The determination of converted-wave statics using P refractions together with SV refractions

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ABSTRACT

In order to improve the static solution of converted (P-SV) wave data recorded on the radial channel of three-component seismic surveys, shear-wave refractions are used to obtain a model of the near-surface velocities and thicknesses for shear waves, in the same way that P-wave refractions have been used previously. The static shifts due to shear waves are then calculated using ray-tracing. By combining the receiver terms of the shear-wave statics solution with the source terms of P-wave statics solution, the statics solution for converted waves using P-wave and SV-wave refractions, also referred to in this report as the 'P-SV refraction statics solution', is obtained. Any noticeable, large static shifts remaining after application of this method are then readily removed using common-receiver stacked sections. Using an automatic residual statics program on the data then results in a final section with most of the statics shifts removed.

Two static-removal methods, hand-picking and P-SV refraction statics, are applied to the radial component of a compressional-source, three-component, seismic data set from northern Alberta; Slave Lake, Line EUE001. The amount of time required for the entire process is similar for the two methods; however, the resolution and continuity of reflections is improved using the P-SV refraction statics solution. Further, since the P-SV refraction statics solution derives long-wavelength static shifts from an actual model of the Earth, rather than by comparing the shifts seen on reflections across the section, the P-SV refraction statics solution provides a more realistic long-wavelength statics solution.

INTRODUCTION

One of the latest innovations in geophysics has been the advent of attempts to obtain a shear-wave picture of the subsurface. Since shear-wave particle motion is perpendicular to the direction of propagation if isotropy is assumed, it is necessary to record another channel, the radial channel, as well as the vertical channel traditionally used for P-wave surveys, in order to obtain good records of SV-wave motion. To avoid having to use another source as well, converted-wave data uses a compressional source, but the waves have been converted from P to SV by reflection from a layer in the subsurface. However, since shear waves experience much larger static shifts due to the near surface than P waves, static problems in converted-wave sections are more prevelant than P-wave static problems. Traditionally, statics on compressional seismic data have been removed by first accounting for elevation differences and then analyzing P-wave refractions to obtain a model with thicknesses and velocities of the near-surface layers (Gardner, 1939). This model is then used to determine the shift in traveltime of the raypath relative to a chosen datum plane. Similarly, shear-wave refractions can be used to give a model of the near-surface (Lawton, 1989b). The objective of this study is to attempt to solve the converted-wave static problem by using both P and SV refractions to obtain a solution for converted-wave statics.

METHOD

Converted-wave seismic data is generally recorded on three channels; the vertical, radial and transverse channels: hence, the name three-component seismic data is also used when referring to converted-wave seismic data. The usable data on the vertical channel is mostly P-wave data, while the radial and transverse channels record the converted waves, P-SV and P-SH waves, respectively. Each of these channels should be processed separately, since they contain substantially different wave types. The vertical channel is usually processed first since regular P-wave processing flows can be applied. The final P-wave static solution and velocities are then modified and applied to the radial channel. Source-derived statics should remain consistent from the vertical to the radial channel, but receiver statics for the radial channel are expected to increase, since the converted wave travels from the reflector to the receiver as a shear wave. Assuming a Vp/Vs ratio of 2, the statics can be estimated at 1.5 times the P-statics, while the velocities are 0.75 times the P-velocities.

The ratio of P-wave velocity to S-wave velocity is however not constant throughout the seismic section, and is particularly variable in the near-surface (Figure 1). Since the static solution depends on the velocities in the near surface, it would be useful to be able to use both the P refraction and the SV refractions to determine the velocities and thicknesses of near-surface layers for SV waves as well as for P waves. This model could then be applied to the seismic data, rather than applying just a multiple of the P-refraction statics.

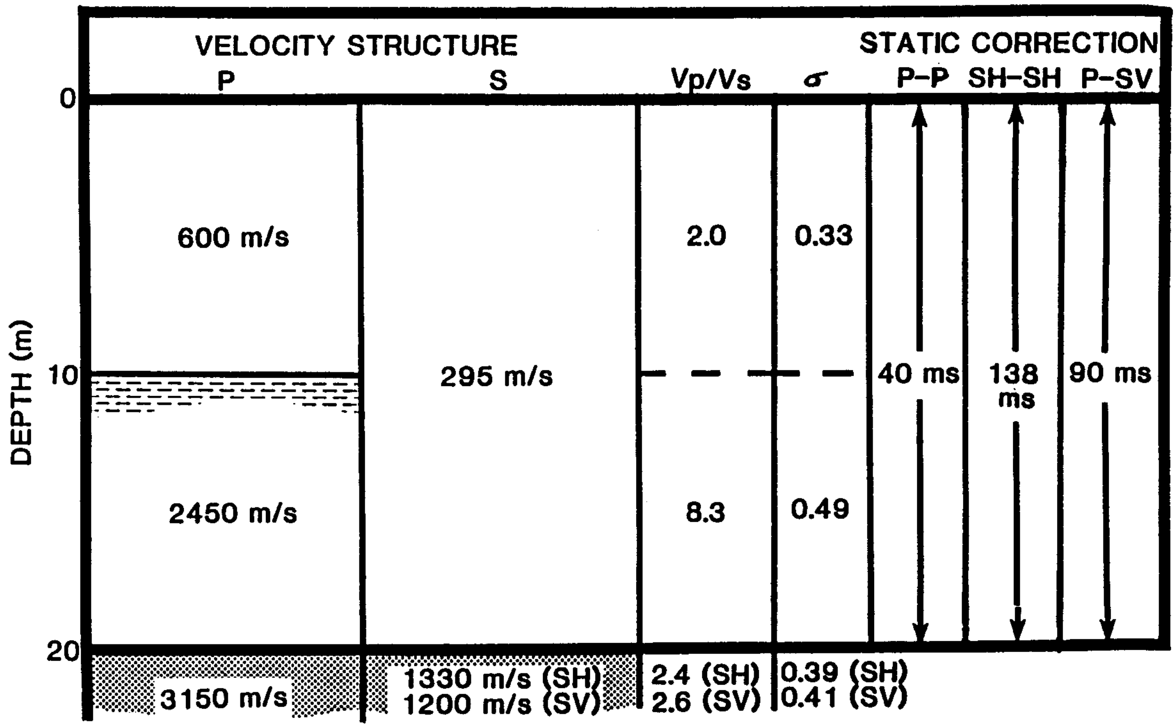

Fig. 1a: Near-surface P-wave and S-wave velocity structures from Jumping Pound, Alberta (from Lawton, 1989b).

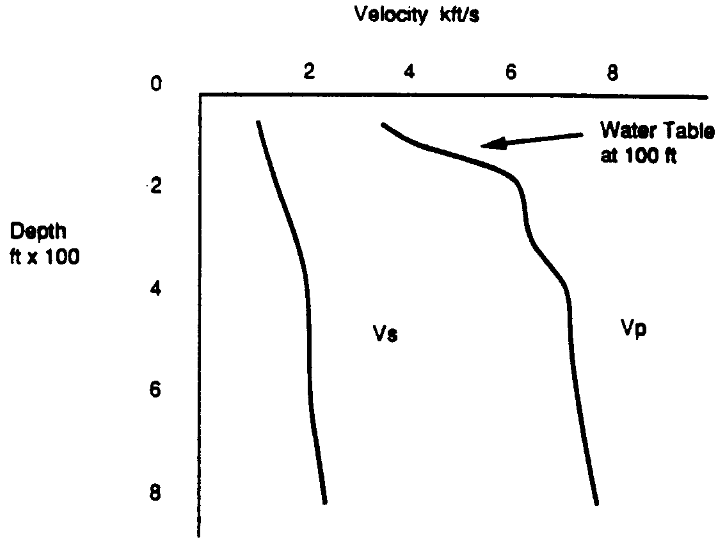

Fig. 1b: P-wave and S-wave velocity profiles for a south Texas site (from Houston, 1989).

This method is applied to a real data set from northern Alberta, Slave Lake Line EUE001. First, the vertical channel of this data is processed using a regular processing outlined below (Harrison, 1989).

DEMULTIPLEX
GEOMETRIC SPREADING COMPENSATION
SPIKING DECONVOLUTION
  100 ms operator, 0.1% prewhitening
CDP SORT
APPLY ELEVATION & REFRACTION STATICS
INITIAL VELOCITY ANALYSIS
AUTOMATIC SURFACE-CONSISTENT STATICS
  Correlation window of 450 to 1100 ms
  Maximum shift of + or -20 ms
VELOCITY ANALYSIS
NORMAL MOVEOUT APPLICATION
MUTE
CDP TRIM STATICS
  Correlation window from 400 to 1200 ms
  Maximum shift of + or -10 ms
STACK
BANDPASS FILTER
  Zero-phase, 12-65 Hz
RMS GAIN
  First window of 300 ms, second of 400 ms,
  subsequent windows of 800 ms length

The brute-stack section, stack section with the final static solution applied, and the f-k filtered stack section with final static solution applied are shown in Figure 2. Since processing the vertical channel in a three-component, compressional-source seismic survey is the same as processing a regular seismic survey using only vertical receivers, these stacked sections are equivalent to those that would be obtained using a standard P-wave seismic survey.

