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HIGH RESOLUTION SHEAR WAVE REFLECTION SURVEYING FOR HYDROGEOLOGICAL INVESTIGATIONS

Final Report

Contract No. 02112405

By
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and
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Prepared for

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PREFACE

Currently available technology is not adequate to assess environmental contamination at Department of Energy (DOE) sites, take permanent remedial action, and eliminate or minimize the environmental impact of future operations. Technical resources to address these shortcomings exist within the DOE community and the private sector, but the involvement of the private sector in attaining permanent and cost-effective solutions has been limited.

During 1990, on behalf of DOE's Office of Technology Development, Argonne National Laboratory (ANL) conducted a competitive procurement of research and development projects addressing soil remediation, groundwater remediation, site characterization, and contaminant containment. Fifteen contracts were negotiated in these areas.

This report documents work performed as part of the Private Sector Research and Development Program sponsored by the DOE's Office of Technology Development within the Environmental Restoration and Waste Management Program. The research and development work described herein was conducted under contract to ANL.

On behalf of DOE and ANL, I wish to thank the performing contractor and especially the report authors for their cooperation and their contribution to development of new processes for characterization and remediation of DOE's environmental problems. We anticipate that the R&D investment described here will be repaid many-fold in the application of better, faster, safer, and cheaper technologies.

Details of the procurement process and status reports for all 15 of the contractors performing under this program can be found in "Applied Research and Development Private Sector Accomplishments - Interim Report" (Report No. DOE/CH-9216) by Nicholas J. Beskid, Jas S. Devgun, Mitchell D. Erickson and Margaret M. Zielke.

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ABSTRACT

The technology associated with the high resolution S-wave method has developed through this research to the point where the technique has been demonstrated to be a powerful tool in mapping subsurface lithology and in conducting groundwater investigations. This research has demonstrated that the resolution obtainable using S-waves in a Coastal Plain environment is more than double than that obtained using conventional reflection technology, which already offers a higher resolution than any other surface method. Where the mapping of thin clay layers functioning as aquitards or thin sand layers functioning as aquifers are critical to the understanding of groundwater flow, S-wave reflections offer unparalleled possibilities for non-destructive exploration. The field experiment at Cooke Crossroads, South Carolina enabled the detection and mapping of beds in the thickness range of one to three feet.

In additional to improving the resolution of subsurface characterizations, the S-wave reflection technique, in combination with conventional P-wave reflection measurements, has the potential to directly detect where confined and unconfined aquifers are present. This is a breakthrough technology that still requires additional research before it can be applied on a commercial basis. Aquifer systems were interpreted from the test data at Cooke Crossroads consistent with the theoretical modeling conducted for this research. Nevertheless, additional research is need in assessing the theoretical response of P- and S-waves to subsurface interfaces within unconsolidated sediments of varying moisture content and lithology. More theoretical modeling is and in situ testing is clearly need to bring our knowledge of these phenomena to the level that oil and gas researchers have done for fluids in sandstones.

HIGH RESOLUTION SHEAR WAVE REFLECTION SURVEYING FOR HYDROGEOLOGICAL INVESTIGATIONS

EXECUTIVE SUMMARY

TECHNOLOGY DESCRIPTION

The main objective of this research has been to develop the technology necessary to make high resolution shear (S-)wave profiling a useful tool in conducting shallow groundwater investigations. Conventional seismic reflection technology using compressional (P-)waves has developed to the point where this technique has become a major component of numerous environmental assessments. Extending this technology to include S-waves offers the potential for greatly enhancing the data which can be extracted from the subsurface, in particular the fluid characteristics of subsurface layers.

The immediate benefit of using S-waves in a high resolution seismic reflection survey is to increase subsurface resolution in soil environments. In hard rock, the S-wave velocity is usually about half of the P-wave velocity, but the predominant frequency is also about half, implying that S-waves will not increase resolution. In a soil environment, however, S-waves can be several times slower than P-waves and have a similar frequency content, implying S-waves can substantially increase resolution.

Another potential benefit of the method is to directly detect confined and unconfined aquifers from the ground surface. The main reason for interest in applying S-wave technology to groundwater problems is the response of an S-wave to fluids. Unlike a P-wave, an S-wave will not travel through a purely liquid medium. The significance of this in a seismic reflection study would be that an unconfined water table could represent an important P-wave velocity contrast visible on a conventional reflection record, but be minimal on the S-wave record and thus be identified by a dual evaluation of the waves. Conversely, a saturated sand lens within a clay layer, a confined aquifer, could be essentially invisible on a P-wave record, but visible on an S-wave record because the S-waves will respond to the lithologic change represented by the sand lens.

S-wave reflections offer a different view of the subsurface than obtained from conventional P-wave profiles and the differences strongly relate to the hydrogeologic conditions of the shallow subsurface.

TECHNOLOGY PERFORMANCE

A field experiment conducted at Cooke Crossroads, South Carolina has confirmed the theoretical basis of the research. The S-wave reflection profile had at least double the resolution obtained with P-waves under similar recording conditions. This increase in resolution using S-waves is by itself an important finding with implications on the means by which subsurface characterization studies are conducted. Figure ES-1 provides the comparison of the P- and S-wave seismic reflection profiles at the location of boring RTB-1, a control boring drilled and logged for the field experiment. The S-wave portion of this figure depicts one of the highest resolutions ever achieved on land by the seismic reflection method within the knowledge of the researchers. Subsurface horizons as thin as one foot thick are resolved on the S-wave section.

The overall goal of the research was to assess the degree to which aquifer systems can be detected from a careful dual evaluation of P- and S-wave records. Several of the reflectors on the S-wave section of Figure ES-1 are not present or are poorly represented on the P-wave section. These are interpreted to be confined aquifers, consistent with theory and consistent with the lithologic log of the control borehole.

APPLICATION TO DOE NEEDS

The proposed research will have potential application whenever subsurface characterization is a concern in an environmental investigation, which is to say in nearly all studies. In particular, the proposed research offers the possibility to substantially improve the resolution of subsurface horizons and to directly detect aquifer systems. Knowledge of detailed stratigraphic and aquifer conditions with minimal borehole control has the potential to have several positive impacts in characterizing a site, as the results of the investigation will:

- Improve the information content and level of confidence of site characterization;
- Reduce risk associated with characterization activities, as the methodology is non-invasive; and
- Reduce the cost for site characterization by reducing the number of borings required to define the subsurface hydrology.

The technology is ready to enter the Demonstration, Test, and Evaluation (DT&E) phase.

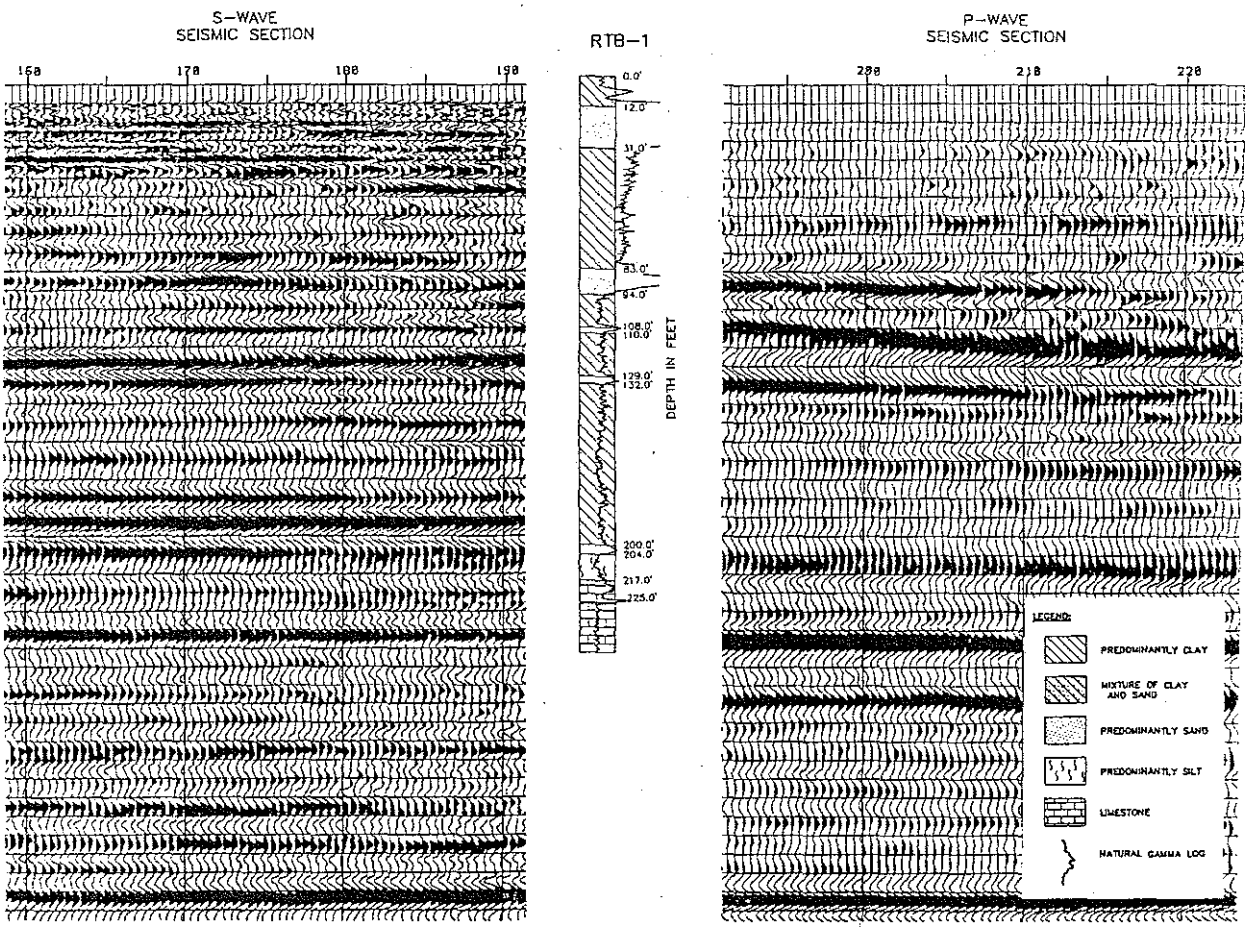


Figure ES-1-Correlation of P- and S-wave depth sections at location of control boring RTB-1, Cooke Crossroads test site.

HIGH RESOLUTION SHEAR WAVE REFLECTION SURVEYING FOR HYDROGEOLOGICAL INVESTIGATIONS

FINAL REPORT

1.0 INTRODUCTION

This final report completes the requirements of Contract No. 02112405 between Paul C. Rizzo Associates, Inc. (Rizzo Associates) and Argonne National Laboratory (ANL). The contract was broken down into four milestones, comprising the scope of work, as follows:

- **MILESTONE 1 - BACKGROUND DATA ACQUISITION**

  This initial milestone reviewed the theory, case histories, and results in terms of defining the basic principles of the proposed research. The Milestone 1 report entitled "The High Resolution Shear Wave Seismic Reflection Technique" was submitted to the Department of Energy (DOE) for publication in April 1991 (Johnson and Clark, 1991).

- **MILESTONE 2 - SITE SELECTION**

  This milestone was completed with the report "Siting of the Shear Wave Field Experiment" submitted to ANL in February 1991. The site selected was located at Cooke Crossroads, South Carolina.

- **MILESTONE 3 - SIMPLIFIED SURVEY**

  The report entitled "Initial High Resolution Shear Wave Reflection Survey" submitted in July 1991 fulfilled the requirements for this milestone. Different sources were tested and compressional and shear wave profiles obtained with separate recordings using off-the-shelf recording equipment.

- **MILESTONE 4 - COMPREHENSIVE SURVEY**

  The scope of this task, as presented in this report, was to define the maximum amount of subsurface information obtainable with the shear and compressional seismic reflection techniques.

1.1 TECHNOLOGY SCOPE

The intent of this final report is to briefly summarize the results of all four milestones within the body of the report. More detailed information is contained in the individual submittals for Milestones 1 through 3.

It is recognized that geophysicists tend to use their own "jargon" when describing data acquisition, processing, and interpretation related to seismic reflection surveying. Although an attempt made to avoid such words, many have managed to sneak their way into the text. The glossary provided in Appendix B to our Milestone 1 submittal provides definitions of the geophysical terminology relevant to this research.

The main objective of this research has been to develop the technology necessary to make high resolution shear (S-)wave profiling a useful tool in conducting shallow groundwater investigations. Conventional seismic reflection technology using compressional (P-)waves has developed to the point where this technique has become a major component of numerous environmental assessments. Extending this technology to include S-waves offers the potential for greatly enhancing the data which can be extracted from the subsurface, in particular the fluid characteristics of subsurface layers.

The proposed research will have potential application whenever groundwater is a concern in an environmental investigation, which is to say in nearly all studies. In particular, the proposed research offers the possibility to directly detect aquifer systems. Knowledge of aquifer conditions with minimal borehole control has the potential to have several positive impacts in characterizing a site, as the results of the investigation will:

- Improve the information content and level of confidence of site characterization;
- Reduce risk associated with characterization activities, as the methodology is non-destructive; and
- Reduce the cost for site characterization by reducing the number of borings required to define the subsurface hydrology.

It is anticipated that many of the DOE sites will have subsurface conditions where S-wave technology will benefit the characterization of groundwater.

1.2 TECHNOLOGY PROGRAMMATIC REQUIREMENTS

This research effort supports the Office of Technology Development (OTD) mission of private sector development of technologies applicable to the cleanup of DOE sites. The S-wave reflection method is applicable to defining subsurface layering and structure, critical to characterizing groundwater flow paths. In addition the technique offers the potential to directly detect aquifer systems while at the same time minimizing the requirements for borings. The use of the method, by reducing the requirements for borings, offers positive advantages to the DOE in terms of the reduction of health and environmental risks, reduction of costs, and improved operations.

Health and environmental risks would be directly reduced by implementation of a high resolution S-wave seismic reflection survey by reducing the number of drill holes usually required to obtain significant information about the subsurface. The survey could be conducted under Level D health and safety protective measures, rather than the Level A or B that could be required for drilling activities.

It is not possible to precisely define the cost benefit that high resolution S-wave surveying could represent to environmental hydrogeological investigations since it will be dependent on site conditions. However, it should be noted that the amount of money spent on conventional P-wave high resolution seismic reflection profiling at the Rocky Flats Plant was one tenth of the money that would have spent on borings to obtain the same information (Irons and Lewis, 1990). Shear wave technology applied to the same high resolution technique could have further improved the cost-benefit ratio.

Reducing the need for boreholes also represents an important improvement in the overall operations associated with a site investigation. If the aquifer targets can be known in advance, then the number of borings needed to provide avenues for measuring, testing, and sampling the aquifer will be significantly reduced.

2.0 METHODOLOGY AND APPROACH

The first step in conducting this research project was to review the theory of compressional (P-) and shear (S-) wave propagation through saturated and unsaturated media, as summarized in Section 2.1 and presented in greater in the Milestone 1 report. The characteristics of Love and Rayleigh waves, surface waves which are a form of coherent "noise" on a seismic reflection recording, were also reviewed. In parallel with this effort, a literature search was conducted which identified a bibliography of publications related to S-waves and case histories of previous research related to obtaining high resolution S-wave reflections as provided in our Milestone 1 submittal.

The review of the case histories yielded significant information, the concepts of which are further discussed in various sections of this report. Some observations which were accounted for and assisted in the planning for this research include the following:

- A variety of sources can be used for S-wave generation. The most common is a wooden plank, with or without spikes on the bottom, with or without a heavy weight on top, which is struck at each end by a sledgehammer. Explosive sources do not appear to work well. Shotgun or "buffalo" gun sources do not work very well and may be dangerous. High frequency vibrators could be feasible, but such sources have not been applied to high resolution S-wave reflection work.

- The ground surface has an important effect on S-wave data acquisition. Love waves can be a problem to good S-wave data acquisition, but they are greatly attenuated if the survey is conducted over a high velocity surface, such as asphalt or concrete. However, a high velocity surface can lead to erroneous depth interpretations from an S-wave survey and Rayleigh waves can be enhanced, which is a detriment to a P-wave survey.

- The correction for surface statics is a significant problem for S-wave data. The P-wave corrections are not valid as they are often influenced by groundwater effects. P- and S-wave refraction surveys should accompany the reflection surveys to characterize near-surface velocities.

- The use of P- and S-waves together requires that common reflections be identified from each data set. This can be difficult, unless downhole or preferably in-hole seismic measurements can be used to relate both P- and S-wave reflections to specific lithologic horizons.

- SH-waves appear to be more useful than SV (line-parallel) (line-traverse) waves when assessing relatively shallow targets (an explanation of these different wave types is provided in Section 2.1).

- When very shallow data is to be obtained, it must be understood that "some types of coherent noise are not coherent in the near field" (Hasbrouck, personal communication, 1990). This implies that it will be necessary to be extremely careful with one- and two-dimensional filtering and that care must be taken to obtain a large signal bandwith. The dynamic resolution of the analog/digital (A/D) converter should be high, i.e. having a large number of bits of digitization is vital, if good data are to be obtained.

The case histories led to the overall conclusion that the type of site suitable as a starting point for high resolution S-wave research would be low velocity sediments without excessive structural complexities. This was the most important criterion which led to the identification of Cooke Crossroads, South Carolina as being a suitable site for the field experiment. The geologic setting of the Cooke Crossroads site is presented in Section 2.2.

The field experiments were set up to obtain P- and S-wave reflections, initially using conventional equipment with simple recording procedures described in Section 2.3 and subsequently with more sophisticated equipment and recording procedures as described in Section 2.4. The downhole seismic measurements described in Section 2.5 were not designed to be an experiment, but rather a determination of the arrival times of P- and S-waves at discrete sedimentary horizons. As it turned out , minor time and depth uncertainties with the downhole data did not allow for a definitive lithologic/reflection correlation to be established and it was necessary to obtain in-hole P- and S-wave sonic logs to resolve the uncertainties, as presented in Section 2.6. These data allowed for the interpretation of the P- and S-wave reflection profiles in terms of the subsurface hydrogeology.

2.1 BACKGROUND THEORY

A seismic wave is simply a localized disturbance of relative particle positions within a medium as the wave propagates through a specified volume of the medium. Depending on how the volume or the shape of the propagation medium is affected, seismic waves propagate in a variety of modes. For the most part, compressional, or P, waves are associated with changes in volume. Shear, or S, waves are associated primarily with changes in shape.

A good analogy that can be used to visualize the propagation of a P-wave can be obtained with the use of a coiled telephone cord. If the cord is placed on a surface such as table and is made taught, squeezing together the coils at one end of the cord and then releasing them will produce a P-wave that propagates to the opposite end of the cord. The wave consists of compressed and rarefied coils. The telephone cord can also be used to exemplify S-wave particle motion. By making the cord taut, pulling a few coils to one side and suddenly releasing them, a wave will propagate down the cord in which the coils are distorted and the motion of the coils is side to side.

The direction of S-wave particle motion may lie anywhere in the plane perpendicular to the ray, depending mainly on the direction of motion induced at the source. For measurements near the earth's surface, the S-wave particle motion can be resolved into a component parallel to the surface (SH) and a component in the vertical plane (SV).

P-waves are faster than S-waves. In rock, they typically travel at about twice the speed of the S-wave. Where accurate velocity measurements have been made, the ratio of the S-wave velocity to the P-wave velocity (V_s/V_p ratio) has been shown to have a relationship to lithology. Neidell (1985) reports the V_s/V_p ratios for shale, sandstone and limestone to be 0.5, 0.62 and 0.56, respectively. In unconsolidated sediments, this "rule of thumb" that the P-wave is about twice as fast as the S-wave may be incorrect. Where unconsolidated sediments are saturated, they tend to have the P-wave velocity of water, about 5200 ft/s, but the S-wave velocity can be much lower than half this value. Suyama et al. (1987) report S-wave values less than 400 ft/s with a V_s/V_p ratio of 0.07 at a saturated soil site in Japan.

The seismic reflection technique consists of measuring the travel time required for a seismic wave generated at or near the surface to return to surface or near surface detectors (geophones) after reflection from acoustic interfaces between subsurface materials (Figure 1). The geophones are usually located at distances from the source which are relatively small when compared to the depth of the reflector. Variations in the reflection arrival times can be used to map structural features in the subsurface. Depths to reflecting interfaces can be determined from the travel times using velocity information that can be obtained from the reflected signals or from borehole surveys.

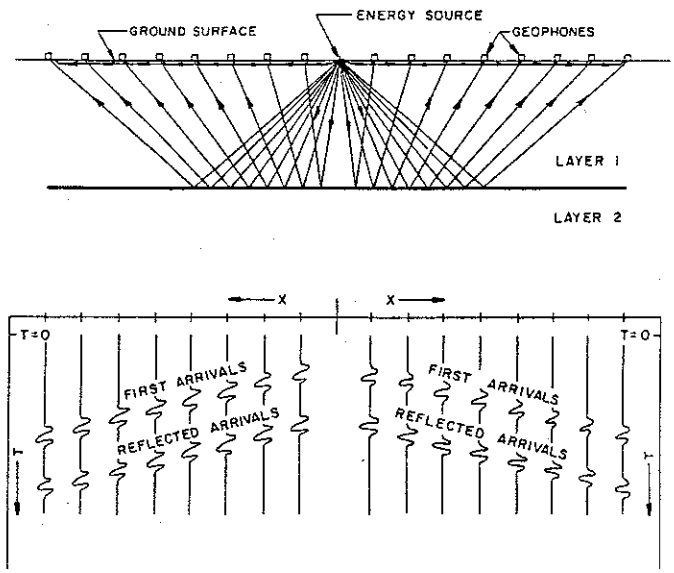


Figure 1 - Seismic reflection principle and schematic of reflection data record

The underlying principle of the reflection technique is acoustic impedance. This is the criterion which determines whether an interface will produce reflections or not.

The acoustic impedance for a material is equal to the product of wave velocity and density. The reflection coefficient, R, across an interface is the ratio of the amplitude of the displacement of a reflected wave to that of the incident wave and is given by (Dobrin, 1960):

$$R = \frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1}$$

where:

R	= Reflection coefficient
ρ_1, ρ_2	= Mass density of materials on sides 1 and 2 of interface
V_1, V_2	= P-wave velocities on sides 1 and 2 of interface

The sign of R determines the polarity of the reflected wave. If R is negative, the polarity of the reflected wave is opposite to that of the incident wave. The reflection coefficient for S-wave reflections is similar to that for P-waves, except that S-wave velocities are substituted for P-wave velocities and the + and - signs are reversed.

The ability of the seismic reflection method to detect an individual sedimentary bed is not only a function of the acoustic impedance at the top and bottom of the bed, but also depends on local noise, the layer thickness, and the predominant reflection frequency. A sedimentary layer cannot be clearly depicted if the amplitude of the reflected wave is less than the ambient noise, although the problem of noise can be somewhat mitigated with special recording and processing techniques. Assuming that a vertical incidence reflection signal is just detectable above the noise, the dimension of the thinnest layer that can be detected at this amplitude of the reflected wave is one way of describing the resolution of the technique (Farr and Peace, 1979).

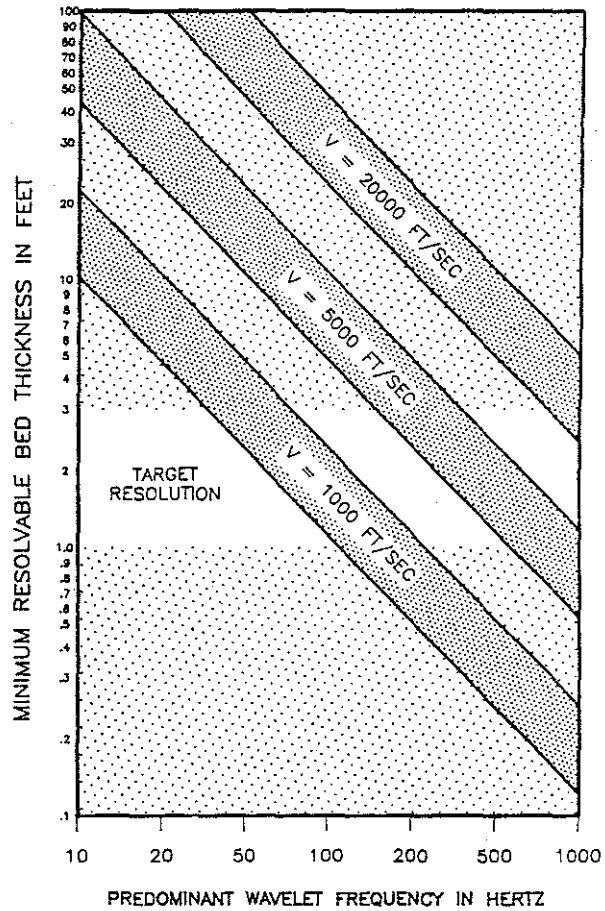


Figure 2 - Minimum resolvable bed thickness as a function of predominant reflection frequency and velocity

(The upper and lower bounds for each velocity assume that the minimum resolvable bed thickness ranges from $\lambda/4$ to $\lambda/8$, where λ is the length of the seismic wavelet in the ground.)

