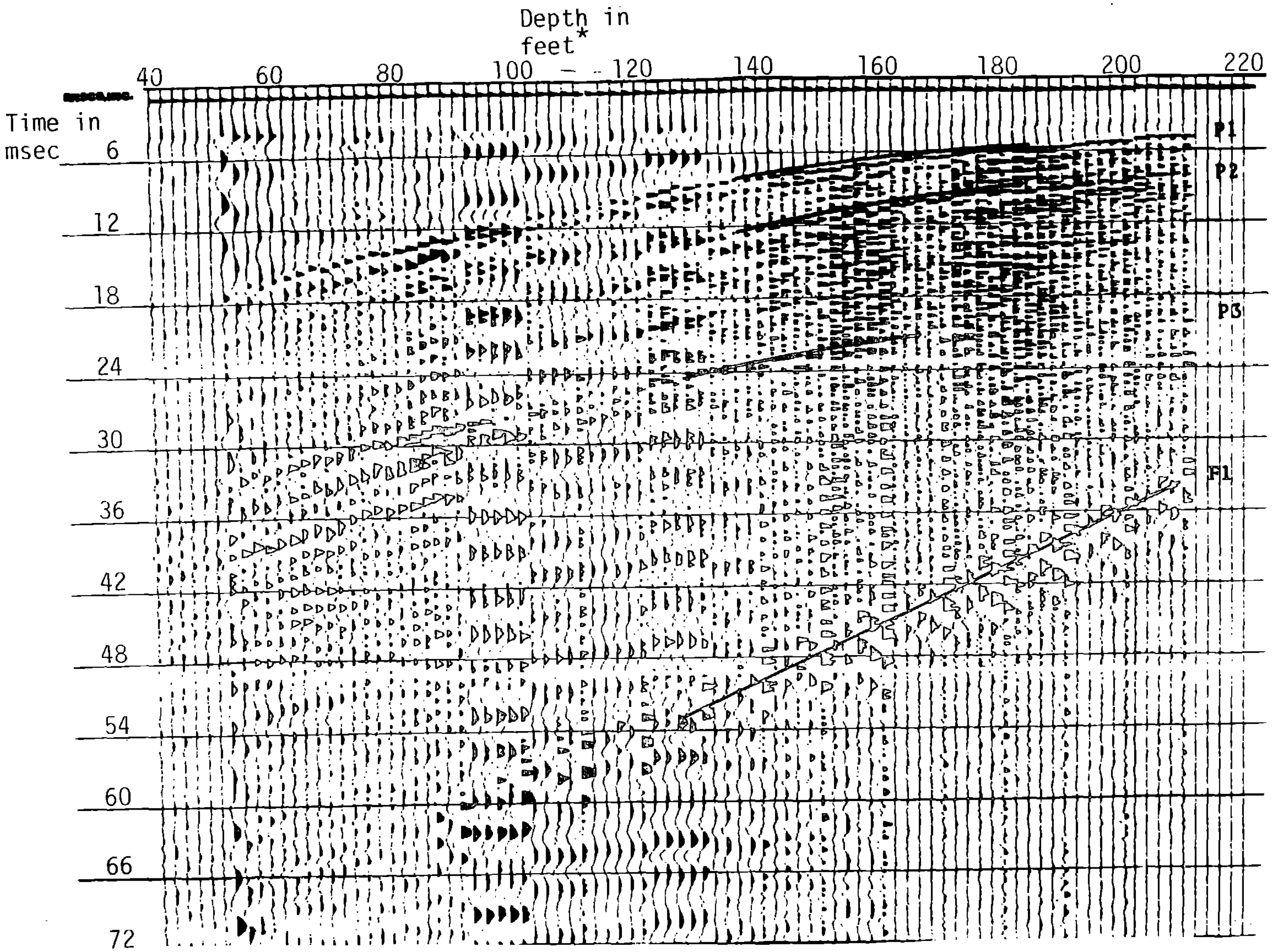
*(1 ft = 0.305 m)

Figure J9. Acoustic signals received in Hole 2 with source at 210 feet in Hole 3.



*(1 ft = 0.305 m)

Figure J10. Acoustic signals received in Hole 2 with source in Hole BRP-27.



*(1 ft = 0.305 m)

Figure J11. Acoustic signals received in Hole 3 with source in BRP-27.