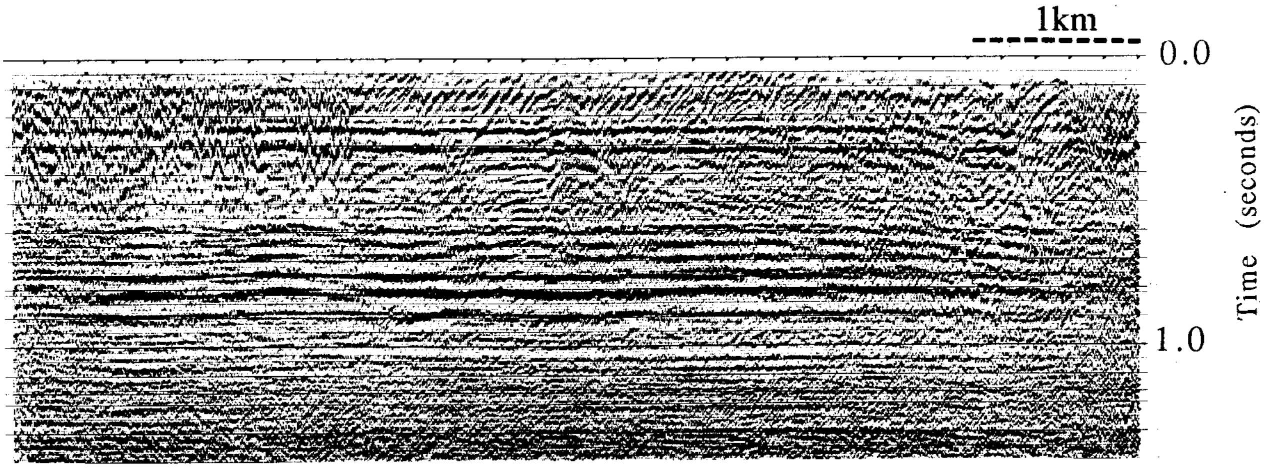

Fig. 2a: Brute stack section of the vertical (P-P) component data from Line EUE001, Slave Lake, northern Alberta

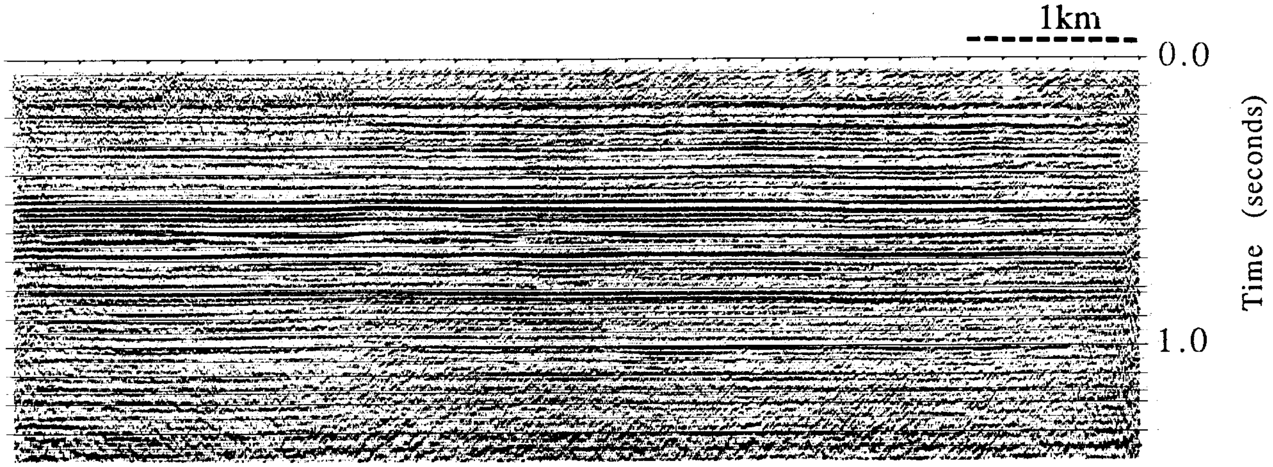

Fig. 2b: Vertical (P-P) component stack section with final statics applied.

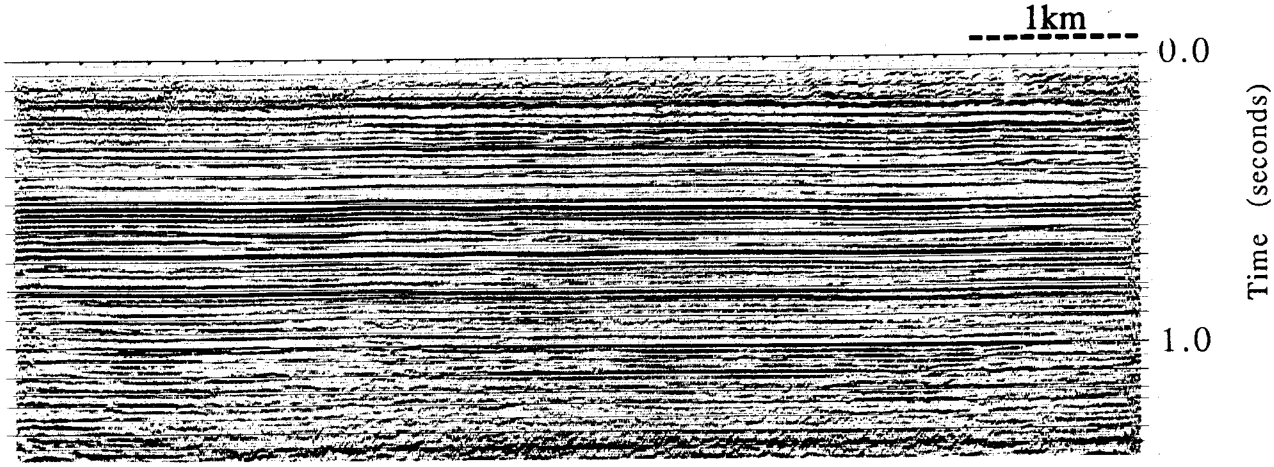

Fig. 2c: Vertical (P-P) component stack section with f-k filter applied.

Next, the radial channel was processed following the adapted basic processing flow for converted-wave data given below.

DEMULTIPLEX
GEOMETRIC SPREADING COMPENSATION
SPIKING DECONVOLUTION
    120 ms operator, 0.1% prewhitening
REVERSE THE POLARITY OF TRAILING SPREAD
APPLY FINAL P-WAVE STATICS
INITIAL VELOCITY ANALYSIS
APPLY HAND STATICS FROM SURFACE STACKS
AUTOMATIC SURFACE-CONSISTENT STATICS
    Correlation window from 600 to 1700 ms
    Maximum shift of + or -25 ms
CDP STACK
CONVERTED WAVE REBINNING
    Vp/Vs of 1.95 used
VELOCITY ANALYSIS
NORMAL MOVEOUT APPLICATION
MUTE
STACK
BANDPASS FILTER
    Zero-phase, 7-35 hz
RMS GAIN
    First window of 300 ms, second of 600 ms,
    subsequent windows of 900 ms length

Following this method, the statics for the radial channel are obtained by first applying the final P-static solution from the vertical channel. Next, the data is separated into common-sourcepoint and common-receiver stacked sections (Figure 3). Since the common-sourcepoint stacked section (Figure 3a) consists of the NMO-corrected, stacked, P waves, for which static corrections have been applied, there should not be any static problems left. However, the common-receiver stacked section (Figure 3b) has considerable static problems visible on it, since it consists of NMO-corrected, stacked S waves to which P-wave statics have been applied. In order to avoid cycle skipping by the automatic residual static program (Figure 4), the receiver-term statics must first be hand-picked from the common-receiver stacked section. The picking of statics by hand is, however, very time-consuming due to the difficulty in aligning reflectors which are extremely incoherent.

It is due to the laborious nature of picking the statics by hand that another method of applying static corrections was attempted. This method, which shall be referred to as P-SV refraction statics, involves using the source terms of the compressional-wave refraction statics solution combined with the receiver terms of a shear-wave refraction statics solution.