The minimum resolvable bed thickness is commonly taken to be 1/4 to 1/8 the wavelength of the seismic reflection. Some researchers have postulated that this minimum resolution should be as small as 1/12 of the wavelength, but it is our experience that noise usually prevents resolution better than 1/4 to 1/8 of the wavelength. As an example, if the velocity of the propagating medium is 5,000 ft/s and the predominant wavelet frequency is 100 Hertz, then the wavelength is 50 feet and the minimum resolvable bed thickness would be 6.25 to 12.5 feet. The relationship between the minimum resolvable bed thickness and predominant wavelet frequency and velocity is depicted graphically on Figure 2.

Most of the research with respect to the S-wave reflection technique has been conducted by the oil and gas industry, where they are looking in deep sedimentary rock environments for hydrocarbon traps. Improved resolution is not a goal of research. As noted by Helbig (1987): "Although S-waves have much shorter wavelengths than P-waves of the same frequency, S-wave sections rarely have higher (and often even lower) resolution than P-wave sections. It is more difficult to generate S-waves of high frequency...." In essence, S-waves in rock typically have predominant frequencies of about half that of P-waves which balances the potentially increased resolution caused by their having a slower velocity. The end result is no increase in resolution. This situation changes when unconsolidated sediments are considered.

If the S-wave velocity of soil is much less than half of the P-wave velocity, then the resolution obtainable with S-waves could be much greater than that obtainable with P-waves, even if the S-waves are of a lower predominant frequency. For example, as shown on Figure 2, the minimum resolvable thickness for a water-saturated soil (Vp = 5,200 ft/s) and a predominant frequency of 200 Hertz (achievable in a high resolution survey) would be about three to six feet. If the soil were soft with an S-wave velocity of 500 ft/s and the S-waves had a predominant frequency of 100 Hertz, then the minimum resolvable bed thickness would be about half to one foot, representing a much higher resolution.

Several characteristics of P- and S-waves make them potentially useful for characterizing shallow groundwater conditions. Some of the characteristics, which will be further discussed in this section, include the following:

- S-wave velocities are not severely affected by saturating an unconsolidated sediment with water, but the opposite is true with P-wave velocities. For example, S-wave velocities of sands and clays are usually significantly different whether they are saturated or unsaturated. This statement also applies to P-wave velocities, if the sediments are dry, but saturated sands and clays are frequently difficult to distinguish on the basis of P-wave velocity alone.

- The ratio of P-wave to S-wave velocity (V_p/V_s ratio) can be an indicator of lithology, which would be significant in defining aquifer systems. The V_p/V_s ratio can also be significant in defining the presence of groundwater when the lithology is known.

- S-waves are much more susceptible to the effects of anisotropy (directionally controlled differences in propagation properties) than are P-waves. The assessment of S-wave anisotropy can help define lithology and also the presence of fractures, both of which are useful in defining groundwater conditions.

In general, the interpretation of groundwater conditions requires a comparison of P- and S-wave data together.

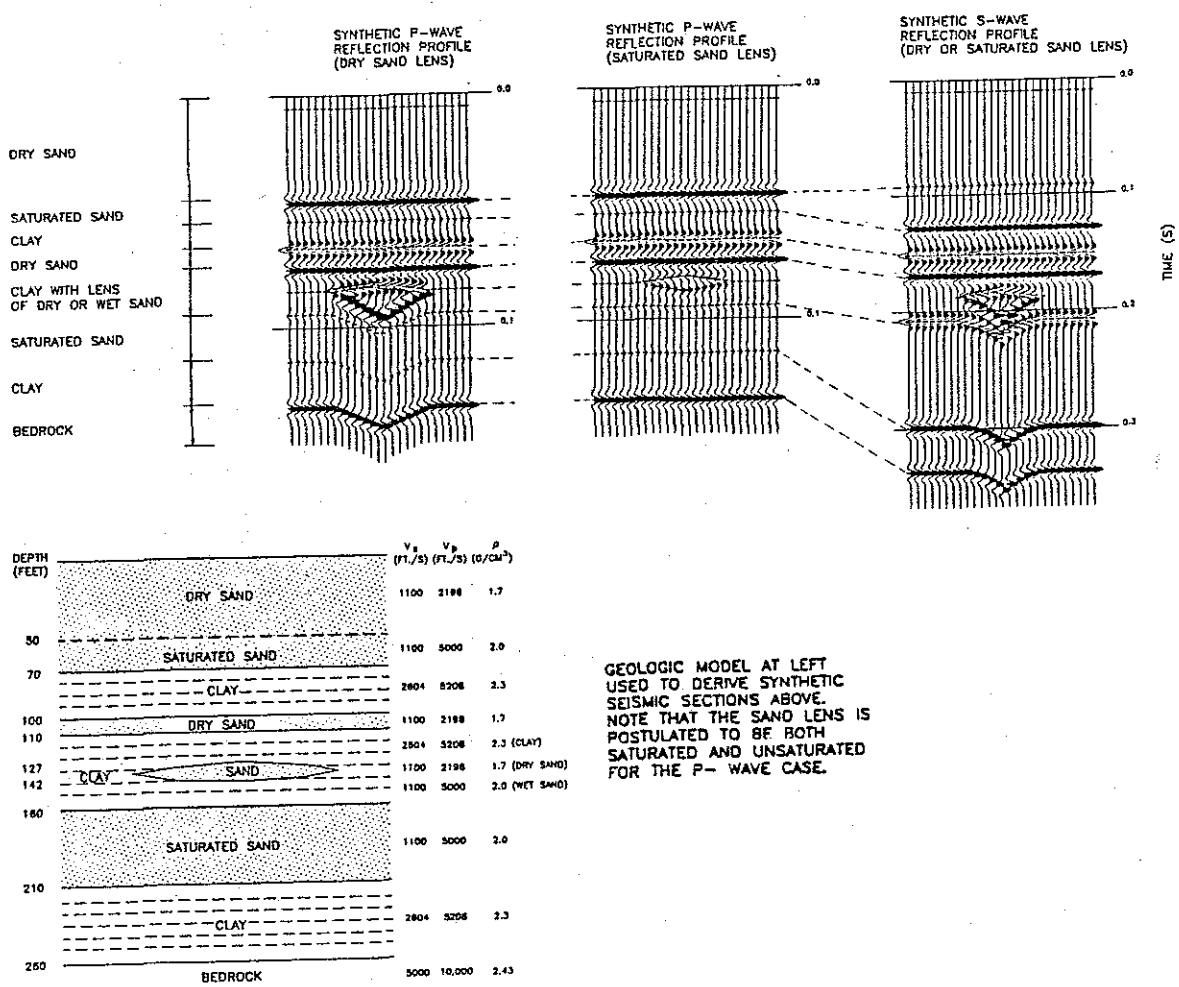


Figure 3 - Response of vertically incident P- and S-waves to a geologic model containing an unconfined aquifer and a confined sand lens.

Figure 3 displays a simplified model consisting of sand/clay layers and a sand lens located within a clay layer. This model poses a classic problem for hydrogeologic investigations:

- The presence of a sand lens which may or may not be an aquifer is extremely difficult to detect by means of borings because the target is so small.

- If borings have not been utilized, conventional geophysical measurements, including techniques other than seismic, such as resistivity, electromagnetic, etc., have considerable difficulty in distinguishing a water table from a clay layer. If the sand lens is saturated, it may be nearly invisible to any geophysical technique if it is enclosed by clay.

Given good data quality, the use of both P- and S-wave data can resolve the problem of aquifer detection. Figure 3 also displays three synthetic seismic models which were computed from the stratigraphic model. Two of the models are P-wave models in which the sand lens was varied from dry to saturated. Only one S-wave model is displayed because there is no discernable difference between the dry and saturated versions of the model. The V_p/V_s ratio for the model was arbitrarily set at 2.0 to facilitate a display of the waveforms. In reality, the ratio would be higher with unconsolidated deposits and would vary with depth. Several observations can be made from these models:

- The P-wave models show a reflection from the unconfined water table. The S-wave model shows only a very slight response, which would easily be missed if noise were introduced into the model.

- The sand lens exhibits a marked anomaly when dry and an extremely subtle anomaly when the lens is saturated on the P-wave record. Additionally, reflections below the dry lens exhibit considerable velocity sag (due to the relatively low velocity of the sand as compared to the clay which it replaces) while the wet sand case does not.

- The S-wave section exhibits a marked anomaly regardless of whether the sand lens is saturated or not. Also, the velocity beneath the sag is unaffected by the degree of saturation of the sand lens.

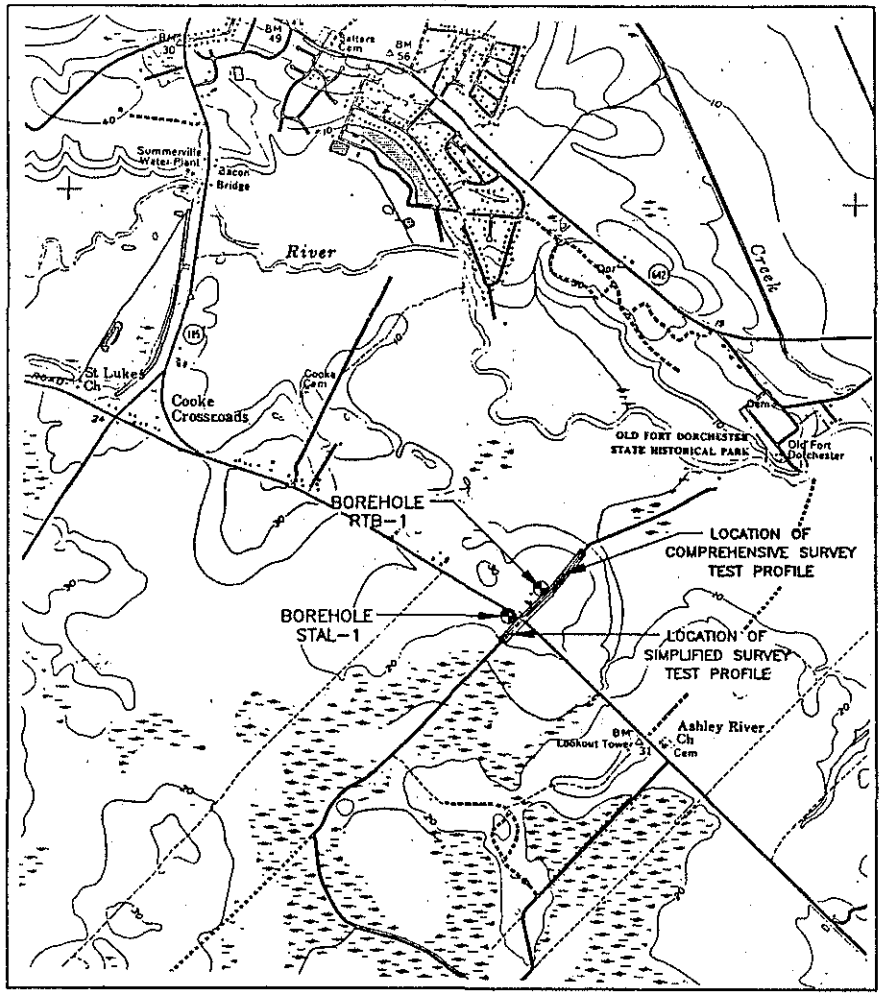
It should be noted that the synthetic sections have been simplified by considering only vertical incidence to illustrate the relative differences in the P- and S-wave response to a conceptual soil model. The synthetic sections are completely free of noise which can be a severe and sometimes overwhelming problem to the interpretation of actual data. The exclusion of anything other than vertical incidence eliminates diffractions which would likely be observed at the edges of the sand lens. The synthetic sections basically appear as if real records had been subjected to perfect processing, where all random and coherent noise has been removed.

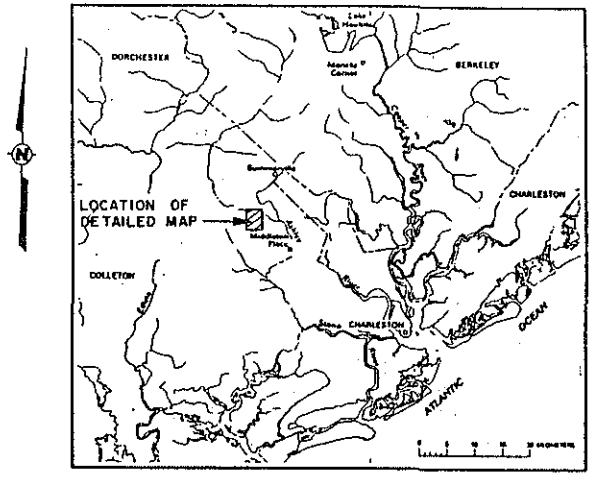
Both P- and S-wave data are needed to make an unambiguous interpretation of both the lithology and the water content of the subsurface. The S-wave reflections can be used to differentiate the sand from the clay, but cannot be used to discern saturated sand from dry sand. The P-wave response is different for saturated and dry sand, but is nearly the same for saturated sand and clay. Together, the records can be used to directly infer the presence of aquifers that would otherwise be difficult to detect.

2.2 GEOLOGIC SETTING OF THE COOKE CROSSROADS SITE

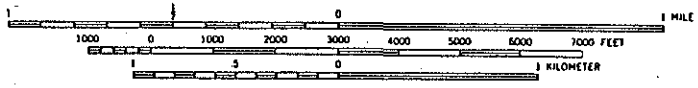
The Cooke Crossroads site is located in Dorchester County, South Carolina approximately 15 miles northwest of Charleston (Figure 4). The Milestone 2 Report "Siting of Shear Wave Field Experiment" (Paul C. Rizzo Associates, 1991) indicated an acceptable site at Clubhouse Crossroads, approximately ten miles west-southwest of the Cooke Crossroads site. The test site was relocated after discussions with Dr. Gregory S. Gohn of the U.S. Geological Survey (USGS) in Reston, Virginia, who was able to provide better well control in the Cooke Crossroads area.

The location of the initial test line at the Cooke Crossroads site was selected to tie in with USGS borehole STAL-1 (Figure 4). The lithology of STAL-1, as interpreted from geophysical logs and samples, is provided on Figure 5. The Cooper Formation, encountered to a depth of 220 feet from ground surface, is predominantly a low permeability fine-grained carbonate deposit, except for thin phosphatic sand layers. These sands are marked by natural gamma highs, contrary to what would be expected (clays normally have natural gamma highs because of the presence of uranium minerals associated with the phosphatic portions of the sand. The thickest sand layer between depths of 78 and 94 feet made Cooke Crossroads attractive as a test site. Based on theoretical considerations, such a sand layer, assumed to be saturated as it is below sea level, might not be visible on a P-wave record, but should be a moderately strong reflector to S-waves.





SCALE OF DETAILED MAP



REFERENCE:

UNITED STATES GEOLOGICAL SURVEY, STALLSVILLE QUADRANGLE, SOUTH CAROLINA, 7.5 MINUTE QUADRANGLE SERIES, 1957, PHOTOREVISED 1979

Figure 4 - Locations of Cooke Crossroads test sites.

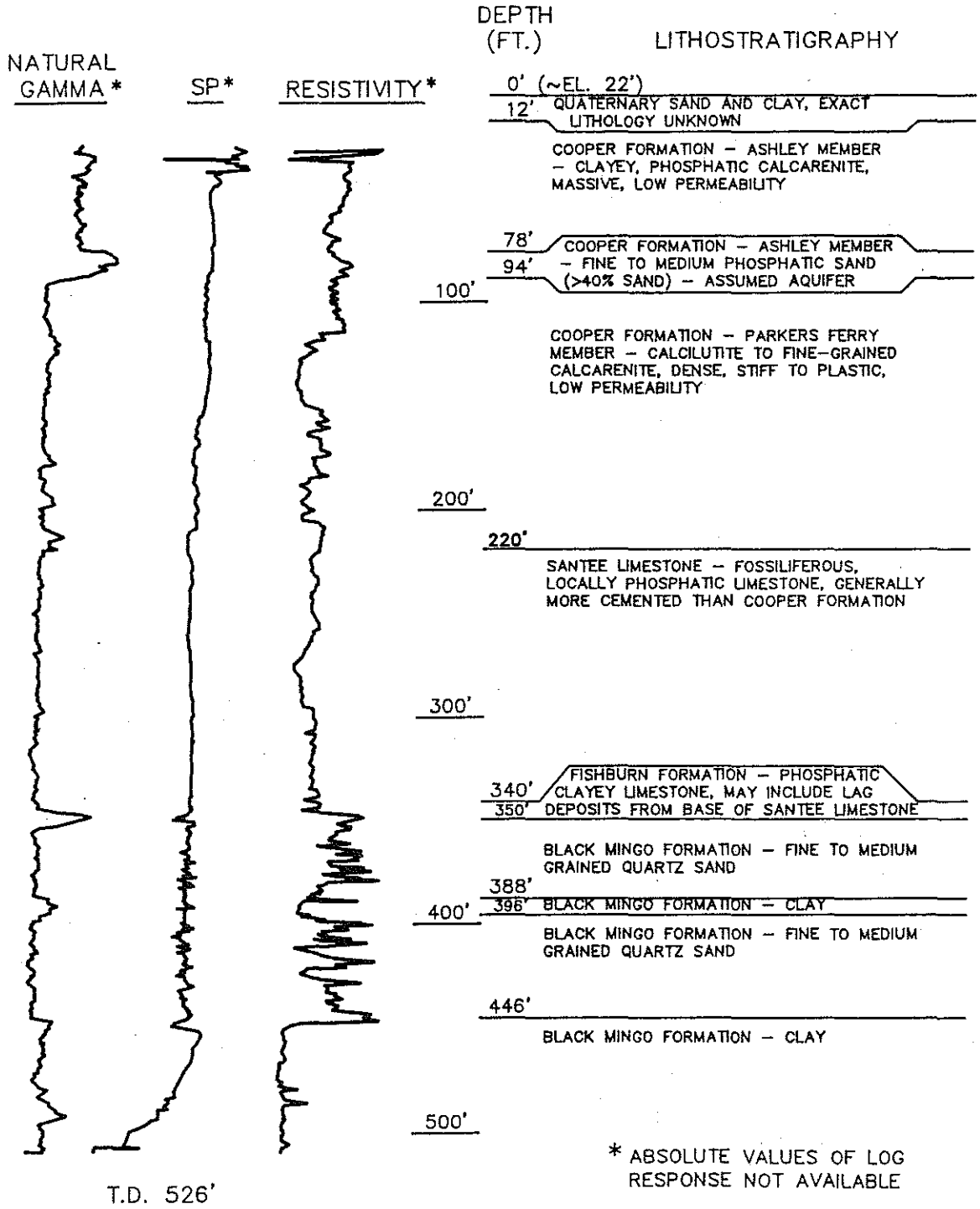


Figure 5 - Lithostratigraphy at Borehole STAL-1 (from unpublished information provided by G. S. Gohn of the U.S.G.S.).

Beneath the Cooper Formation, the Santee Limestone is of a composition similar to the Cooper Formation, but is generally more cemented. A thin phosphatic limestone layer has been identified at the base of the unit and classified by Dr. Gohn as the Fishburn Formation. Beneath the Fishburn Formation is a quartz sand unit present from a depth of 350 to 446 feet with a clay split from a depth of 388 to 396 feet. This unit is also a confined aquifer within the Black Mingo Formation.

Additional subsurface control for the field experiments was established by drilling a 250-foot boring designated as RTB-1 (Figure 4). This boring encountered a lithology essentially identical to that encountered in STAL-1. The base of the Quaternary was encountered at a depth of 12 feet. Within the Ashley Member of the Cooper Formation, sand layers were encountered between 12 and 31 feet and between 83 and 94 feet. Beneath the Ashley Member, the Parkers Ferry Member was predominantly calcareous silty clay (calcilutite), except for sand layers encountered from 108 to 110 feet, 129 to 132 feet and 200 to 204 feet. Based on a comparison of gamma log response with STAL-1, the top of the Santee Limestone begins at a depth of 229 feet, although from a lithologic standpoint limestone was encountered after 217 feet. The lithostratigraphy of RTB-1 is provided on Figure 6.

Figure 7 provides an interpreted lithologic cross section between boreholes STAL-1 and RTB-1. The continuity of beds is also inferred from an interpretation of the seismic reflection profiles, further discussed in Section 3.0.

2.3 INITIAL FIELD EXPERIMENT

The purpose of the initial field test was to achieve the following goals:

- Confirm the suitability of the test site;
- Assess which source type, e.g. hammers, explosives, rifle/shotgun, is most efficient for this site; and
- Determine the effectiveness of acquiring S-wave data with single-component geophones and separate P- and S-wave recordings.

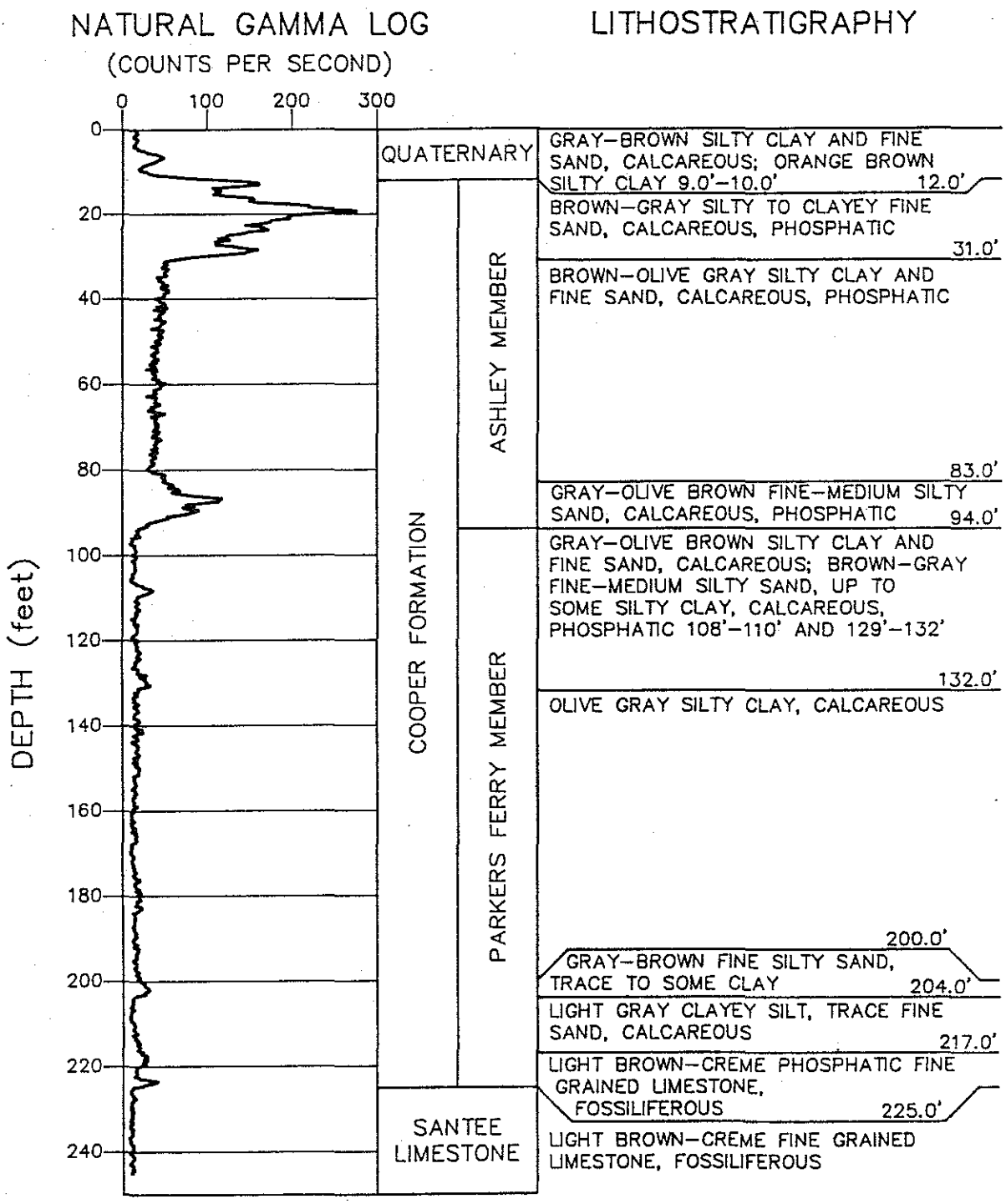


Figure 6 - Lithostratigraphy of Borehole RTB-1.

