Converted-wave statics methods comparison

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ABSTRACT

Various static-removal methods; hand-picking, time-difference refraction statics, EGRM Gauss-Seidel refraction statics and Monte-carlo simulated annealing statics are applied to the radial component of a compressional-source, three-component, seismic data set from northern Alberta; Slave Lake, Line EUE001. While hand-picking provides the most continuous solution, it is extremely tedious and time-consuming for the processor. The refraction statics methods are also quite time-consuming since the S-wave refraction had to be hand-picked. However, these methods provide a more realistic long-wavelength statics solution since refraction methods derive the long-wavelength static shifts from an actual model of the Earth, rather than by arbitrarily comparing the shifts seen on reflections across the section. Monte-Carlo simulated annealing provides a reasonable solution with very little processor input, but it takes hours of computer time.

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. Usually, in the processing of the radial channel, it has been necessary to hand-pick the common-receiver stacked sections before any further residual statics analysis could be performed. Since refraction statics methods have long been used on compressional seismic data, it is only natural to attempt to use refraction methods on converted-wave data also. P-wave refraction methods remove static shifts 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), and thus help to solve for static shifts on converted-wave data. Another method which has been receiving more attention as the speed of computers is increasing is Monte-Carlo simulated annealing statics (Vasudevan et. al., 1991 and Eaton et. al., 1991). This method attempts to maximize the stacking power while making random perturbations of the data. The objective of this paper is to compare the application of these methods to converted-wave data.

DATA SET

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.
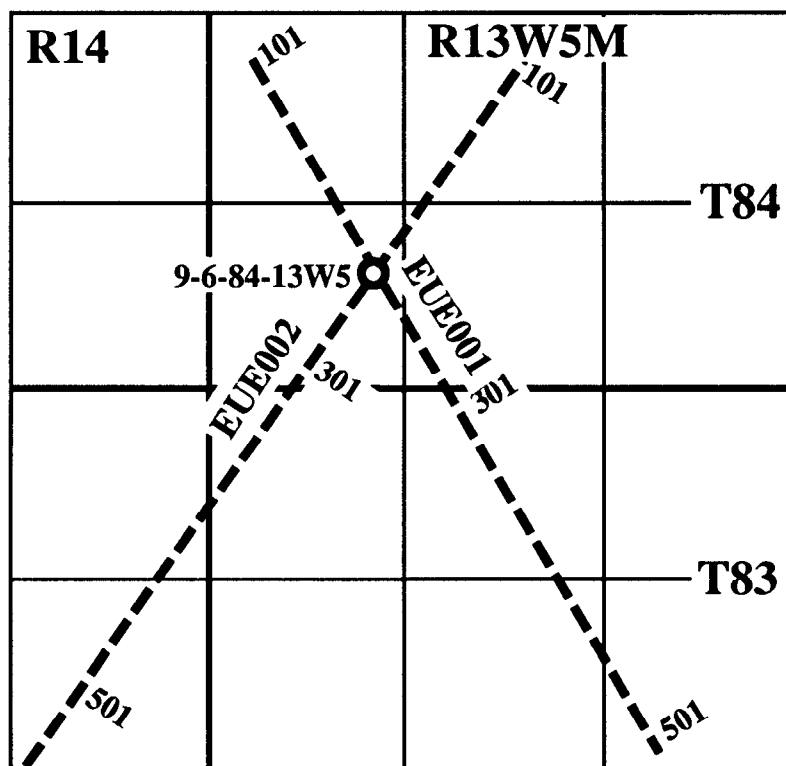

FIG. 1. Location of line EUE001 of the Slave Lake three-component seismic survey, northern Alberta.

This data set used for this comparison is a three-component survey from Slave Lake, Line EUE001. Slave Lake is located in T83-T83, R13-R14 W5M (Figure 1). These data are dynamite data, shot using a four hole pattern and 120 receivers. The processing flow used for the vertical channel of this data is outlined below (Harrison, 1989).
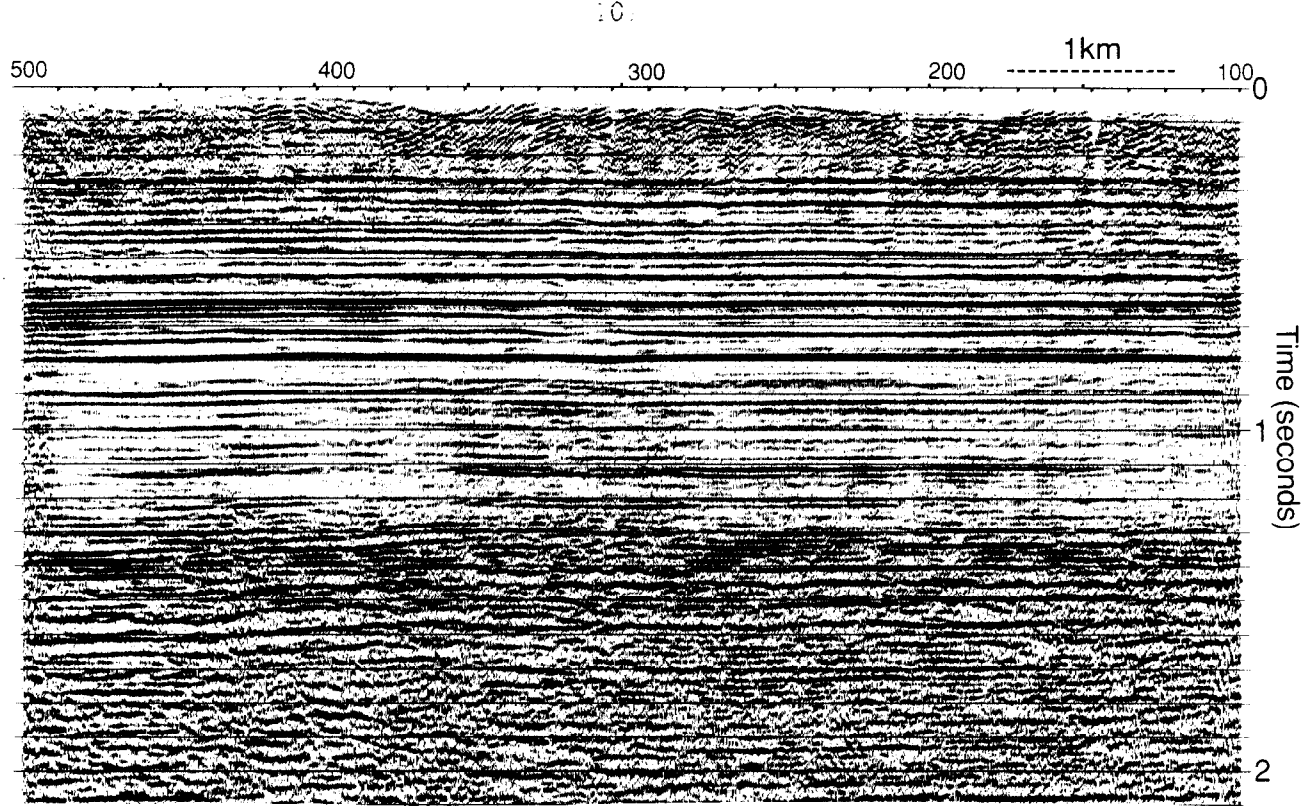
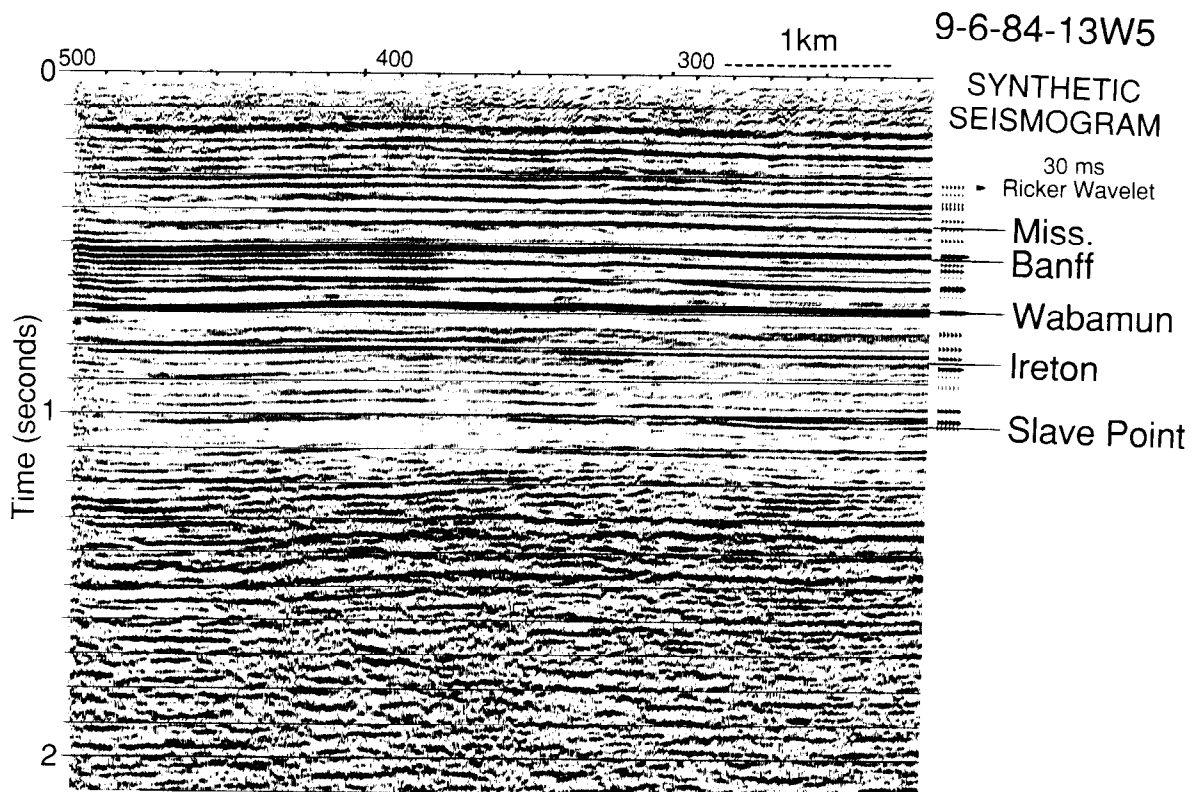FIG. 2a. Vertical (P-P) component final stacked section.