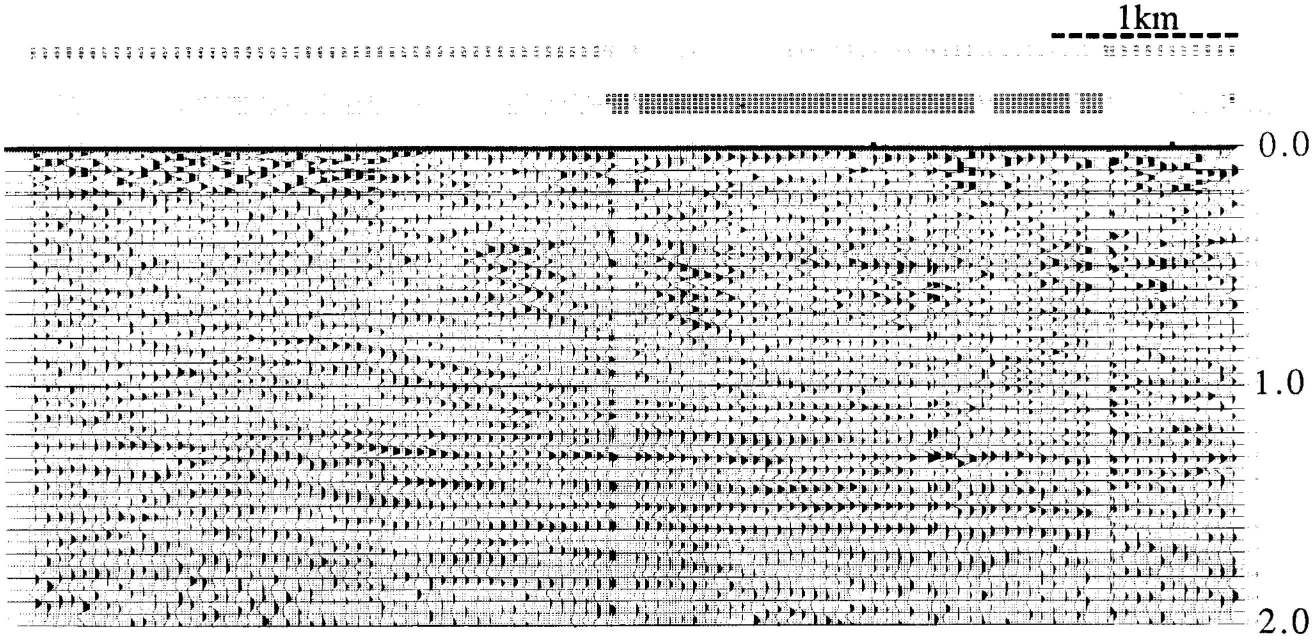

Fig. 3a: Common soucepoint stack section for the radial (P-SV) component data.

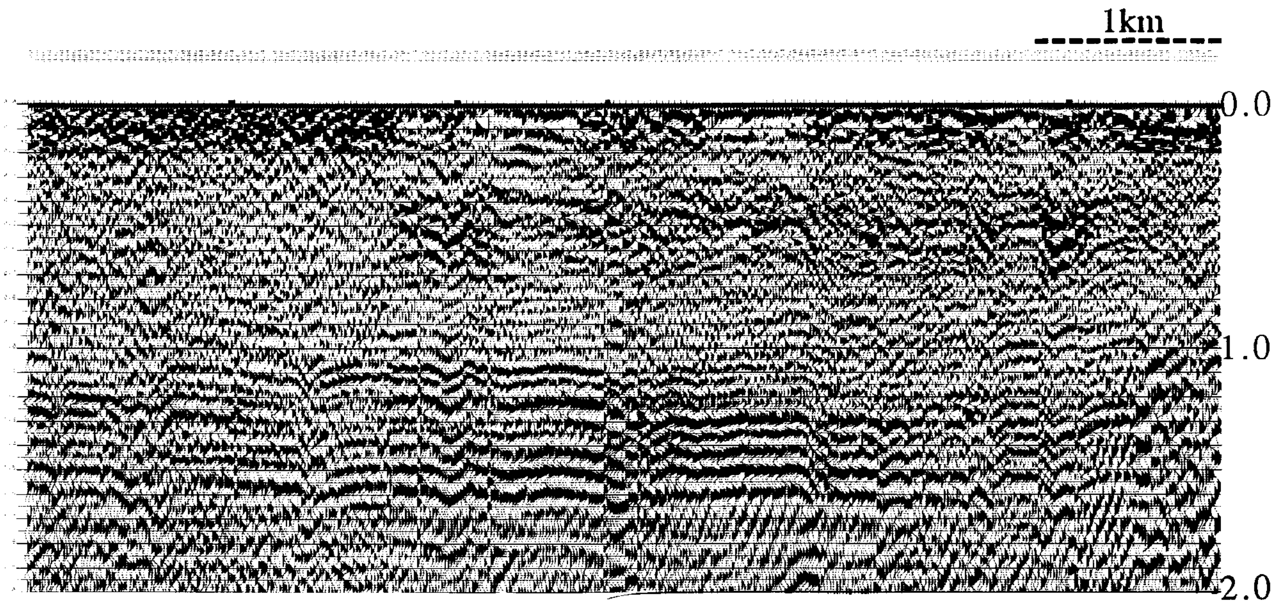

Fig. 3b: Common-receiver stack section for the Radial (P-SV) component data.

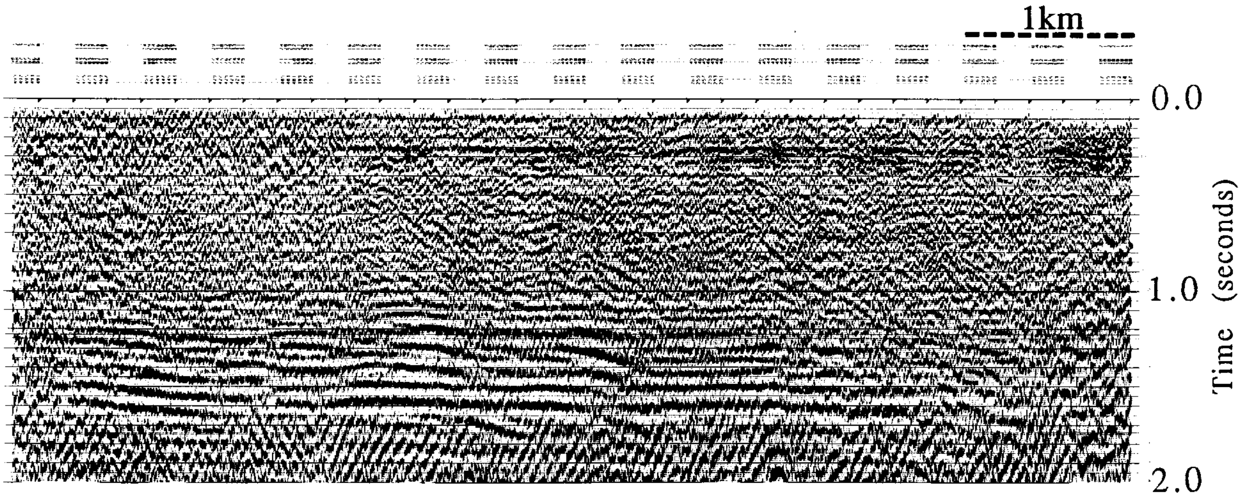

Fig. 4a: Brute stack section of the radial (P-SV) component data from Line EUE001, Slave Lake, northern Alberta.

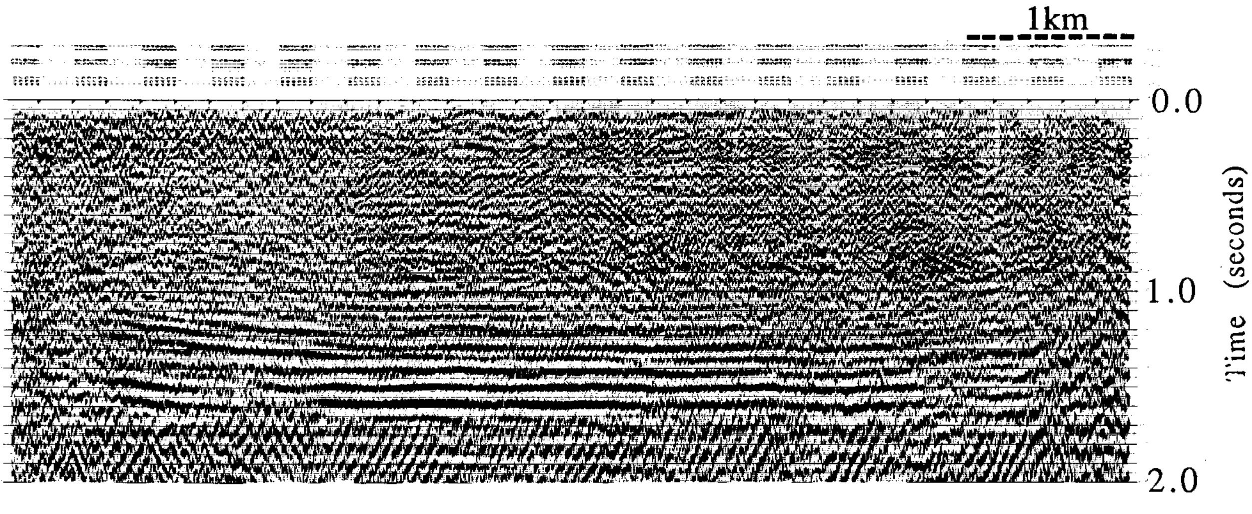

Fig. 4b: Radial (P-SV) component stack section with final statics applied.