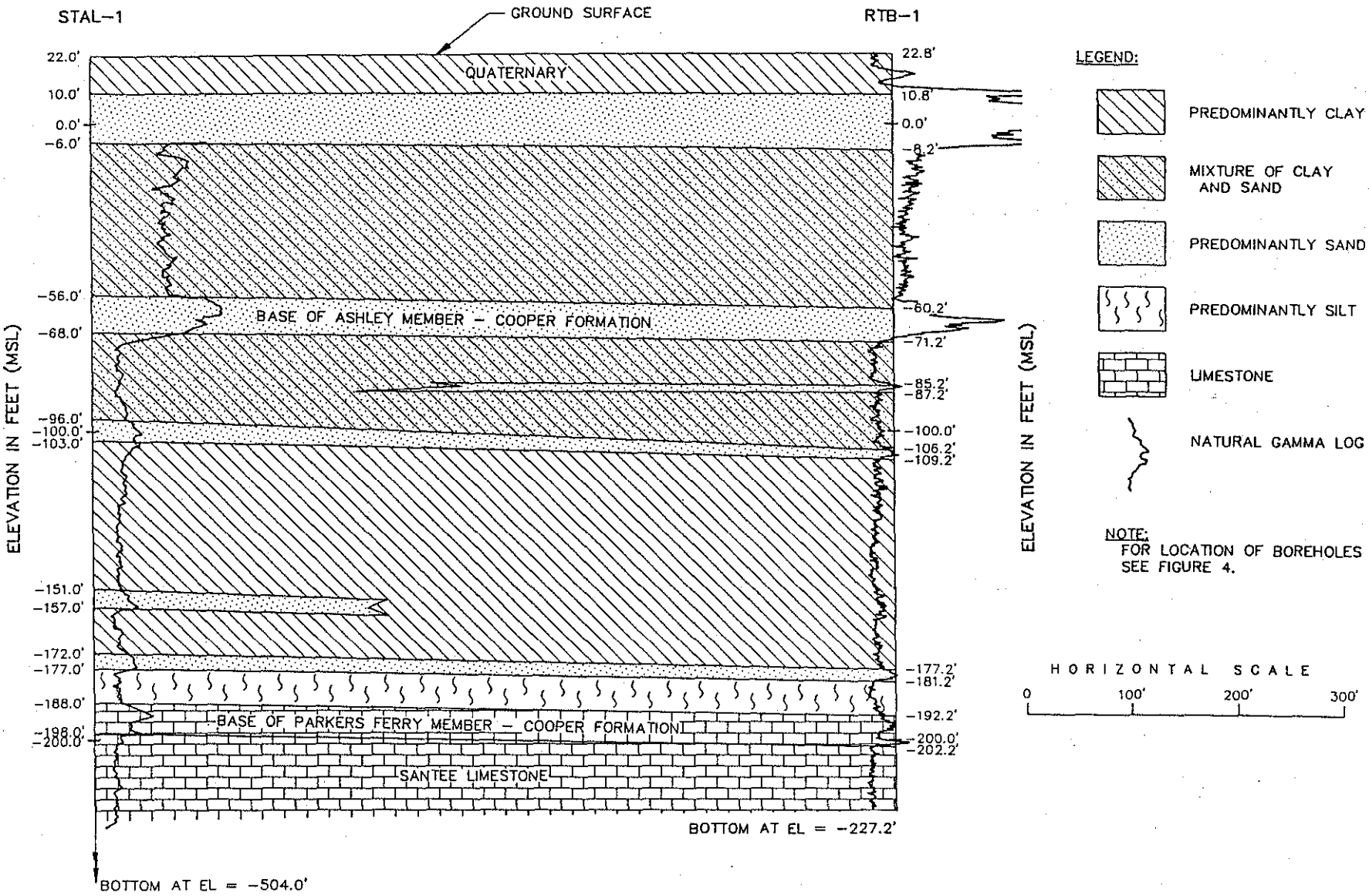


Figure 7 - Lithologic cross section along comprehensive survey test line.

The initial field experiment is also referred to as the simplified survey, as the field procedures followed were similar to those followed for conventional high resolution seismic reflection surveys.

The field work was initiated by surveying 750 feet of test line at a 5-foot interval as located on Figure 4 and shown on Photograph A of Figure 8. The geophysical crew mobilized to the site on May 16, 1991 and completed the field work on May 25. The following sections discuss the equipment used, field procedures followed, and the processing conducted on the seismic recordings obtained during the field survey.

2.3.1 Equipment

The data acquisition equipment used for this initial S-wave reflection survey was intended to be off-the-shelf items that would be readily available should the technique evolve into common usage. As such, the equipment consisted of a combination of components commonly used for engineering geophysical applications and by the oil and gas industry. The basic components consisted of a recorder; a computer used for data storage and analysis; surface ground motion sensors (geophones); cables; and a switch used to vary the geophones that recorded the seismic data at any given time, usually called a common-depth-point (CDP) roll-along switch. These components are specified as follows:

- Recorder:
  - Bison 9024 digital instantaneous floating point signal enhancement seismograph;
  - Channels: 24;
  - Sample rate: 50, 100, 200, 500, 1000, 2000, 4000 microseconds;
  - Record lengths: 500, 1000, 2000, 5000, 10,000 milliseconds;
  - Frequency response: 4-2000 Hertz; and
  - Method of storage: mass memory.

- Storage/Analysis Device: Toshiba T-5200, 80386 based computer (used for permanent storage after data transfer from the Bison 9024).

- Geophones:
  - Oyo two component SMC-70 series;
  - Natural frequency - horizontal, 40 Hertz; vertical, 28 Hertz;

- Spread Cables: Mark Products 120 pair cables;
  - 6 geophone takeouts per cable; 55 feet between takeouts; and

- CDP Roll-Along Switch: Input /Output RLS-240M Rotalong switch.

Photograph B on Figure 8 depicts the recording equipment and the CDP roll-along switch utilized in the field.

In addition to the recording equipment, several types of P- and S-wave sources were used in various stages of the survey. These sources can be grouped into various hammer sources, where different sized hammers strike different types of anvils, as well as shotgun/rifle sources, as follows:

- Steel plate, one-inch thick, one by one foot square;

- Steel cylinder, three-inch diameter, one foot length, six-inch by six-inch base plate (Photographs A and C on Figure 8);

- One-inch diameter pipe, six inches in length, attached to a three-inch diameter base plate;

- Railroad tie, three feet in length, eight inches by one foot in cross section, capped at each end with steel plates (Photograph D on Figure 8);

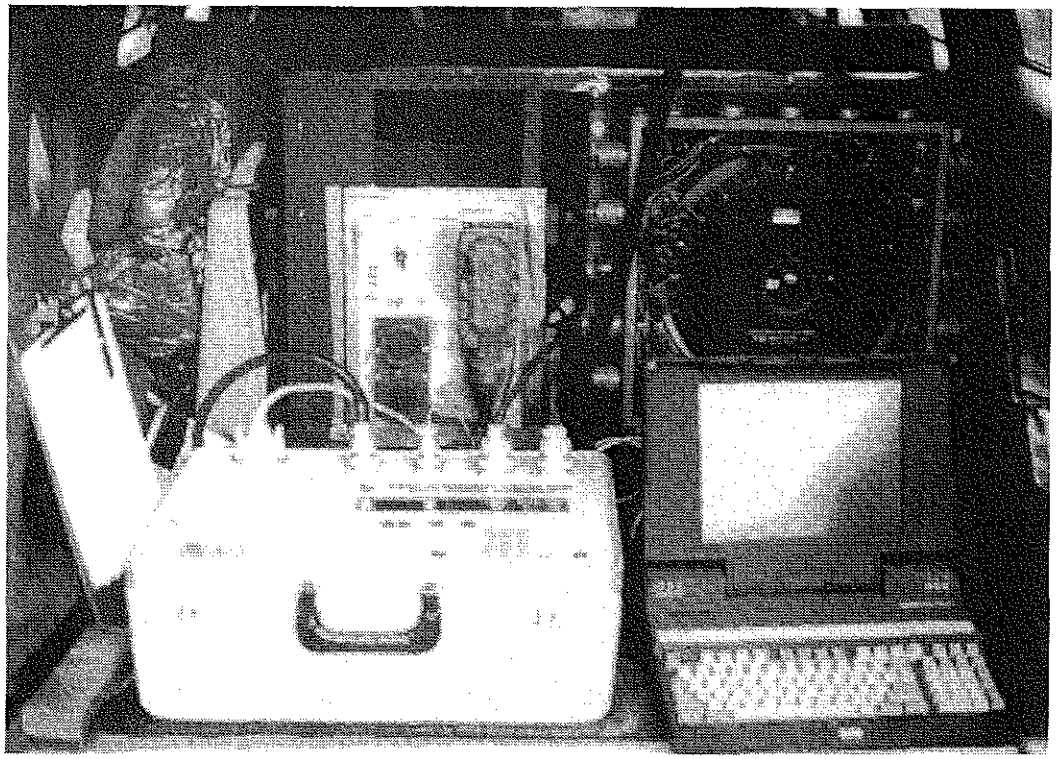
- 22 caliber rifle with a vent hole drilled at the end of the barrel;

- Betsy Downhole Seisgun, a downhole percussion "buffalo gun" capable of firing 8, 10, and 12 gauge shotgun shells; and

- One-inch diameter pipe, one foot in length, open at both ends.

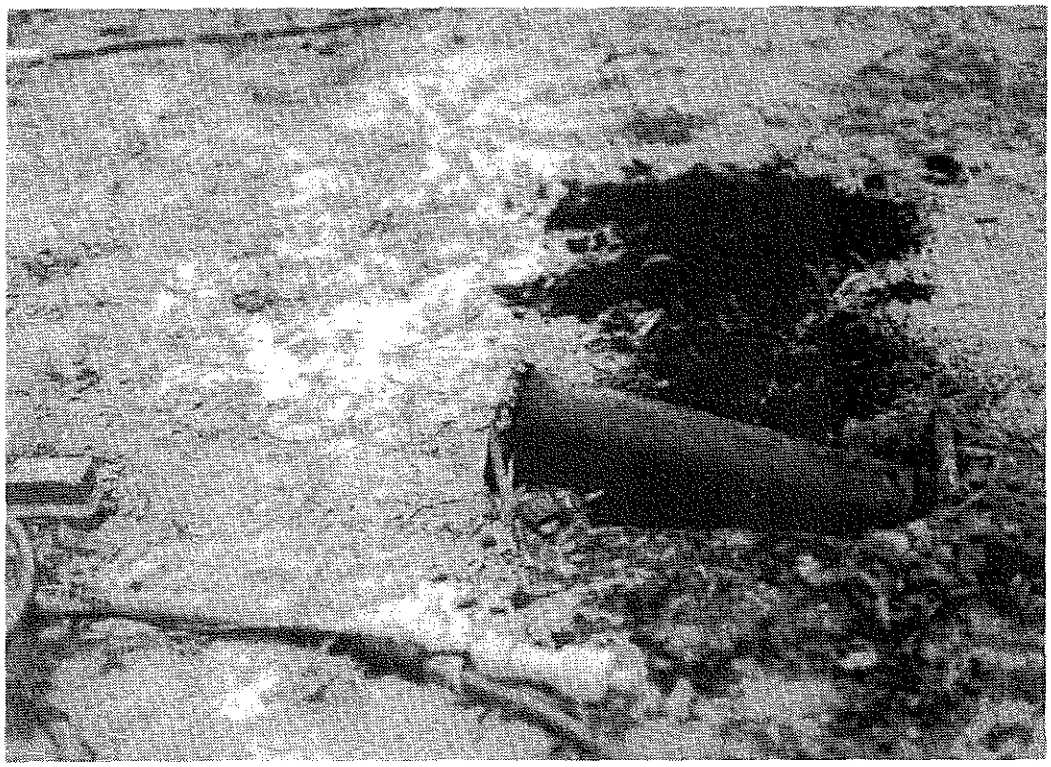
All of the above sources require the impact of a hammer to initiate. In the case of the steel cylinder, the steel plate, the railroad tie, and the pipes, three different hammers were used: a 16-pound sledge hammer; a three-pound hammer; and a ballpeen or carpenter's hammer. The Betsy Downhole Seisgun was equipped with a special hammer that was used to trigger the shotgun shell.

Photograph A - General view of test line and 3-inch cylinder in vertical position for P-wave acquisition.

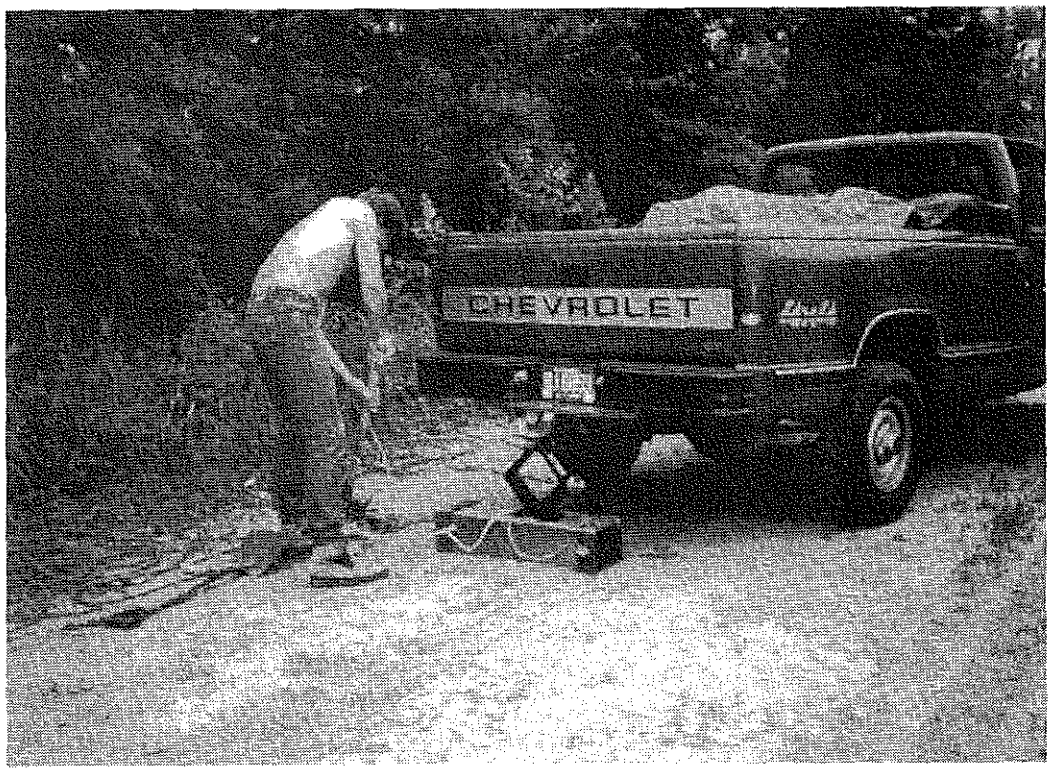


Photograph B - Recording equipment (Bison 9024 seismograph, Toshiba T-5200 computer, and Input/Output RLS-240M Rotalong Switch).

Figure 8 - Photographs of field operations, initial survey.



Photograph C - 3-inch cylinder in horizontal position for S-wave acquisition (Oyo horizontal geophone is at left edge of photo).



Photograph D - Railroad tie source under compressive load of pickup truck.

Figure 8 - Photographs of field operations, initial survey. (Continued)

2.3.2 Field Procedures

2.3.2.1 Source Spread Configuration And Equipment Testing

During the first week of field work, the various sources were tested at different locations along the test line. The effectiveness of different spread configurations was also evaluated, as well as the relevant aspects of the recording equipment performance. Figure 9 provides an example of field recordings made from the testing of different S-wave sources.

2.3.2.2 Test Line Program

Upon completion of the source testing, five test lines were acquired:

- A P-wave line using a ten-foot station interval and a ten-foot source array; split-spread configuration. Source: Steel cylinder in vertical position.
- A P-wave line using a ten-foot station interval with no source array; off-end configuration. Source: Steel cylinder in vertical position.
- A P-wave line using a 2.5-foot station interval with no source array; split-spread configuration. Source: Steel pipe with base plate in vertical position.
- S-wave line using a ten-foot station interval; off-end configuration. Source: Steel cylinder in horizontal position.
- S-wave line using a 2.5-foot station interval; split-spread configuration. Source: Steel pipe with base plate in horizontal position.

Both of the S-wave test lines used a double source acquisition technique. The source was oriented perpendicular to the direction of the line and eight impacts were recorded at each station location. The source was then oriented in the opposite direction and eight additional impacts were recorded on a separate record. The purpose of the source change was to enable the discrimination of S-waves from potential contamination by P-waves by subtracting the S-wave records which would be of opposite polarity.

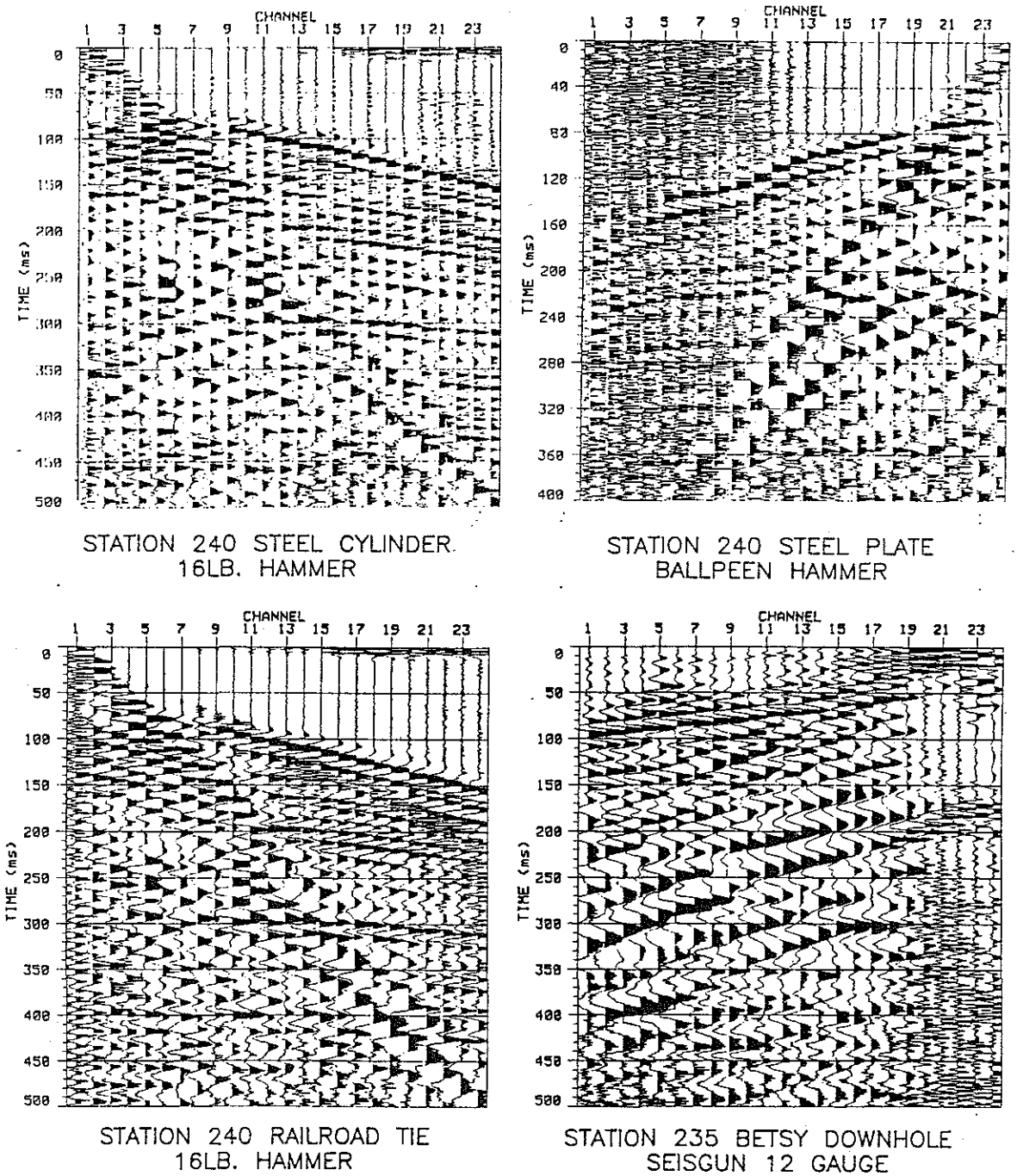


Figure 9 - Comparison of representative S-wave field records from various sources.

2.3.2.3 Seismic Refraction Test

In support of the seismic reflection method, a seismic refraction test was conducted between Stations 10 and 480 on the profile line to obtain information on the distribution of near-surface velocities and the depth of low-velocity surface sediments (essentially the contact of Quaternary sediments with the Cooper Formation). The seismic refraction method consists of measuring the time required for P- or S-waves to travel from an impulsive source at or near the surface to a surface receiver, using varying source-receiver spacings. The direct wave travels through the near-surface layer along the shortest path between the source and receiver. The critically refracted wave travels along layer boundaries where the lower layer has an appreciably higher wave velocity than the upper layer (Figure 10).

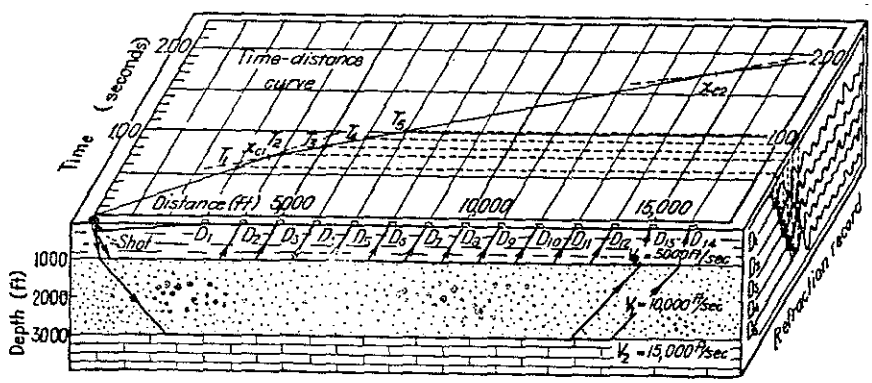


Figure 10 - The seismic refraction technique - wave paths, schematic record, and time-distance curve for a three-layered subsurface (from Dobrin, 1960).

For subsurface materials that can be represented by a sequence of horizontal layers whose wave velocity increases appreciably with depth, the first arrival for small source-receiver spacings will be the direct wave through the uppermost layer. As the source-receiver spacing is increased, the first arrival will become a critically refracted wave from the boundary of the first and second layers with an observed apparent wave velocity equal to the wave velocity of the second layer. The Cooke Crossroads site represents relatively simple, two-layer conditions in the shallow subsurface.

Information suitable for a refraction analysis was gathered with every record obtained for the seismic reflection survey, both for the P- and S-waves. To enhance the information obtained from the reflection data, full spread length off-end shots were made from each end of the geophone spread. The reflection data were not interpreted to derive a cross section of the uppermost low velocity layer (the Quaternary sediments), but used to assess traveltime delays associated with variations of surficial velocity or variations in depth of the first layer (statics correction), as noted in Section 2.3.3.1. A typical field record taken from an S-wave shot as well as the travel time plots for both P- and S-waves are shown on Figure 11.

2.3.3 Data Processing

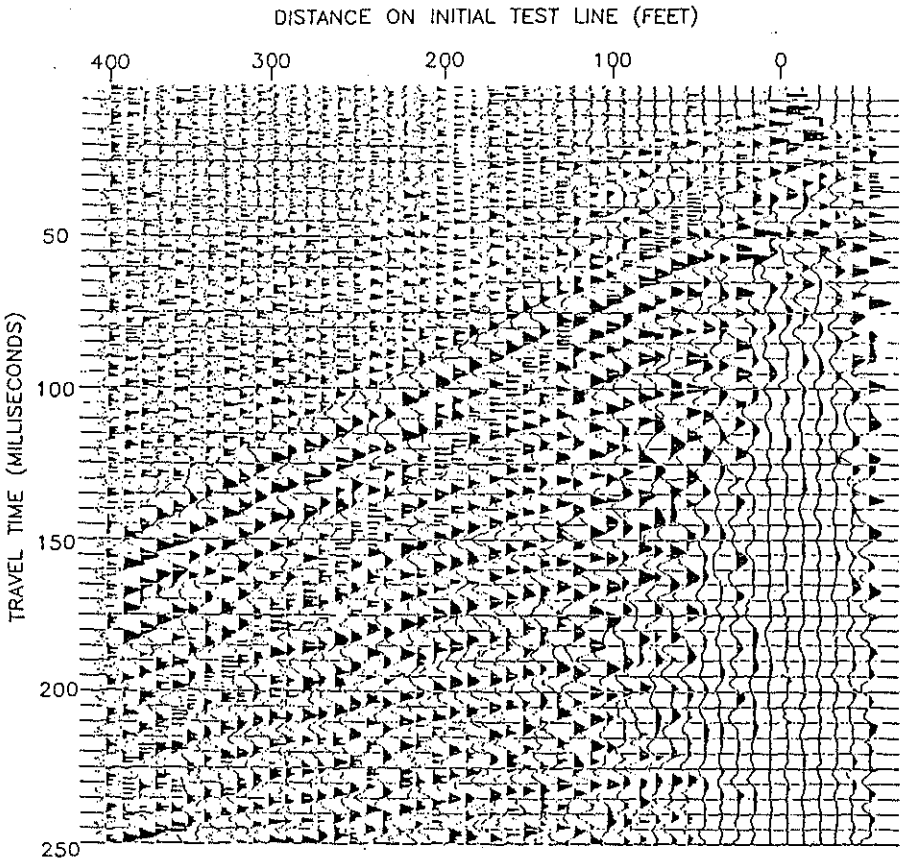
Comprehensive processing of the seismic reflection data was performed by Production Geophysical Services (PGS), of Englewood,Colorado. Partial processing of some of the data was also performed at Apex Geophysical Corporation (Apex), using the PC-based SEISTRIX software package written by Interpex of Golden, Colorado. The dual processing by PGS and Apex offers the opportunity to compare comprehensive professional processing with a relatively simple processing currently capable of being conducted on a PC system in the field.

A significant detriment to the processing resulted from data transfer problems between the Bison recorder and the computer. About 90 percent of the extremely high resolution P-wave line (2.5 foot geophone spacing) was lost in the transfer process. No attempt was made to process this line. Approximately 75 percent of the P-wave line using no source array was also lost. The remaining data were co-processed with the other P-wave data set. About 60 percent of the S-wave line using a 10-foot spacing was lost, but the line could still be successfully processed. The end result of the data loss was that only three lines could be processed, two S-wave profiles, and one P-wave. The problem proved to be inherent to the Bison recorder and has been corrected in their later units.