Figures J7 through J11 show other source/receiver configurations. Note that the strength of the tube wave decreases as the distance between the source hole and receiver hole increases. Figure J8 shows strong P wave reflection arrivals denoted by P2 and P3. These could be from geologic layers below the area of interest. Figure J10 shows a strong shear arrival (denoted by S1) coming in behind the first P arrival. By examining the P wave and shear wave arrivals, it is possible to obtain velocity information between the various holes.

Figures J12 through J17 show another series of tests in which the source was near the surface. There are several things to note with these figures. The frequency context of the signal is lower. Most of the energy is in the 250 Hz to 1 kHz range. The tube waves are much stronger than when the source is deeper.

It is difficult to see major changes in velocity by examing the P and S waves; however, the tube waves do show shear modulus changes at depth. The major features in these figures are the refraction arrivals.

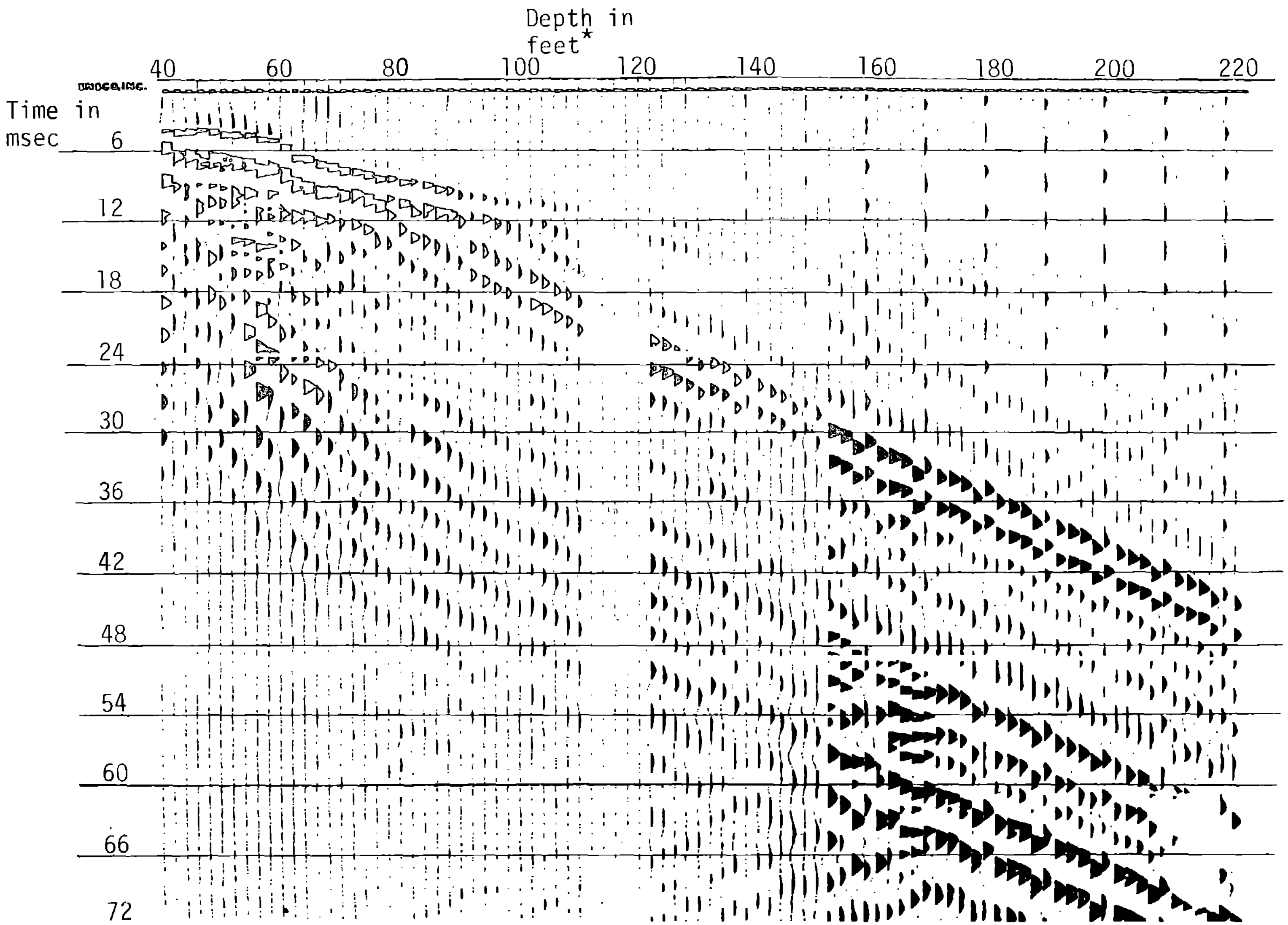
When a source is at a shallow depth and a receiver is at a long distance from the source, the first arrival may not be the direct path arrival. This can be seen in Figure J14. Here the earliest arrival is at 88 feet (26.8 meters). This means that the velocity at that level is fast enough that the pulse can travel down 30 feet (9.1 meters) and along the interface to Hole 1 faster than the direct arrival can get there. Figure J16 shows a refractor of 56 feet (17.1 meters). Figures J16 and J17 also show refraction arrivals.