The P-wave refraction static solution has already been determined in the processing of the vertical channel. Therefore, it is simply necessary to separate the source terms from the receiver terms and apply the source terms to the radial channel. The S-wave refraction statics solution, however, must first be obtained by picking the shear-wave refractions (Figure 5) on a workstation, then using an inversion routine (Boadu, 1988; de Amorim et. al., 1987) to solve for a model of the near-surface velocities and thicknesses for shear waves (Figure 6). This model is then ray-traced to determine the static shifts it would cause, and the source and receiver terms are separated. The receiver terms are then also applied to the radial channel to complete the P-SV refraction statics solution.

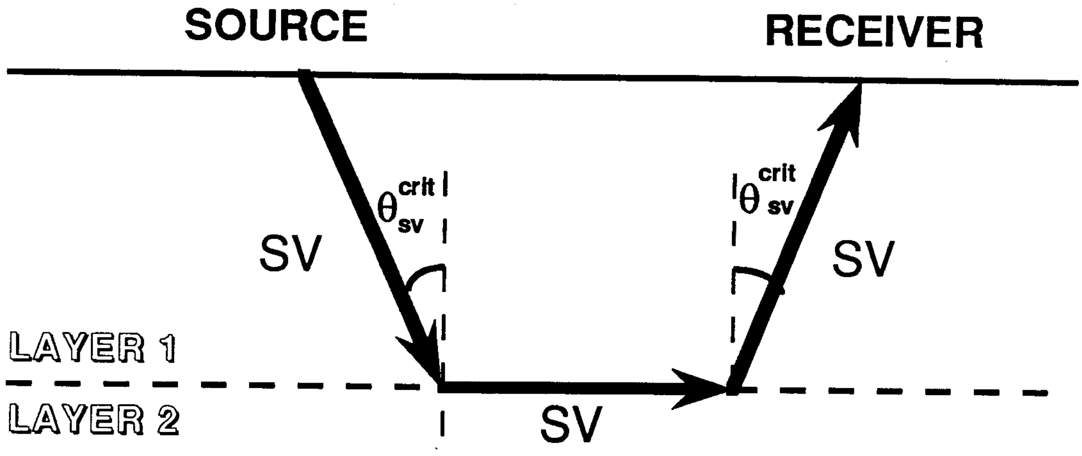

Fig. 5: Raypath diagram for a shear (SV-SV-SV) refraction.

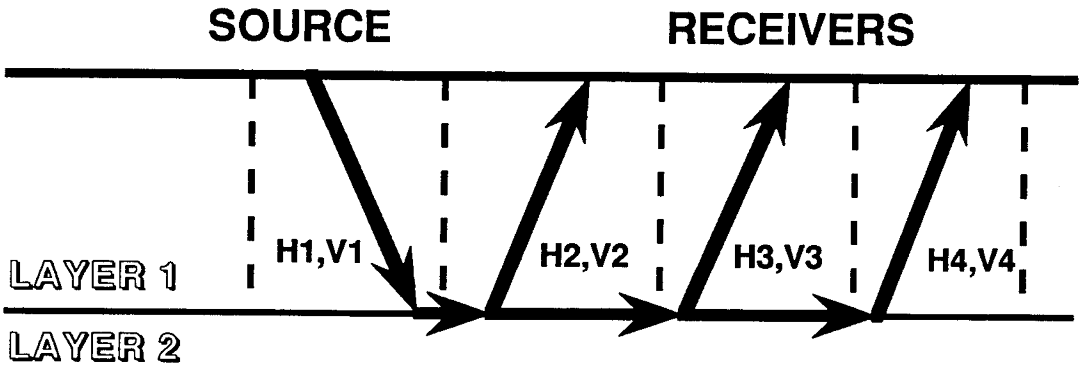

Fig. 6: Raypath diagram demonstrating tomographic inversion for refractions.

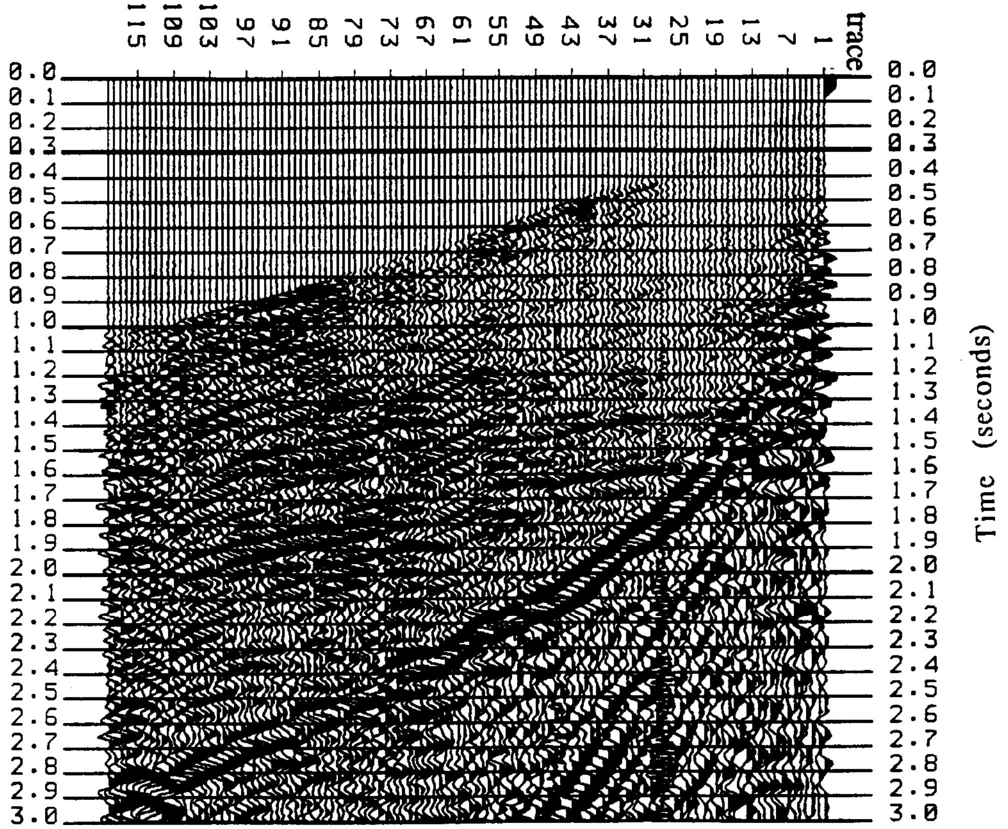

Fig. 7a: End-on, radial (P-SV) component shot record.