2.3.3.1 Comprehensive Processing

The data processing conducted by PGS for the P-wave sections can be summarized as follows:

- Reformat data to SEG Y;
- Trace edit;
- Spherical divergence correction;
- Refraction statics analysis, datum 35 feet;
- Surface consistent deconvolution 30 ms operator;
- Zero phase spectral whitening 40-400 Hertz;

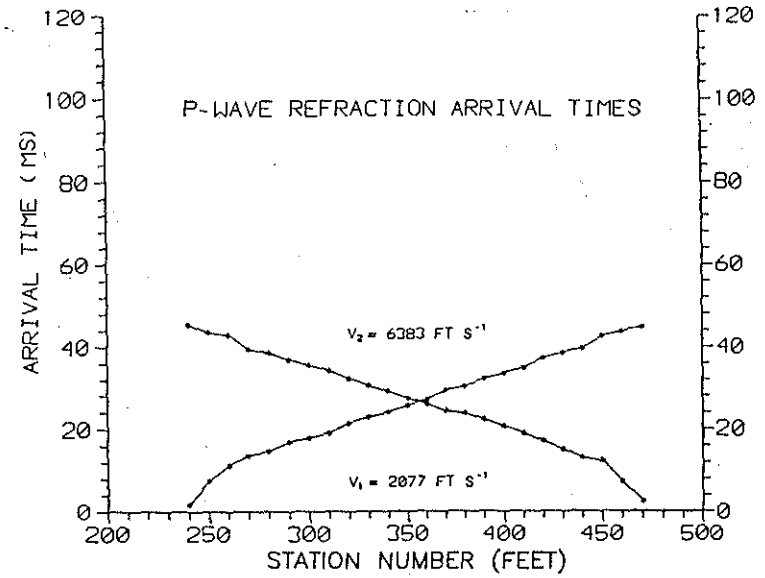


TYPICAL S-WAVE SEISMIC REFRACTION FIELD RECORD

NOTE:

V_1 = VELOCITY OF THE TOP SUBSURFACE LAYER

V_2 = VELOCITY OF THE BOTTOM SUBSURFACE LAYER



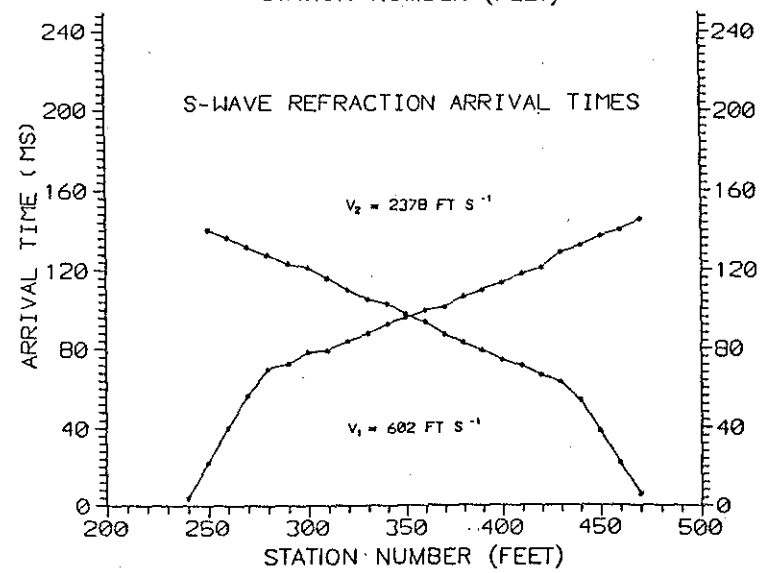


Figure 11 - Seismic refraction data, Cooke Crossroads test site.

- Statics application;
- Velocity analysis - constant velocity stacks;
- Surface consistent automatic statics;
- CDP consistent statics;
- CDP stack;
- Phase compensation;
- Post stack enhancement, F-X deconvolution;
- Bandpass filter 128-400 Hertz; and
- Scaling (AGC) 25 ms.

The processing sequence for the S-wave data was as follows:

- Reformat data to SEG Y;
- Trace edit;
- Equalize left and right direction components;
- P-wave cancellation (sum left and right components);
- Spherical divergence correction;
- Refraction statics analysis, datum 50 feet;
- Surface consistent deconvolution;
- Zero phase spectral whitening 30-300 Hertz;
- Statics application;
- F-K filter;
- Velocity analysis - constant velocity stacks;
- Surface consistent automatic statics;
- CDP consistent statics;
- CDP stack;
- Phase compensation;
- Post-stack F-X deconvolution;
- Bandpass filter 40-300 Hertz; and
- Scaling (AGC) 50 ms.

The processing performed at PGS used state-of-the-art technology in transforming the field records into zero offset reflection seismograms. The basic processing steps can be grouped into the following topics: format conversion; P-wave cancellation (in the case of S-wave processing); signal conditioning and filtering; statics resolution; noise reduction/signal enhancement; velocity determination and application; CDP stacking; post-stack noise reduction/signal enhancement; instrument and geophone de-phasing; and AGC. Should the reader desire to have a more detailed understanding of the processing, the book "Seismic Data Processing" by Yilmaz (1987) is recommended.

2.3.3.2 Simplified Processing

The data processing undertaken at Apex Geophysical was of a less detailed nature than that performed at PGS. The intent of this parallel processing was to perform limited analysis of the field data and to produce preliminary sections of some of the data to serve as guides for report preparation using a system. This effort allowed for the comparison of the output of a relatively modern and well-known processing package designed for use on a PC system (SEISTRIX produced by Interpex, Limited of Golden, Colorado) with the results that can be obtained from a firm specializing in data processing.

2.4 COMPREHENSIVE FIELD EXPERIMENT

The main goal of the comprehensive survey was to acquire the highest possible quality, simultaneously recorded P- and S-wave data using the most sophisticated recording and processing systems currently available. A second goal was to provide additional borehole control to the survey by drilling a borehole and conducting downhole seismic measurements. The downhole data would then allow for a refined interpretation of hydrogeologic conditions beyond what previously could be defined.

The field work was initiated by surveying approximately 1,500 feet of test line at a 7.5-foot interval as located on Figure 4. The geophysical crew mobilized to the site on September 25, 1991 and completed the survey on October 5, 1991. The following sections discuss the equipment used, field procedures followed, and the processing conducted on the seismic recording obtained during the field survey.

2.4.1 Equipment

Acquisition equipment for this phase of work was similar to that used in the initial survey in that they were commercially available, although not as commonly applied to engineering or groundwater studies as the equipment used in the initial survey. Components of the acquisition system were updated from that of the initial survey with equipment more suited to handling the higher data volume of this survey. Specifically, two recording instruments with 48 channel capacity were substituted for the single recorder of the previous survey. This was necessary to meet the subsurface coverage and offset requirements of this survey. Two CDP roll-along switches (devices enabling rapid advancement of the seismic survey line) and supporting cabling

equipment were significantly modified from the earlier survey to enable the simultaneous recording of three components into the two seismic recorders. Modifications to the equipment were done in-house at Apex Geophysical. The specific components of the acquisition system were:

- Recorders:
  - Two Bison 9048 digital instantaneous floating point signal enhancement seismographs
  - Channels: 96 total (48 each instrument)
  - Sampling intervals: 100, 200, 500, 1000, 2000, and 4000 microseconds
  - Record lengths (in samples): 500, 1000, 2000, 5000
  - Frequency response: 4-2,000 Hertz
  - Mass Memory: 18 megabytes nonvolatile memory

  Storage/Analysis device: Toshiba T-5200 (80386 based laptop), and Tandy 1000 TL3

- Geophones
  - Oyo Geospace two component horizontal 40 Hertz
  - Oyo Geospace one component vertical 100 Hertz

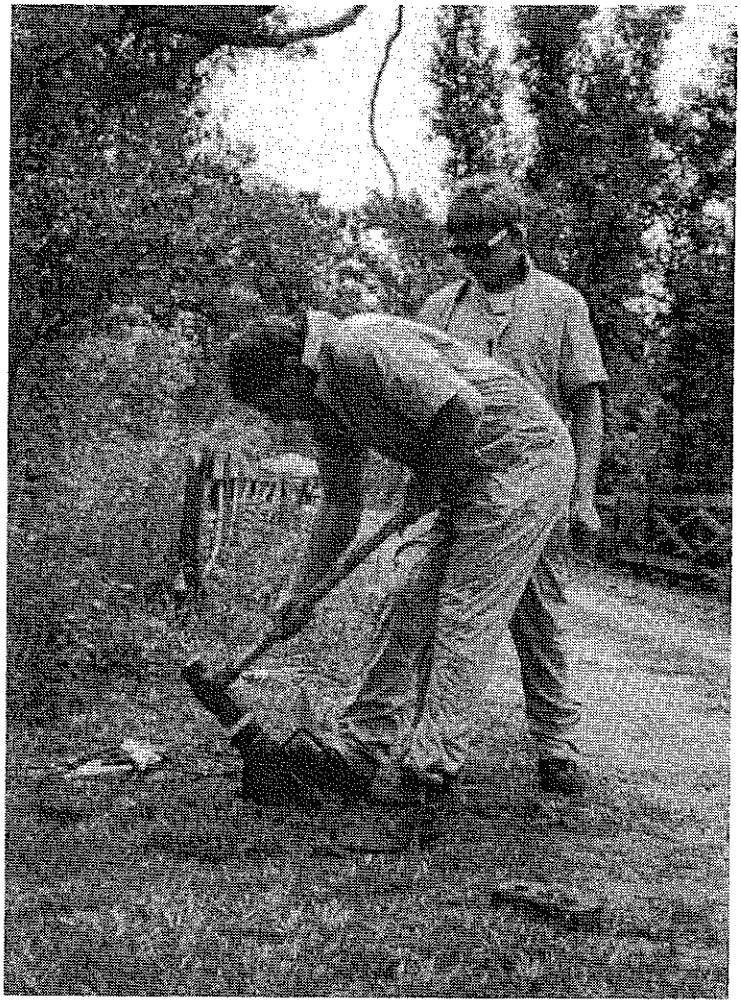


Figure 12 - Steel cylinder used as source (note it is mounted in a frame such that the impact is at a 45-degree angle to the ground surface to simultaneously generate both P- and S-waves).

- Recording Cables
  - Mark Products 52 pair cables; 24 geophone takeouts per cable; 13.5 feet between takeouts;

- CDP Roll-Along Switch
  - Two Input/Output RLS-240M Rotalong Switches

The source used was a 3½-inch diameter steel cylinder struck with a 16-pound sledgehammer, consistent with the results of the source testing conducted during the initial survey. A difference between using this source as part of the comprehensive versus the simplified survey was that the cylinders were mounted at a steeper angle to allow for the measurement of both P- and S-waves. Figures 12 and 13 illustrate the equipment used and the field setup.

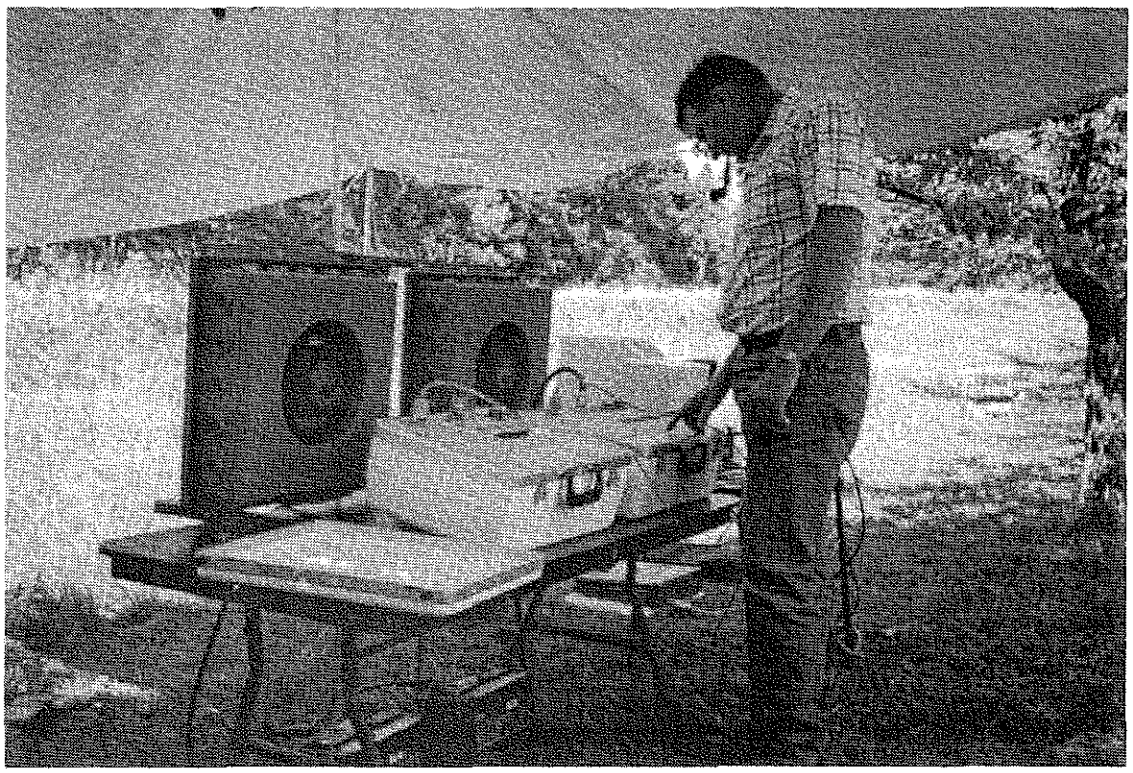


Figure 13 - Setup of recording equipment (two Bison 48-channel seismographs; two input/output Rotalong switches; and two computers).

2.4.2 Field Procedures

Data acquisition for this survey consisted of the simultaneous recording of a P-wave component and two S-wave components. The acquisition parameters were determined with the results of the preliminary survey conducted in May of 1991. The parameters were:

- Line length: 1462.5 feet (295 stations at an interval of 7.5 feet);
- Source Interval: 7.5 feet;
- Number of channels: 32 per component;

- Coverage: 32 fold;
- Recording Filters: 100 Hertz low cut, 1000 Hertz high cut (all components);
- Sample Interval: .25 ms.;
- Record Length: 0.5 seconds (all components);
- Source pattern: double off-end yielding an effective 64 channel split-spread record; and
- Number of sums into one production record: 8.

The survey design parameters included two "shooting" crews in order to meet the fold and offset parameters in a more efficient manner. In the field, these crews operated 49 stations apart (accounting for a spread length plus shot gap between them). The survey was started with the front crew walking the source point into the line. When they were advanced enough, the back crew began at the same starting point, and full fold acquisition commenced.

The sequence was as follows:

- Crew 1: P-motion; SH-motion perpendicular to line (left and right directions, yielding two records); SV-motion parallel to line (along a portion of the line) forward and backward directions, yielding two records.
- Crew 2: This crew would repeat the same sequence of records. In the time between the different source motions, the crew not currently recording would advance its position and equipment to the next source location.

The use of two source crews reduced acquisition down time, a potential problem in commercial applications of this technology.

Data recording proceeded as mentioned, until the memory capacity of the recording instruments was reached. At this point, a portable generator was started to power the computers used to download data from the recording instruments. Even at the highest transfer rate, this process typically took 50 minutes when the memory was full. During this time, assigned crew members disconnected geophones and rolled up cables, and transferred them to their next location at the

front of the line. Memory capacity limited progress to a maximum of 12 source point advances per crew between downloading of data. Somewhat slower progress was possible under full component acquisition.

The acquisition crew consisted nominally of four people, although more people were available at certain times. The additional personnel were utilized to relieve other members or to work ahead. Such predata acquisition site preparation work included but were not limited to preparing source point locations (by digging a small hole in which to set the steel cylinder), planting and orienting geophones, and laying out cable. These tasks were accomplished ahead of time when the activities were enough removed from current recordings so as not to affect data quality.

The recording instruments were initially operated by two observers. Once the field procedures were established, one person was able to efficiently operate both recorders. Under favorable conditions, a four man crew was able to make steady progress.

2.4.3 Data Processing

Data processing was conducted by Production Geophysical Service (PGS) in a manner nearly identical to the processing conducted for the initial survey, as outlined in Section 2.3.3.1. The only difference was applying a pre-stack filter to the P-wave data set.

Additional data processing, beyond that conducted for the initial survey, consisted of converting time sections to depth sections based on the results of downhole measurements. The preparation of depth sections is discussed with the interpretation provided in Section 3.1. Similarly, different attribute analyses were incorporated in the processing as an aid to interpretation and are also discussed in Section 3.1

2.5 DOWNHOLE SEISMIC MEASUREMENTS

The goal of the downhole seismic measurements was to obtain P- and S-wave velocity data which could be used to help correlate the P- and S-wave sections and the stratigraphy to each section. As such, the downhole measurements were not part of the field experiment, but a means to establish control to the interpretation of the reflection profiles. The survey was conducted in borehole RTB-1 between November 8 and 11, 1991. The following sections discuss the equipment used, field procedures followed, and the processing conducted on the seismic recordings obtained from the borehole.

2.5.1 Equipment

The equipment used for the survey was as follows:

Recorder: Oyo Geospace M^{C} Seis 160-MX configured for 3-channel recording.

Transducer: Oyo Borehole Pick, 3-component downhole geophone.

The source used was the same as that used for the reflection surveying, a 3½-inch diameter steel cylinder used either in a vertical position or in a near horizontal position.

2.5.2 Field Procedures

Recordings of seismic wave arrivals were made at different depths of borehole RTB-1 by striking the steel cylinder at the surface and recording the wave arrivals with the downhole 3-component geophone (one vertical, two horizontal components) pushed against the borehole wall. Data were acquired at five-foot intervals from a depth of 10 feet to 140 feet and ten-foot intervals from 140 feet to 250 feet. Five records were made at each recording level:

- Orientation of source horizontal and perpendicular to line between source and borehole - positive polarity;
- Orientation of source horizontal and perpendicular to line between source and borehole - negative polarity;
- Orientation of source horizontal and parallel to line between source and borehole - positive polarity;
- Orientation of source horizontal and parallel to line between source and borehole - negative polarity; and
- Orientation of source vertical.

Initially a severe tube wave (a wave that travels the inside casing) was observed at all levels in the borehole. The amplitude of this wave was such that the S-wave arrivals were completely obscured. A solution to this problem was found by bailing the water out of the hole. Paper copies of each record were obtained in the field to make sure that good P- and S-wave arrivals were being recorded. If wave arrivals were not clear, the measurement was repeated until clear data were obtained.

2.5.3 Data Processing

The processing of the data was achieved by simply observing the waveforms and visually identifying P- and S-wave arrivals. S-wave arrivals were picked by overlaying the "positive" and "negative" records. The onset of the S-wave was identified as the time where the polarity of the waveforms reversed. The arrival times were noted and then corrected to account for the offset of the source from the borehole. The corrected times represent the amount of time that P- and S-waves would take if their raypath had been vertical. The wave arrivals at the measurement depths are provided in Table 1.

2.6 IN-HOLE SEISMIC MEASUREMENTS

P- and S-wave velocities were measured using an Oyo PS Suspension Logging System from control Borehole RTB-1 between January 13 and 14, 1992. The purpose of these measurements was to identify P- and S-wave velocity contrasts associated with layers which might be too thin to be characterized by the downhole measurements discussed in Section 2.5. Whereas the downhole velocity measurements optimize the determination of average velocities, the in-hole measurements optimize the identification of velocity contrast between individual sedimentary layers This information allows for the development of synthetic P- and S-wave seismograms that can then be compared with actual reflections on the seismic sections, in turn allowing for a correlation of reflection on the seismic sections, in turn allowing for a correlation of reflections to specific sedimentary horizons. These measurements were not part of the scope of work for this contract, but were made to allow for an independent confirmation of the correlation of the P- and S-wave sections. As further discussed in Section 3.1.3, these measurements are considered preferable to the down-hole measurements as a means to correlate the P- and S-wave reflections.

2.6.1 Equipment

The equipment used for the in-hole seismic measurements was the Oyo PS Suspension Logging System. This system consisted of a pair of three component transducers which are separated by a distance of one meter in the borehole. An impulsive source is at one end of the sonde and is separated from the nearest transducer by a distance of two meters. The source is polarized in that each measurement consist of an impulse in the "positive" direction and an impulse in the "negative" direction. Shear wave velocities are measured through the movement of the lower portion of the tool which generates shear waves (where the wave length is much greater than the diameter of the

TABLE 1
DOWNHOLE TRAVELTIME MEASUREMENTS

	SHEAR WAVE		COMPRESSIONAL WAVE	
DEPTH (ft)	AVERAGE VELOCITY-V_s (ft/ms)	CORRECTED TWO WAY TRAVEL TIME (ms)	AVERAGE VELOCITY-V_p (ft/ms)	CORRECTED TWO WAY TRAVEL TIME (ms)
10	0.5955	33.6	2.1757	9.2
15	0.6934	43.3	2.5754	11.6
20	0.7764	51.5	2.7951	14.3
25	0.8038	62.2	3.1677	15.8
30	0.9583	62.6	3.3287	18.0
35	1.0628	65.9	3.6401	19.2
40	1.1769	68.0	4.0656	19.7
45	1.2311	73.1	4.2821	21.0
50	1.2822	78.0	4.2072	23.8
55	1.3377	82.2	4.4003	25.0
60	1.4277	84.1	4.5175	26.6
65	1.4317	90.8	4.6107	28.2
70	1.3867	101.0	4.6077	30.4
75	1.4856	101.0	4.6341	32.4
80	1.4554	109.9	4.5959	34.8
85	1.5194	111.9	4.6544	36.5
90	1.5148	118.8	4.7336	38.0
95	1.5340	123.9	4.7643	39.9
100	1.5932	125.5	4.8712	41.1
105	------	------	------	41.7
110	1.5922	138.2	5.0189	43.8
115	------	------	------	45.4
120	1.6556	145.0	5.1653	46.5
125	------	------	------	48.6
130	1.7042	152.6	5.0235	51.8
135	------	------	------	53.2
140	1.6928	165.4	5.1539	54.3
150	1.6788	178.7	5.1343	58.4
160	1.6885	189.5	5.2495	61.0
170	1.7100	198.8	5.3078	64.1
180	1.7547	205.2	5.3151	67.7
190	1.7806	213.4	5.4117	70.2
200	1.8000	222.2	5.4144	73.9
210	1.8314	229.3	5.4589	76.9
220	1.8148	242.5	5.5004	80.0
230	1.8762	245.2	5.5657	82.6
240	------	------	------	86.3
250	1.9344	258.5	5.6411	88.6

borehole). The wave forms at each of the transducers are digitized and recorded on 3.5 inch floppy diskettes. The time required for a P- or S-wave to travel the one meter between the two transistors yields the propagation velocity.

2.6.2 Field Procedures

Field procedures for the in-hole measurements consisted of lowering the sonde into the hole and taking measurement every half meter (Figure 14). The measurement process consisted of simply recording the wave form from the "plus" direction and the wave recorded before moving on to the next downhole position. It should be noted that these measurement need to be conducted in a fluid filled borehole.

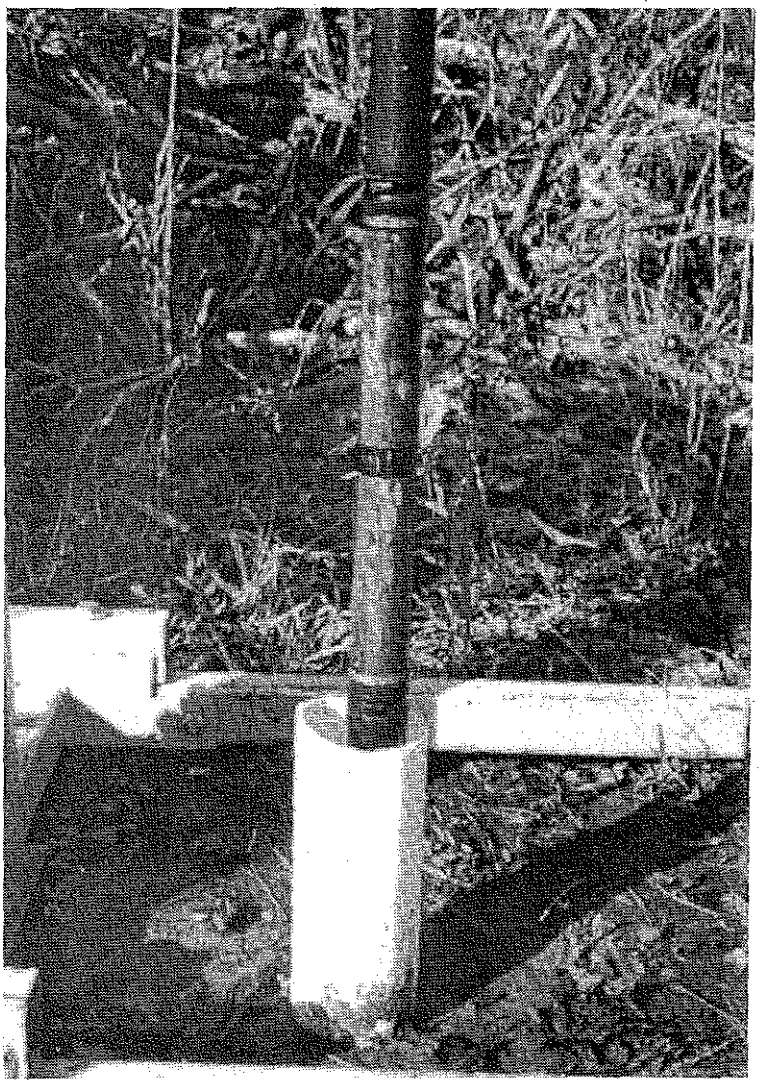


Figure 14 - Oyo PS Suspension Logging System in position to be lowered down Borehole RTB-1.