FIG. 2b. Correlation of the vertical (P-P) component final stacked section with a P-wave synthetic.

```
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 final stacked section of the vertical component data is given as Figure 2a. The final P-wave stacked section correlates well with a P-wave synthetic spliced into its approximate location on the line (Figure 2b). Processing of the radial channel is similar to that of the vertical channel except for the need to reverse the polarity of the trailing spread, the use of converted-wave rebinning and hand-picking of the receiver statics. The processing flow used for the radial channel is the adapted basic processing flow for converted-wave data given below (Harrison, 1989).

```
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-wave static solution from the vertical channel. Then, it would be possible to assume a V_p/V_s ratio of two, and apply twice the P-statics to the receivers. However, the ratio of P-wave velocity to S-wave velocity is not constant throughout the seismic section (Lawton, 1989b; Wattrus, 1989), and is particularly variable in the near-surface (Figure 3). Thus, it was necessary to seperate the data into common-sourcepoint and common-receiver stacked sections (Figure 4) in order to pick the statics for each separately. Since the common-sourcepoint stacked section (Figure 4a) consists of the NMO-corrected, stacked, P waves, for which static corrections have been applied, there should not be any large static problems left. However, the common-receiver stacked section (Figure 4b) has considerable static problems visible on it, since it consists of NMO-corrected, stacked S waves to which P-wave statics have been applied.

For comparison purposes, the common-sourcepoint and common-receiver stacked sections for the vertical component data are also included (Figure 5). Since the statics on the vertical component (15 ms) are not as large as those on the radial component (100ms), it was possible to succesfully apply automatic residual statics to the vertical component, but not to the radial component. Western Geophysical's automatic residual statics program cycle-skipped and otherwise failed on the radial component due to the inability of the program to seperate shots and receiver statics. In order to obtain a proper static solution and to avoid cycle skipping by the automatic residual static program, the receiver-term statics must first be hand-picked from the common-receiver stacked section for the radial component. The common-receiver stacked section after hand picking has only some high frequency statics remaining (Figure 6a), which are succesfully removed by the automatic residual statics program (Figure 6b). The final stacked section after application of hand statics and residual statics has good signal continuity with no apparent statics problems (Figure 7a). The picking of statics by hand is, however, very time-consuming due to the difficulty in aligning reflectors which are extremely incoherent, and several passes had to be completed before a reasonable solution could be obtained.
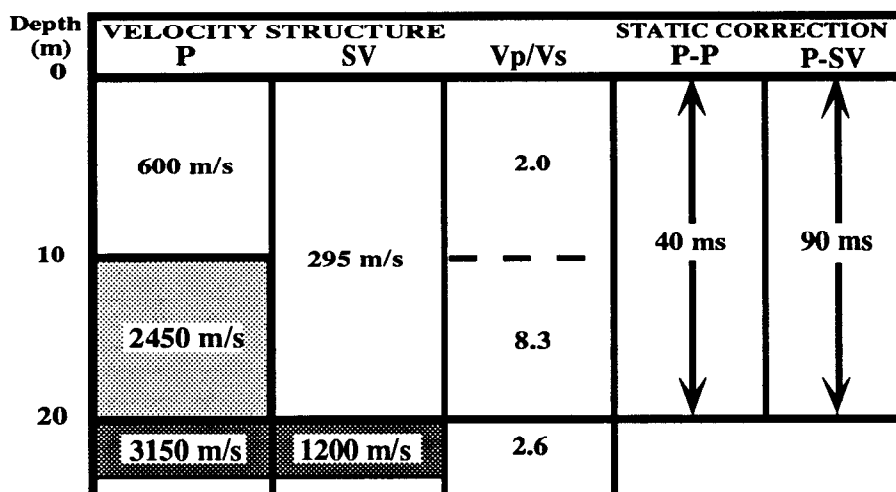
Depth (m)	VELOCITY STRUCTURE			STATIC CORRECTION	
0	P	SV	Vp/Vs	P-P	P-SV
	600 m/s		2.0	↑	↑
10		295 m/s	— — —	40 ms	90 ms
	2450 m/s		8.3		
20				↓	↓
	3150 m/s	1200 m/s	2.6		

