IMPROVING SUBSURFACE RESOLUTION WITH THE SEISMIC REFLECTION METHOD: USE S-WAVES

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ABSTRACT

The conventional high resolution seismic reflection technique is based on inducing a seismic disturbance at or near the ground surface and measuring the arrival times of compressional or P-waves reflected from subsurface horizons. Over the past few years, this method has developed into a power tool for subsurface characterizations as part of ground water or geotechnical studies. The main difficulty is resolution. The resolution achievable with a high resolution reflection survey is a function of the frequency of the seismic signal. Recovering a coherent high frequency signal can be difficult and costly.

The use of shear or S-waves offers the possibility to substantially increase resolution over a conventional survey under commonly encountered subsurface conditions. 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 the 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. In a field experiment conducted at Cooke Crossroads, South Carolina in a coastal plain environment, the resolution obtained using S-waves was more than double that obtained using P-waves with a similar effort spent in data acquisition and processing. The results indicate that the high resolution S-wave reflection technique can be more effective in conducting subsurface investigations than using conventional technology.

INTRODUCTION

The determination of the presence and continuity of thin subsurface horizons can be a vexing problem in many hydrogeological investigations. In some areas, thin clay layers can have a major impact on ground water flow. Similarly, thin sand lenses within an otherwise confining medium can control the migration of contaminants. Thin subsurface layers, whether they are aquitards or aquifers, can be difficult targets for conventional drilling and sampling programs. Sampling intervals normally used may be inadequate for detecting thin beds and it is commonly difficult to prove the continuity of individual horizons based on borings alone. Geophysical methods are often used, especially to define continuity, but results are often unsatisfactory because of the lack of resolution.

One of the most powerful tools for conducting an engineering or ground water investigation is the high resolution seismic reflection technique. This method normally uses compressional (P-) waves to provide acoustic images of the subsurface. Resolution is dependent on the frequency content of the waves and the velocity of the subsurface materials. This is also true if shear (S-) waves are used instead of the P-waves. The difference is that the S-waves travel with different velocities and at different predominant frequencies, which implies that their ability to resolve subsurface layers will also be different. This paper briefly reviews the theoretical basis for defining environments where S-waves could improve subsurface resolution and presents the results of a field experiment where the merits of the S-wave reflection technique are demonstrated.

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 (Vs/Vp ratio) has been shown to have a relationship to lithology. Neidell (1985) reports the Vs/Vp 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 Vs/Vp 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.

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

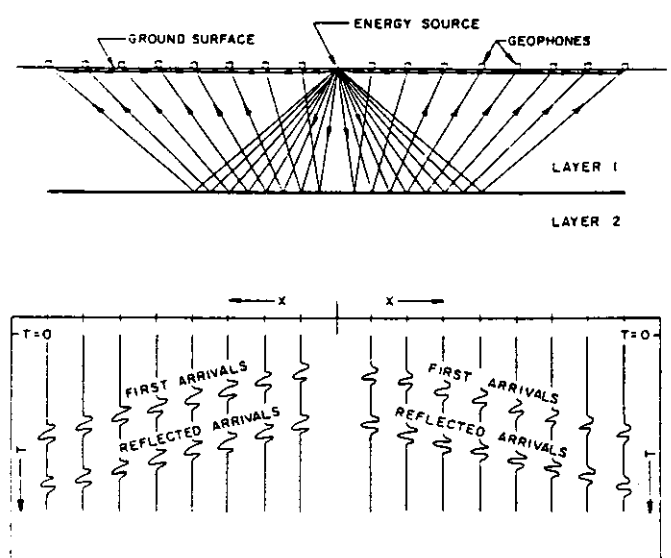

Figure 1 - Seismic reflection principle and schematic of reflection data record

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):

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

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).

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.

