Amplitude-versus-offset analysis using the vertical seismic profile.

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ABSTRACT

The use of a walkaway vertical seismic profile (WVSP) geometry is shown to have application to amplitude versus offset (AVO) analysis of reflected P-waves and mode-converted (P-SV) waves. Three-component processing of a synthetic WVSP data set results in true amplitude P-wave and SV-wave gathers. The amplitudes of these gathers are shown to correlate with the theoretical Zoeppritz equation solution suggesting that an inversion of the WVSP amplitudes can be used to obtain the Poisson's ratio contrast across an elastic boundary.

INTRODUCTION

AVO analysis has been considered for some time as a useful exploration tool (Chacko, 1990; Ostrander, 1984). The main thrust of AVO analysis is to obtain subsurface rock properties using conventional surface seismic data. The Poisson's ratio change across an interface has been of particular interest. These rock properties can then assist in determining lithology, fluid saturants, and porosity. This paper considers the use of a WVSP to help resolve the uncertainties that may be associated with surface seismic AVO analysis.

It has been shown through solution of the Knott energy equations (or Zoeppritz equations) that the energy reflected from an elastic boundary varies with the angle of incidence of the incident wave (Muskat and Meres, 1940). This behavior was studied further by Koefoed (1955, 1962): He (1955) established that the change in reflection coefficient with the incident angle is dependent on the Poison's ratio difference across an elastic boundary. Poisson's ratio is defined as the ratio of transverse strain to longitudinal strain (Sheriff, 1973), and is related to the P-wave and S-wave velocities of an elastic medium by equation (1). Koefoed (1955) also proposed analyzing the shape of the reflection coefficient vs. angle of incidence curve as a method of interpreting lithology.

$$\sigma = \frac{1/2(V_p/V_s)^2-1}{(V_p/V_s)^2-1} \qquad (1)$$

Ostrander (1984) introduced a practical application of the amplitude variation with incident angle phenomenon. He used the Zoeppritz amplitude equations (eg. Aki and Richards, 1980) to analyze the reflection coefficients as a function of the angle of incidence for a simple three-layer, gas- sand model. The model consisted of a sand layer encased in two shale layers. By using published values of Poisson's ratio for shales, brine saturated

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sands, and gas saturated sands, he determined that there is a significant enough change in reflection coefficient with angle of incidence to discriminate between gas saturated sands and brine saturated sands. He tested his theoretical observations with real seismic data and determined that AVO could be used as a method of detecting gas sands.

AVO analysis in general, is limited by the assumptions and approximations inherent in surface seismic acquisition, processing, and interpretation. These factors include receiver arrays, near surface velocity variations, differences in geometrical spreading from near offset to far offset, dispersive phase distortion, multiples interfering with primaries, wavelet phase, source directivity and array effects (pers. comm. R. R. Stewart, 1990). In addition, AVO analysis requires accurate determination of the angle of incidence at an interface, the accuracy of which depends on an accurate velocity model. Common midpoint sorting is based on the common mid point assumption which may not be valid for dipping layers or antisymetric ray paths. Although these assumptions and limitations may be insignificant for many surface seismic applications they may overwhelm a subtle effect such as AVO.

There are several borehole measurements available to obtain the P-wave and S-wave velocities, such as the full waveform sonic tool and the vertical seismic profile (VSP). Sonic measurements can yield accurate Vp/Vs ratios and can be used to model the seismic AVO response, but these measurements are in the 10-20 kHz. range, while seismic measurements are in the 5-100 Hz range. As the VSP can be used to correlate well logs to surface seismic measurements, the VSP can be used to associate surface seismic measurements and borehole sonic measurements.

Vertical Seismic Profiling

The VSP can be used to gain insight into wavefield propagation. There are several aspects of the VSP which can often be used to an advantage.

- The downgoing wavefield is recorded, and can be used to design a deconvolution operator which eliminates many of the wavefield propagation effects (such as multiples).

- The zero phase and largely multiple free response to the earth's reflectivity can be obtained through deconvolution based on the downgoing wave.

- A good correlation of seismic events with lithological boundaries can be made.

- The amplitude of the downgoing wavefield is recorded, and can be used to obtain a good estimate of the seismic reflection coefficient of an interface.

- The incident and reflected amplitudes can be measured immediately above the interface, eliminating most wavefield propagation effects.