FIG. 3. Near-surface P-wave and S-wave velocity structures from Jumping Pound, Alberta (from Lawton, 1989b).
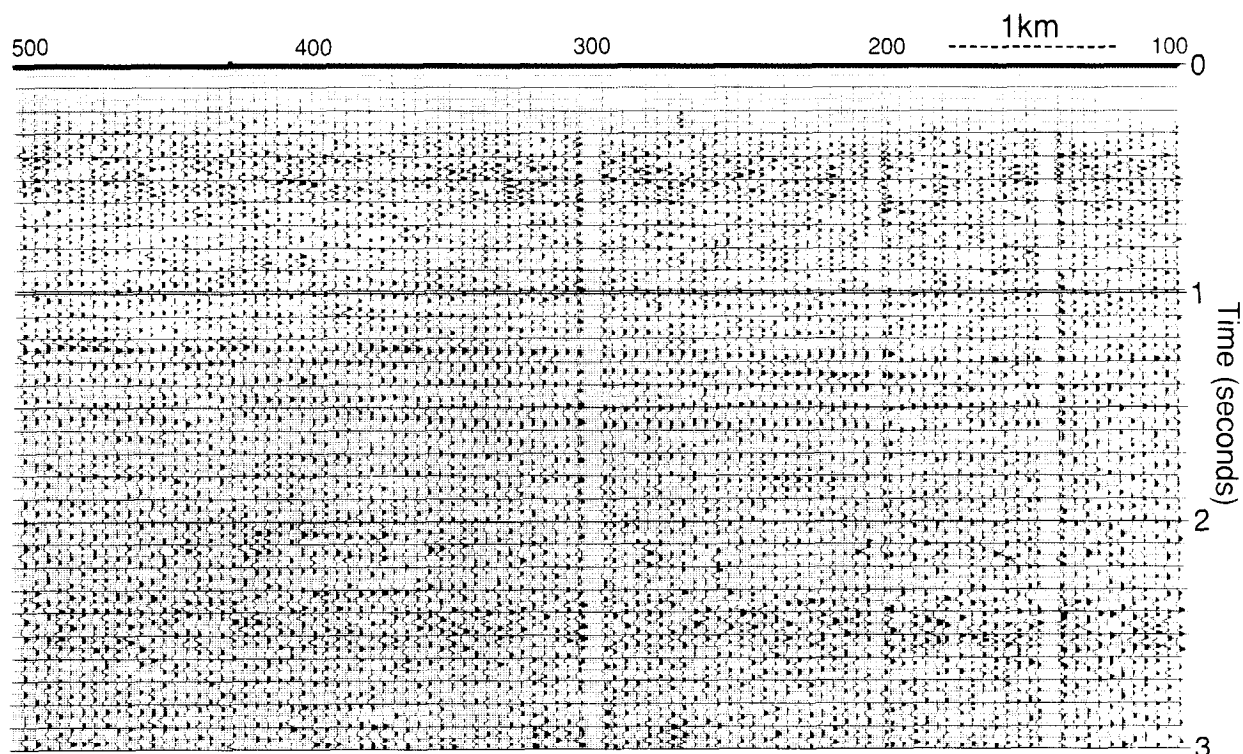
FIG. 4a. Radial (P-SV) component common-sourcepoint stacked section without any statics applied.
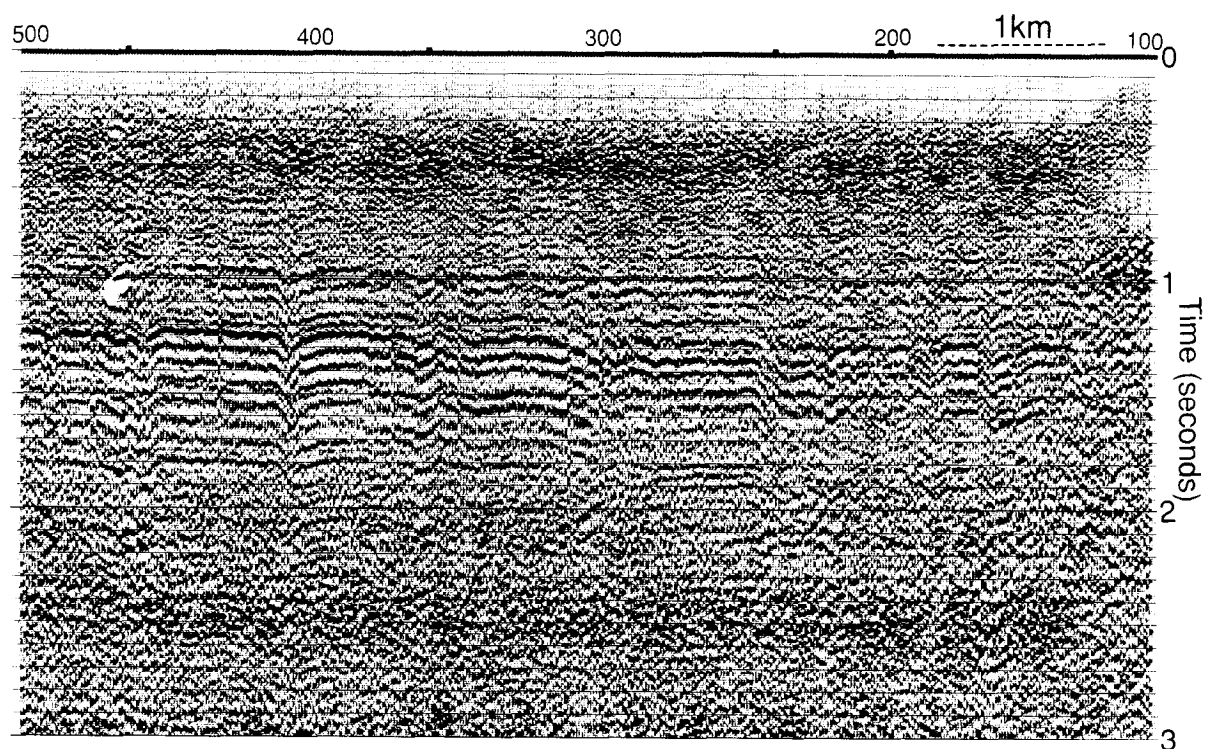

FIG. 4b. Radial (P-SV) component common-receiver stacked section without any statics applied.
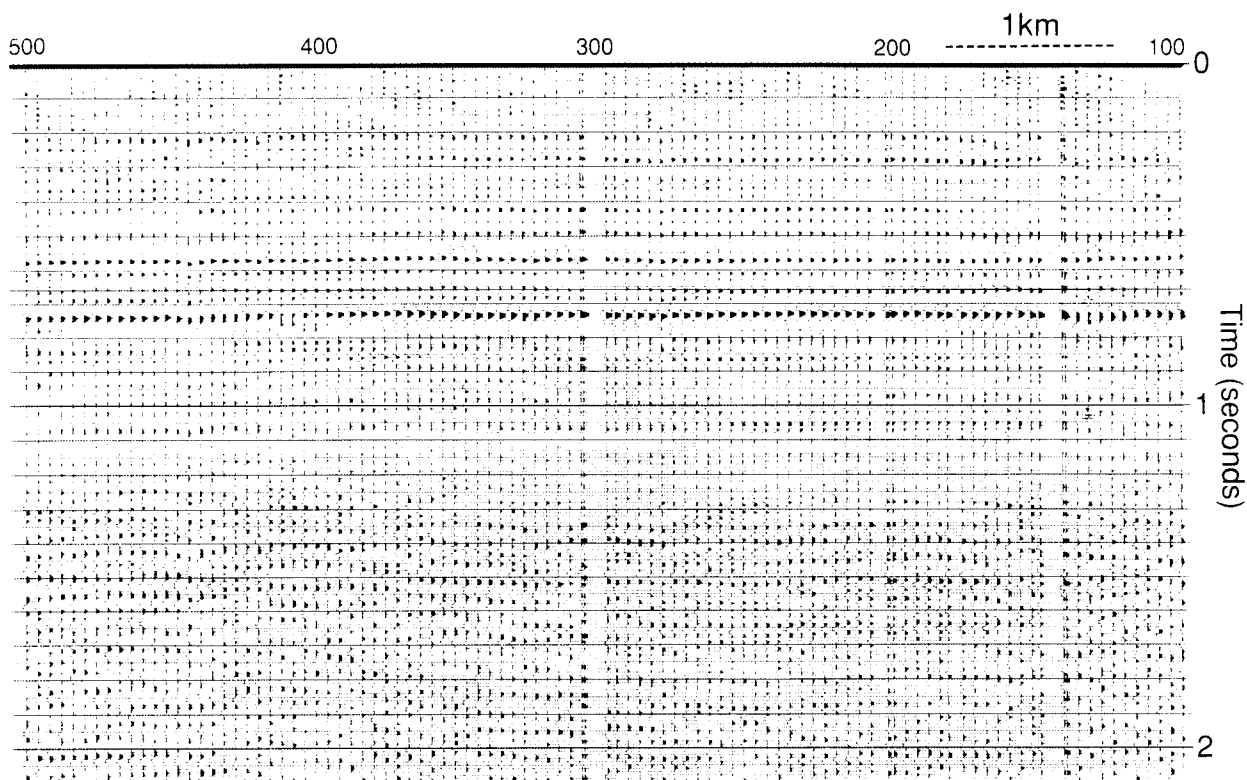
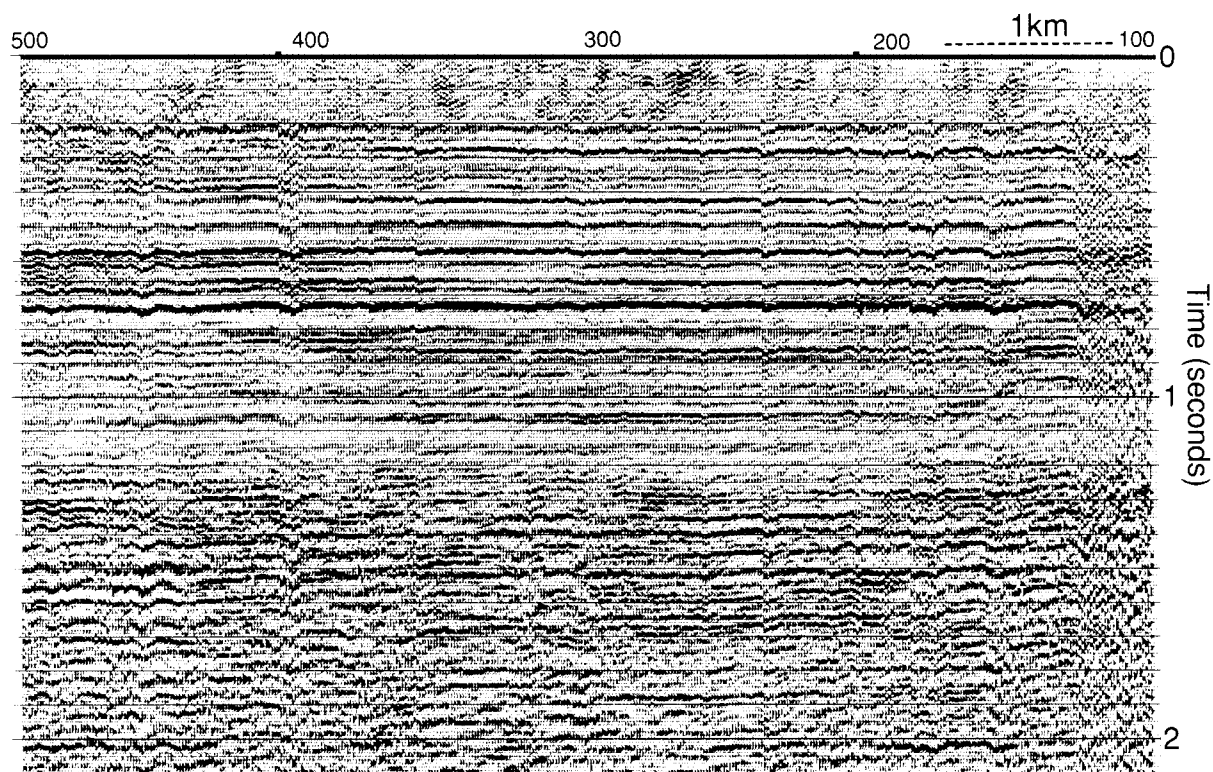FIG. 5a. Vertical (P-P) component common-sourcepoint stacked section without any statics applied.