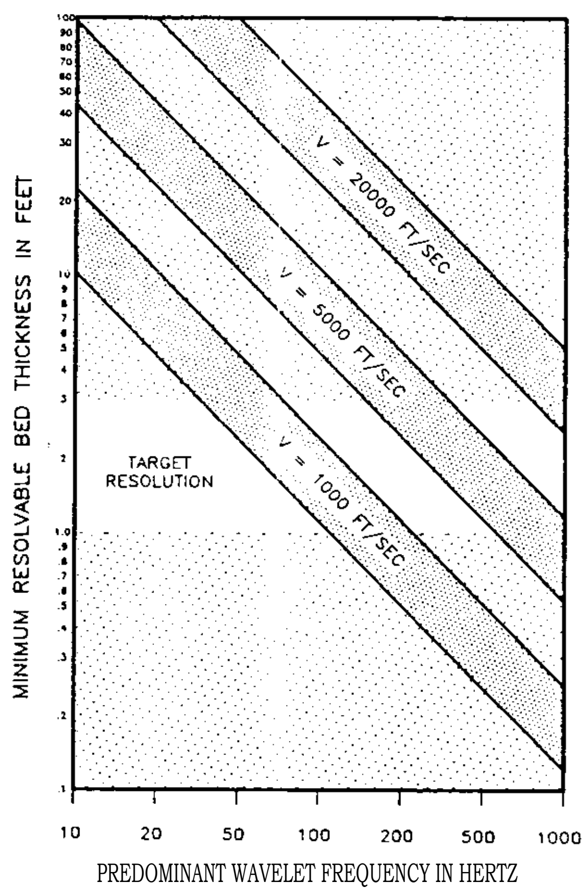

Figure 2 - Minimum resolvable bed thickness as a function of predominant reflection frequency and velocity

(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.)

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. A field experiment was conducted with a goal to determine the degree to which resolution could be improved using S-waves in a high resolution reflection survey at a site with deep unconsolidated sediments.

FIELD EXPERIMENTS

Field experiments to assess the effectiveness of recording and interpreting S-wave reflections were conducted between May and October 1991 at a site near Cooke Crossroads, South Carolina, about 15 miles northwest of Charleston. The lithology of the site was known from a boring drilled by the U.S. Geological Survey (USGS) as part of an investigation to assess the origin of the 1886 Charleston Earthquake and borehole RTB-1 drilled specifically for this investigation.

The lithology of RTB-1, as interpreted from geophysical logs and samples, is provided on Figure 3. The Cooper Formation , encountered to a depth of about 225 feet from ground surface, is predominantly an impermeable fine-grained carbonate deposit, except for some thin phosphatic sand layers. Beneath the Cooper Formation, the Santee Limestone is a of a composition similar to the Cooper Formation, but is generally more cemented.

The field experiments were broken down into two phases. In the first phase, simple procedures using a Bison 9024 digital instantaneous floating point, 24-channel, signal enhancement seismograph were used along with separate 40-Hertz horizontal and 28-Hertz vertical geophones manufactured by the Oyo Corporation. In the second survey, two Bison 9048, 48-channel recorders were used along with two-component horizontal 40-Hertz and 100-Hertz vertical component geophones manufactured by the Oyo Corporation. In essence, the main difference between the two experiments was that in the initial survey, separate P- and S-wave recordings were obtained; in the second phase, three components of motion were simultaneously recorded. Overall results in terms of data quality were similar from both experiments.

Several sources were tested, including a downhole shotgun device, a .22 caliber rifle, and several hammer sources including a steel cylinder, railroad tie, steel plate, and steel pipe. Different sized hammers including a sledge hammer, a three-pound hammer and ballpeen or carpenter's hammer were used with all but the shotgun and rifle sources. The best overall source for both P- and S- waves was the three-inch steel cylinder, as the overall data quality from this source was good and it was logistically easy to use. Other sources could also be used if conditions warranted, however. The downhole shotgun would be more effective than the steel cylinder for targets at depths greater than about 150-200 feet. The .22 caliber rifle could be effective for an extremely high resolution P-wave survey, while the railroad tie could be a preferred source for pure S-wave generation.