2.6.3 Data Processing

The processing of the data was performed using a program called PSLOG proprietary to Oyo Geospace. With this program velocities are calculated by picking the arrivals of the S- and P-waves at each of the transducers and dividing the time difference by the distance between the transducers. Using this program it is not necessary to identify the actual onset of the P- and S-waves but rather to identify a portion of the wave which is identical at the respective transducers. The software allows the user to display all three components from each transducer in the computer screen simultaneously and to identify the significant portion of the P- and S-waves and mark them on each component. The program then displays the velocities calculated from the passage of the energy passed to the transducers. The results of the in-hole measurements are presented on Figure 15.

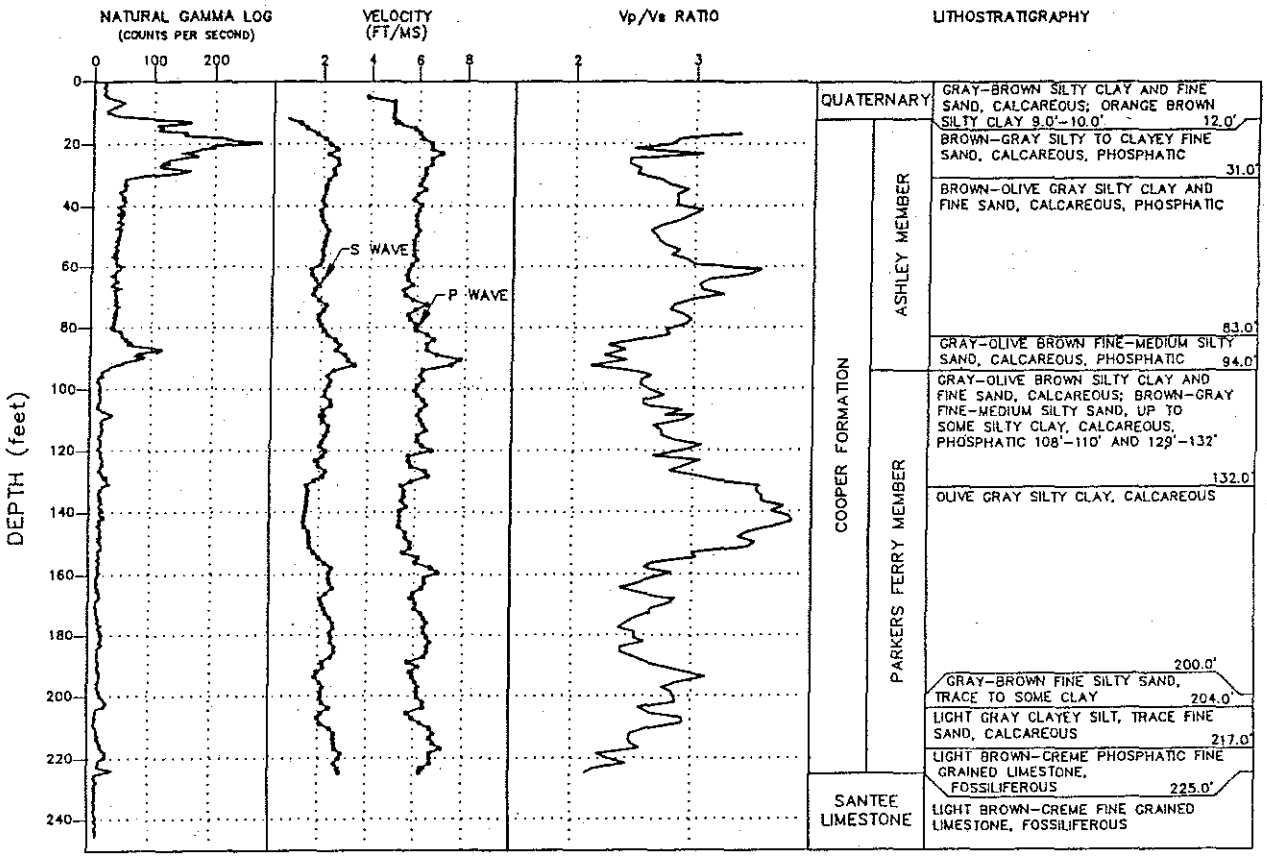


Figure 15 - Geophysical logs and lithostratigraphy at Borehole RTB-1.

2.7 QUALITY ASSURANCE

The Quality Assurance program for the project was conducted in a manner consistent with the program described in the project contract documents. The theoretical background for the research was subjected to a peer review prior to the preparation of the April 1991 report "The High Resolution Shear Wave Seismic Reflection Technique," (Johnson and Clark, 1991) which incorporated the peer review comments. The field program was implemented using of quality control procedures and checks so that technically accurate data were obtained and that they were properly interpreted.

During the data acquisition phase, the most critical aspect of quality control was to verify equipment performance. Specifically, tests were conducted to verify that the "zero" time for the trigger was the same as the "zero" time for the recorder. The changing of scales was assessed to determine that waveforms were amplified or deamplified consistent with the scale settings.

Geophones were assessed by means of "tap" tests where a sharp blow was applied to each geophone and the amplitude and polarity of each output was assessed for consistency with the others. During the survey, an Observer's Log was maintained such that the significant aspects of each measurement and the overall operations were documented.

The data processing involved the use of industry standard programs which are proprietary to Production Geophysical Services, Inc. so that proper procedures were followed using the proprietary software, a Rizzo Associates representative was present to monitor the processing sequence. One of the most fundamental tests of good processing is repeatability. The final processed seismic profiles from the comprehensive survey were found to closely match the results from the simplified survey, indicating that the processing has produced consistent results that represent actual subsurface conditions.

The research has produced relatively few calculations. The most significant calculation has been related to picking wave arrivals from the downhole survey. Arrival times were independently checked and calculation(s) are maintained in our project files, consistent with our corporate Quality Management policies. This report has been audited by our Quality Assurance staff.

3.0 RESULTS AND DISCUSSION

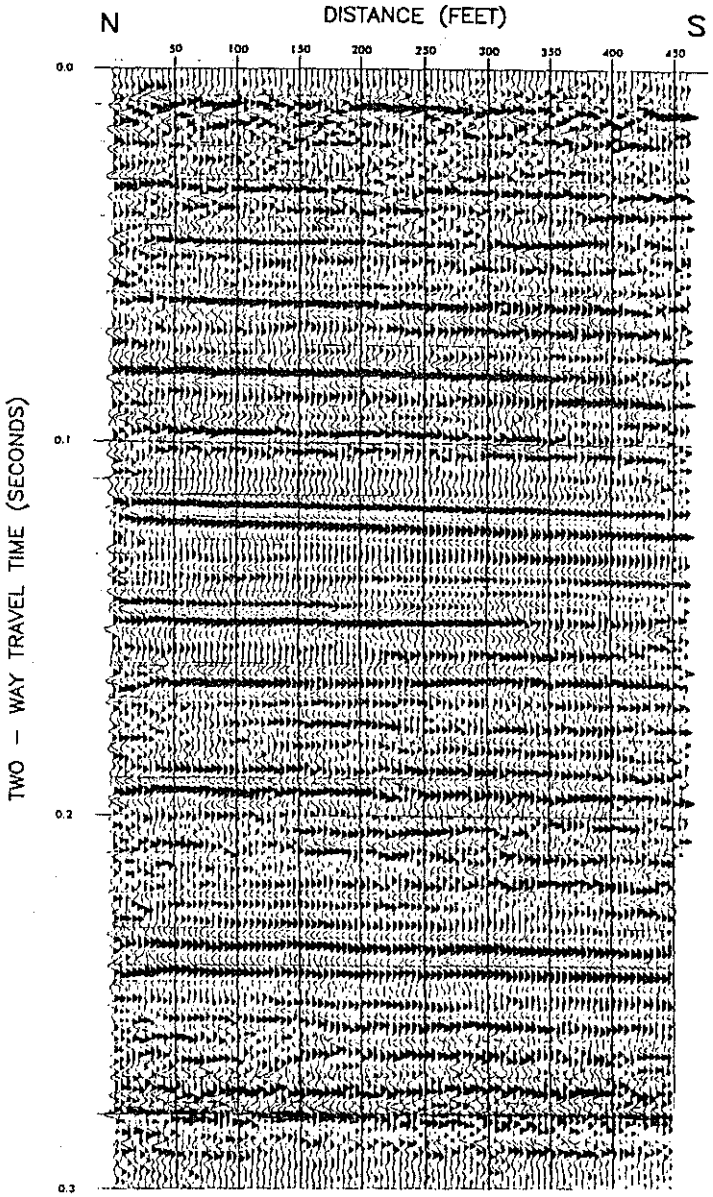
The results of this survey can be defined in terms of the quality of the P- and S-wave profiles obtained over the initial and comprehensive survey test lines. The conclusions of the study relate to the ability of the high resolution S-wave reflection technique to assess subsurface hydrogeology, and the field and processing procedures necessary to optimize the results. The following sections discuss these topics separately, as well as the lessons learned.

3.1 GEOPHYSICAL INTERPRETATION

3.1.1 High Resolution Seismic Reflection Profiles

The results of the survey from a technical standpoint can be summarized in terms of the processed seismic sections produced from the test lines. The final profiles from the initial test line prepared by Production Geophysical Services (PGS) for the P-wave and S-wave are presented on Figures 16 and 17, respectively. A result of the survey in terms of a short S-wave profile from the initial test line using a one-inch pipe with a base plate as a source and using a 2.5-foot geophone spacing is provided on Figure 18. An example of the results of simplified processing using the P-wave data from the initial survey is presented on Figure 19. The profiles obtained from the comprehensive survey for the P- and S-waves are provided on Figures 20 and 21, respectively.

The overall quality of the test profiles processed by PGS are excellent, except that the experiment using the one-inch diameter steel pipe with a base plate and a 2.5-foot geophone spacing was not successful, as seen by the poor quality of the profile shown on Figure 18. An evaluation of the problems associated with this attempt at an extremely high resolution survey are discussed in Section 3.1.5. The high quality of the results shown on Figures 16, 17, 20, and 21 is self evident. The quality of the initial test results on Figures 16 and 17 persists in spite of the loss of a large percentage of the records for both profiles during the process of downloading the data from the Bison recorder to the computer. A data "bust" present between Stations 125 and 175 on the S-wave profile (Figure 17) is due to the loss of data during the downloading process, but even this concentrated data loss does not seriously impede the data presentation.



ACQUISITION:

SOURCE	16 LB HAMMER	GEOPHONES	OYO 40 HZ
SP ARRAY	10 FT	SPREAD	SPLIT 5-115 FT
SP EFFORT	10 POPS	TRACES/RECORD	24
GROUP INTERVAL	10 FT	SAMPLE RATE	.5 MS
SP INTERVAL	10 FT	FIELD FILTER	64/12-500/72
FOLD	1200%	NOTCH	OUT
RECORD LENGTH	500 MS		
INSTRUMENT	BISON 9024		

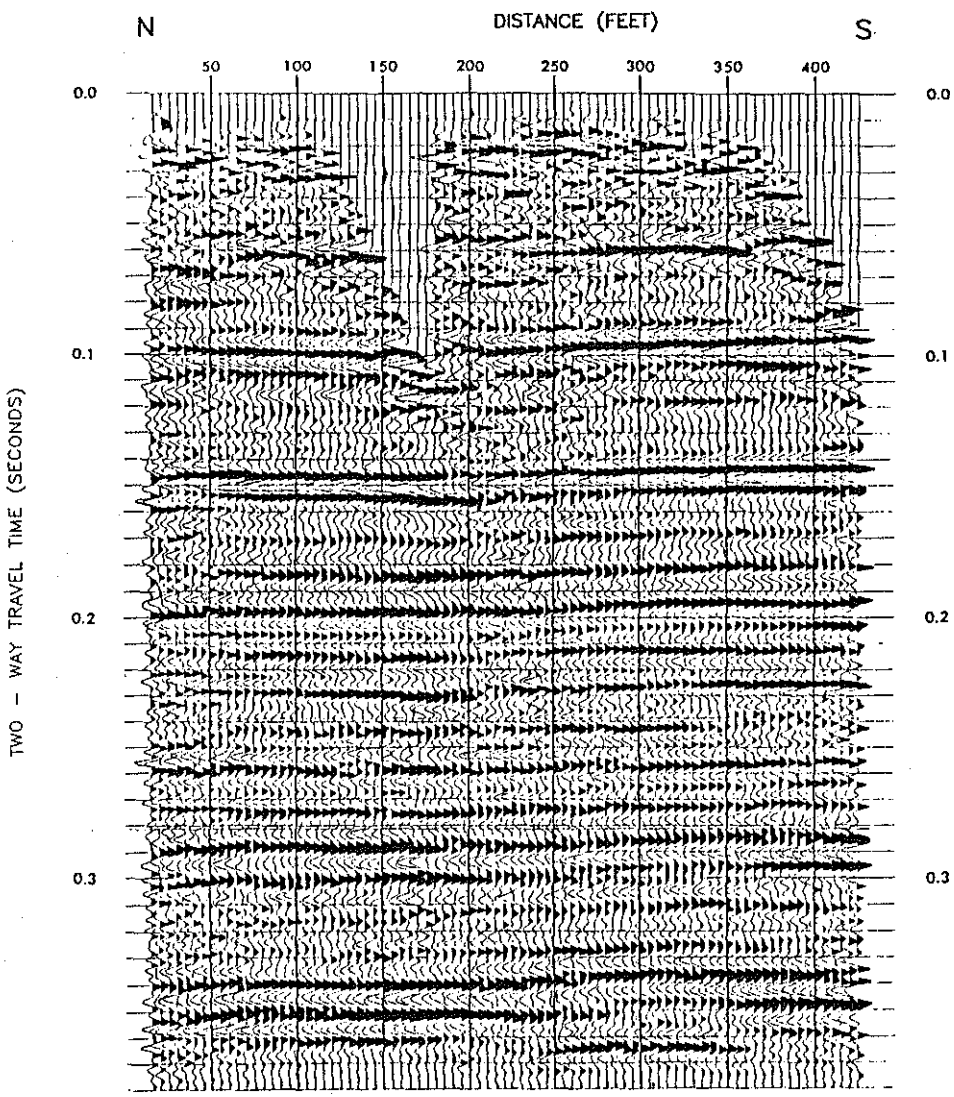
PROCESSING:

REFORMAT
  BISON TO HOUSE SEGY
  TRACE EDIT
SPHERICAL DIVERGENCE CORRECTION
  AREA VELOCITY FUNCTION
REFRACTION STATICS ANALYSIS
  PROCESSING DATUM 35 FT
SURFACE CONSISTENT DECONVOLUTION
  SHOT/RECEIVER/OFFSET 30 MS OPR
ZERO PHASE WHITENING
  40-400 HZ
GEOMETRY STATICS UPDATE
  DATUM + WEATHERING STATICS APPLICATION
VELOCITY ANALYSIS -
  2 PASSES CV STACKS
SURFACE CONSISTENT STATICS
  1 PASS WINDOW 20-260 MS
CDP CONSISTENT STATICS
  WINDOW 20-300 MS 1 MS MAXSTATIC
STACK
  ROOTN COMPENSATION
PHASE COMPENSATION
  GEOPHONE DECON INSTRUMENT
POST STACK ENHANCEMENT
  FX DECON 5 TRC PREDICTION FILTER
POST STACK BANDPASS FILTER
  128/72-400/120 HZ/DB 0-.3 SEC
SCALE
  TRACE AMPLITUDE BALANCE 25 MS

NOTE:

FOR LOCATION OF LINE SEE FIGURE 4.

Figure 16 - Final P-wave section, initial survey line.



ACQUISITION:

SOURCE	16 LB HAMMER	GEOPHONES	OYO 28 HZ
SP ARRAY	AT STATION	SPREAD	OFFEND 0-230 FT
SP EFFORT	16 POPS L/R	TRACES/RECORD	24
GROUP INTERVAL	10 FT	SAMPLE RATE	.2 MS
SP INTERVAL	10 FT	FIELD FILTER	128/12-500/72
FOLD	1200%	NOTCH	OUT
RECORD LENGTH	400 MS		
INSTRUMENT	BISON 9024		

PROCESSING:

REFORMAT
- BISON TO HOUSE SEGY
- TRACE EDIT

SOURCE VECTOR CONSISTENT SCALING

COMPONENT SUMMATION
- LEFT + RIGHT SOURCES

SPHERICAL DIVERGENCE CORRECTION
- AREA VELOCITY FUNCTION

REFRACTION STATICS ANALYSIS
- PROCESSING DATUM 50 FT

SURFACE CONSISTENT DECONVOLUTION
- SHOT/RECEIVER/OFFSET 60 MS OPR

ZERO PHASE WHITENING
- 30-300 HZ

GEOMETRY STATICS UPDATE
- DATUM + WEATHERING STATICS APPLICATION

FK FILTER
- REJECT 7-9-15-25 MS/TR

VELOCITY ANALYSIS
- 3 PASSES CV STACKS

SURFACE CONSISTENT STATICS
- 2 PASSES WINDOW 50-350 MS

CDP CONSISTENT STATICS
- WINDOW 30-350 MS 3 MS MAXSTATIC

STACK
- ROOTN COMPENSATION

PHASE COMPENSATION
- GEOPHONE,DECON,INSTRUMENT

POST STACK ENHANCEMENT
- FX DECON 5 TRC PREDICTION FILTER

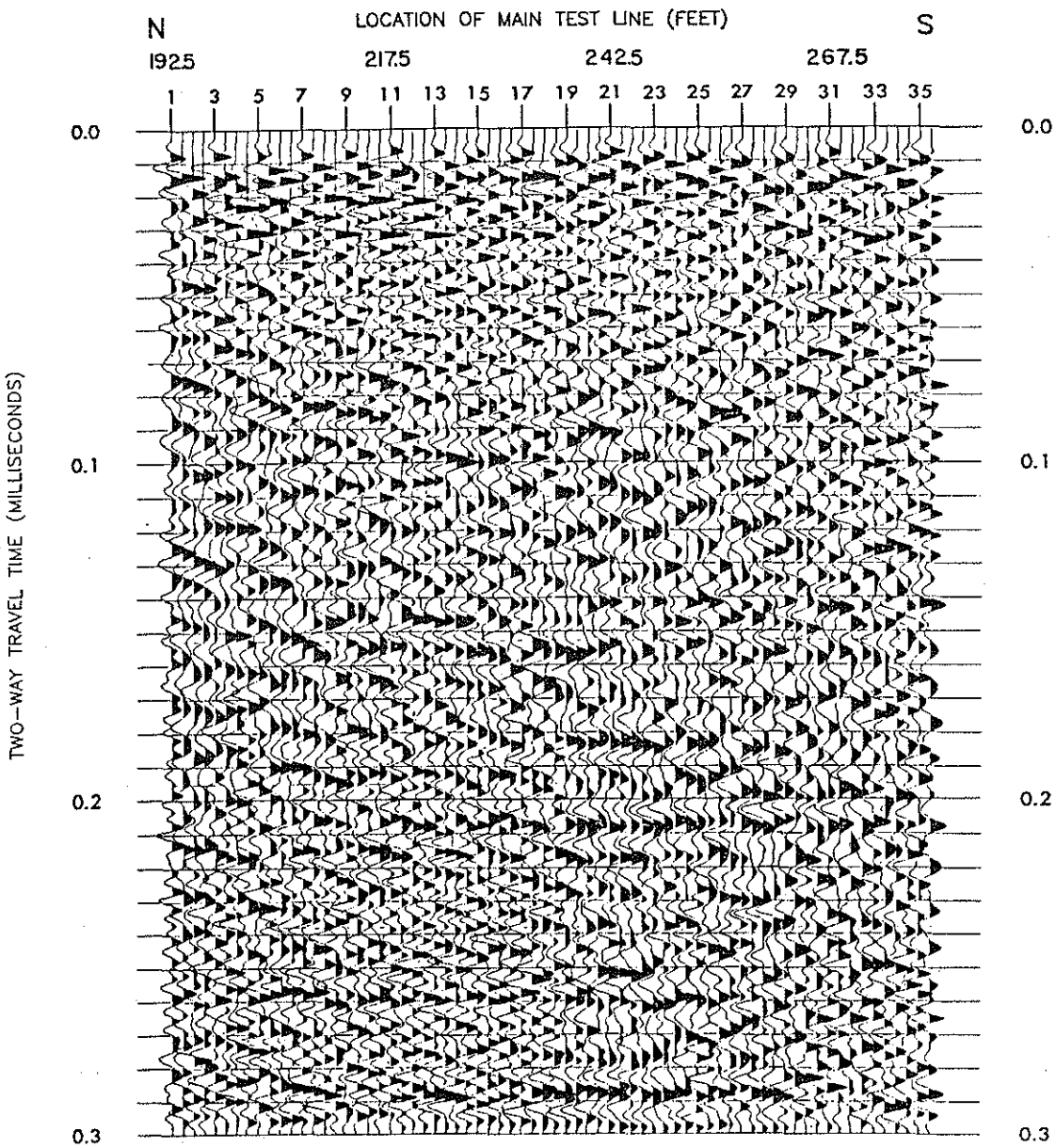
POST STACK BANDPASS FILTER
- 40/72-300/120 HZ/DB 0-.4 SEC

SCALE
- TRACE AMPLITUDE BALANCE 50 MS

NOTE:

FOR LOCATION OF LINE SEE FIGURE 4.

Figure 17 - Final S-wave section, initial survey line.



ACQUISITION:

SOURCE	LB BP HAMMER	GEOPHONES	OYO 28 HZ
SP ARRAY	AT STATION	SPREAD	OFFEND 0-57.5 FT
SP EFFORT	8 POPS L/R	TRACES/RECORD	24
GROUP INTERVAL	2.5 FT	SAMPLE RATE	.2 MS
SP INTERVAL	5 FT	FIELD FILTER	128/12-500/72
FOLD	1200%	NOTCH	OUT
RECORD LENGTH	200 MS		
INSTRUMENT	BISON 9024		

PROCESSING:

REFORMAT
- BISON TO HOUSE SEGY
- TRACE EDIT

SOURCE VECTOR CONSISTENT SCALING

COMPONENT SUMMATION
- LEFT + RIGHT SOURCES

SPHERICAL DIVERGENCE CORRECTION
- AREA VELOCITY FUNCTION

SURFACE CONSISTENT DECONVOLUTION
- SHOT/RECEIVER/OFFSET 60 MS OPR

ZERO PHASE WHITENING
- 30-300 HZ.

GEOMETRY STATICS UPDATE
- DATUM STATICS APPLICATION

FK FILTER
- REJECT 5-7-15-25 MS/TR

VELOCITY ANALYSIS
- VELOCITY FROM SSSH

STACK
- ROOTN COMPENSATION

POST STACK BANDPASS FILTER
- 30/72-300/120 HZ/DB 0-.4 SEC

SCALE
- TRACE AMPLITUDE BALANCE 50 MS

NOTE:

FOR LOCATION OF LINE SEE FIGURE 4.

Figure 18 - Final S-wave section, portion of initial survey line (one-inch pipe with base plate as a source; 2.5-foot geophone spacing).