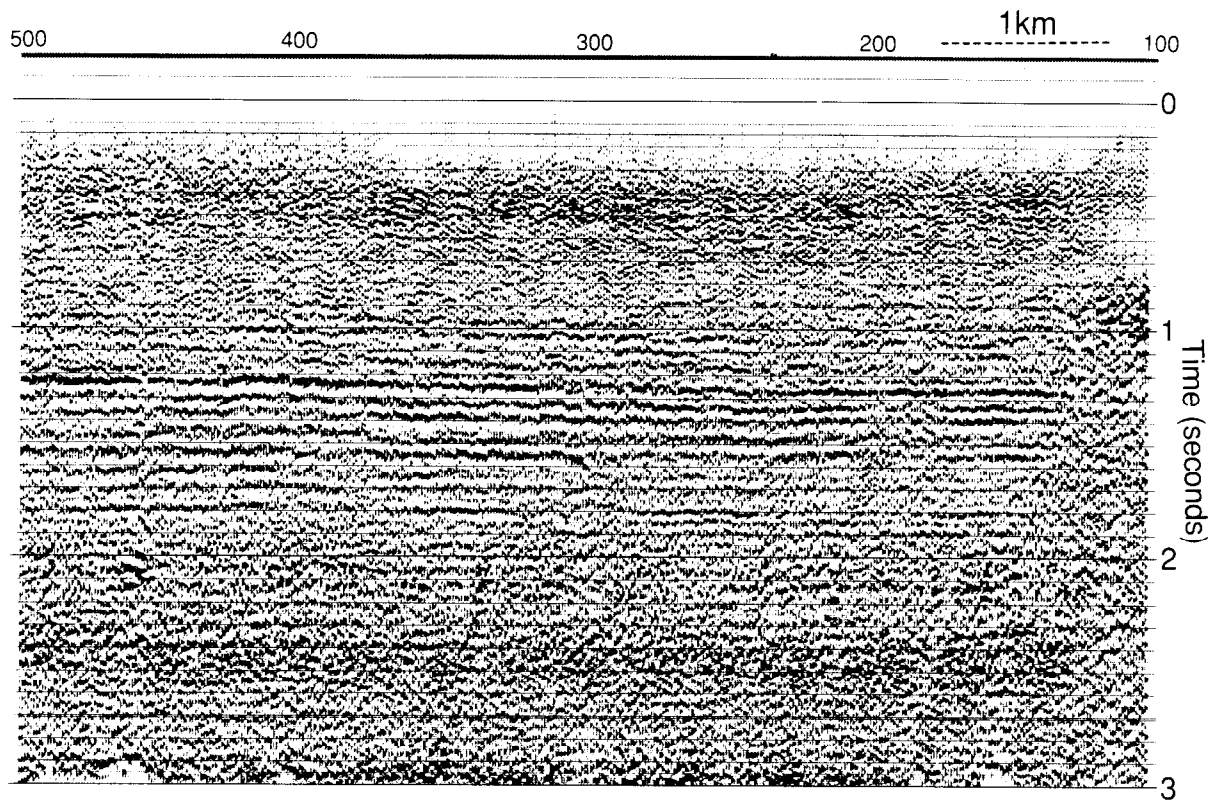FIG. 5b. Vertical (P-P) component common-receiver stacked section without any statics applied.

FIG. 6a. Radial (P-SV) component common-receiver stacked section with hand statics applied.
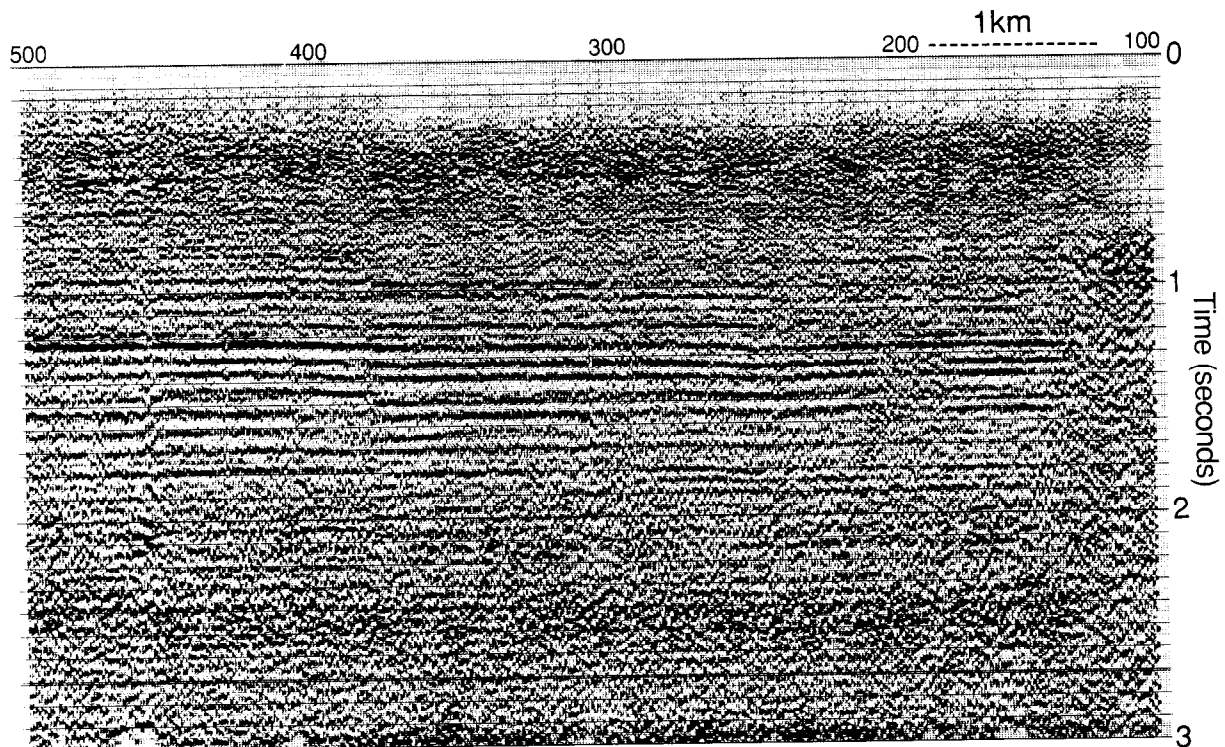