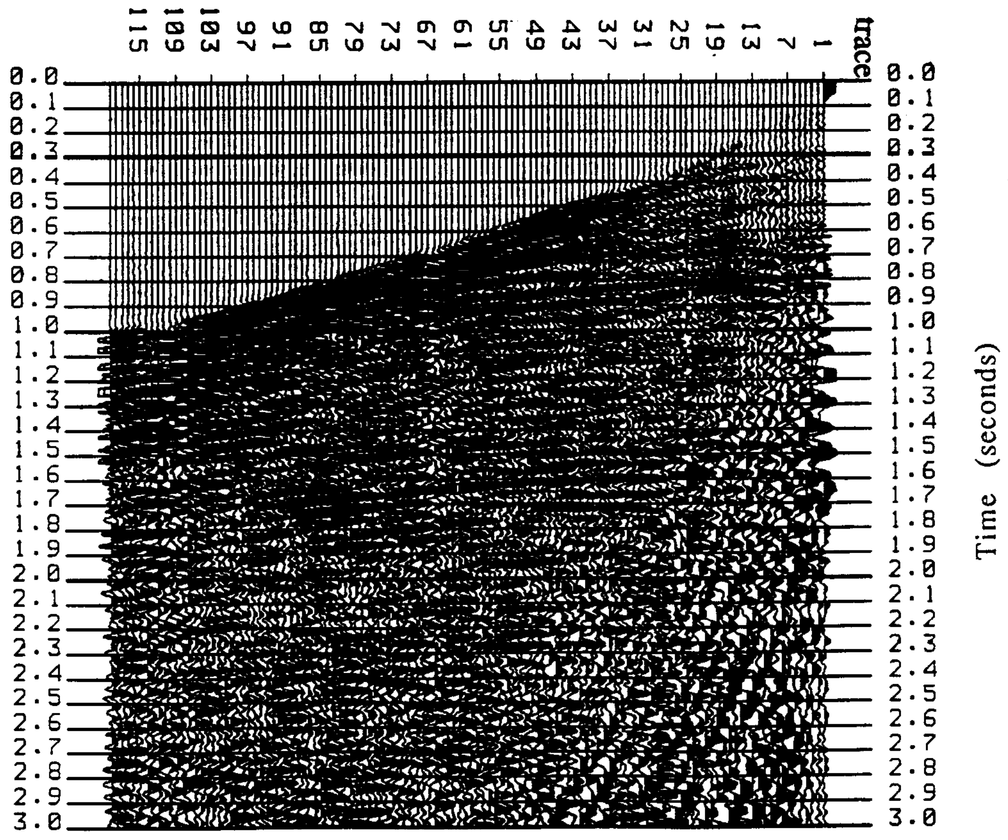

Fig. 7b: End-on, vertical (P-P) component shot record.

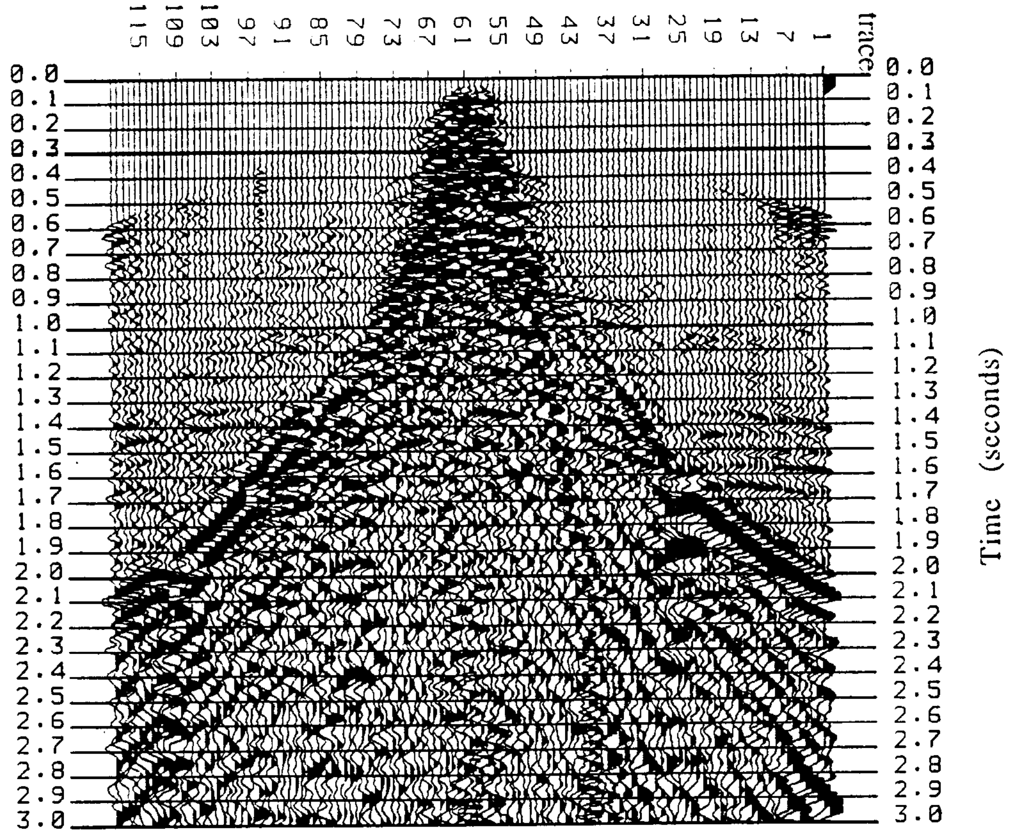

Fig. 8a: Split-spread, radial (P-SV) component shot record.

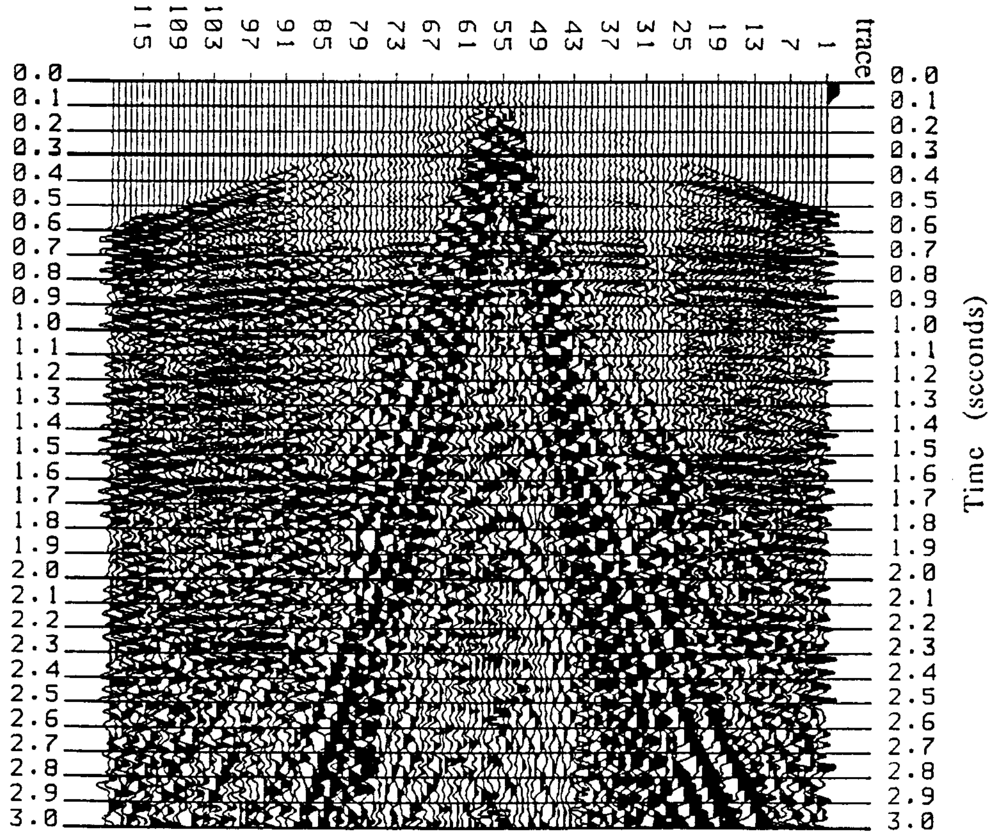

Fig. 8b: Split-spread, vertical (P-P) component shot record.

A shear-wave refraction is identified on the radial component shot records as an event which extends from the surface at the source point to 2.8 seconds at the far offsets (Figures 7a and 8a). This event is identified as being a shear refraction, since several layers are observed, with lower velocities than the P-wave refractions. Further, this event is not likely to be a Rayleigh wave, commonly called 'ground roll', since it does not appear on the vertical channel (Figures 7b and 8b). Rayleigh waves are polarized in the xz-plane, having retrograde elliptical particle motion from the inline horizontal to the vertical directions. Hence, Rayleigh waves would appear on both the vertical and the radial channels. Finally, the possibility of this event being a Love wave is ruled out by the fact that Love waves should be seen only on the transverse channel, while this event is predominantly observed on the radial channel. Thus, the event was identified as a shear-wave refraction and treated as such in order to obtain the refraction solution for shear waves.

The existence of shear refractions on compressional-source, seismic data may appear to be questionable, since very little shear energy is generated by a perfectly spherical explosion. However, it is possible for compressional waves to convert to shear waves soon after they have been generated, then to travel as shear waves back to the receiver. In this manner, refracted waves result which are close to being entirely shear-wave refractions. It is assumed for the purpose of finding the shear- wave static solution that the refractions observed are indeed true shear refractions and the traveltime as a compressional wave is ignored. The justification for not considering the P-wave part of the refractions is that the traveltime as a P wave is minimal compared to the traveltime as a shear wave due to the shorter distance travelled and higher velocity of the P-wave component.