Furthermore, the VSP can be used to measure the shear wavefield through three component recording and processing. This yields two separate amplitude measurements from the same interface. Consequently the results of the S-wave AVO analysis can be used to verify the results of the P-wave AVO analysis. Therefore, the VSP is a promising method of observing AVO because of its independence of many of the assumptions involved in surface seismic processing.

A WVSP geometry (Figure 1) is used to record data specifically for the analysis of the AVO behavior for a particular interface. Several offsets are necessary to obtain a value of the reflection coefficient for several P-wave angles of incidence. The wave field is recorded at eleven levels in the borehole to accommodate multichannel wavefield separation filters. Recording the wavefield directly above the reflector is a major advantage of the VSP. This receiver geometry eliminates most of the wavefield propagation assumptions (attenuation and spherical spreading), and should yield an accurate measurement of the reflection amplitude by measuring the ratio of the incident wave to the reflected waves.

METHOD

Seismic Model

This study involves the processing and interpretation of a synthetic data set in the interest of true amplitude recovery and AVO analysis. The geologic model, source positions, and receiver positions are shown in Figure 1. The velocities are shown in Figure 2. The model is purposely simple, with the interface in question being shale over a gas sand using the velocities and densities (for a gas sand and shale) given by Ostrander (1984). The synthetic WVSP data set consist of 5 offsets with 11 levels each recorded at offsets of 50 m, 200 m, 400 m, and 600 m giving a range of incident angles from 0 to 45 degrees. The data were generated by ray tracing and convolution with a 35 Hz zero phase wavelet. The synthetic data include the P-wave direct arrival, P-P reflection, P-SV reflection, and S-wave direct arrival. The data were processed using the 3-component processing flow outlined in Figure 3.

Processing

The first step in the processing flow was to separate the data into the four wavefields; the downgoing P wavefield, the downgoing S wavefield, the upgoing P wavefield, and the upgoing S wavefield. This was accomplished using a parametric inversion technique (Esmersoy, 1989). The separation of the vertical and radial channels (Figure 4) into the four wavefields for the 400 m offset is shown in Figure 5.

Waveshaping deconvolution is an important step in the 3-component processing flow. In this process, an operator is designed which collapses the downgoing P wavefield into a zero phase wavelet. The operator is then applied to the upgoing P wavefield and upgoing S wavefield to obtain the zero phase and largely multiple free seismic response to the earth's reflectivity. Using waveshaping deconvolution to obtain the zero phase and multiple free reflections implies that the true amplitudes can be picked with minimal assumptions about phase or multiples.

Following waveshaping deconvolution each WVSP was corrected for normal moveout (NMO). The P-waves and S-waves of each WVSP were corrected for NMO using the velocity model shown in Figure 3. The NMO correction algorithm outputs the NMO corrected traces in two-way P-wave traveltime (Geis et al.,1990). The waveshaping deconvolved, flattened, and bulk shifted downgoing P wavefield of the 400 m offset WVSP is shown in Figure 6. Note the zero phase wavelet. The NMO corrected P-P and P-SV traces of the 50 m offset WVSP are also shown in Figure 6.

The final processing step was to stack the data at each offset and gather into a pseudo CMP gather. This was done to increase the signal to noise ratio of the data. The P-wave and S-wave gathers are shown in Figure 7. The two events are the reflections from the top and base of the gas sand. Before gathering each offset, the reflected amplitudes were normalized by the amplitude of the incident P-wave so the gathers are true amplitude.

RESULTS

The method was tested by plotting the processed data amplitudes and the theoretical reflection coefficients versus incident angle. The amplitudes of the P-wave and S-wave reflections from the top of the gas sand were extracted from the P-wave and S-wave gathers. The angle of incidence for each offset of the walkaway survey was obtained from ray tracing through the model shown in Figure 1. The theoretical reflection coefficients were calculated using the Zoeppritz amplitude equations, and superimposed on the reflection coefficient versus angle of incidence plot (Figure 8). There is a good correlation between the processed data amplitudes and the theoretical amplitudes. The final step in the AVO analysis of real data would be to obtain a value of Poisson's ratio using forward modeling or a generalized linear inversion technique (Russell, 1988).