FIG. 6b. Radial (P-SV) component common-receiver stacked section with hand statics and residual statics applied.
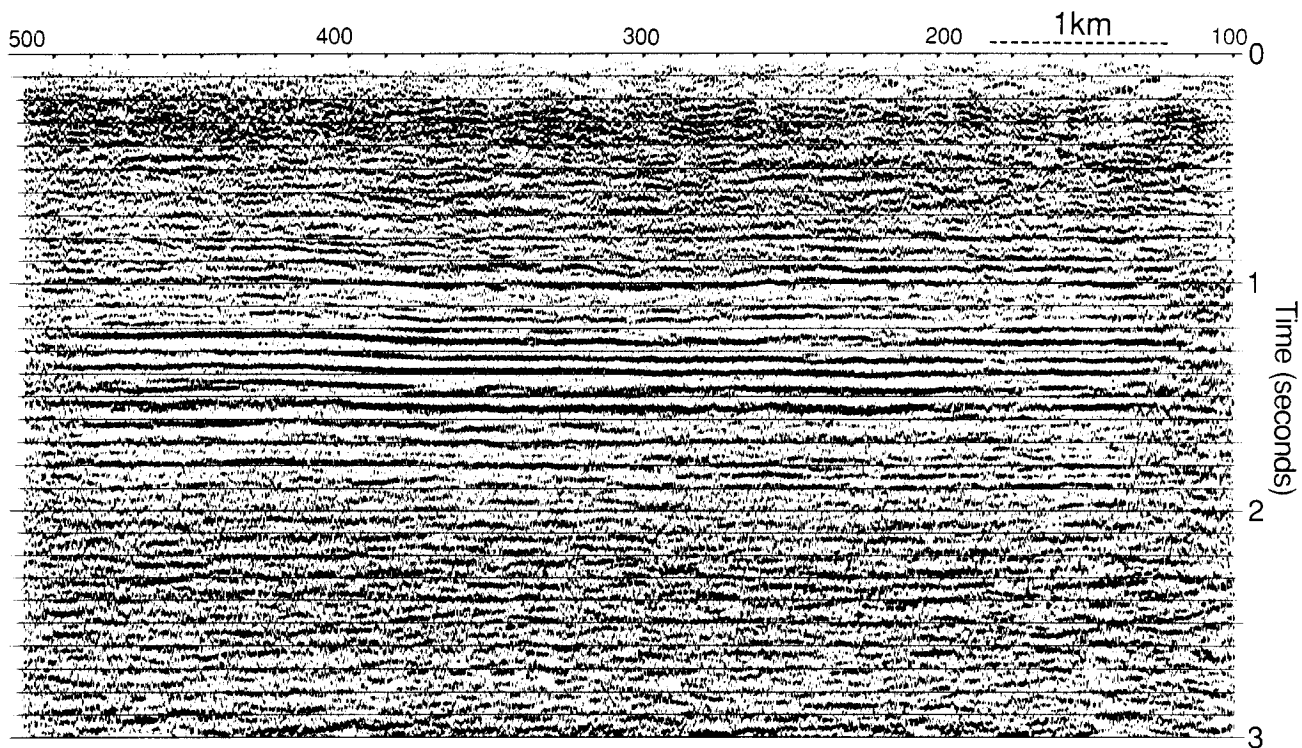
FIG. 7a. Radial (P-SV) component final stacked section with hand statics and residual statics applied.
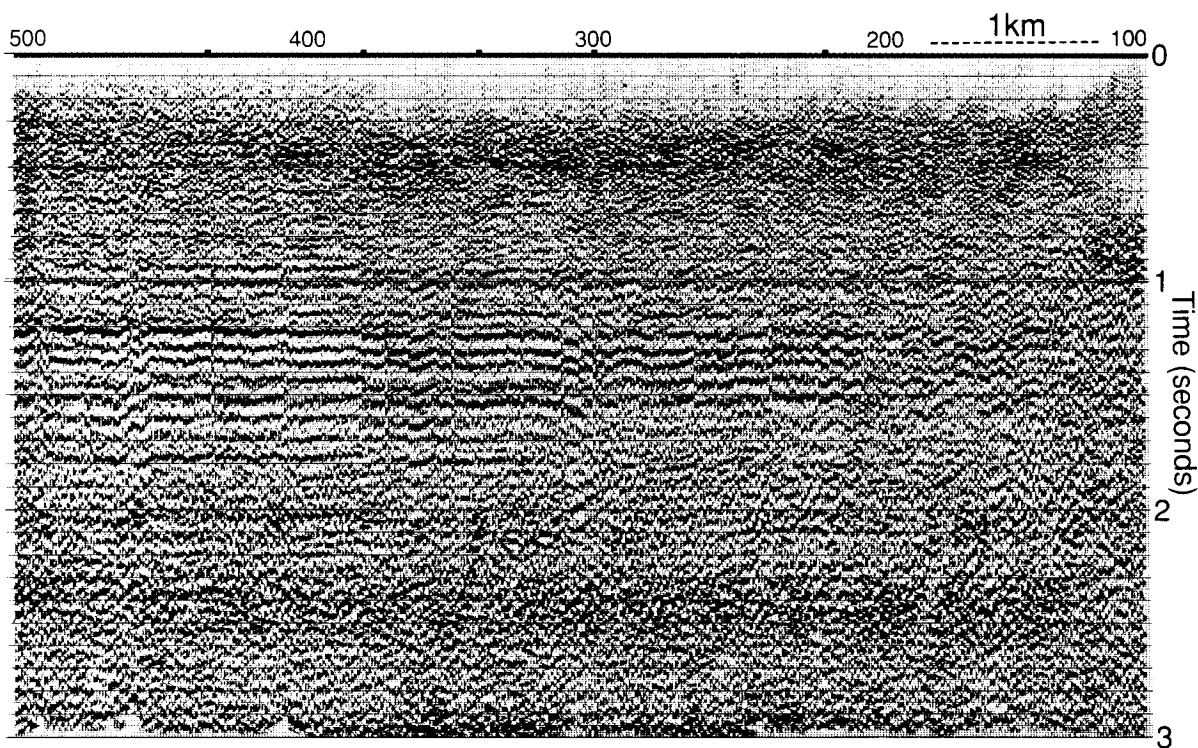

FIG. 7b. Radial (P-SV) component common-receiver stacked section with EGRM Gauss Seidel refraction statics applied.

REFRACTION METHODS

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 (Figure 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 (Figure 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 (Mari, 1984), 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 theoretically, 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.

Assuming that this event is indeed an S refraction, these refractions could be picked and used to obtain an S-wave refraction statics solution in the same way that P refractions have been used to obtain a P-wave refraction statics solution. A full refraction statics solution for converted-wave data involves using the source terms of the compressional-wave refraction statics solution combined with the receiver terms of a shear-wave refraction statics solution. 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 P-wave source terms to the radial channel. The receiver terms from the S-wave refraction static solution are then added to the radial component to complete the refraction statics solution. Computer-picking of the S refraction is theoretically possible, but fails due to the fact that the S refractions are masked by major P-SV reflections, while P refractions always preceed P reflections. The S refractions therefore were picked on an interactive workstation. This is rather time-consuming since the full data must be stored at once in to pick the S refractions, since the S refractions cover a range from zero to three seconds (Figure 8a).