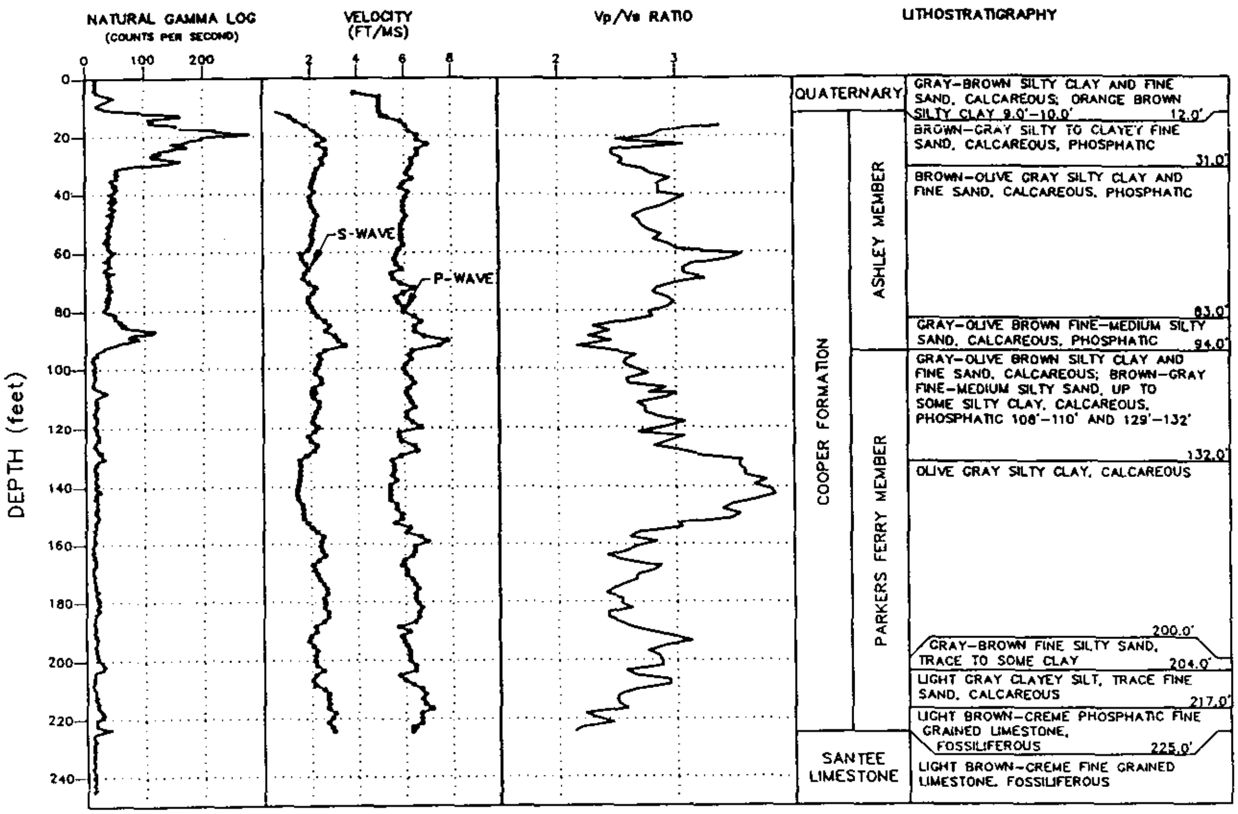

Figure 3 - Geophysical Logs and Lithostratigraphy at Borehole RTB-1

The final test line was surveyed over distance of about 1,500 feet using a geophone spacing of 7.5 feet. P- and S-wave (SH) data were recorded simultaneously with 32-fold coverage. The final test line used a double source acquisition technique with the three-inch steel cylinder as the source. The cylinder 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 this was to enable the discrimination of S-waves from potential P-wave contamination by subtracting the S-wave record which would be of opposite polarity.