The data presented allow us to construct a generalized map of the area. Figure J18 shows such a map. The P and shear velocities are shown for various depths between the holes. The major reflection interfaces below the holes are also shown.

CONCLUSION

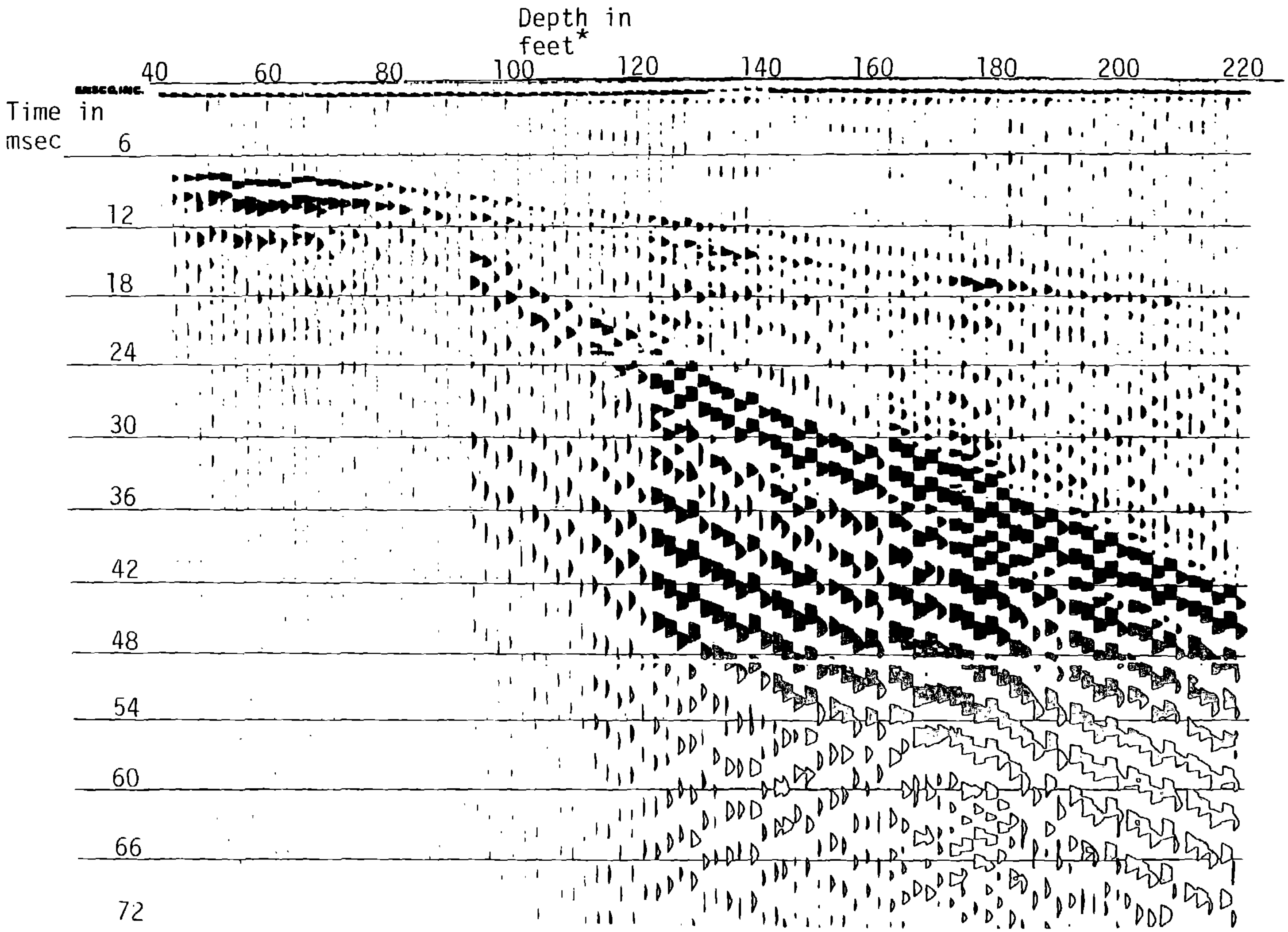
The map shown in Figure J18 is not extremely detailed. In order to get detailed data, it is necessary to use borehole logging tools. These tools, however, do not respond to changes away from the vicinity of the borehole. The crosshole tools are able to map the bulk between the holes but in so doing give up resolution. The crosshole techniques do show major changes in the acoustic velocity, and thus in the competency of the rock. These changes take place at 80 feet (24.4 meters), 135 feet (41.1 meters), and 175 feet (53.3 meters). Using these data and the logging data, it should be possible to obtain accurate detailed maps of the area.