CONCLUSION

The AVO WVSP is a new approach to the problem of interpreting subsurface rock properties using the reflectivity versus angle-of-incidence phenomenon. The WVSP geometry and 3-component processing flow have been shown to result in true reflectivity gathers for P-waves and mode-converted S-waves. This suggests that the gathers can be used independently in an AVO analysis, and compared with surface seismic to possibly resolve some of the uncertainties that may be present in the surface seismic AVO analysis. Therefore with true amplitude processing and both P-wave and mode-converted S-wave reflectivities, the AVO WVSP has promise to enhance conventional AVO analysis.

FUTURE WORK

Possible future work includes a detailed AVO analysis of surface seismic and WVSP data with a comparison of the surface seismic results with the WVSP results. Determining the optimal use of mode-converted S-waves in AVO analysis through modeling and real data analysis. Also, continued work on the problem of thin bed effects on AVO as initiated by Chung (1989) and Treadgold et al. (1990).

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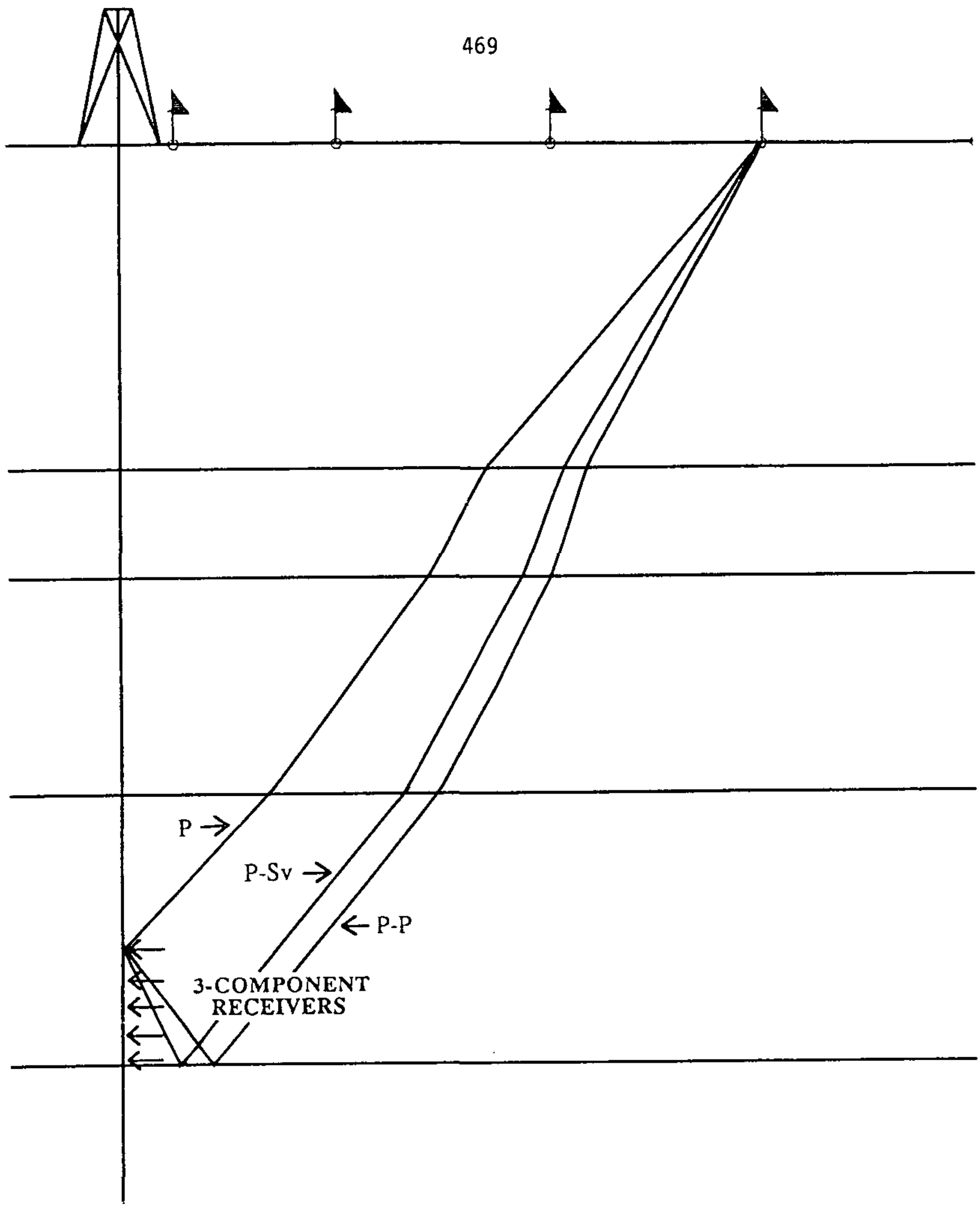

Figure 1: AVO walkaway vertical seismic profile geometry.