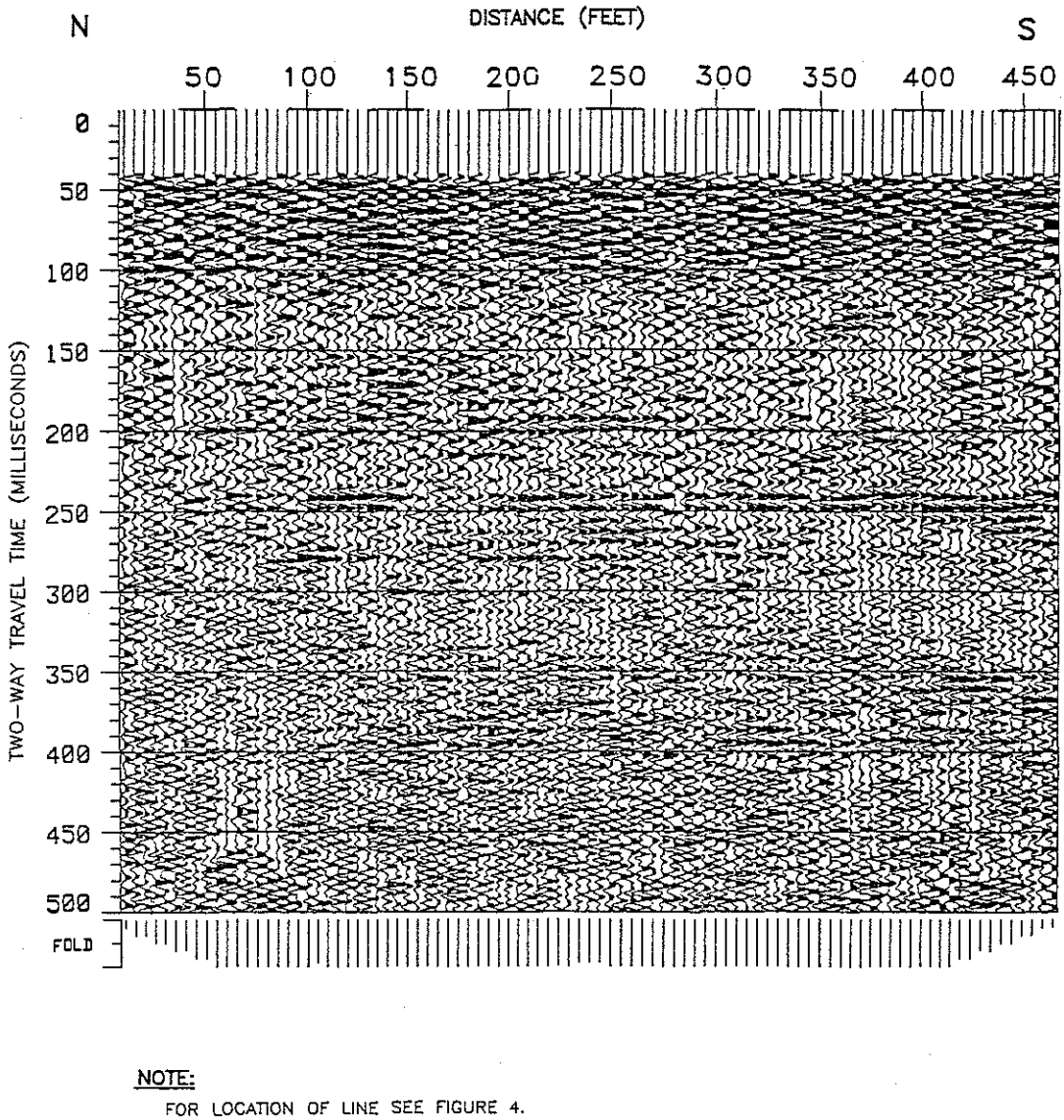
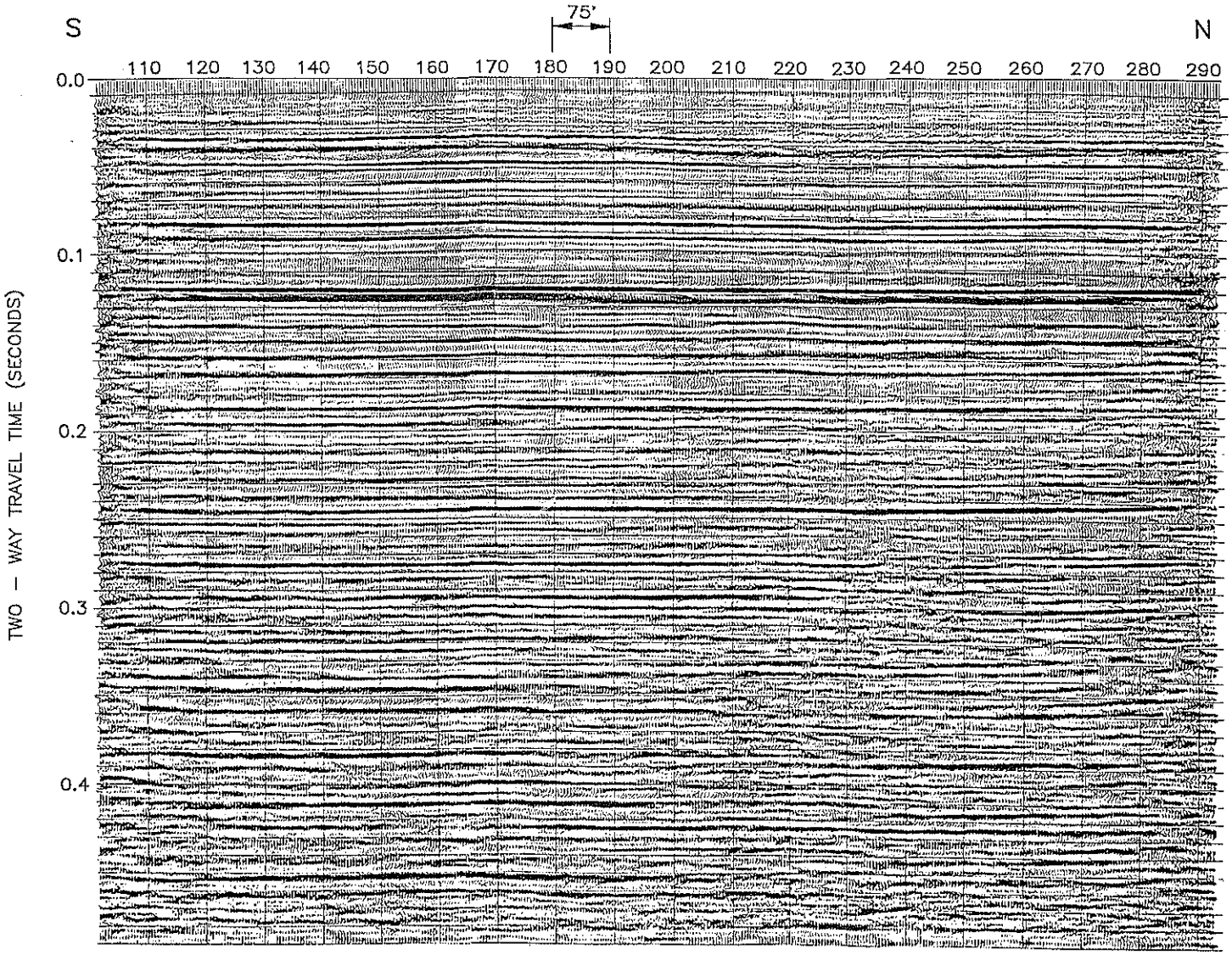


Figure 19 - Results of P-wave profile of initial survey line using simplified PC-based processing

As previously discussed in Section 2.4, the main differences between the initial and comprehensive surveys were that in the comprehensive survey P- and S-wave data were recorded simultaneously and that a line-transverse (SH) source could be compared to a line-parallel (SV) source. The generation of SV waves and recording them with a line-parallel geophone component did not yield good results. The SV profile is not reproduced as a report figure. It is sufficient to note that the SV results appear similar to the profile on Figure 18.



Acquisition:

SOURCE	16 LB HAMMER	GEOPHONES	OYO 100'HZ
SP ARRAY	7.5 FT	SPREAD SPLIT	7.5-158 FT
SP EFFORT	10 POPS	TRACES/RECORD	64
GROUP INTERVAL	7.5 FT	SAMPLE RATE	.25 MS
SP INTERVAL	7.5 FT	FIELD FILTER	100/12-1000/72
FOLD	3200%	NOTCH	OUT
RECORD LENGTH	490 MS		
INSTRUMENT	BISON 9048		

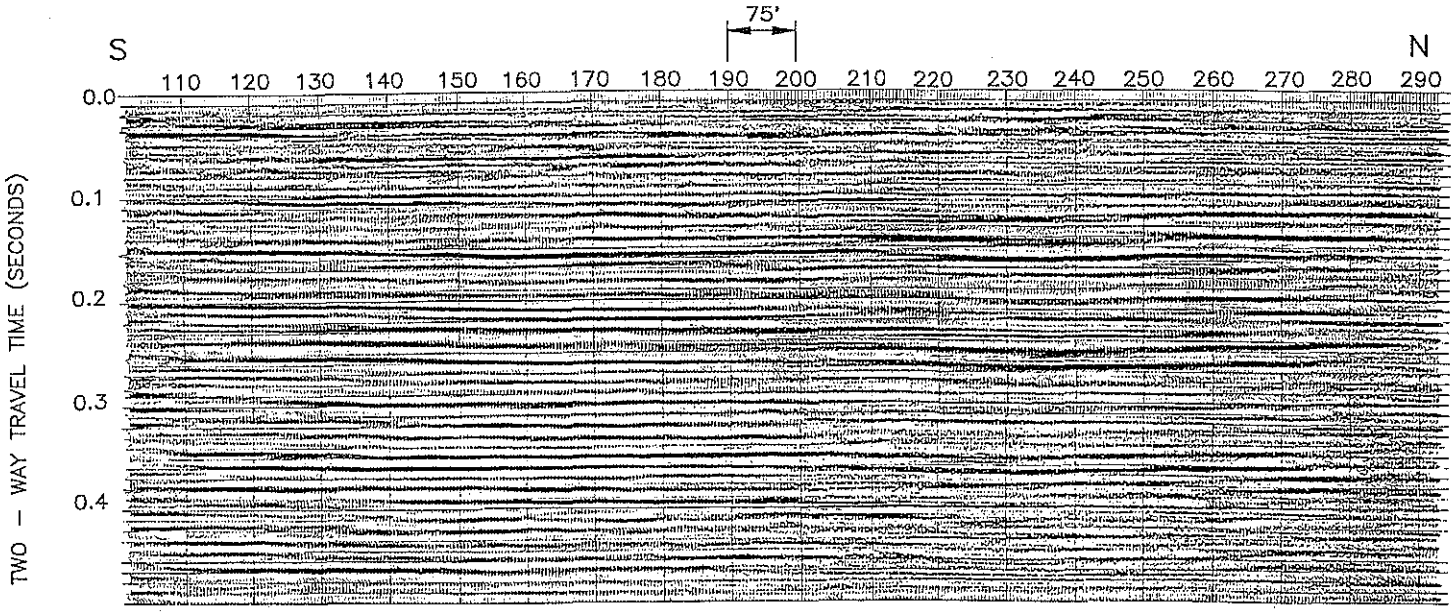
Processing :

REFORMAT
  BISON TO HOUSE SEGY
  TRACE EDIT
SPHERICAL DIVERGENCE CORRECTION
  AREA VELOCITY FUNCTION
REFRACTION STATICS ANALYSIS
  PROCESSING DATUM 60 FT
SURFACE CONSISTENT DECONVOLUTION
  SHOT/RECEIVER/OFFSET 30 MS OPR
ZERO PHASE WHITENING
  40-500 HZ
GEOMETRY STATICS UPDATE
  DATUM + WEATHERING STATICS APPLICATION
FK FILTER
  REJECT 6-7-20-30 MS/TR
VELOCITY ANALYSIS
  2 PASSES CV STACKS
SURFACE CONSISTENT STATICS
  1 PASS WINDOW 30-460 MS
CDP CONSISTENT STATICS
  WINDOW 30-400 MS 4 MS MAXSTATIC
STACK
  ROOTN COMPENSATION
PHASE COMPENSATION
  GEOPHONE,DECON,INSTRUMENT
POST STACK ENHANCEMENT
  FX DECON 7 TRC PREDICTION FILTER
POST STACK BANDPASS FILTER
  128/72-400/120 HZ/DB 0-.3 SEC
SCALE
  TRACE AMPLITUDE BALANCE 50 MS

NOTE: FOR LOCATION OF LINE SEE FIGURE 4.

FIGURE 20

FINAL P–WAVE SECTION,
COMPREHENSIVE SURVEY LINE



Acquisition:

SOURCE	16 LB HAMMER	GEOPHONES	OYO 40 HZ
SP ARRAY	7.5 FT	SPREAD	SPLIT 7.5-158 FT
SP EFFORT	10 POPS	TRACES/RECORD	64
GROUP INTERVAL	7.5 FT	SAMPLE RATE	.25 MS
SP INTERVAL	7.5 FT	FIELD FILTER	100/12-1000/72
FOLD	3200%	NOTCH	OUT
RECORD LENGTH	490 MS		
INSTRUMENT	BISON 9048		

Processing :

REFORMAT
- BISON TO HOUSE SEGY
- TRACE EDIT

SPHERICAL DIVERGENCE CORRECTION
- AREA VELOCITY FUNCTION

REFRACTION STATICS ANALYSIS
- PROCESSING DATUM 60 FT

SURFACE CONSISTENT DECONVOLUTION
- SHOT/RECEIVER/OFFSET 60 MS OPR

ZERO PHASE WHITENING
- 30-350 HZ

GEOMETRY STATICS UPDATE
- DATUM + WEATHERING STATICS APPLICATION

FK FILTER
- REJECT 7-9-20-30 MS/TR

VELOCITY ANALYSIS
- 3 PASSES CV STACKS

SURFACE CONSISTENT STATICS
- 2 PASS WINDOW 30-460 MS

CDP CONSISTENT STATICS
- WINDOW 30-230 MS 15 MS MAXSTATIC
- WINDOW 240-480 MS 15 MS MAXSTATIC

STACK
- ROOTN COMPENSATION

PHASE COMPENSATION
- GEOPHONE,DECON,INSTRUMENT

POST STACK ENHANCEMENT
- FX DECON 7 TRC PREDICTION FILTER

POST STACK BANDPASS FILTER
- 30/72-300/120 HZ/DB 0-.3 SEC

SCALE
- TRACE AMPLITUDE BALANCE 150 MS

NOTE: FOR LOCATION OF LINE SEE FIGURE 4.

FIGURE 21

FINAL S–WAVE SECTION,
COMPREHENSIVE SURVEY LINE

3.1.2 Resolution

As spectral analysis of the P- and S-wave recordings indicates that the S-wave reflections had a frequency content ranging between about 40 and 300 Hertz with a predominant frequency of about 100 Hertz. the P-waves from the same location had a higher frequency content, ranging between about 60 and 500 Hertz with a predominant frequency of about 180 Hertz. The amplitude spectra from typical P- and S-wave recording at a single geophone location are provided on Figure 22.

The P-wave velocity was typically found to be in the range of 5,000 to 7,000 ft/s whereas the S-waves velocity ranged between about 1,000 to 3,000 ft/s (Figure 2-18). The average V_s/V_pratio was 0.37 ($V_p/V_s = 2.67$) in the Cooper Formation, although significant variation was measured (Figure 15).

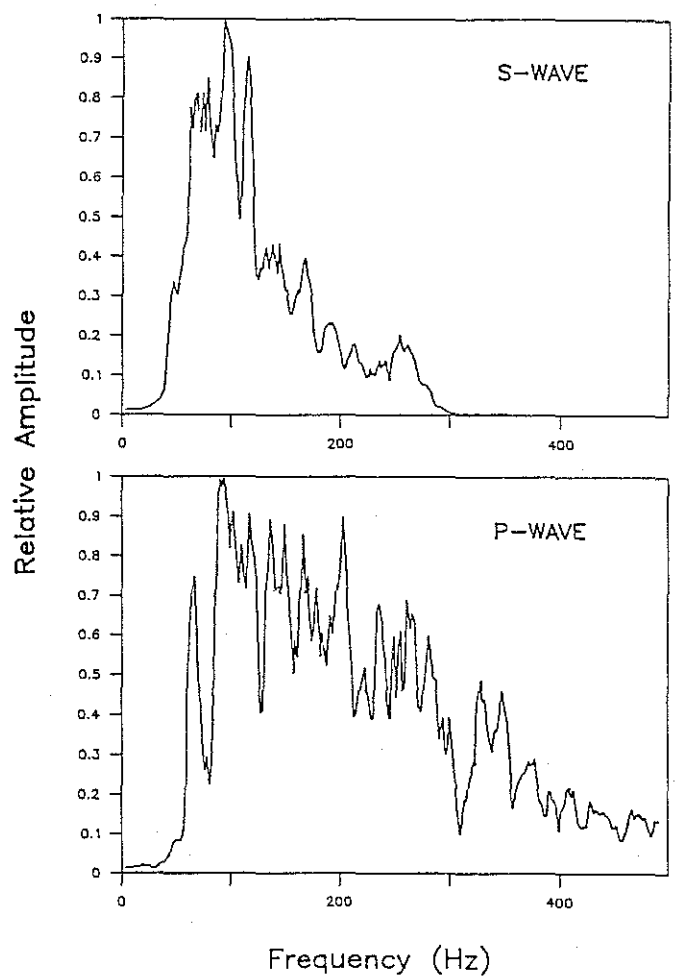


Figure 22 - Amplitude spectra of P- and S-wave reflection signals.

The resolution achieved with the P- and S-waves is depicted on Figure 23 in terms of minimum resolvable bed thickness. In consideration of the overall frequency content and wave velocity, the S-waves could resolve beds thinner than about three feet. A bed thickness of one to three feet was considered to be the targeted resolution of the survey, as beds as thin can control ground waste flow and are as thin as would normally be logged from a borehole. This resolution would not have been readily achievable using P-waves and similar recording parameters. In general, the S-waves allowed for close to triple the resolution obtained from the P-waves.

3.1.3 Correlation of P- and S-wave Reflections

One of the most difficult aspects of interpreting the combined P- and S-wave reflection data proved to be the correlation of specific reflections from one wave type to the other. As seen from the initial data results indicated on Figures 16 and 17 and the comprehensive survey profiles on Figures 20 and 21, many more reflections can be observed from the S-wave data. It therefore becomes problematic to correlate a specific S-wave reflection to a specific P-wave reflection, although such a correlation is essential if the data are to be used for a sophisticated interpretation, such as to derive the presence of groundwater and/or lithology.

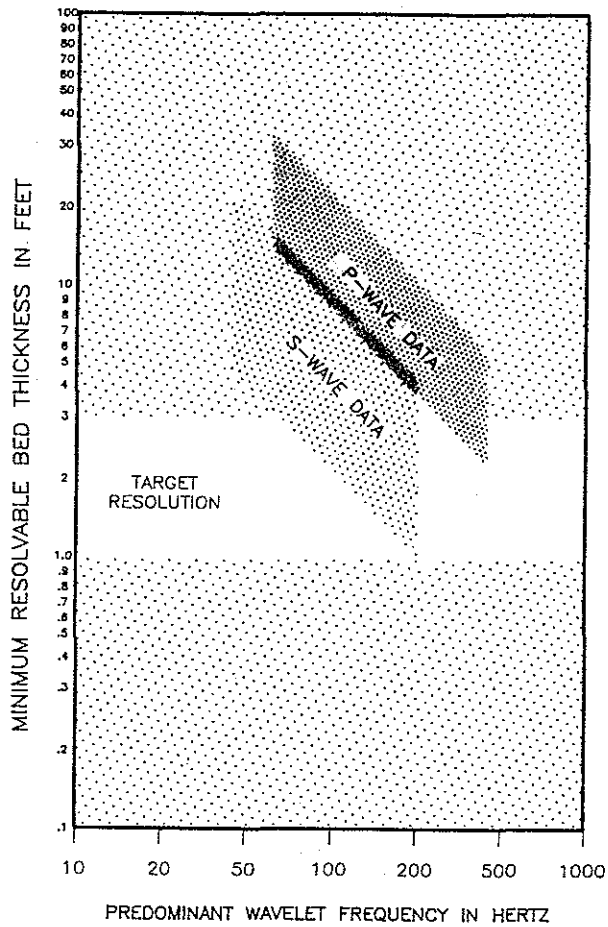


Figure 23 - Comparison of P- and S-wave signals in terms of resolution achieved from the field experiments.

The initial P- and S-wave sections were correlated without borehole control from RMS velocity derived during the data processing. The sections from the comprehensive survey were correlated on the basis of using the downhole velocity data to derive depth sections. The independent correlation from the two data sets proved to be consistent with one another, but it was not until in-hole measurements were made that these interpretations could be confidently verified. The following paragraphs review the overall process of correlating the P- and S-wave reflections.

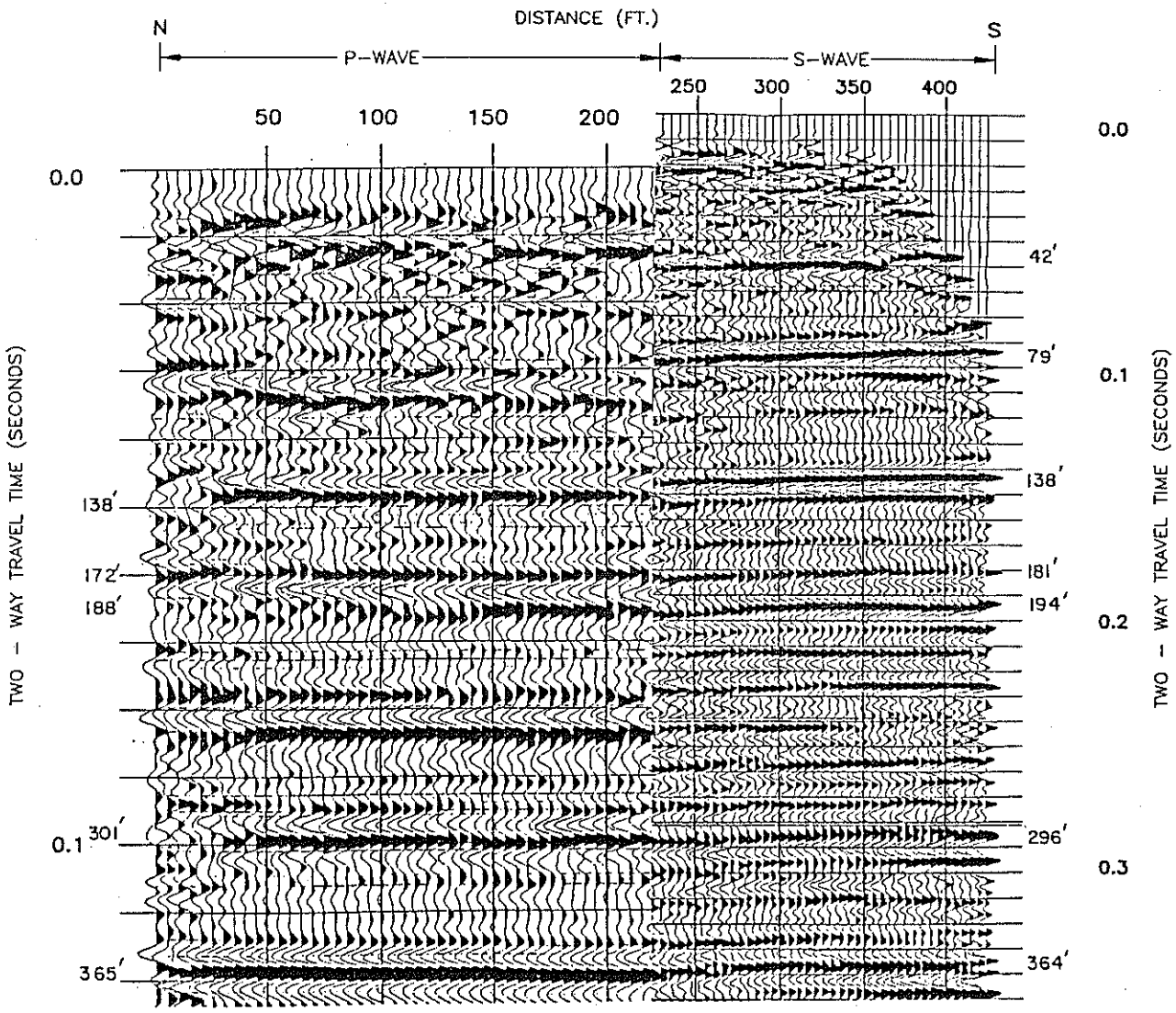
The P- and S-wave reflection profiles from the initial survey were correlated by reducing the scale of the S-wave section consistent with a ratio of the P-wave to S-wave velocity (V_p/V_s ratio) of 2.67 based on rms velocities and then matching reflections. By starting with the deeper

reflections where the V_p/V_s ratio is fairly constant, a good match of P- to S-wave reflectors was established, as shown on Figure 24. This procedure of correlating P- and S-wave reflections by matching deep reflections and moving up the section is described by Tatham and McCormack (1991). On Figure 24, the zero time line on the S-wave section is higher than that of the P-wave section. This is because the V_p/V_s ratio increases to as high as 3.5 in the surficial sediments, which is not accounted for by reducing the S-wave section by a constant factor. This discrepancy is accounted for by converting the time sections to depth sections.

The downhole travel time data provided in Table 1 were used to convert the time sections from the comprehensive survey into depth sections, but the actual correlation still proved challenging. Part of the problem of correlating the P- and S-wave sections stems from the extremely high resolution of the S-waves. There are simply so many S-wave reflections that it is difficult to judge the best means to relate them to the P-wave reflections. In an attempt to compare "apples to apples," a low pass filter was applied to the S-wave data to eliminate the minor reflections observed only at the highest frequency. This filtered S-wave depth section is compared to the P-wave depth section on Figure 25. The filtering of the S-wave section reduces the S-wave resolution by making the S-wave data appear to be similar to the P-wave data. In other words, it was easier to match the P- and S-wave reflections after the S-wave data were filtered.

The calculation of depth sections from the downhole velocity data essentially confirms the matching of reflections from the initial survey data made on Figure 24. In establishing the P- to S-wave correlation, as provided on Figure 25, it did prove necessary to slightly shift the sections to obtain a stratigraphic match, however. This appears to be due to slight differences in establishing the "zero" time line between the P- and S-wave sections. As noted by Tatham and McCormack (1991), it is the change in V_p/V_s ratio that is more important in correlating P- and S-wave sections than absolute time values. This approach was taken in matching the reflectors, but this leads to an uncertainty in the absolute depth of ±10 feet to any given reflection.