In order to obtain a statics solution from the refractions, a refraction statics program must be used. 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 an inversion routine (Palmer, 1980; Hampson and Russel, 1984; de Amorim, et al., 1987; Boadu, 1988). Western Geophysical's EGRM refraction program, which is a variation of the delay-time method, as well as the time-differenced method (Lawton, 1989b) are used to derive the earth models from the refractions, from which static shifts can be calculated. Since the radial channel records
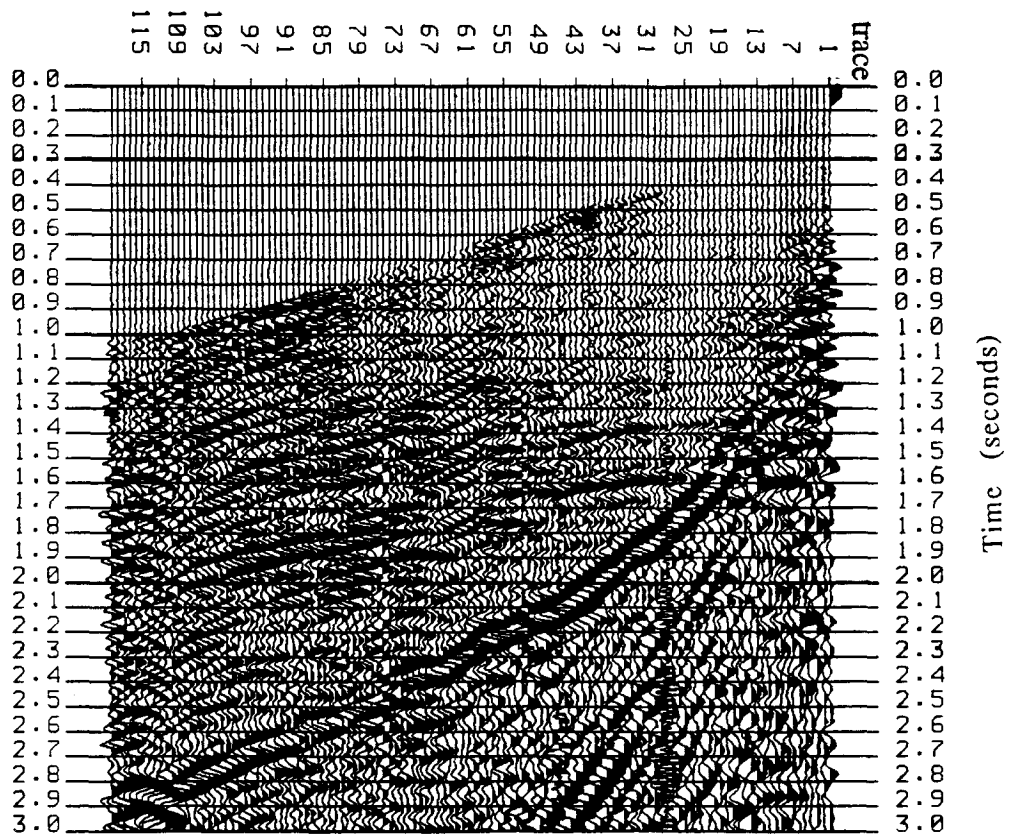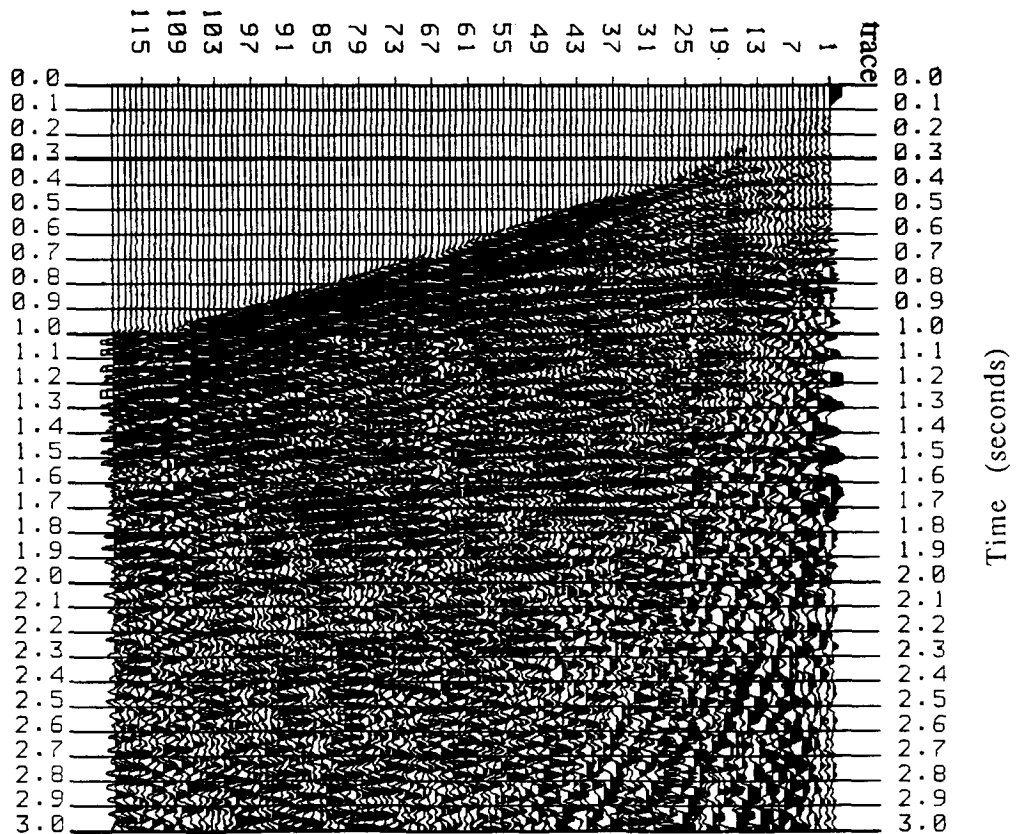
FIG. 8a. Radial (P-SV) component shot record.

FIG. 8b. Vertical (P-P) component shot record.

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 components of the shear-refraction statics model are actually applied to the radial component data. Similarly the source terms of the P-wave statics model are applied to the data in order to compute the refraction statics solution for converted waves on the radial component data.

Time-difference refraction statics

The time-difference refraction statics method was postulated and the algorithm was coded by Dr. Don Lawton of the University of Calgary in 1989 (Lawton, 1989b). Time differences, or delay-times, at shots and receivers are used to find the velocities and thicknesses of the refractors. This method is similar to the delay-time methods (Barry, 1967), except that it uses time differences, which are really the 'generalized half-intercept time', as introduced by Palmer (1980). The primary advantage of this method is that it does not require the common receiver to lie between the two shotpoints, therefore both forward and reverse spreads are not required, as they are for the reciprocal methods (Barry, 1967).
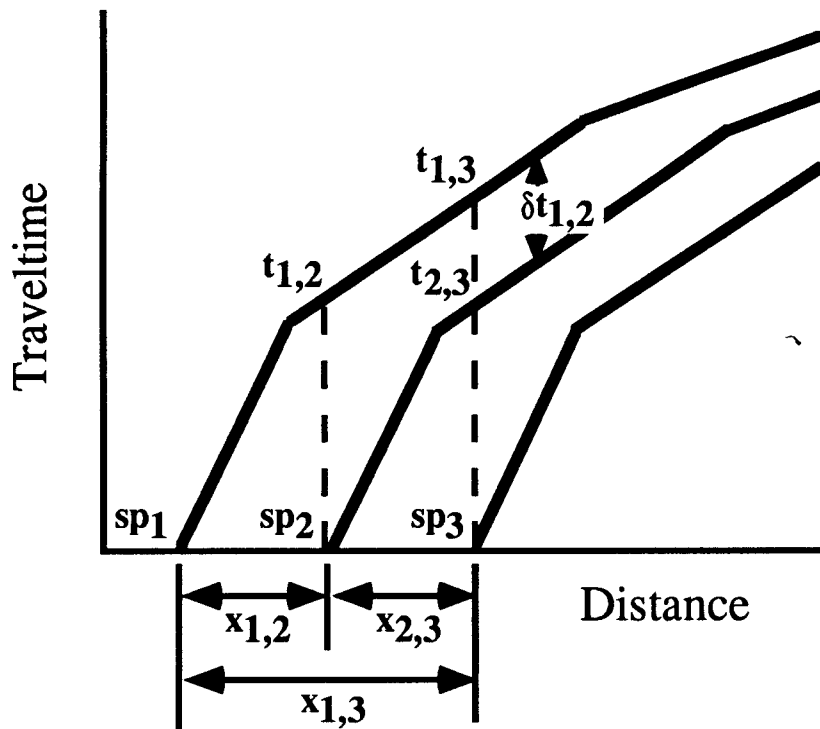
FIG. 9. Definition of traveltimes, time differences, and source-receiver offsets for the time difference method.

From Lawton (1989b), the delay time at shotpoint (sp) k , for difference window n, is given by

$$t_d(\text{sp}_k)_n = (1/j_{\text{tot}}) \sum_{j=1}^{j_{\text{tot}}} (t_{j,k} - \delta t_{j,k}) / 2, \tag{1}$$

where 'time-difference windows' are defined as the zones over which common-receivers involve common refractors, j_{tot} is the number of records with overlapping difference windows at sp_k, $t_{j,k}$ is the traveltime from sp_j to a receiver at sp_k, and $\delta t_{j,k}$ is the time difference between common receivers on shotpoints j and k (Figure 9).