The next step in obtaining a static solution is to use the traveltimes observed from the shear refractions to determine a model of the near-surface. There are several options available to accomplish this, including the slope/intercept method (Gardner, 1939, 1967), delay-time method (Barry,1967; Lawton, 1989a) and some form of a inversion routine (Palmer, 1980; Hampson and Russel, 1984; de Amorim, et al., 1987). A general slope/intercept method was first applied to the shear refraction data, followed by a traveltime inversion method in order to refine the result. Even though an inversion method such as the one used should help to refine the result, it failed in this application since it served to increase the errors seen between the calculated and observed traveltimes from the slope/intercept method. One possible explanation for this failure is that the picks were too variable both laterally and vertically due to the difficulties in separating the refractions from the noise in the shallow part of the shot record and reflection data deeper in the shot record. An attempt at picking the shear-refractions using an automatic picking routine also failed, likely due to the same problems as just outlined.

For these reasons, the slope/intercept solution derived from hand-picked traveltimes of shear refractions was used as the best model of the near surface (Figure 9a). Since the radial channel records converted waves which travel as P waves from the source to the reflector, but travel as SV waves to the receivers, P-wave source statics and shear-wave receiver statics should be applied to the radial component data. Thus, only the receiver component of the shear-refraction statics model (Figure 9a) is actually applied to the radial component data. Similarly the source terms of the P-wave statics model (Figure 9b) is applied to the data in order to compute the P-SV-refraction statics solution for converted waves on the radial channel.

Following application of the P-SV refraction statics, the data is again separated into common-sourcepoint and common-receiver stacked sections in order to provide a check for each part of the solution (Figure 10). Minor static shifts are still necessary for the receiver terms before application of automatic residual statics. Finally, an f-k filter is applied to the

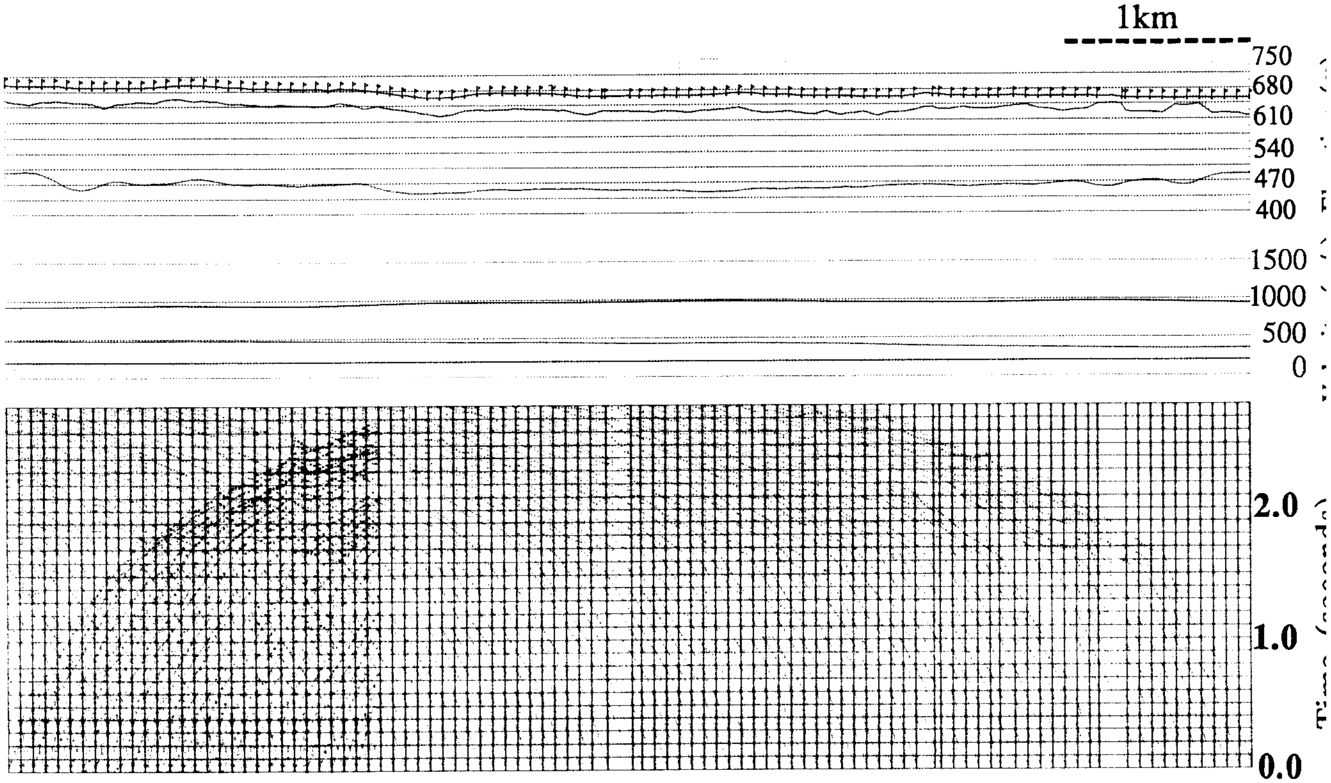

Fig. 9a: Shear-wave refraction picks and solution of S-wave thicknesses and velocities of the near surface.

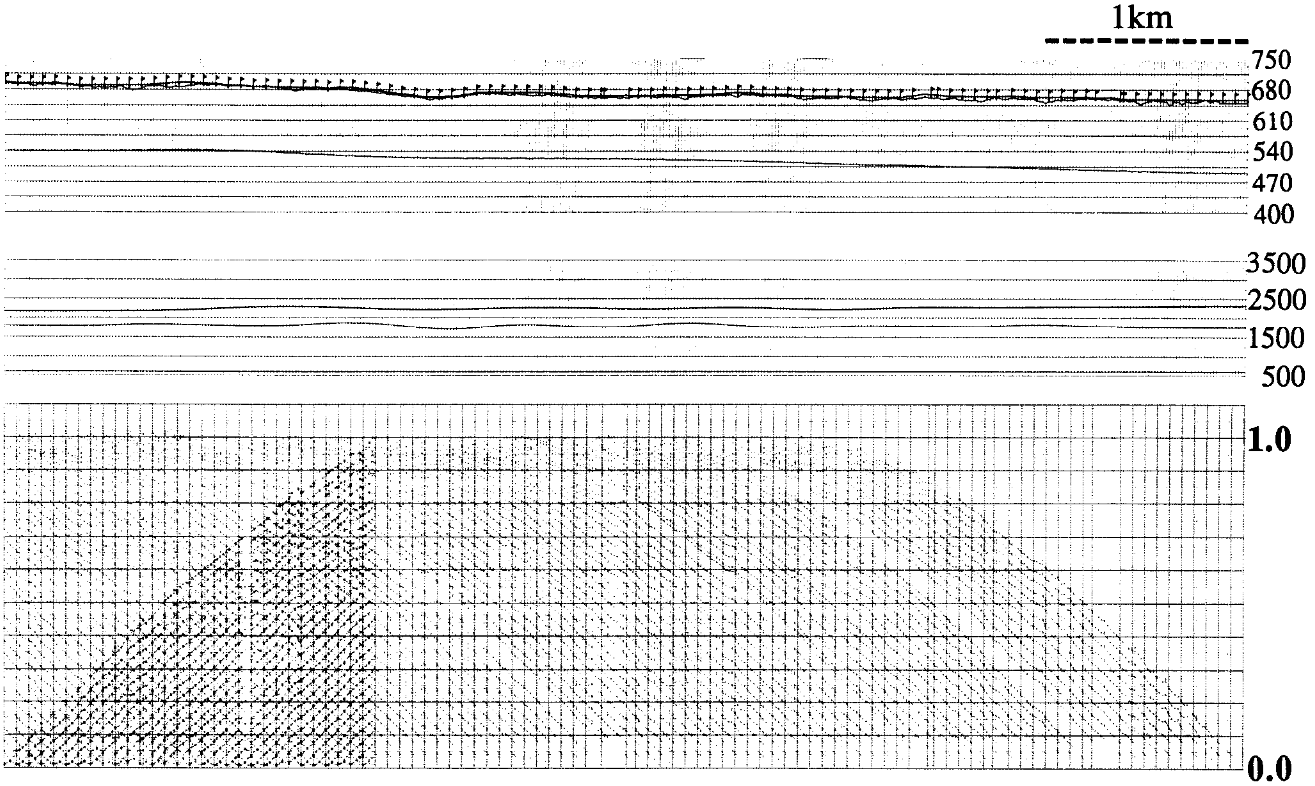

Fig. 9b: P-wave refraction picks and solution of P-wave thicknesses and velocities of the near surface.