The evaluation of seismic attributes was also used as a tool to correlate the P- and S-wave sections. A seismic attribute is a property derived from a seismic waveform. One type of attribute is trace amplitude, which is simply the amount of trace deflection, both to the right and left, displayed at each vertical sample along the trace. Trace deflections are numeric values and the range of these values can be displayed as a color spectrum. Figure 26 is a color display of the trace amplitudes for the composite depth section, with the color scale shown to the right. Every third original trace is overlaid for reference.



NOTES:

CALCULATED DEPTHS BASED ON STACKING VELOCITIES ARE INDICATED IN THE MARGINS FOR SELECT REFLECTORS ON THE P- AND S-WAVE SECTIONS (AT THE TIME THIS CORRELATION WAS PREPARED, DOWNHOLE VELOCITY DATA WERE NOT AVAILABLE. WHEN AVAILABLE, THE DOWNHOLE DATA CONFIRMED THIS CORRELATION, ALTHOUGH THE ASSIGNED DEPTHS ARE ONLY APPROXIMATE).

FOR LOCATION OF LINE SEE FIGURE 4.

Figure 24 - Comparison of P- and S-wave sections, initial survey line.

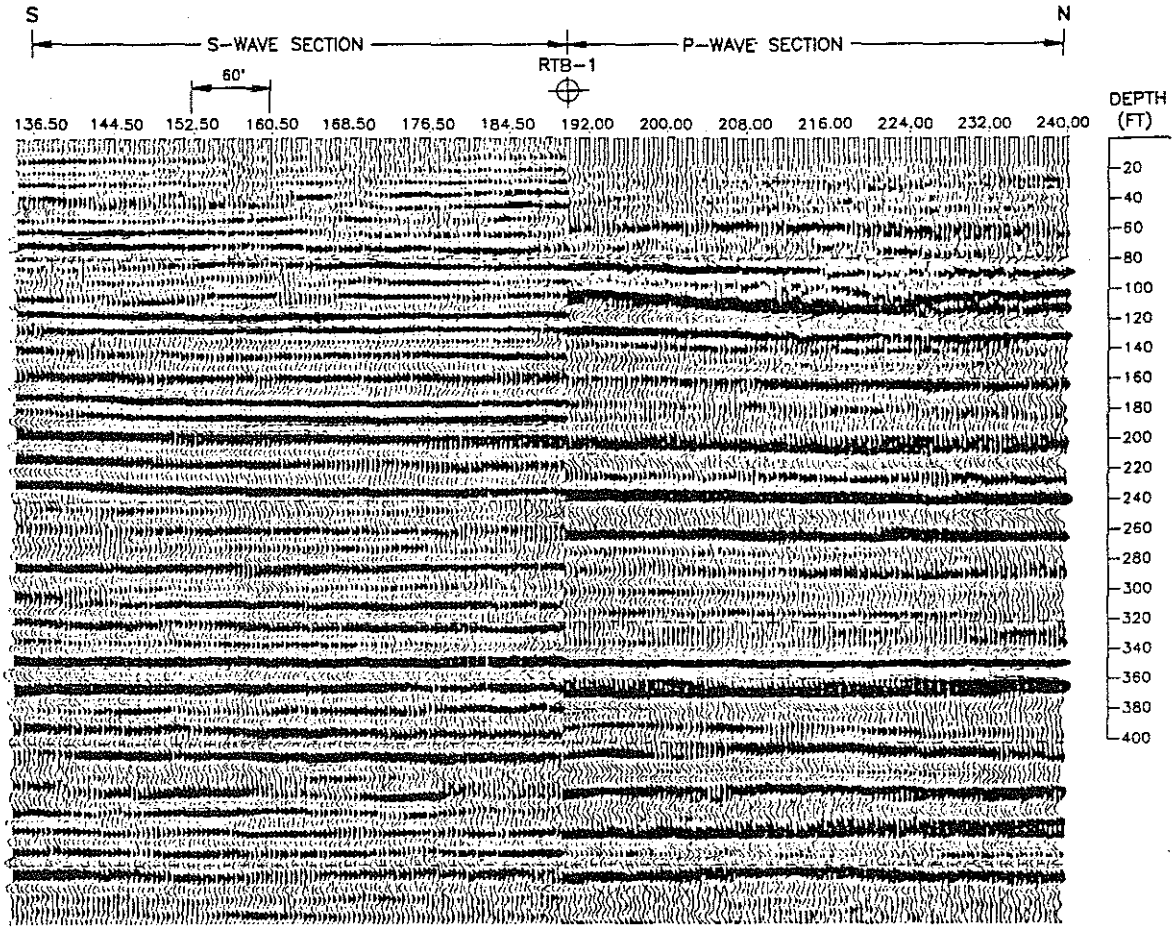


Figure 25 - Correlation of P- and S-wave depth sections at location of control boring RTB-1.

The effect of color is to increase dramatically the human eye's ability to distinguish subtle amplitude changes. Events which have different P- and S-wave responses have obvious amplitude differences. Events not showing a difference in P- and S-wave response carry their amplitude through the sections. Lateral amplitude changes also become more obvious.

Several other seismic attributes are generated by computing the Hilbert transform of the seismic trace and using the seismic trace itself and its Hilbert transform to compute a variety of functions, each of which is said to be an "attribute" of the seismic trace. This is a complex subject and the reader is referred to discussions by Yilmaz (1987) or Sheriff (1991) for more detailed information.

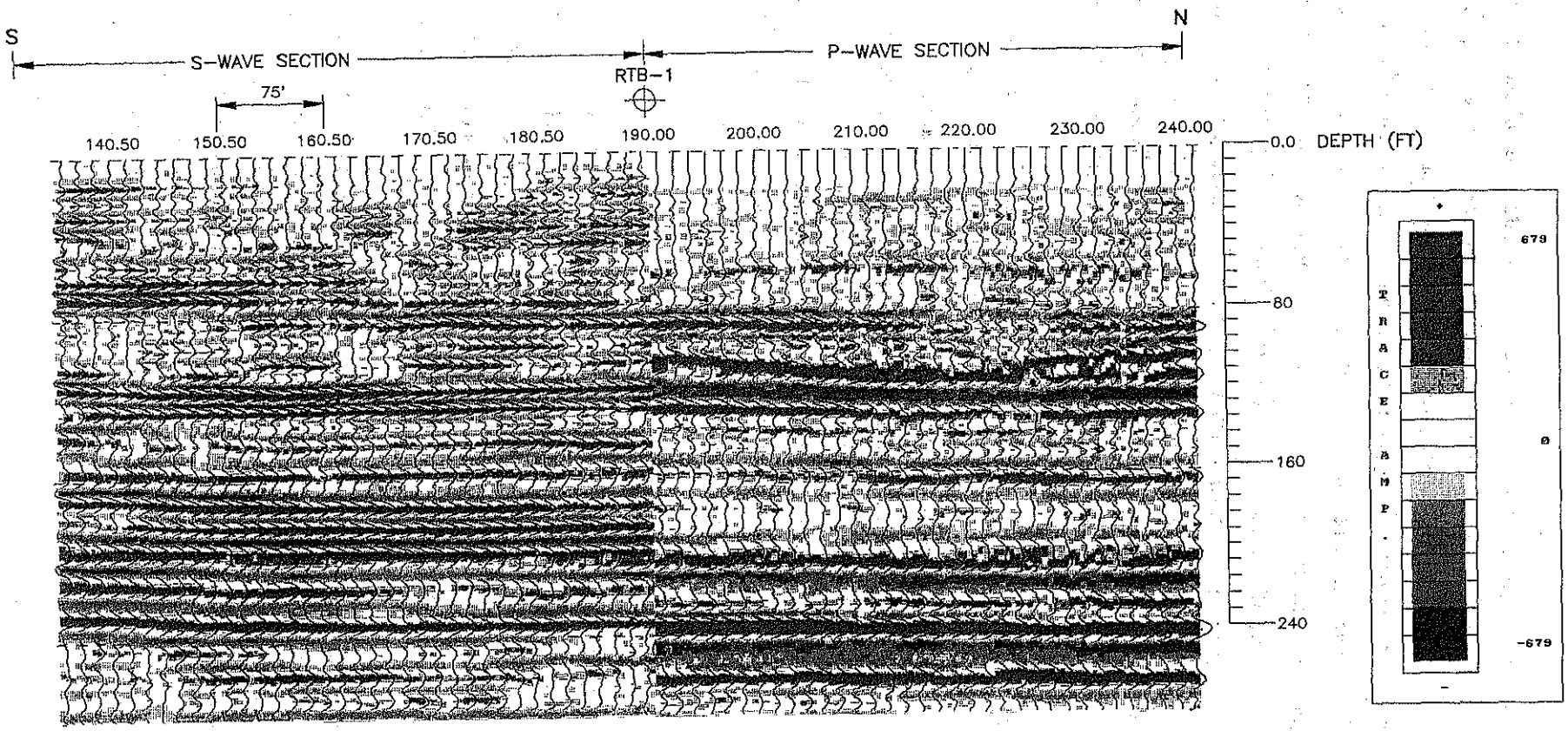


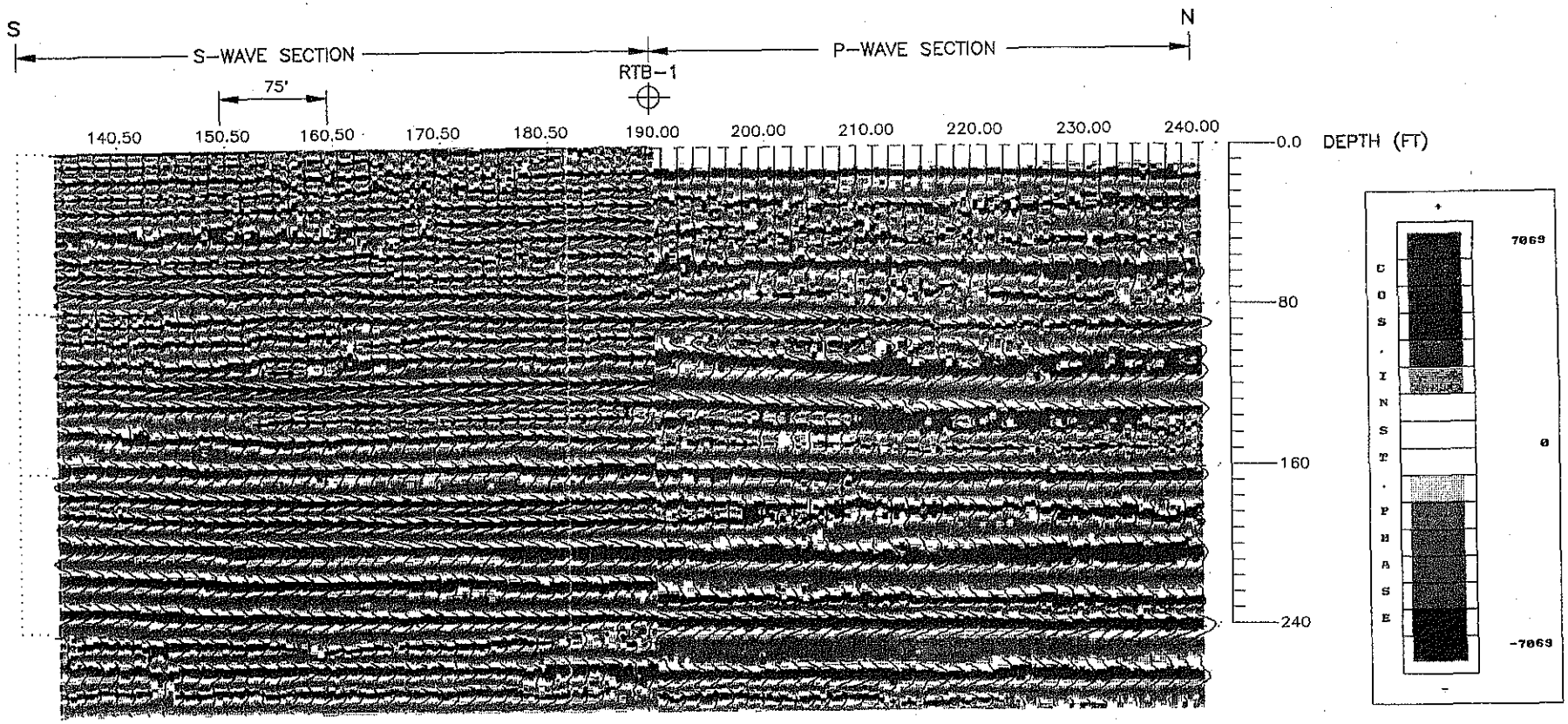
Figure 26 - Trace amplitude displayed on the combined depth section.

A popular Hilbert Transform attribute is the cosine of instantaneous phase. From a practical interpretation aspect, cosine of instantaneous phase is effective in delineating and enhancing bed boundaries. It preserves the conformable look of the seismic section, but removes the subtle amplitude expressions and has the appearance of an amplitude normalized section. The main applications of the cosine of instantaneous phase are to increase the number and continuity of possible horizons for structural mapping, to show unconformities and stratigraphic variations more clearly, and to track specific weak events. Figure 27 is a color display of the cosine instantaneous phase of the composite depth section, with every third original trace overlaid for reference. Certain events which did not previously appear to correlate from the P- to the S-wave sections now display some continuity. While the ability to map horizons stratigraphically and structurally is still superior on the S-wave section, the resolving power of the P-wave section has been enhanced by this display.

Another attribute derived from the Hilbert Transform is the amplitude envelope which takes into account the whole wavetrain, both peaks and troughs, at a point in the section, not just the data sample amplitude described by the trace amplitude. Practically speaking, it can be described as the amplitude of an event package comprised of a few oscillations of peaks and troughs. Figure 28 is a color display of the amplitude envelope of the composite depth section again with every third original data trace overlaid for reference. Only event packages of significant amplitude come out in this display. It is interesting to observe that, in general, the S-wave data show more sensitivity to lateral amplitude variations, which implies lateral stratigraphic variations, than the P-wave section using this display.

The goal in using seismic attributes, and color for that matter, is to accentuate the subtle changes in the seismic trace in terms of amplitude and phase which are important for interpreting the subsurface. Even through the process of conversion to a depth section, the critical character changes of the seismic traces are preserved. The attribute analyses of the combined depth sections supports the correlation interpreted on the basis of downhole travel times and stratigraphy.

In spite of the reasonableness of the correlation established by using the downhole velocity data, there existed an uncertainty in the absolute depth to any given reflection of ± 10 feet. With this amount of uncertainty, a negligible uncertainty to data processors accustomed to working with deep oil and gas reflection data, it is very difficult to comfortably discuss the difference in P- and S-wave response of a specific, 10-foot thick sand layer, for example. This problem was resolved by gathering in-hole seismic data with the Oyo PS Suspension Logging System, as further discussed in Section 2.6.



NOTE: FOR LOCATION OF LINE SEE FIGURE 4.

Figure 27 - Cosine instantaneous phase displayed on the combined depth section.

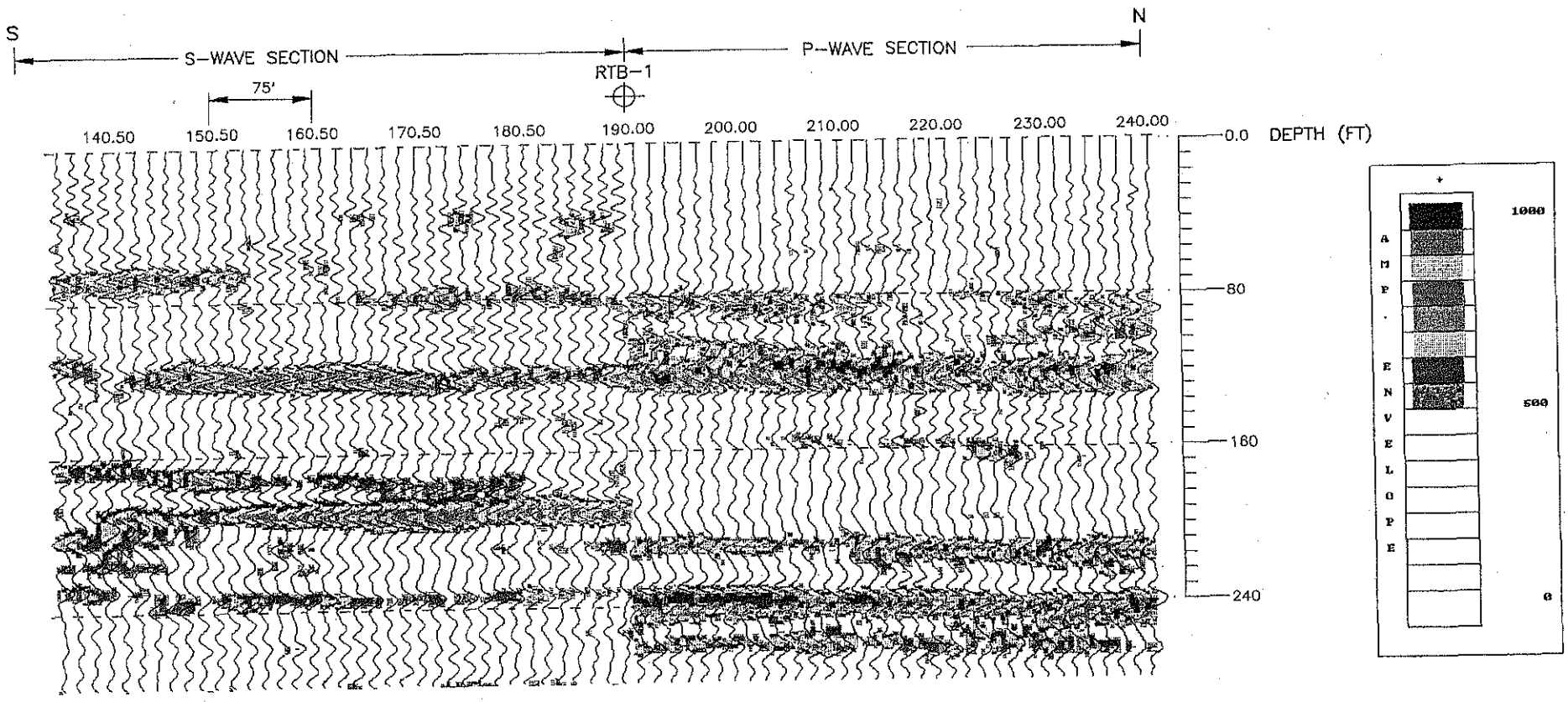
The in-hole velocity logs depicted on Figure 15 were used to develop a synthetic seismogram using Geotrace Technologies seismic modeling software. This software allows the user to display the synthetic seismogram in either the time or depth domain. The basis purpose of deriving a synthetic seismogram is to allow for the correlation of specific reflections to specific depths in the control borehole, allowing for the establishment of the relationship between reflections and lithologies. Figure 29 present the interpretation of true depth to the P- and S-wave sections. Although excellent correlation between the synthetics and real sections was achieved, better amplitude control based on knowledge of both velocity and density would have been preferable. For future surveys it is recommended that density logs also be obtained. The actual scale shift between the depth section interpreted from the downhole data on Figure 25 and that from the in-hole data on Figure 29 based on the derivation of synthetic seismograms proved to be about eight feet. The P- and S-wave correlation was confirmed by the new information.

3.1.4 Evaluation of the Effectiveness of Different Sources

As noted in Section 2.3, the source testing was conducted on the initial test line. Every effort was made in the field to provide identical conditions at each location while testing various sources. The following conditions, however, may have led to some bias with respect to an ideal source comparison:

- **Soil Saturation:** During the source test period, the weather was a contributing factor to the variation of source performance. Soil conditions ranged from dry at the surface to completely saturated. Weather ranged from very rainy to very hot and the effects of source coupling, especially with the S-wave, were observed even while testing the same source. In general, P-wave generation improved with wet, muddy conditions, whereas the S-wave quality deteriorated.

- **Source Location:** Although attempts were made to locate the sources in exactly the same location, this was not always possible. For example, the mounting of the truck on top of the railroad tie dictated that the railroad tie be located slightly off center of the line. Additionally, after digging a hole for the steel cylinder, it was not possible to place another source in exactly the same location. The Betsy was also located off line by several feet due to the obvious need to drill a hole somewhat away from the geophones. The observation of first arrivals on several of the lines indicated that the near surface material was indeed highly variable in nature, implying that minor differences in source location could artificially bias the comparative results.



NOTE: FOR LOCATION OF LINE SEE FIGURE 4.

Figure 28 - Amplitude envelope displayed on the combined depth section.

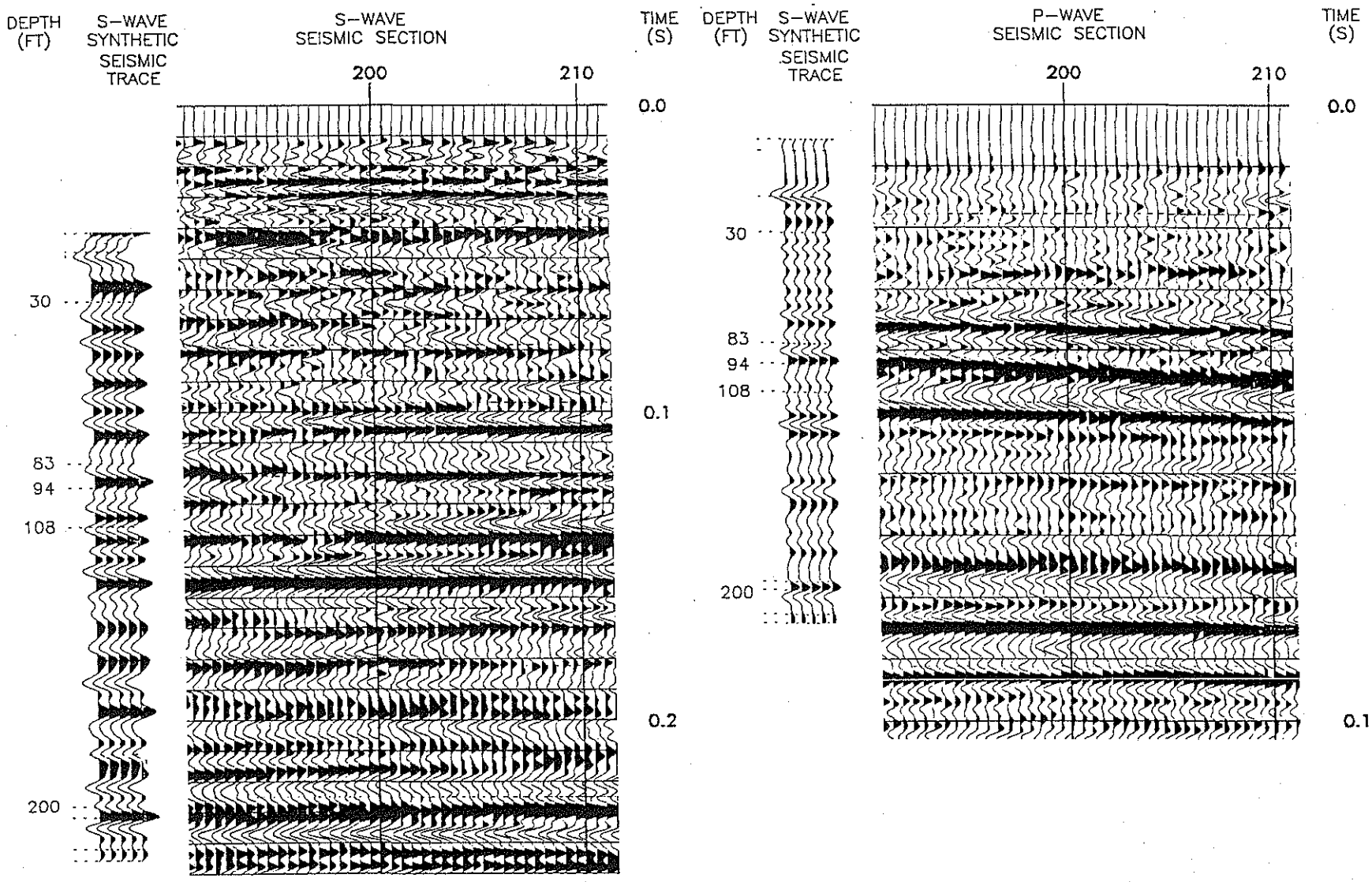


Figure 29 - Comparison of real and synthetic time sections for both P- and S-waves.

During the source testing, the individual sources were evaluated by orienting their angle with respect to ground surface such that either P- or S-wave generation would be emphasized. The Betsy Downhole Seisgun was the exception in that blowouts would occur with small angle holes and a 45-degree declination was used. The use of separate source orientations for P- and S-waves enhances the data acquisition process when the component recordings are separate. When simultaneous P- and S-wave recordings are to be made, then the flexibility of the source to simultaneously generate P- and S-waves must be addressed. From this standpoint, the following observations were made:

- The three-inch diameter steel cylinder appears to be the most versatile of the hammer sources tested in that it can be oriented to essentially any angle to the ground surface.

- The railroad tie is extremely limited in the amount of combined P- and S-wave energy it can produce. The steel plate has a similar limitation.

- The Betsy Downhole Seisgun has the opposite problem of other sources in that it is not practical to segregate P- and S-wave production modes.

Despite the variable ground conditions, the field source evaluation was reasonably effective. Source comparisons were based not only on the apparent frequency and strength of reflections observed, but were also based on the practicality of using each source in a P- or S-wave mode. The ability to achieve high production rates in the field directly affects the cost of any type of seismic reflection survey. The depth of the target horizon, however, could dictate the type of source to use.