This expression is also equivalent to

$$t_d(\text{sp}_k)_n = \sum_{m=1}^{m_{\text{tot}}} (z_m(\text{sp}_k)\cos(i_{mn}) / v_m), \tag{2}$$

where z_m is the thickness of layer m at sp_k, v_m is the velocity of layer m, and i_{mn} is the crritical angle; $i_{mn} = \sin^{-1}(v_m/v_n)$ (Figure 10). Equation (2) can be rearranged to solve for the thickness z_m for $n-1$ layers of the depth model.

The velocity of layer n is given by

$$v_n = (1/j_{\text{tot}}) \sum_{j=1}^{j_{\text{tot}}} (x_{j,k} / (t_{j,k} - t_d(\text{sp}_j)_n - t_d(\text{sp}_k)_n)). \tag{3}$$

Since there is not always a shot at each receiver location, the delay time $t_d(r)$ for a receiver location r is determined as

$$t_d(r)_n = (1/j_{\text{tot}}) \sum_{j=1}^{j_{\text{tot}}} (t_{j,r} - t_d(\text{sp}_j)_n - x_{j,r} / v_n). \tag{4}$$

Application of this method to the S refractions on the radial component of the Slave Lake dataset results in shear-wave earth models (Figure 11). Note that the general magnitude of the velocities and thicknesses of the model correspond reasonably well with those from the foothills (Figure 3).
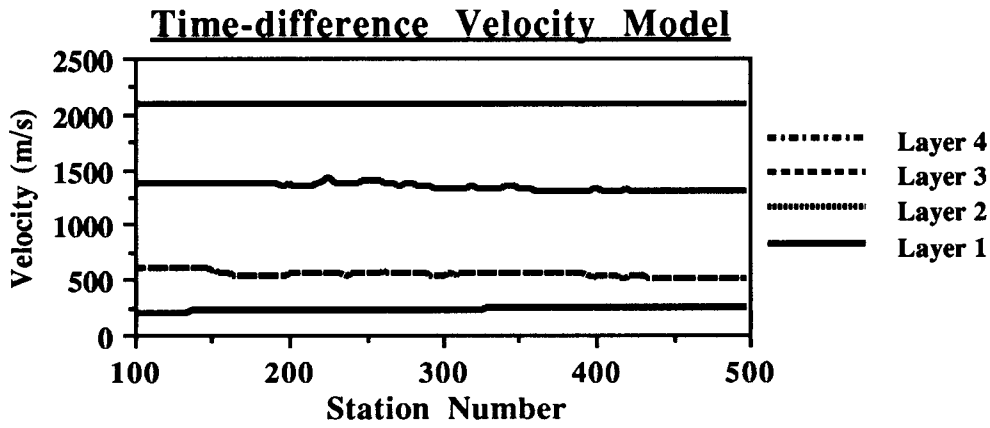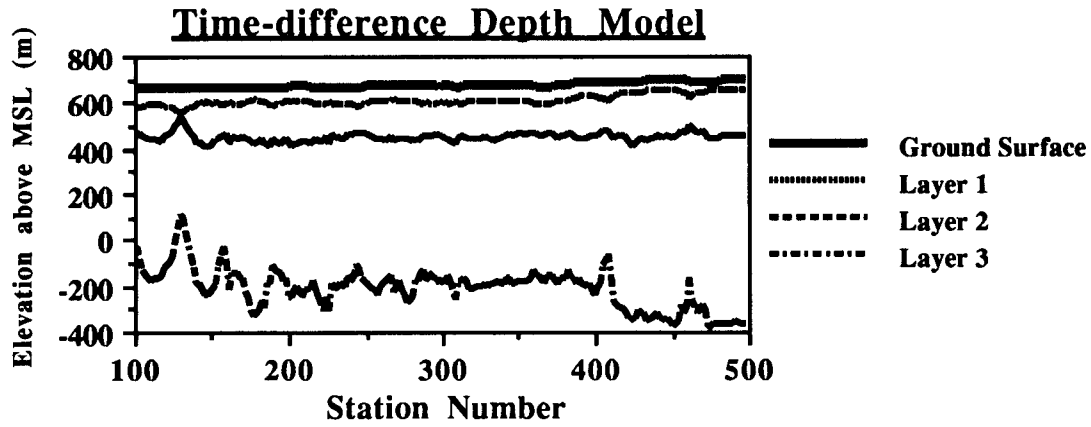
Time-difference Depth Model

(a)

Time-difference Velocity Model

(b)

FIG. 11. Time-difference S-wave earth model of (a) thicknesses and (b) velocities.

EGRM Gauss-Seidel Refraction Statics

This method is a combination of EGRM and Gauss-Seidel refraction statics. The 'Extended Generalized Reciprocal Method', or EGRM, algorithm is based of the 'Generalized Reciprocal Method', the GRM, of refraction interpretation introduced by Palmer (1980). The EGRM adds and subtracts combinations of travel paths to estimate velocities and intercept times. Velocities are derived from a plot of time differences between shots ahead and those behind the receiver versus the differences in offset. One half of the slope using a least squares linear fit is taken to be the velocity of the refractor. Time depths to each receiver are then calculated using the formula

$$t_d(sp_k)_n = (t_{a,r} + t_{b,r} - t_{a,b}) / 2 = \sum_{m=1}^{m_{tot}} (z_m \cos(i_{m,n}) / v_m), \qquad (5)$$

where z_m is the thickness of layer m at sp_k, v_m is the velocity of layer m, and i_{mn} is the crritical angle; $i_{j,n} = \sin^{-1}(v_j/v_n)$ (Figure 10).
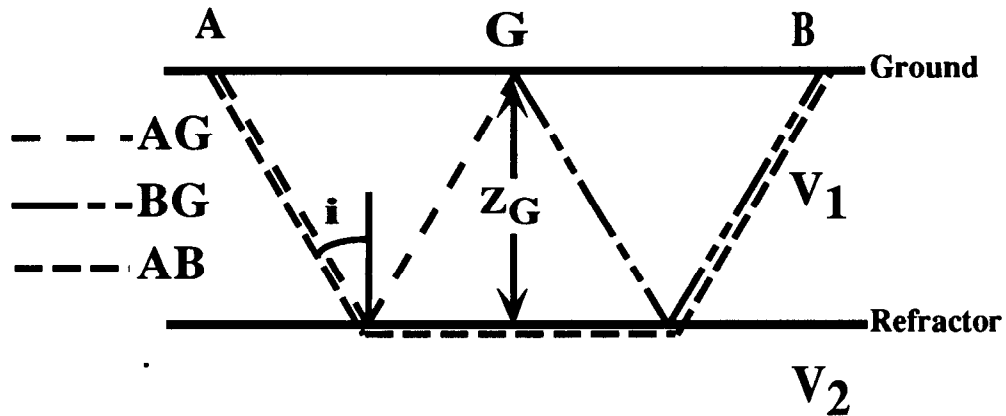

FIG. 10. Definition of thickness at the receiver; and forward, reverse, and total travelpaths for a one-layer model.

This is essentially twice the definition of the intercept time used in the intercept method (Barry, 1967). These time depths are then used by the Gauss-Seidel method in order to calculate the refractor thicknesses and velocities. The Gauss-Seidel method is based upon the assumption that the traveltimes from receiver a to receiver b is given by the sum of the delay time at a and b, plus an offset dependent term;

$$t_{a,b} = t_d(a) + t_d(b) + x_{a,b}/v_{n+1} \tag{6}$$

Rearranging this equation allows for a solution for v_{n+1}, using the delay times obtained from the EGRM analysis:

$$v_{n+1} = x_{a,b}(t_{a,b} - t_d(a) - t_d(b)) \tag{7}$$

The program then calculates the dalay time at sp_a, keeping the delay time at sp_b constant, and using the new velocities v_{n+1}. At the ends of the line, or where ever the Gauss-Seidel algorithm failed to find a velocity, the velocity derived from EGRM is used. The program iteratively calculates the delay times to achieve a final solution for the delay time at each shot and receiver. The thicknesses can then be calculated using

$$z(r)_n = (t_d(r) - \sum_{j=1}^{j_{tot}} (z_j \cos(i_{j,n})/v_j))(v_n/\cos(\phi)), \tag{8}$$

where $\phi = \sin^{-1}(v_1/v_2)$.