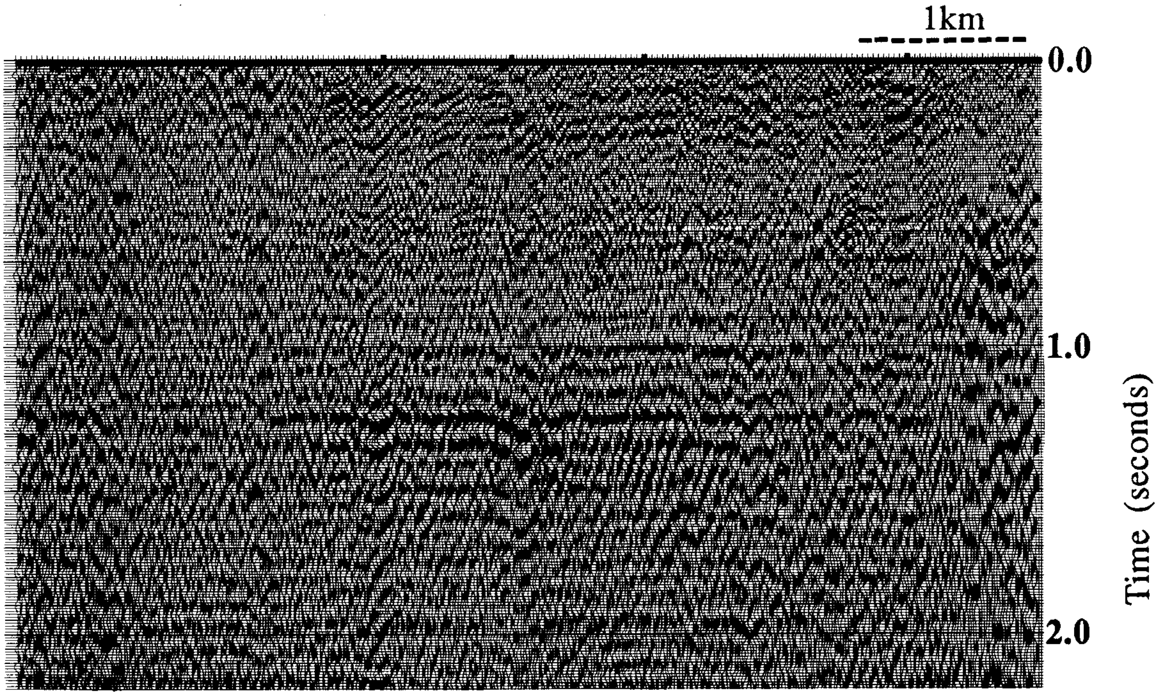

Fig. 10a: Common-receiver stacked section for the radial (P-SV) component data with P-SV refraction statics applied.

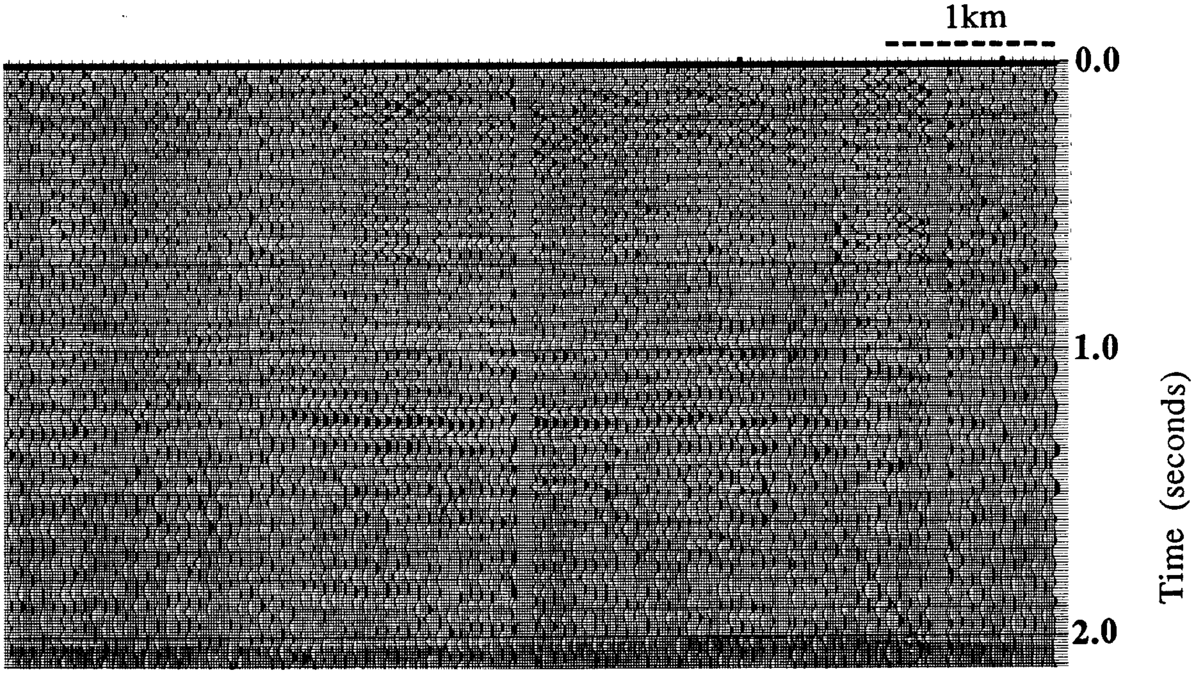

Fig. 10b: Common-sourcepoint stacked section for the Radial (P-SV) component data after P-SV refraction statics.

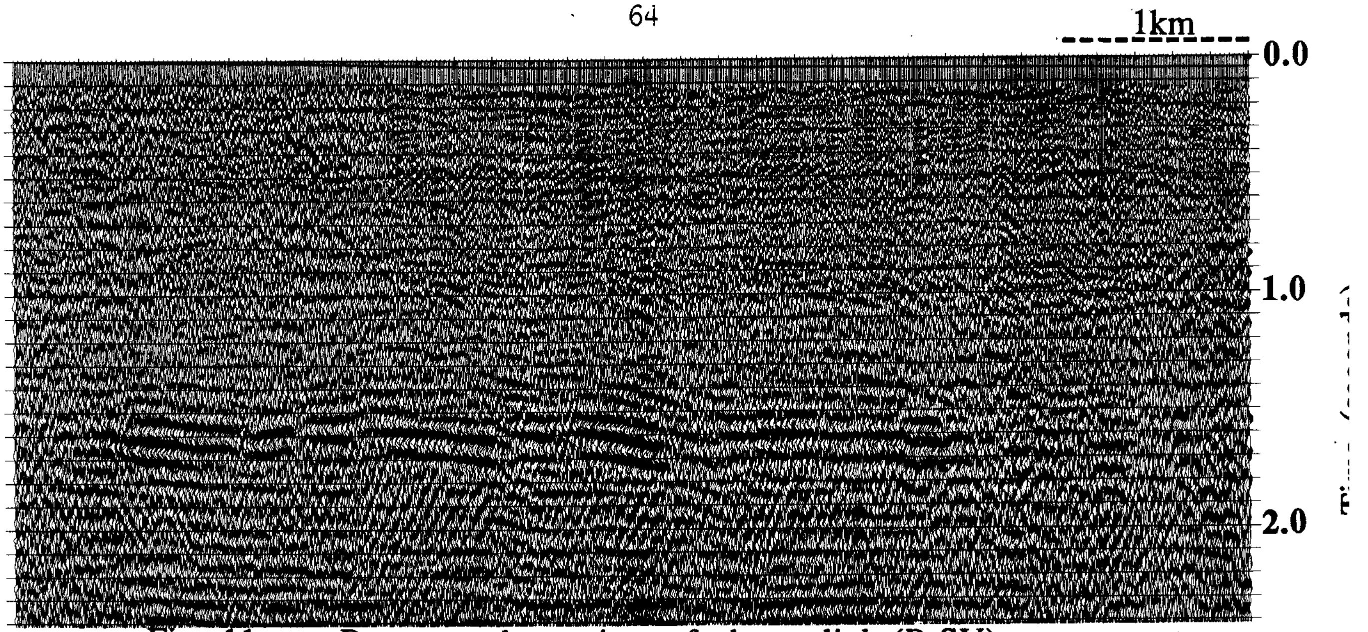

Fig. 11a: Brute stack section of the radial (P-SV) component data from Line EUE001, Slave Lake, northern Alberta.