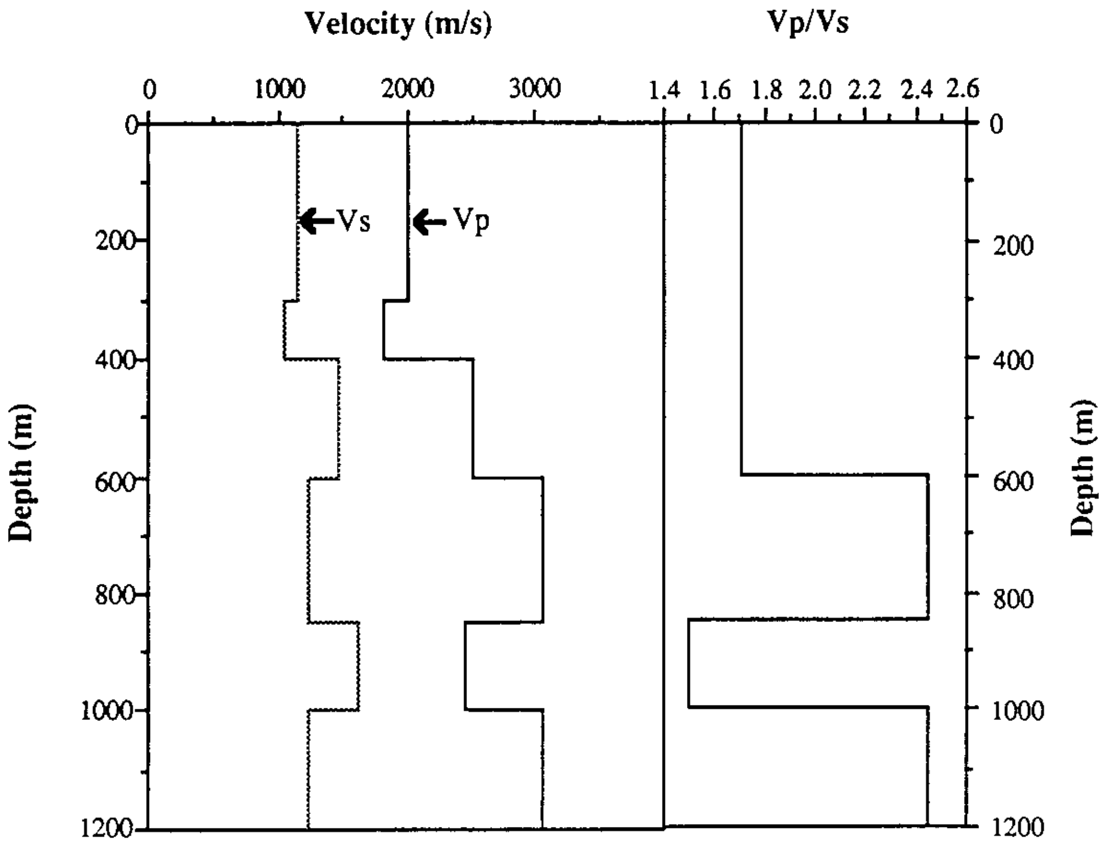

Figure 2. Velocities and Vp/Vs ratio.

3 COMPONENT PROCESSING FLOW

Parametric Inversion
(wave field separation)

⇓

Waveshaping Deconvolution

⇓

Normal Moveout Correction

⇓

Stack Each Walkaway VSP

⇓

Gather Walkaway Stacks

Figure 3: 3-Component processing flow.