The acoustic system shows great promise for evaluating the rock fracturing and layering by means of the crosshole velocity and reflection mapping, and the mapping of the signal attenuation. This is clearly shown by the correlation between the signal attenuation between Holes 1 and 2 and the fracturing exhibited by the boring from Hole 1. This type of response should be examined in other types of rocks. If the correlation holds and it is possible to develop an empirical relationship , it would appear that the developing geophysical system used in this study may prove to be very useful to the geotechnical industry.



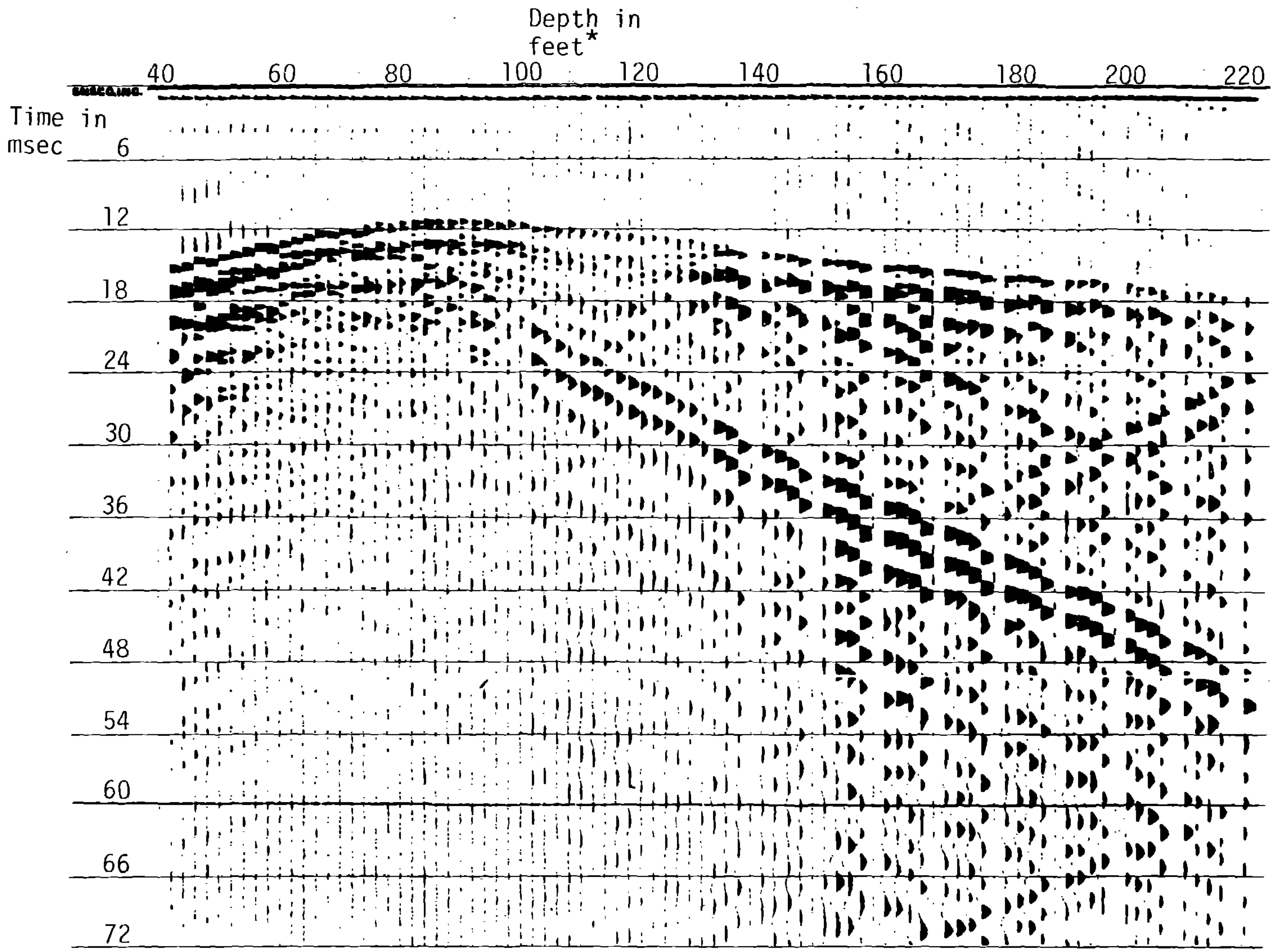
*(1 ft = 0.305 m)