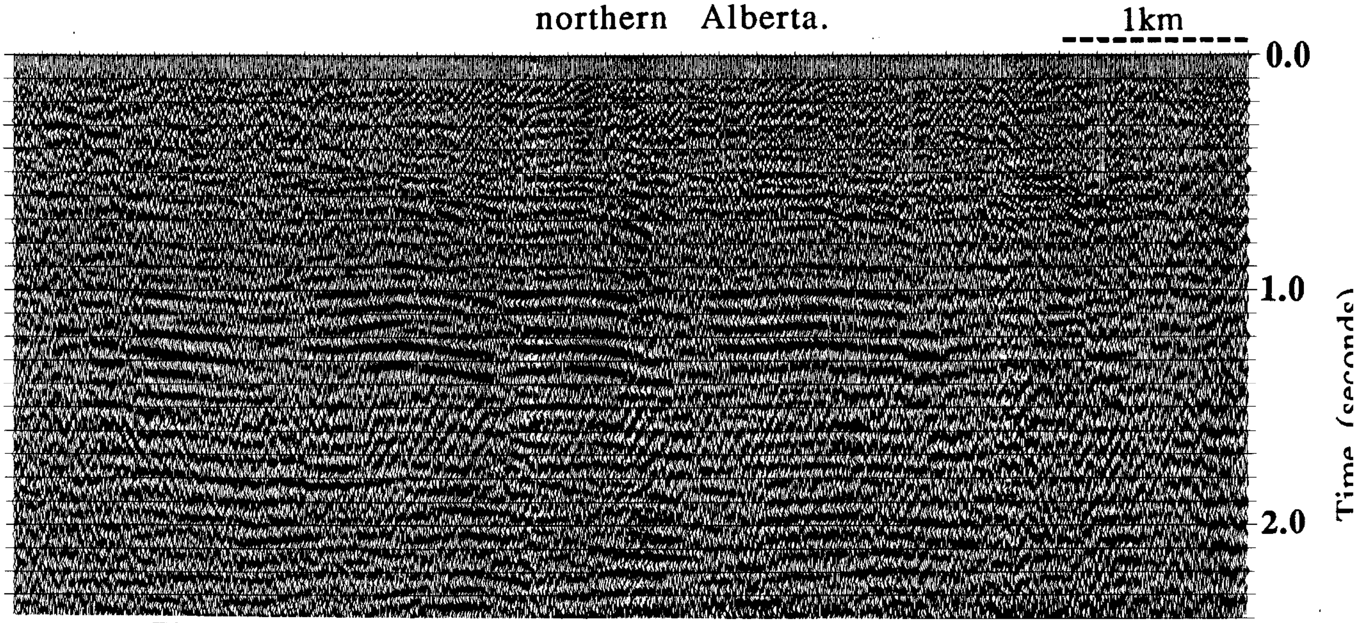

Fig. 11b: Radial (P-SV) component stack section with P-SV refraction statics applied.

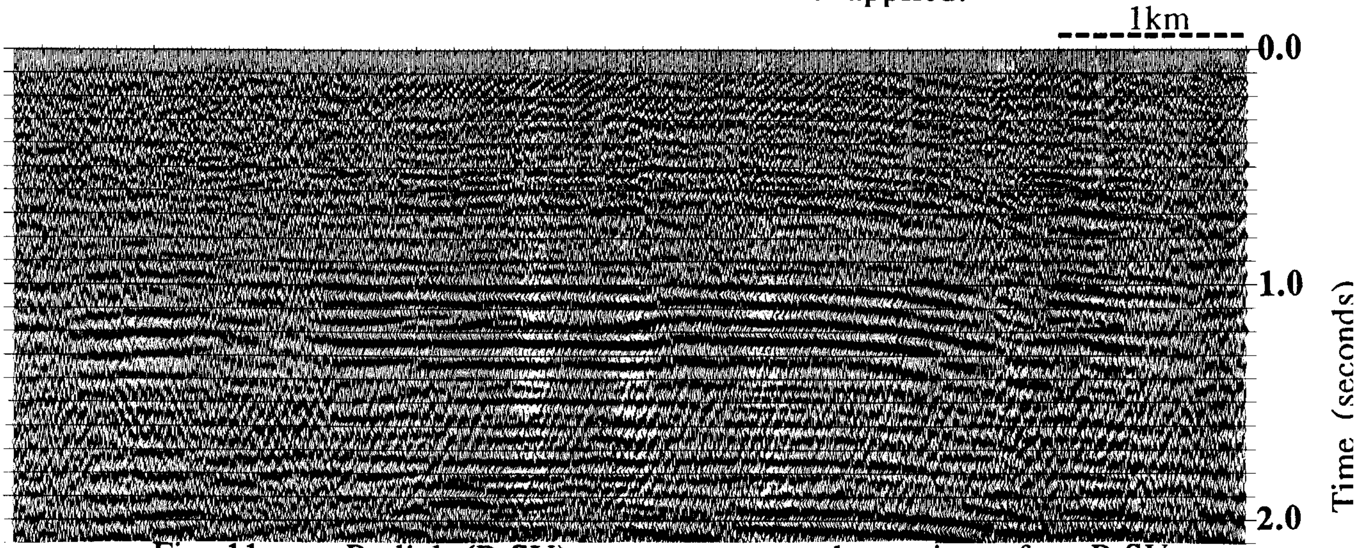

Fig. 11c: Radial (P-SV) component stack section after P-SV refraction statics and residual statics.

stacked section with P-SV refraction statics applied (Figure 11b) to remove some of the dipping noise (Figure 11c).

RESULTS

Using SV refractions in a similar to that in which P refractions were used, a model of the thickness and velocity of the near-surface for shear waves can be obtained. The shear-wave model of the near-surface is indeed vastly different than the P-wave model as expected (Figure 9). The shear-wave model has a thickened weathering layer, which has also been observed in a separate survey in the foothills of the Rocky Mountains (Lawton, 1989b). The magnitude of the velocities and thicknesses of the other layers also correspond to those from the foothills (Figure 1a), as well as those from the the upper part of a well from Texas (Figure 1b).

The statics solution derived from this model serves to improve the continuity of the radial component data as well as flattening out already continuous reflections (Figure 11a and 11b). Even though it is still necessary to pick some statics by hand from common-receiver stack sections before automatic statics could be applied, the work required in picking the statics is greatly reduced relative to the same task without any shear-refraction statics. Further, the stacked section obtained by using P-SV refraction statics (Figure 11c) has increased continuity of the high-frequency, shallow reflections compared to the final statics section without P-SV refraction statics (Figure 4).

DISCUSSION AND LIMITATIONS

The problem with picking shear refractions on a 3-component data set shot with a compressional source is that shear refractions may not always be visible enough to pick. Various source and receiver configurations may serve to suppress the shear refractions and thereby eliminate the possibility of using this method. A further drawback of this method is the amount of time required to pick the shear refractions on a work station. Automatic picking could save a lot of time, but it is also hampered by noise before the shear refraction and can not override this noise using logical reasoning as the human mind can. One possible solution to the noise problem is to apply polarization filtering to remove everything except the shear refraction, since a shear refraction should have a unique direction of particle motion at the surface. Another possibility might be a time-variant velocity filter to selectively enhance the shear refraction relative to the background. Finally, instantaneous amplitudes or frequencies could also be used to assist in enhancing the shear refraction.

Further compounding the problem of picking the shear refractions is the fact that while the shear refractions are prominently visible on the deeper refracting layers, the static solution places emphasis on the upper two layers. Indeed, in order to correspond to the layers used in the P-wave statics solution as well as for ease of computation, only a weathering layer and one other layer, a two-layer solution, are considered for the shear-wave solution. A better solution could be obtained if a three-layer model is used in the calculating the static shifts.

Close examination of the S-wave near-surface model (Figure 9a) indicates that while ther appear to be static pockets present on the S-wave refractions, they are not modelled appropriately by the algorithm used. One possible reason for the failure of the program to accurately portray the static pockets is that a built-in smoothing function has been used. Smoothing of the model layers is useful for P-wave refraction modelling, but S-wave refraction modelling appears to require a much more extreme, higher frequency solution and therefore smoothing nay remove some of the static pockets.

However, despite all of the difficulties involved in picking the shear refraction, the solution obtained using this method is better than the one obtained from picking the static shifts by hand. Finally, using P-SV refraction static corrections gives a correct long-wavelength solution for the receiver terms, which hand-picking may not.

CONCLUSIONS

Shear-wave refractions can be used to estimate the velocities and thicknesses of the near-surface (Figure 9a). From this model, the static shifts corresponding to the receiver static terms of converted-wave seismic data can be calculated. Combined with the source statics terms calculated from P-wave refraction statics analysis, the static solution for converted waves can be achieved. This method is an improvement over hand-picking the statics from common-receiver stacked sections since it provides us with a long-wavelength solution, as well as offering improved continuity of the reflectors.

FUTURE WORK

Possible future work includes enhancing the shear refractions using various filters, such as polarization filtering and velocity filtering. Automatic picking of the shear refractions could also be developed further.

ACKNOWLEDGEMENTS

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