Subsurface control was provided by measuring P- and S-wave velocities at five-foot intervals down borehole RTB-1 by impacting the steel cylinder from the surface. Additional control was provided through the courtesy of the Oyo Corporation, who provided the P- and S-wave velocity logs shown on Figure 3 that were obtained with their Suspension PS logging system. A definitive correlation between the P- and S-wave sections would have been extremely difficult without the in-hole measurements provided by the Oyo Corporation.

RESULTS

A spectral analysis of the P- and S-wave recordings indicates that the S-wave reflections had a frequency content ranging between about 40 and 200 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 350 Hertz with a predominant frequency of about 180 Hertz. The amplitude spectra from typical P- and S-wave recordings at a single geophone location are provided on Figure 4.

The P-wave velocity was typically found to be in the range of 5,000 to 7,000 ft/s whereas the S-wave velocity ranged between about 1,000 to 3,000 ft/s (Figure 3). The average Vs/Vp ratio was 0.37 (Vp/Vs = 2.67) in the Cooper Formation, although significant variation was measured (Figure 3).

The resolution achieved with the P- and S-waves is depicted on Figure 5 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 as this can control ground water flow and are as thin as would normally be logged form 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 form the P-waves.

Evidence of the resolution achieved using S-waves with the seismic reflection technique can be observed from the actual S-wave profile (Figure 6). Numerous reflections can be observed in the top 50 feet and even within the top 12 feet. In terms of lithology, many of these reflections correspond to layers as thin as two feet.

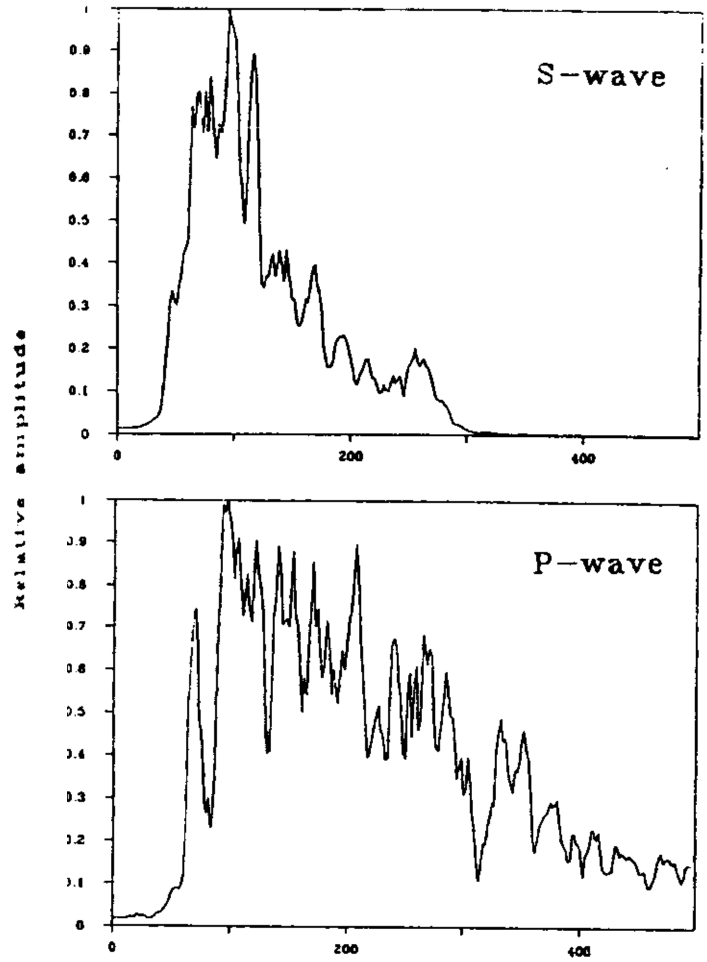

Figure 4 - Amplitude spectra of P - and S-wave reflection signals

This section is believed to be one of the highest resolution seismic reflection profiles ever recorded on land.