Application of this method to the Slave Lake dataset results in similar shear-wave earth models (Figure 12) as those obtained using the time-difference method (Figure 11).
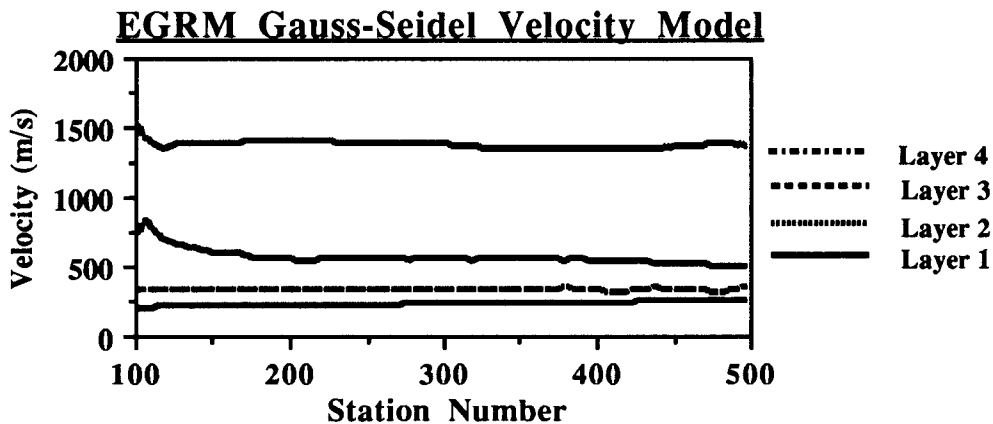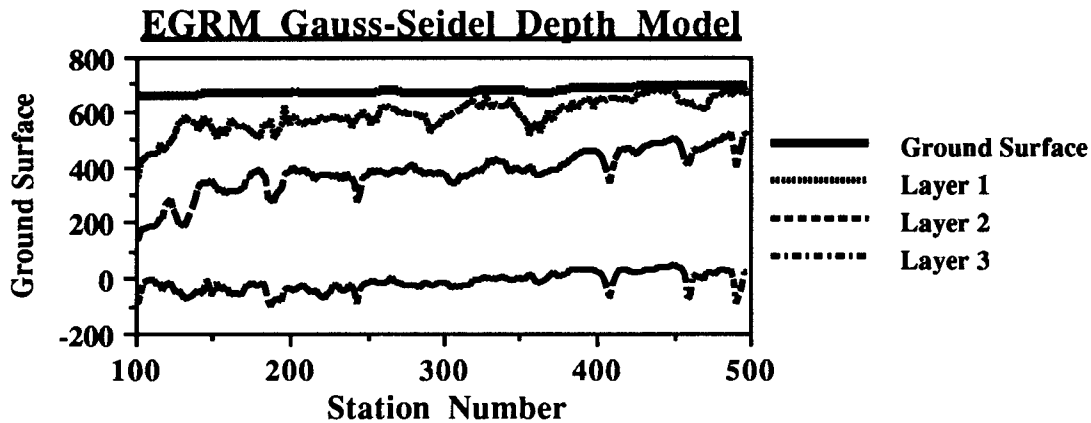
EGRM Gauss-Seidel Depth Model

(a)

EGRM Gauss-Seidel Velocity Model

(b)

FIG. 11. Time-difference S-wave earth model of (a) thicknesses and (b) velocities.

MONTE-CARLO SIMULATED ANNEALING

The Monte-Carlo simulated annealing method is a combination of a totally random, Monte-Carlo search technique and a controlled gradient-descent method (Eaton et al., 1991). The advantage of combining these two methods is that it allows the algorithm to descend into a local minimum in an iterative manner, yet retaining the option of jumping into another local minimum, which is perhaps an even better minimum. The critical, or annealing, temperature controls the random-search versus the gradient-descent aspects of this method. This method has been applied to the Slave

Lake data set with moderate success. For further details of this method and its use on the Slave Lake data set, see Eaton (1991), in this volume.

STATICS METHODS COMPARISON

Since the receiver statics are the main cause of the problem with converted-wave statics (Figure 4), the ability of the statics methods to solve for receiver statics is taken as the main criterion for determining the success of these methods (Figure 13).
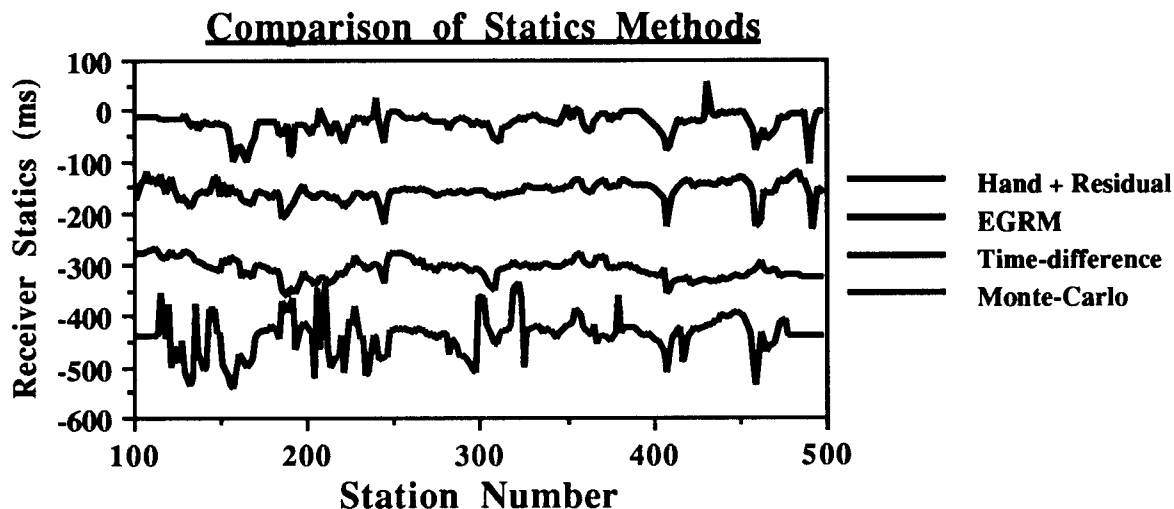

FIG. 13. Comparison of the receiver statics solutions.

It is assumed that the hand statics and residual statics solution offers the best solution to compare the others with, since it results in the best common-receiver stacked section (Figure 6b). However, even though hand-picking involved several passes of careful manual picking of the static shifts on common-receiver stacked sections, it still appears that there are some mispicks, due to the glitches which are present on the receiver statics profile (Figure 13), such as the abrupt positive spike at roughly station 420.

The EGRM Gauss-Seidel refraction statics solution matches the hand-picked solution well on the far end of the line, but fails to match large static pockets observed on the hand-picked solution on the near end of the line. This is likely due to the low fold and far near offsets found on the near end of the line, while the far end of the line has higher fold and no near offset.

The time-difference refraction statics solution does not match the hand-picked solution as well as the EGRM solution does. Further, the static pockets that do match are of a decreased magnitude relative to the hand-picked solution. However, both refraction methods do offer the advantage of providing a more meaningful, physically realistic short- and long-wavelength static solution since their solution is based on a model of the Earth.

The Monte-Carlo simulated annealing method matches some of the static pockets of the hand-picked solution, but the magnitude of some of the static shifts are too large. There are also a number of nonphysical, sudden spikes created by the method since its primary requirement is to maximize the stacking power, and there is no physical validity requirement, as in the refraction methods.

DISCUSSION AND LIMITATIONS

While the refraction methods do give a reasonable result, they are very time-consuming for the processer, or operator-intensive, since it is necessary to pick the S refraction. 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 masking 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.

Monte-Carlo simulated annealing statics also gives a moderately good result, at the expense of increased computer time. By using a simple gradient-descent method, it is possible to obtain a very similar solution at a fraction of the computer time (Eaton et al., 1991). Hand-picking gives the best result, but it is very operator-intensive. Both of these methods are also bothered by nonphysical glitches occuring due to a lack of physical validity requirements by these methods.

CONCLUSIONS

1) Converted-wave statics are best solved using hand-picked common-receiver stacks, which is very operator-intensive.

2) Refraction statics methods provide a good result, including a proper long-wavelength solution, but are operator-intensive due to the picking of the S refractions.

3) Monte-Carlo simulated annealing methods give a fairly good solution; which is not operator intensive, but is computer-intensive.

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