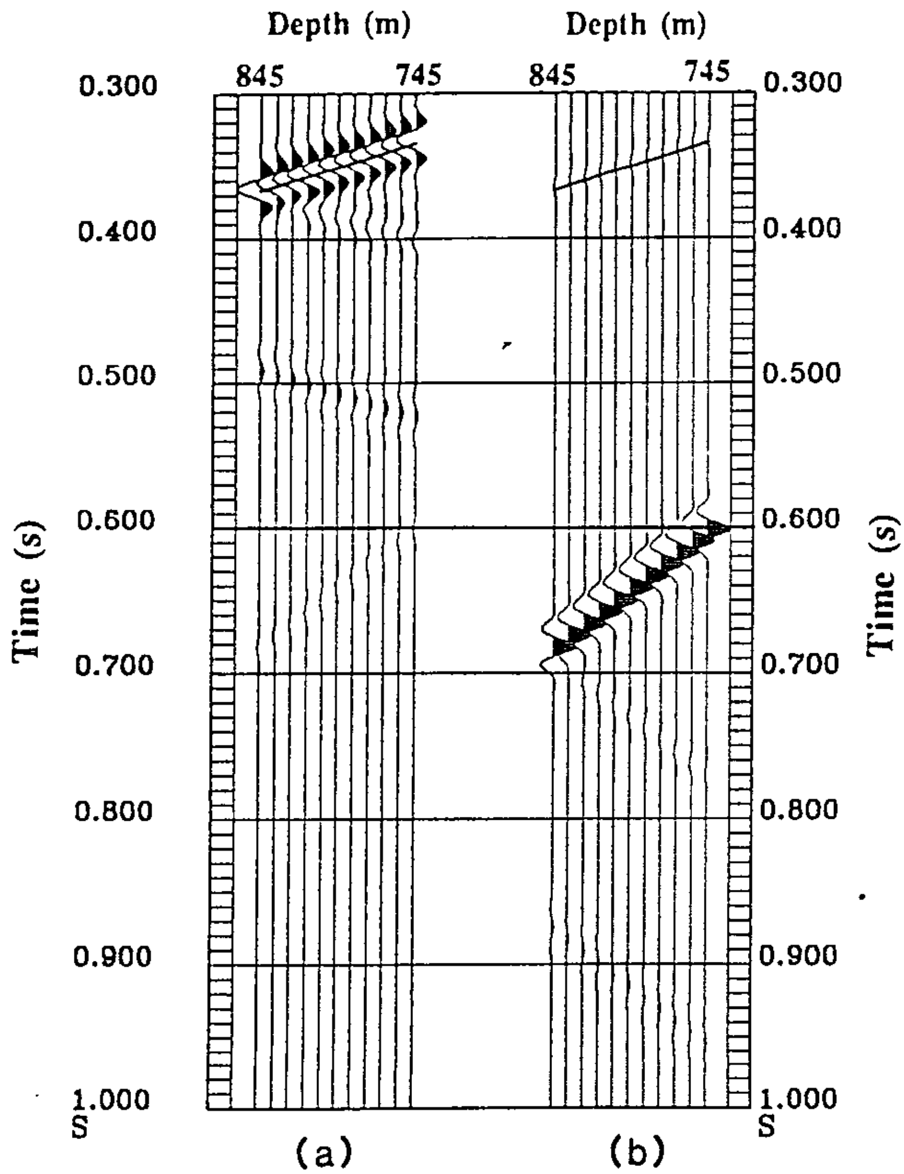

Figure 4: (a) Raw vertical channel. (b) Raw radial channel.