When a direct comparison is made between the P-wave and S-wave sections, after both have been converted to a common depth scale, the improvement in resolution using S-waves in obvious (Figure 7). Many more reflections are visible on the S-wave section than on the P-wave section, even though both are of excellent quality. Improved resolution is an important factor in determining the reason why so many additional S-wave reflections are present, but other factors also contribute to this effect. P-wave reflections are not present or are poorly defined where saturated sands are present. This is interpreted to be due to the water saturation obscuring the P-wave velocity contrast between the sand and clay. As the S-waves are not affected by the fluid content of the sediments, they essentially respond to the lithologic contrast between the sand and clay and show up as strong reflections (Johnson and Clark, 1992). The data from the field experiments indicate that it is possible to directly detect confined and unconfined aquifers from a careful comparison of the P- and S-wave data.

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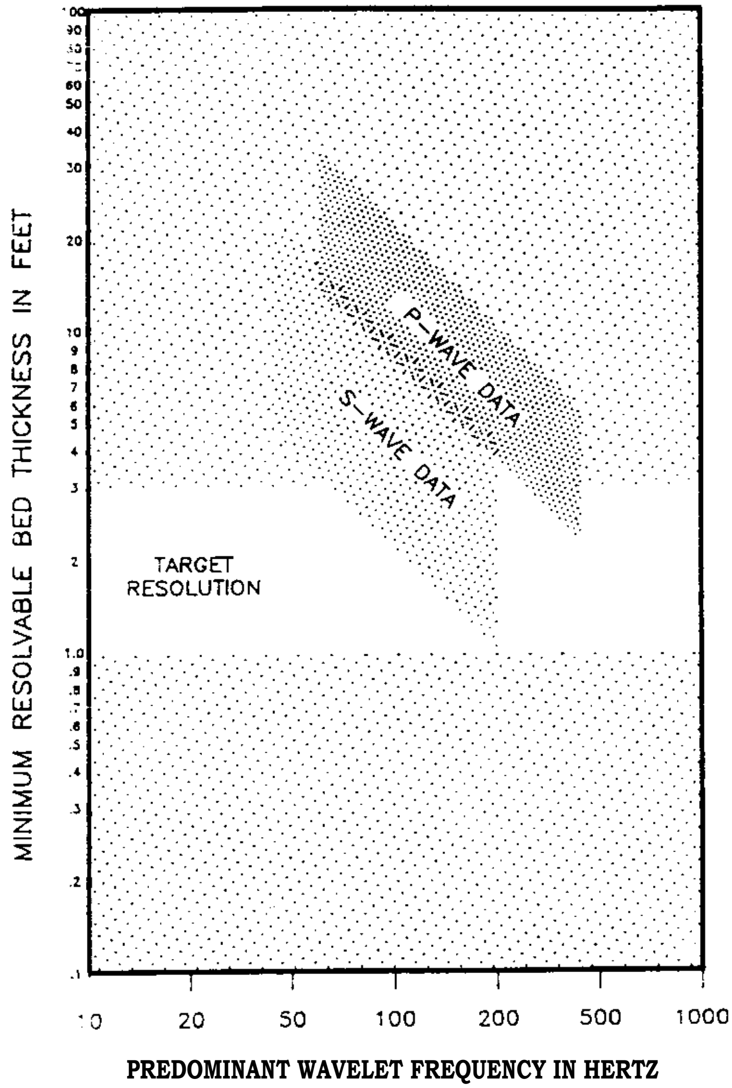

Figure 5 -Comparison of P- and S-wave signals in terms of resolution achieved from the field experiments