Figure J12. Acoustic signals received in Hole 1 with source at 40 feet in Hole 2.



*(1 ft = 0.305 m)

Figure J13. Acoustic signals received in Hole 1 with source at 40 feet in Hole 3.



*(1 ft = 0.305 m)

Figure J14. Acoustic signals received in Hole 1 with source at 50 feet in Hole BRP-27.

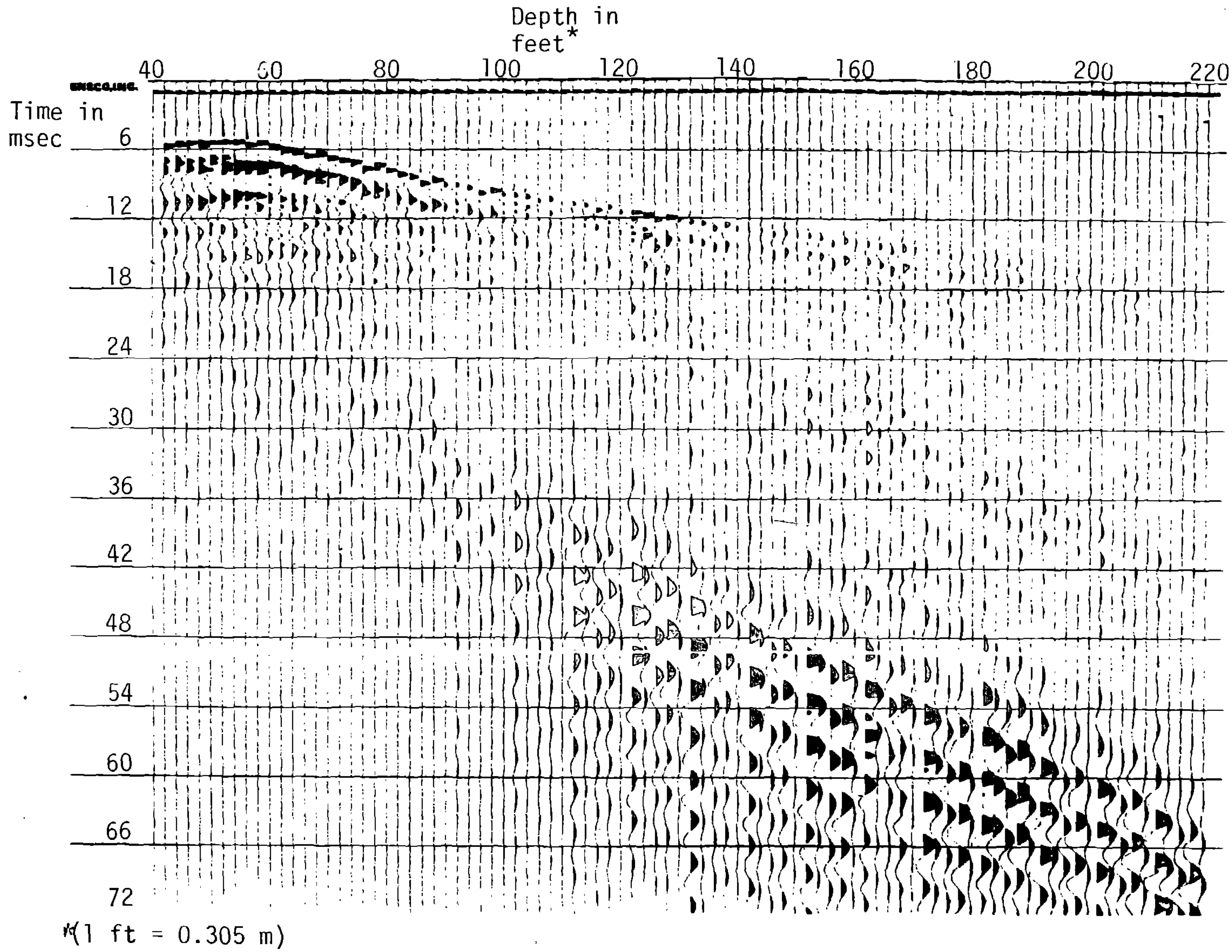
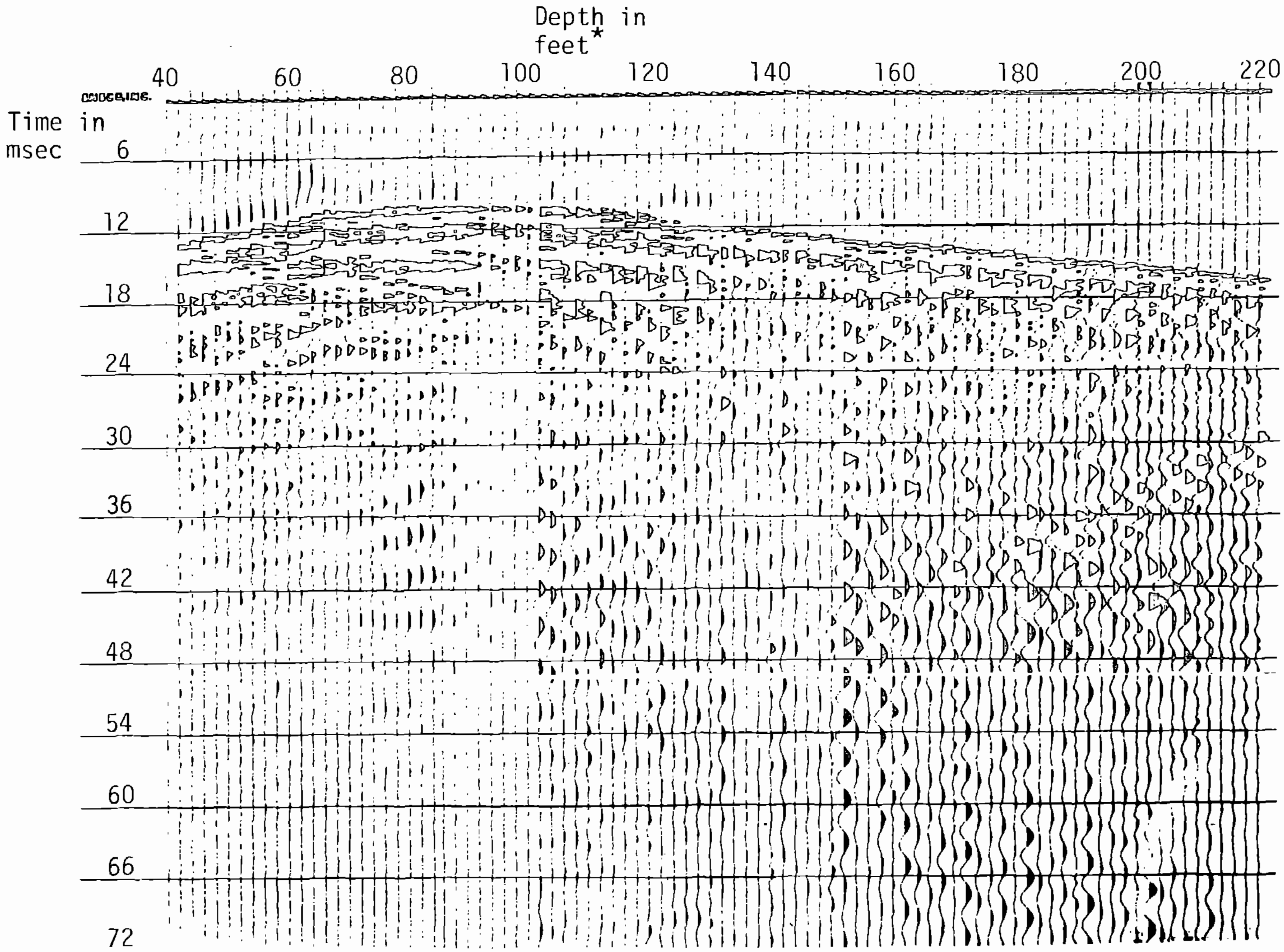
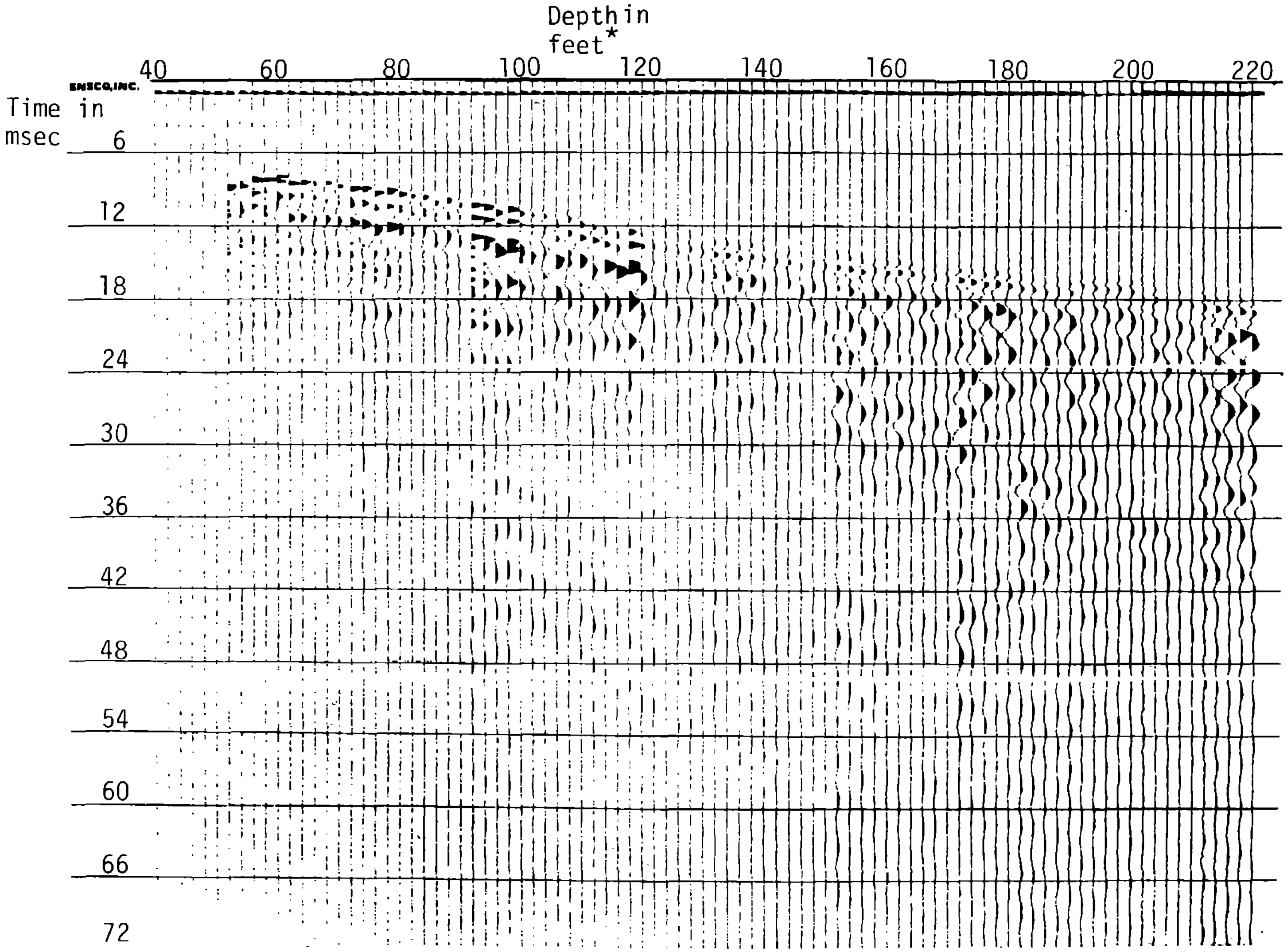