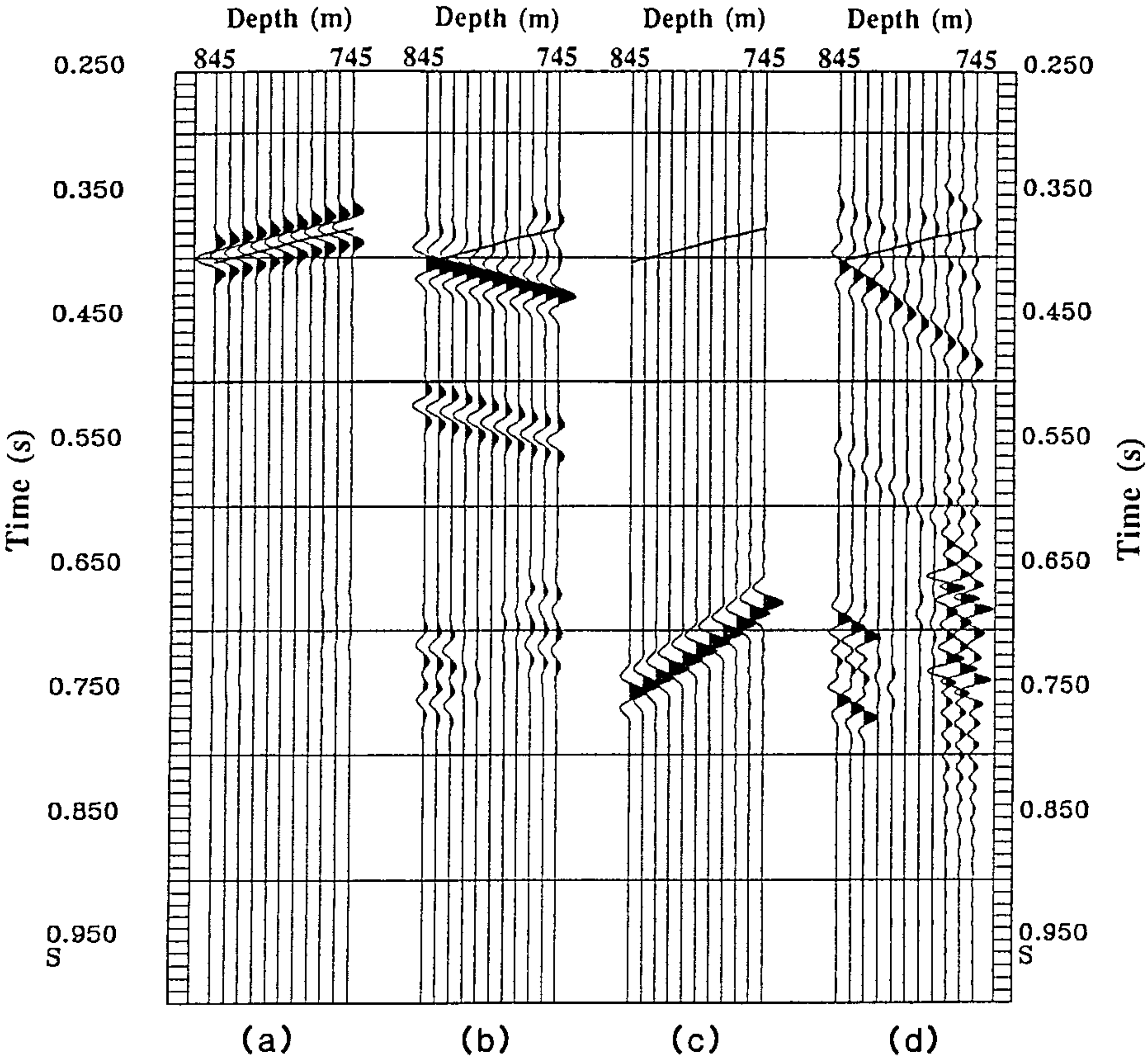

Figure 5. Wavefield separation for the 400 m offset WVSP. (a) Separated downgoing P wavefield. (b) Separated upgoing P wavefield. (c) Separated downgoing S wavefield. (d) Separated upgoing S wavefield.