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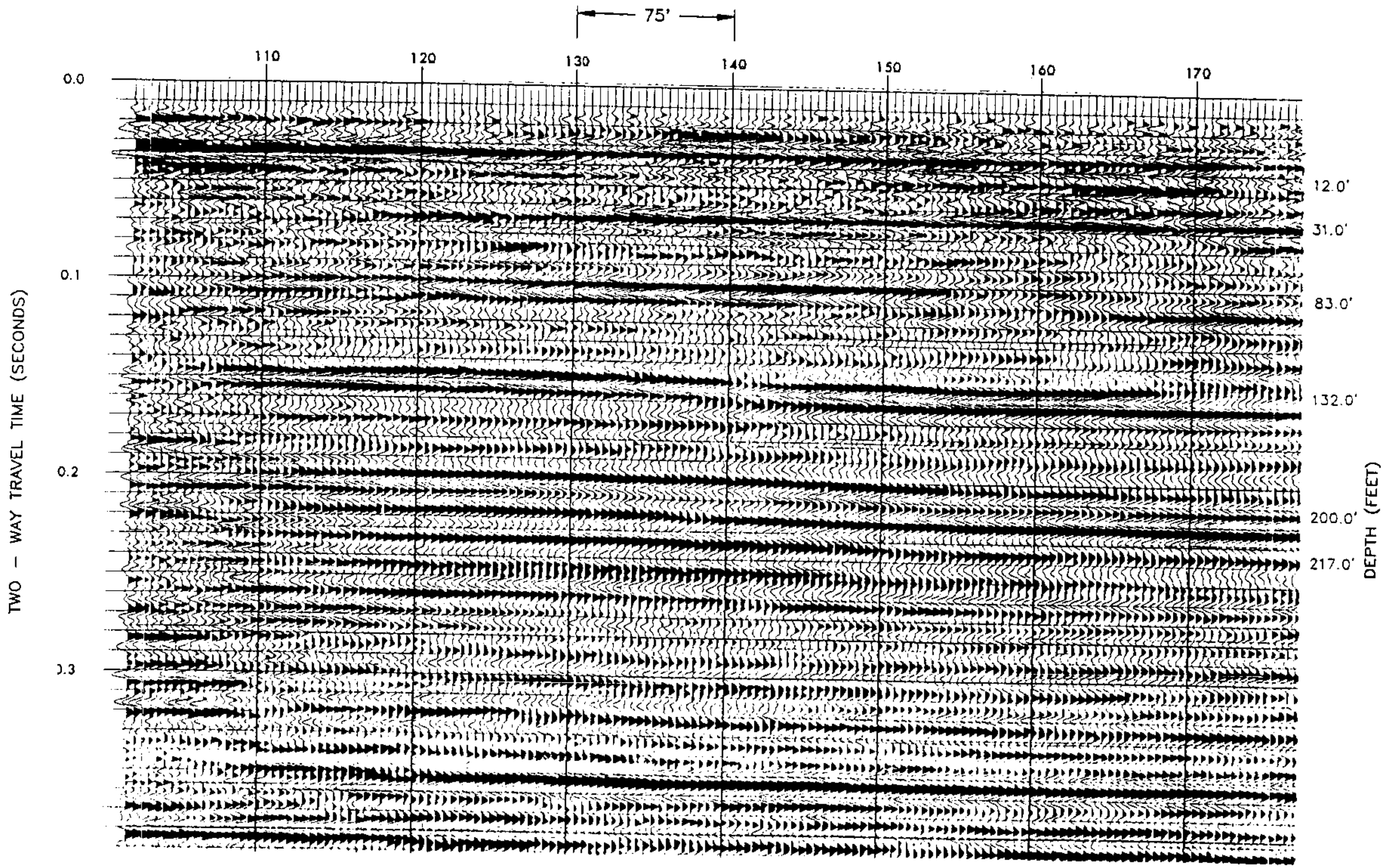