Figure J15. Acoustic signals received in Hole 2 with source at 40 feet in Hole 3.



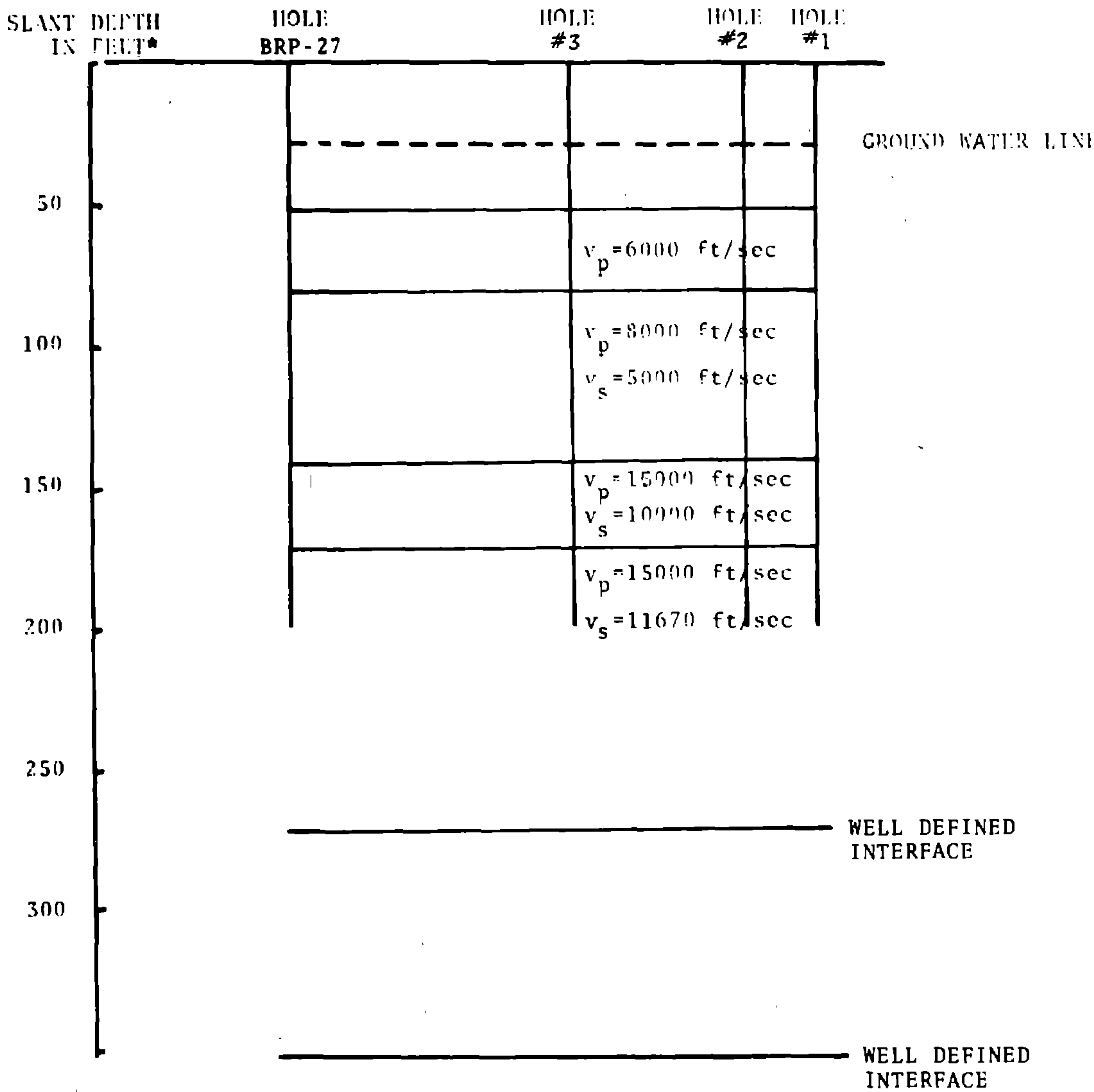
*(1 ft = 0.305 m)

Figure J16. Acoustic signals received in Hole 2 with source at 50 feet in Hole BRP-27.



*(1 ft = 0.305 m)

Figure J17. Acoustic signals received in Hole 3 with source at 40 feet in Hole BRP-27.



*(1 ft = 0.305 m)

Figure J18. Acoustic map for Forest Glen.

* U. S. GOVERNMENT PRINTING OFFICE 1982 381-428/2326