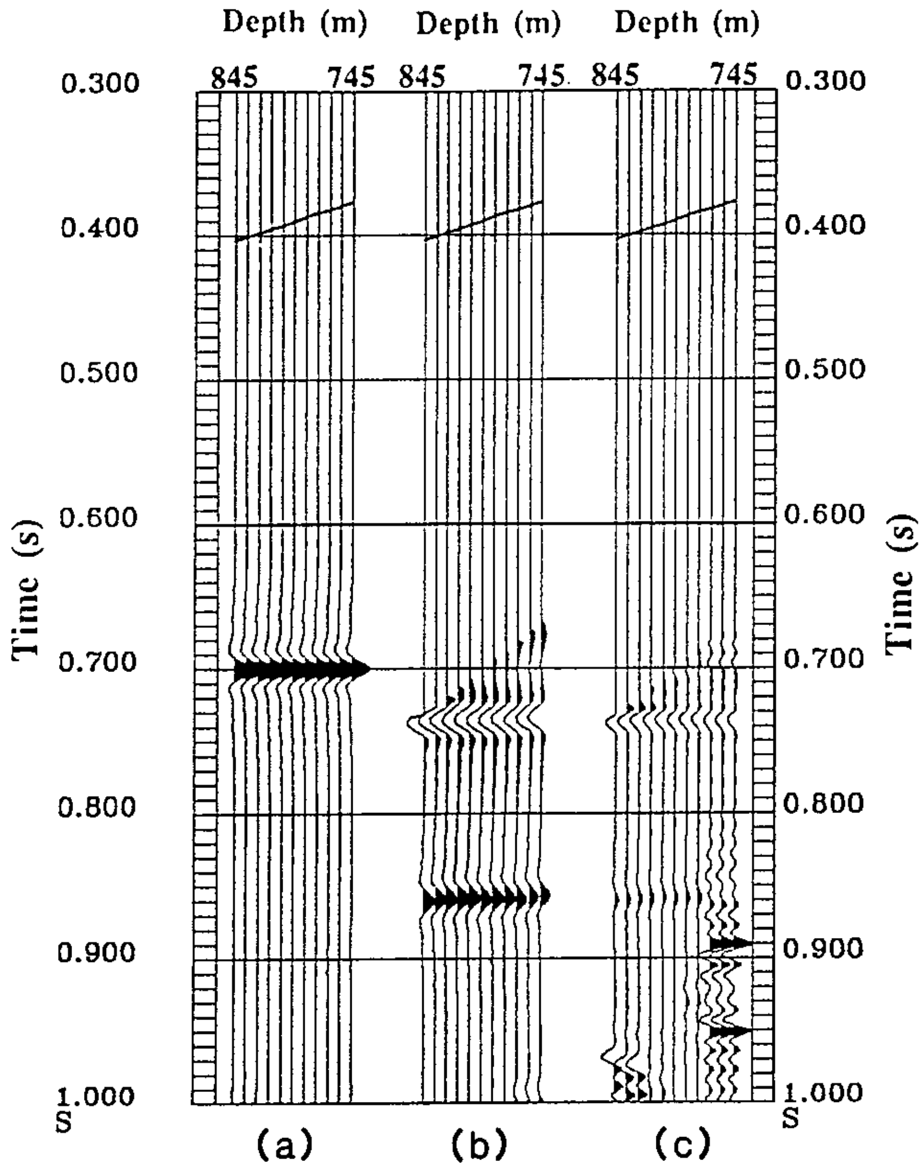

Figure 6. (a) Aligned downgoing P-wave. (b) NMO corrected upgoing P-wave. (c) NMO corrected upgoing SV-wave.

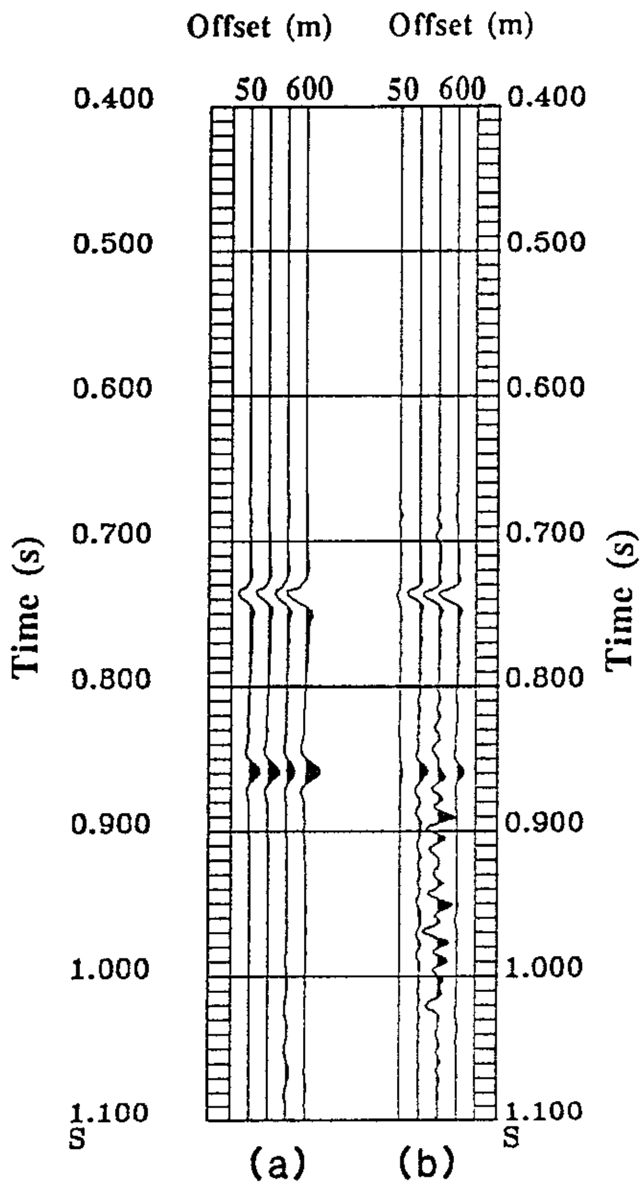

Figure 7. (a) P-wave gather. (b) S-wave gather.