Figure 6 -Portion of S-wave reflection profile obtained from the final field experiment at Cooke Crossroads Test Site

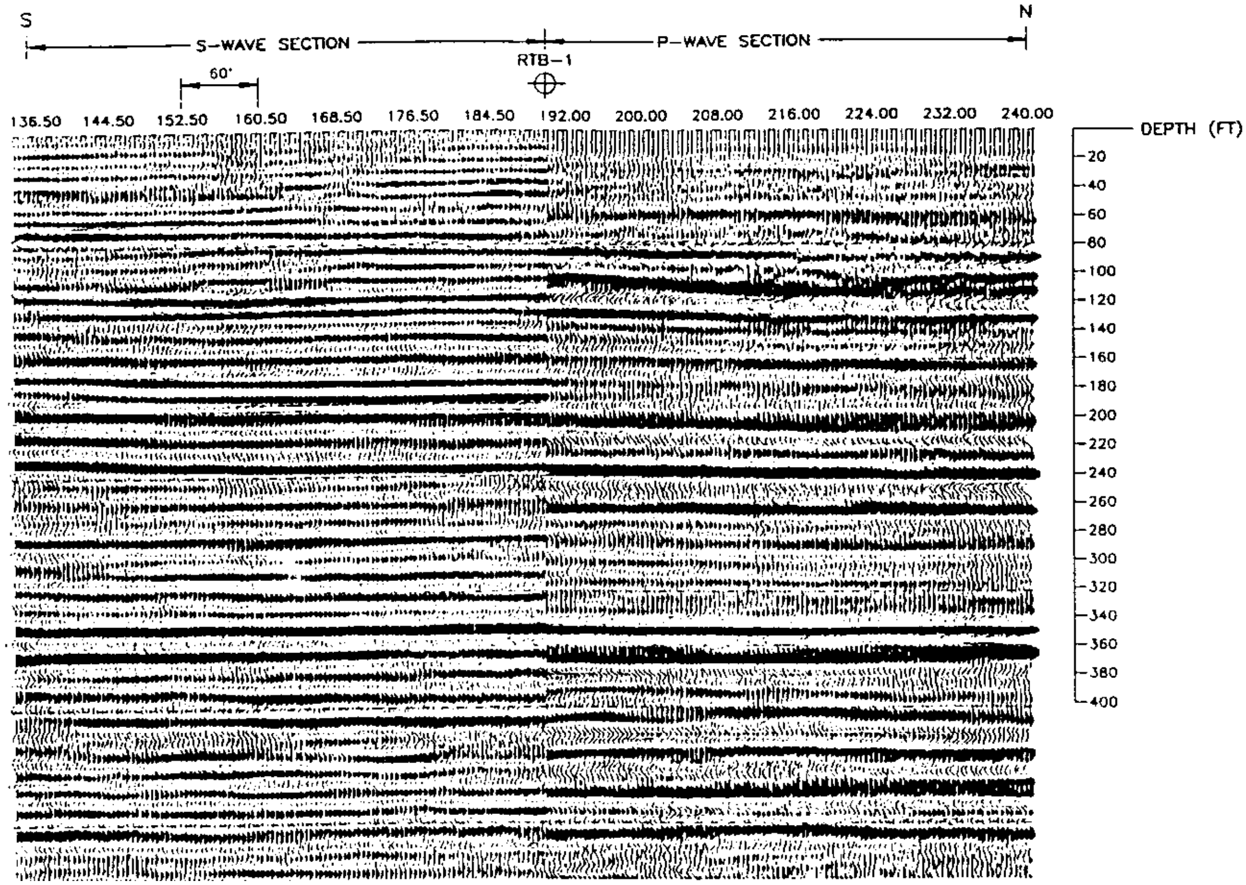

Figure 7 - Correlation of P- and S-wave depth sections at location of control boring RTB-1, Cooke Crossroads Test Site