The overall conclusion reached from the source testing was that the steel cylinder was both logistically the easiest to use and did provide one of the best signals for most applications of shallow seismic investigation. Although data from the small pipe with the base plate were lost due to data transfer difficulties, the analysis from the monitor records indicates that the small pipe with a small hammer could be a suitable source for extremely shallow investigations. For targets deeper than about 150-200 feet, some of the lighter sources such as the steel pipe and steel cylinder become less effective, whereas a strong source such as the Betsy Downhole Seisgun increases its effectiveness. The comprehensive survey recorded S-wave reflections to a depth of at least 500 feet and P-wave reflections to more than 1300 feet.

3.1.5 Evaluation of the Effectiveness of Different Recording Procedures

The initial field experiment differed from the comprehensive survey in that two components of ground motion were recorded separately, as opposed to three components recorded simultaneously. In the simplified survey, 24 channels from geophones with a 10-foot spacing were recorded for each component, either vertical (V) for P-wave generation or transverse horizontal for SH-wave generation. A total of 32 channels per component were recorded from geophones with a 7.5 foot spacing during the comprehensive survey. Three components (V, SH and in-line horizontal, SV) were recorded simultaneously accounting for 96 channels of data. The maximum offset for both surveys was 240 feet.

The results from the comprehensive survey as shown on Figures 20 and 21 exhibit slightly better data quality than the corresponding results from the initial survey on Figures 16 and 17. The main difference between the two results is interpreted to be due to the loss of about 50 percent of the data during the initial survey, rather than any improvements due to simultaneously recording the P- and S-wave data. The comprehensive survey benefited from having a closer geophone spacing and a higher fold coverage which increased the near surface resolution and this also made a difference.

Our interpretation is that if separate P- and S-wave recordings had been made at a 7.5 foot station spacing and the S-waves had been generated with a near horizontal source, that data quality would have been as good or better than the simultaneously recorded P- and S-wave data. If a 48-channel recorder had allowed for increasing the offset to 360 feet, then the data quality would probably have been better than either survey. Our basic conclusion is that it is not worth the substantial cost increase to simultaneously record the P- and S-wave data in three components, unless a goal of the survey is to assess fracture orientation from S-wave anisotropy.

3.1.6 Lessons Learned

3.1.6.1 Contrast Between Oil and Gas Equipment and Engineering (Shallow) Equipment for High Resolution Seismic Reflection Surveys

A best effort was made to integrate the best characteristics of both oil and gas equipment and the more portable engineering seismic equipment to conduct the field investigation. Philosophically, oil and gas equipment is made to look deeper and is highly production oriented. Contrasting this, in general, the shallow engineering seismic equipment is designed to acquire relatively short lines

where the use of roll (CDP or common depth point) cables is not necessary and portability and light weight are stressed. Oil and gas equipment, on the other hand, is usually truck mounted and the cables have numerous pairs of wire so that a great many geophones can be accessed by the recording equipment at one time. Additionally, oil and gas equipment generally writes the data to a nine-track tape and the field record is produced on a read-after-write basis so that the data can only be displayed if it were truly written on tape.

Due to the necessities of portability, low power is a primary consideration on engineering seismographs. Consequently, engineering seismographs either retain the data in memory or they write to a floppy diskette, a small tape device, or to a PC-type hard disk. To use processing facilities for standard (oil and gas) type data processing facilities, these seismic records must be converted to a 9-track tape type of format, although several processing systems are now able to read diskettes.

With respect to the recording seismographs, several manufacturers/vendors were contacted. The following are inherent drawbacks to the engineering seismographs:

- **Availability:** Although 12- or 24-channel seismographs are readily available, 48-and 96-channel seismographs are available only in limited quantities.

- **Filters:** The availability of filters on some of the seismographs varies widely. Some seismographs have no low cut filters and contain only an anti-alias high cut filter. Other engineering seismographs have a variety of low cut filters, but the filters have very gentle slopes. This greatly reduces the ability to eliminate low frequency noise when performing a high resolution seismic survey.

- **Analog to digital (A to D) converters:** Some seismographs have a straight 12-bit A to D converter with only a fixed gain. This presents problems when trying to record the wide dynamic range inherent in seismic reflection signals. Other seismographs have instantaneous floating point amplifiers or 20+ bit A/D converters, but they are of limited availability and are much more expensive.

Seismic cables available for standard engineering surveys are also limited in their capabilities. Most engineering seismographs are configured to go into a 24-pair cable. A roll switch configured for a 24-pair cable would mean that a 24-channel seismograph could look at any 24 channels of 48 total channels on the ground if, and only if, the recorder were located exactly between the two 24-pair cables. Standard oil and gas spread cables contain considerably more pairs of wire than the total number to be recorded and are broken into smaller pieces. This enables the recording instrument to be located at more positions on the line and enables the recorder to "see" more stations on the ground at one time. In the case of the spread cables used for the simplified survey, 120 channels could have been laid out on the ground and any 24 of those 120 could have been recorded. The cable used in the comprehensive survey, constructed specifically of this survey, allowed for 100 channels to be laid out and any 32 selected for recording.

3.1.6.2 Comparison of Comprehensive Professional Processing with Simplified PC-Based Processing

A comparison of professional processing with PC-based processing was not a goal of research. A PC-based processing package (SEISTRIX produced by Interpex, Limited of Golden. Colorado) was used as a field tool to evaluate the quality of the field data. Other programs could have been selected, but this program was readily available, known to be relatively user-friendly, and not expensive. Through the use of this program, the limitations that we believe to be typical of PC-base processing were made apparent. Our observations should not be considered as a condemnation of this specific software package, but rather as general considerations that should be taken into account when using any PC-based processing software. PC-based software is constantly being improved, as we understand is the case with SEISTRIX, and it is expected that the limitations we encountered will gradually disappear with time. The following discussion presents our experience (valid for 1991) with PC-based processing.

With respect to data processing, many shallow engineering surveys are processed on PC's with very basic software. While oil and gas data processing packages offer a virtually unlimited range of software applications, the software applications available to a PC-based system are limited. This is primarily due to the type of computers on which the respective packages run. Oil and gas software runs on very large mainframe (and even super) computers, whereas the engineering software runs on the 80386- or 486-based PC's. The SEISTRIX processing package used in the field had the advantage that data quality could be assessed and a preliminary idea of results could be obtained. The limitations of this simplified means of processing can be summarized as follows:

- **Rigid data acquisition requirements:** The sorting routine required rigid input. Flexibility with respect to data acquisition was not easily tolerated by the package. For example, the field acquisition procedure of moving the source points through a geophone spread to obtain higher fold coverage towards the ends of the lines was rejected by the program.

- **Need for hard copy output:** The package provided a great many analysis options, but the graphical output to a printer was limited.

- **Hardware limitations:** The PC hardware naturally runs slower than a mainframe and many applications require a considerable length of time to execute. This is not a problem with the software, but an available hardware drawback.

The results of the simplified processing as exemplified on Figure 19 illustrate the difference in quality when compared to the comprehensive processing results for the same line shown on Figure 16. The simplified processing does not provide enough detail to be suitable as an interpretive tool. Although it is possible to produce a seismic section with adequate detail for many reflection surveys using the SEISTRIX software package, the processing requirements for this survey, especially the S-wave portions, are beyond the current capabilities of this package. The various specialized scaling, summing, deconvolution, and noise rejection routines are not available in a PC-based processing system. The utility of this software at the Cooke Crossroads site was the facility it provided for the analysis of acquisition parameters in the field. A further advantage was the ability to rapidly produce a basic CDP stack section of the data without the requirements of time and effort involved in copying, documenting, and sending the data to a processing center.

3.1.6.3 Pitfalls Encountered in Field Operations

Several problems were encountered with the field data acquisition. Some problems were beyond control. Some problems could have been controlled and were, and some problems could have been controlled had we known they were occurring. The following summarizes these problems:

- **Coupling:** As discussed in Section 3.1.2, coupling of the source to the ground appeared to be dependent on the saturation of the soil. As the weather conditions changed from

day to day during the initial survey, it was apparent that the coupling varied. A field crew would be well advised to have alternative sources, should field conditions cause the preferred source to lose its effectiveness. It would be advisable not to change sources while still acquiring data along a given line, as this would affect various statistical processes during the processing effort later. During the comprehensive survey it was noted that data quality for both P- and S-wave data was notably degraded when the line traversed an area of dry sand. This may imply that the method may not be as effective in areas where dry sandy soils are predominant.

- **Number of data channels:** Shallow reflections were difficult to identify in the field because of coherent noise. With only 24 closely-spaced channels as used in the preliminary survey there was not enough offset to resolve the reflections from the noise. It readily became apparent that it would be desirable to have 48 or even 96 channels available for ground recording. The near-field problem is shown on Figure 18. In this example, S-waves were recorded with 2.5-foot spacing to resolve the shallowest reflections. With only 24 channels, however, there was not enough offset to distinguish the reflections from the noise and even the comprehensive processing by PGS could not extract coherent reflections from the data set. If the survey had been conducted with 48 or 96 channels, it is anticipated that extremely shallow reflections could have been resolved. Figure 11 depicts what a 48-channel recording might look like. Numerous reflections observed on the far geophones help identify reflections in the near field.

- **Cables:** As previously discussed in Section 3.1.3.1, most engineering seismic cables are manufactured to handle only 24 channels. To obtain recording versatility for the preliminary survey, 120-channel cables from the oil and gas industry were used. These proved to be cumbersome due to the amount of slack between stations. More specialized cables were used in the comprehensive survey.

- **Data transfer reliability:** With the system used for the initial simplified survey, there was no absolute method to ensure that the data from the seismograph had been accurately transferred to the computer. Data files were checked for their size and content but it was not possible to quickly plot each file to show that the transfer had been successfully achieved. Unfortunately, roughly 50 percent of the field data were not correctly transferred to the

computer. This was indeed unfortunate as it severely hampered our ability to analyze the techniques employed in the field using any sort of processing technology. During the comprehensive survey, the data transfer problem was resolved after an evaluation of the problem with the recorder manufacturer and extensive spot checking was conducted.

A major lesson learned from this problem was that, depending on the type of seismograph and data storage used, it is well worth the expense of having a high speed printing device, such as a laser printer, in the field to verify that the records transferred on a daily basis were indeed recorded accurately.

3.1.6.4 The Need for In-Hole Velocity Logging

One of the main results of the comprehensive survey was that it is extremely difficult to conclusively correlate reflections on P- and S-wave reflection profiles. Even when accurate layer velocities are known, it is only possible to establish a "best fit" correlation by calculating V_p/V_s ratios, determining relative depth profiles, and then visually determining the best match based on stratigraphic sequences. After all this is done, however, the absolute depth to individual reflections may not be precisely defined, even if the P- and S-wave reflections are properly correlated. The problem arises from not knowing if the zero times on the P- and S-wave sections precisely correspond. Discrepancies of a few milliseconds may be beyond the ability of the data processor to precisely define, as was the case with the comprehensive survey for this research. These discrepancies are not significant when deep oil and gas exploration targets are being assessed, but become very important when depths need to be resolved to within a few feet. Additional control is necessary where discrepancies occur and this control is best achieved by means of in-hole velocity logs. It is also recommended that density logs be obtained to allow for a quantified calculation of reflection coefficients.

As discussed in Section 2.6, in-hole seismic measurements were made in control boring RTB-1 at the Cooke Crossroads test site. This information allowed for the development of synthetic seismograms which in turn provided for a confirmation of the correlation of the P- and S-wave sections and quantified the depth of individual reflections. This type of survey is essential if both P- and S-wave data are to be gathered. Average velocity, however, is still more accurately acquired with a downhole survey and it is concluded that both in-hole and downhole velocity data are need if a quantitative interpretation is to be made from combined P- and S-wave reflection data.

3.1.7 Summary of Geophysical Interpretation

In summary, the field experiments have resulted in several significant observations and lessons learned:

- In an environment where sediments are not lithified, the resolution of an S-wave reflection profile can be more than double that of a conventional P-wave profile.

- Good quality data can be obtained with two component separate P- and SH-wave recordings. The simultaneous recording of 3-component data did not result in significantly higher data quality.

- Although a steel cylinder appears to be the most effective source for both P- and S-wave generation, surface conditions and/or target depth may dictate that other sources be used.

- P- and S-wave velocity data obtained from both downhole and in-hole measurements in a control borehole are mandatory if a definitive correlation is to be established between the P- and S-wave reflection profiles and if absolute depths need to be assigned to individual reflections; i.e. if the reflections are to be related to lithology.

- Field processing on a PC, while useful, does not replace the need for comprehensive processing by a professional processing firm.

- Field recordings need to be obtained with a minimum of 32 channels to fully characterize shallow reflectors. Existing, readily available engineering seismographs are not fully adequate.

- The field recording system needs to have steep low-cut filters to enable proper identification of reflections.

- A means to verify the accurate transfer of data from the seismic recorder to the field computer must be established.

The major positive lesson learned during the field investigation was that it is just as easy to record high quality S-wave reflections as it is to follow conventional technology to record P-waves. In this experiment, the S-wave data had the higher quality.

3.2 HYDROGEOLOGICAL INTERPRETATION

The correlation between lithology and P- and S-wave reflections allowed by the development of synthetic seismographs from the in-hole velocity logging also permits us to interpret hydrogeological conditions from the data. As noted in Section 2.1.3, a saturated sand aquifer in unconsolidated sediments would likely be a good target for an S-wave reflection survey, but be difficult to resolve using P-waves. The sediments of the Cooper Formation proved to have slightly higher velocities than those assumed in the theoretical model, but is was still anticipated that sand aquifers within that unit would be more readily detectable with S-waves than P-waves because of a greater velocity contrast between the sand and clay with the S-waves.

The main target for the survey was a confined sand aquifer present between depths of 83 to 94 feet in control borehole RTB-1. This aquifer is defined both top and bottom on the S-wave section, but the P-waves define only the base of the formation (Figure 30). As the depth of 94 feet marks an unconformity within the Cooper Formation, representing change in consolidation and P- and S-waves velocity, this horizon should be a strong reflector on both sections. The top of the sand is marked by an S-wave reflection not observed with the P-waves. On this basis, a confined aquifer at this depth would be interpreted, consistent with theory. An inconsistency with this interpretation is that the top of the sand is marked by an S-wave reflection which is poorly represented on the synthetic seismogram. A possible explanation for this discrepancy may be that the synthetic seismogram does account for density contrasts, but this is uncertain.

The thin sand horizons beneath the target sand appear to be represented by both P- and S-wave reflections. Similar to the thicker target sand, it is anticipated that these thin sands mark minor unconformities across which there are velocity changes for both P- and S-waves, as indicated on Figure 15. The beds are too thin for their tops and bottoms to both be resolved and it is not practical to identify them as aquifers on the basis of their seismic signature alone.

In general, where a confined aquifer is sufficiently thick, S-waves appear to be useful in mapping the aquifer. It should be recognized, however, that thin aquifers can be missed if there is a velocity contrast across the aquifer. The increased resolution of the S-waves can also allow for

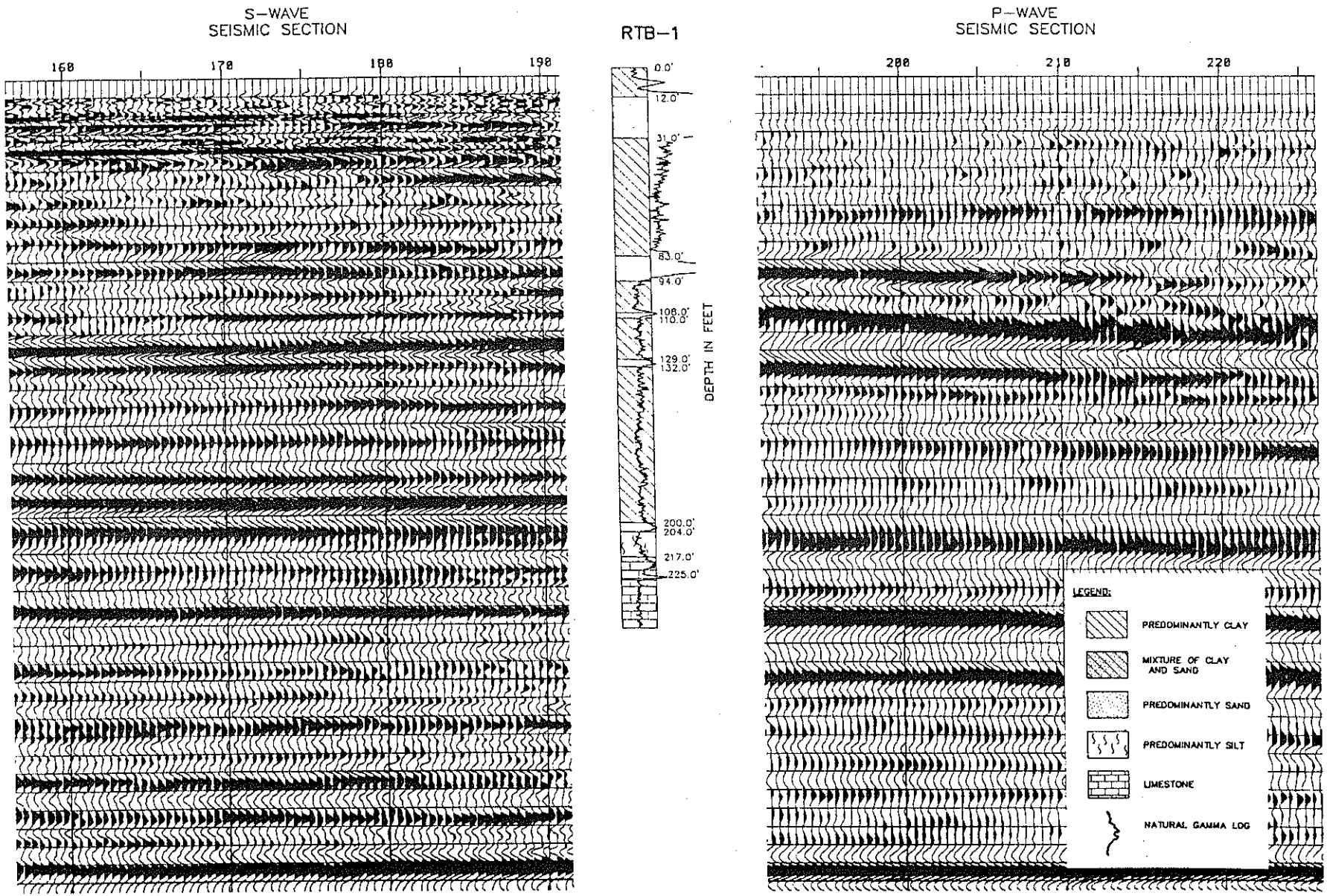


Figure 30 - Correlation of lithology to the combined depth section, Cooke Crossroads test site.

the mapping of subsurface horizons which are not resolved by the P-waves, especially in the shallow subsurface. Careful interpretation will be required if P- and S-wave reflections are used to map aquifers. Perhaps the most significant result of the study in terms of groundwater interpretation is the enhanced resolution offered by S-waves, which can allow for improved mapping of subsurface structure which controls groundwater flow.

4.0 TECHNOLOGY STATUS

4.1 TECHNOLOGY DEVELOPMENT EVALUATION

The technology associated with the high resolution S-wave method has developed through this research to the point where the technique has been demonstrated to be a powerful tool in mapping subsurface lithology and in conducting groundwater investigations. This research has demonstrated that the resolution obtainable using S-waves in a Coastal Plain environment is more than double than that obtained using conventional reflection technology, which already offers a higher resolution than any other surface method. Where the mapping of thin clay layers functioning as aquitards or thin sand layers functioning as aquifers are critical to the understanding of groundwater flow, S-wave reflections offer unparalleled possibilities for non-destructive exploration. The field experiment at Cooke Crossroads, South Carolina enabled the detection and mapping of beds in the thickness range of one to three feet.

In additional to improving the resolution of subsurface characterizations, the S-wave reflection technique, in combination with conventional P-wave reflection measurements, has the potential to directly detect where confined and unconfined aquifers are present. This is a breakthrough technology that still requires additional research before it can be applied on a commercial basis. Aquifer systems were interpreted from the test data at Cooke Crossroads consistent with the theoretical modeling conducted for this research. Nevertheless, additional research is need in assessing the theoretical response of P- and S-waves to subsurface interfaces within unconsolidated sediments of varying moisture content and lithology. More theoretical modeling is and in situ testing is clearly need to bring our knowledge of these phenomena to the level that oil and gas researchers have done for fluids in sandstones.

Where additional research is also needed is in defining the best means to obtain subsurface control for relating the separate P- and S-wave reflections, which is the main step needed to be accomplished before defining where aquifers are present. The Cooke Crossroads test site proved to be so rich in subsurface reflecting horizons, especially for S-waves, that an unambiguous interpretation proved challenging.

An understanding of the merits of this research requires that alternatives to the proposed technology be understood and that the potential benefits to the DOE in terms of its Environmental Restoration and Waste Management program be defined. These topics are discussed separately.

4.1.1 Alternatives

There is no geophysical technique which has the power to resolve in detail the intricacies of subsurface sedimentary layers to depths greater than a few tens of feet better than the seismic reflection method. Ground penetrating radar can also offer high resolution, but usually only to a very shallow depth. The methodology proposed for this research intends only to enhance what is already the most powerful geophysical tool for subsurface characterization. Other methods, specifically electromagnetics (EM) and DC resistivity, can resolve subsurface layering in some cases, but without the resolution associated with seismic reflection. Nevertheless, it should be noted that the EM and DC resistivity methods can respond directly to the presence of contaminants in groundwater because of conductivity anomalies associated with the contamination. In some cases an investigation can benefit by combining seismic reflection with the EM or DC electrical methods. In such cases, the EM or DC electrical methods define the presence of a contaminant plume in the groundwater and the seismic reflection results provide details of the stratigraphic framework of the flow regime.

Borings represent the most common alternative to seismic reflection measurements. However, borings do not define the continuity of individual layers as can be demonstrated with the seismic method and the costs for obtaining a comparable continuity of subsurface information with borings is usually prohibitive. Borings also require that the ground be penetrated, which may not be desirable.

4.1.2 Benefits of the Research

Subsurface characterization, especially as it relates to groundwater flow, is a critical aspect of nearly all environmental restoration and waste management problems. This research offers the possibility to substantially improve the resolution associated with conventional seismic technology. For example, this could represent the possibility of mapping thin clay horizons in a cost effective manner at the Savannah River Site. This research also offers the possibility of directly detecting aquifer systems with a minimum disturbance to the ground. Knowledge of aquifer conditions before drilling numerous boreholes revolutionizes the means by which programs to define subsurface conditions are established. The following sections discuss aspects of specific benefits of the research.

4.1.2.1 Reduction of Health and Environmental Risks

Health and environmental risks will be reduced by implementation of the results anticipated for the proposed research because S-wave high resolution reflection surveys will preclude or reduce drill holes needed to obtain significant information about the subsurface. The surveys could be conducted under Level D protective measures, rather than the Level B or C that could be required for the boreholes.

4.1.2.2 Reduction of Costs

It is not possible to precisely define the cost benefit that the proposed research will represent to environmental hydrogeological investigations as it will be dependent on site conditions. However, it should be noted that the amount of money spent on conventional high resolution seismic reflection profiling at the Rocky Flats Plant was one tenth on the money that would have been spent on borings to obtain the same information (Irons and Lewis, 1990). S-wave technology applied to the same high resolution technique could have improved the cost-benefit ratio.

4.1.2.3 Improved Operations

The S-wave seismic reflection technique offers an important means to improve the operations associated with subsurface investigations by reducing the number of borings needed to characterize hydrogeological conditions. If the aquifer targets can be known in advance, then the number of borings needed to provide avenues for measuring, testing, and sampling groundwater or waste will be significantly reduced.

4.1.2.4 Improved Regulatory Compliance

The main problem with conventional subsurface information, specifically borings, is that they provide a great deal of information for a specific location, but there is often uncertainty about what are the conditions between the borings. Regulators are frequently the ones who question the uncertainty. The high resolution S-wave reflection method is best at defining the continuity of subsurface layers and assuring that the borings find what they are supposed to find. At the Cooke Crossroads test site, the subsurface resolution from S-wave reflections was as good as could be achieved from the control borehole.

4.2 TECHNOLOGY INTEGRATION EVALUATION

The technology associated with this research is now ready for moving to the DT&E phase. The high resolution S-wave reflection technique has been successfully demonstrated at the Cooke Crossroads site, selected because of its relative subsurface simplicity and isolation from cultural interference. S-wave technology has surpassed our expectations at this location and has made a unique contribution to the state of the art of subsurface characterization and groundwater assessment. The next logical step for extending this research would be to apply a similar work scope at a DOE facility with a more complicated sedimentary geology, such as the Savannah River Site.

As noted in Section 4.1, the method offers the potential for improved regulatory compliance by allowing for the definition of the continuity of subsurface horizons. In addition, none of the methodology associated with the method is controversial. There are no issues of environmental impact to be considered, which facilitates public acceptance and also allays regulatory concerns. As none of the technology is proprietary, there are no technical or legal restrictions for directly entering into the DT&E phase. Similarly, it is not necessary to scale up equipment which could be an economic drawback. The technology is ready to be demonstrated.

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