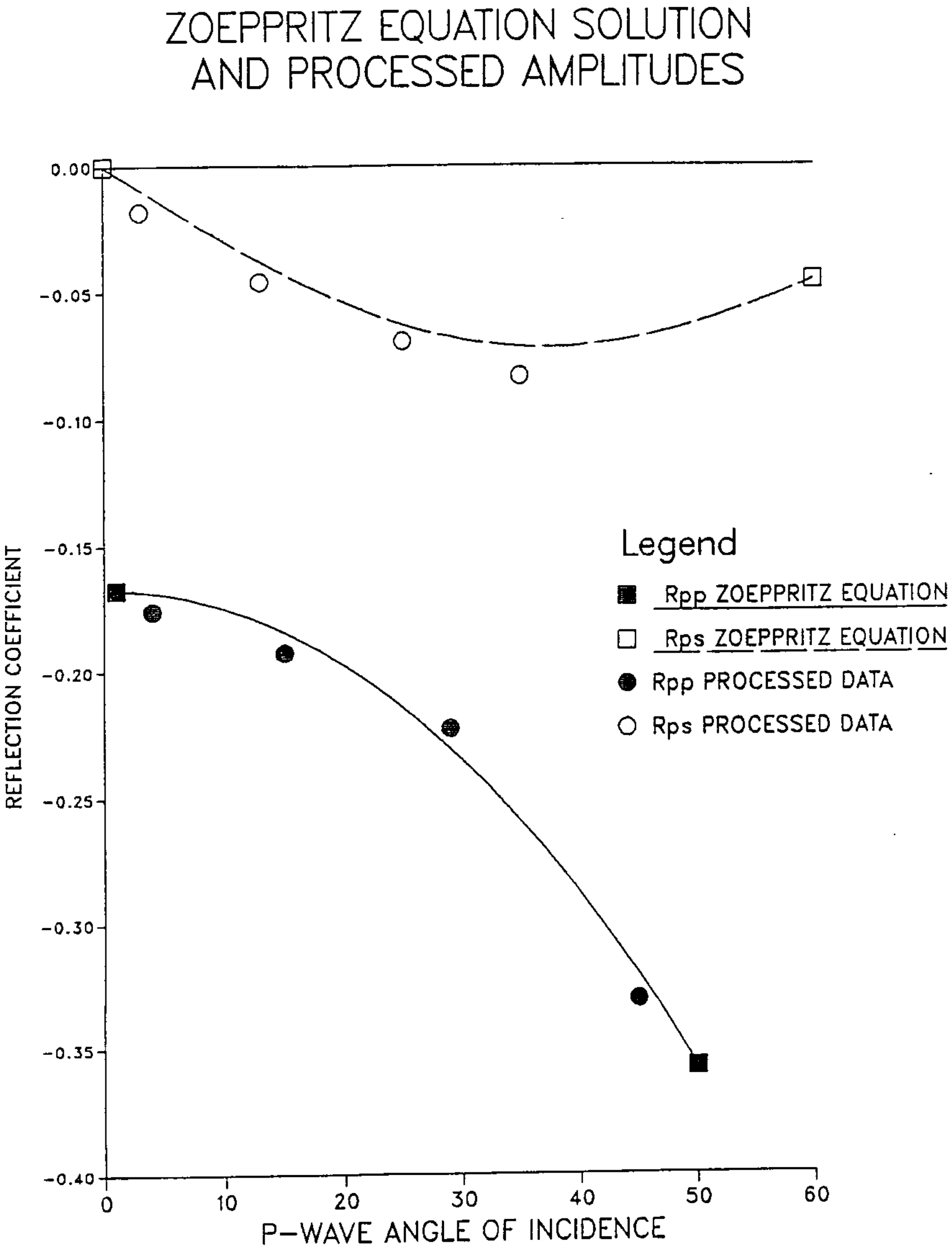

Figure 8. Theoretical Zoeppritz equation solution with processed data amplitudes superimposed.