VSP multi-algorithm shear-wave anisotropy study

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ABSTRACT

A principal application of shear-wave birefringence is the determination of fracture orientation from shear-wave splitting in multicomponent VSPs. Three different analysis techniques for birefringence were implemented and their results are compared.

We have carried out nine-component VSP experiments in central Alberta. These full-wavefield datasets were analyzed by using three different algorithms to see the features of azimuthal anisotropy, the applicability of different algorithms, and how the results from converted shear waves compare to those from direct shear waves. In four-component rotation, shear-wave polarization directions were determined by minimizing energy on off-diagonal components of the 2-by-2 shear-wave data matrix, followed by layer stripping. Shear-wave polarization and time lag were also determined by applying a crosscorrelation modelling algorithm which is based on modelling crosscorrelation between rotated radial and transverse field components. This algorithm can be used for analysis on data acquired with a single source polarization, but it needs layer stripping for local anisotropy information.

Parametric inversion is the algorithm for shear-wave data with a single source polarization. Three unknown parameters (fast and slow shear-wave velocities and polarization direction) can be inverted by modelling a set of up- and down-going orthogonal plane shear waves, The advantage of this algorithm is that it provides the local anisotropy – it does not require shallower information as previous algorithms do, and fracture orientation is not constrained to remain constant with depth.

Even though the three different algorithms measure different aspects of anisotropy in different ways, our final results from the different algorithms corroborate each other. Analysis indicates shear-wave birefringence exists in some of the formations studied.

INTRODUCTION

In recent years there has been much interest in the analysis of azimuthal shear-wave anisotropy, which is also called vertical shear-wave splitting or birefringence. Because the presence of vertical shear-wave birefringence is an indicator of aligned vertical fracturing within reservoirs, many algorithms have been developed to meet the needs of analyzing shear-wave data where vertical shear-wave birefringence occurs.

This paper is concerned with the following aspects: 1) it uses three totally different analysis algorithms over the same anisotropic unit; therefore it examines different algorithms and discusses their applicability and reliability with reasonably good quality of the full-wavefield data; 2) it illustrates details of vertical S-wave

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birefringence in the study area; 3) it compares the vertical S-wave birefringence results from analyzing converted shear-wave data and direct shear-wave data.

A material is defined to be anisotropic if its properties change with direction of measurement at the same location. For the basic concepts of anisotropy, Winterstein's (1990) paper should be referenced. Shear-wave birefringence is a phenomenon wherein two shear waves of different polarizations will travel at different speeds in the same direction. Seismologists are interested in seismic velocity anisotropy, especially shear-wave anisotropy, because shear-wave particle motion splits into two different polarizations (for fast shear and slow shear) when propagating through an anisotropic medium. Also, shear-wave velocities are slower than P-wave velocity (usually they are about half of the P-wave velocity). It takes shear waves longer than P waves to propagate over a particular distance, which provides a characteristic by which to identify shear-wave anisotropy in rocks, The time lag (time difference between fast shear and slow shear) is the most direct evidence for anisotropy.

When anisotropy is studied, the orientation of fast split shear-wave and the time delay between two shear-waves or percentage of anisotropy are the two key parameters to be pursued. To visually identify shear-wave splitting, Naville (1986) suggested that the time delay of 1/4 circle of waveform between two split shear waves is needed. In another word, a minimum delay of 10 ms is needed when the central shear-wave frequency is 25 Hz. The causes of anisotropy can be different and complicated (horizontal layering, system of vertical cracks, in-situ stress field acting on rock, pore, and fracture alignments, crystal or fabric alignments). Horizontal layering (rock stratified) with vertical infinite-fold symmetry was the early model for anisotropic sedimentary rock. This kinds of medium is called Transverse Isotropic medium (TI medium). Such a medium is not birefringent for shear waves with vertical raypaths which implies that multicomponent zero-offset (vertical raypath) or near-offset (close to vertical raypath) VSPs do not show the anisotropy caused by horizontal layering (TI medium). With horizontal raypath, such medium is not birefringent only in two cases: shear-wave polarization is absolutely horizontal or vertical; shear-wave birefringence will occur in the case of offset VSPs.

System of vertical fracturing with one horizontal infinite-fold symmetry is the model to explain how vertical birefringence occurs (two shear waves of different polarization travel at different speeds in the vertical direction). This type of media is called azimuthally anisotropic media (Thomsen, 1988, Alford, 1986)

It is commonly believed that most of vertical shear-wave birefringence results from unequal horizontal stresses (Winterstein and Meadows, 1991). Unless the shear-wave polarization directions are the same as the natural axes of the medium, shear-wave birefringence is potentially observable when raypaths are vertical; which implies that on multicomponent zero-offset or near-offset VSP data, vertical shear-wave birefringence is observable as long as shear-wave polarizations are different from the natural axes.

Since vertical fracture-related anisotropy is of importance as a potential tool for detecting the presence of aligned vertical fracturing within reservoirs for reservoir characterization where cracks occur, shear-wave birefringence might have potential application in reservoir development. For this purpose we are concerned with fracture-related anisotropy in this paper.

METHODS AND ANALYSIS

Many algorithms have been developed for the analysis of vertical shear-wave birefringence according to the availability of shear-wave data. Data sets used in this paper have allowed us use many different algorithms do the shear-wave birefringence analysis.

Two types of datasets have been used in this paper: A synthetic dataset is generated from a VSP model that consists of multiple fractured layers; real seismic data were acquired from a 9-component VSP experiment run by PanCanadian Petroleum Ltd. in the central Alberta area. These datasets allow us to use algorithms for multi-source polarization and algorithms for single-source polarization. We propose to use Alford rotation (Alford, 1986), crosscorrelation modelling, and local parametric inversion. The analysis algorithm for multi-source polarization data (Alford rotation) usually does not work for single-source polarization data. However, analysis algorithms for single-source polarization (such as crosscorrelation modelling, local parametric inversion), in principle, should be applicable to multi-source polarization because multi-source polarization consists of two orthogonal single-source polarizations.

To demonstrate the layer stripping of Alford rotation and crosscorrelation modelling and to compare with the local parametric inversion, we constructed a VSP model that consists of two fractured zones: one is near surface with a strike of 15°; and the other with orientation of 60° is contained within the receiver array located from 690 m to 870 m at intervals of 3.75 m (see Figure 1). The offset P-wave source is 120 m, while the S-wave sources are located near the wellbore.

Multi-source polarization – Alford Rotation

Alford (1986) first developed the algorithm and applied it to a multicomponent-multisource (multi-polarization) shear-wave dataset acquired at Dilley, Texas, to compensate for the shear polarization splitting over an azimuthally anisotropic medium. The direct application of Alford rotation is to find the natural polarization direction through a mathematical operation, assuming the two split shear waves are orthogonally polarized and fracture orientations in the subsurface remain constant with depth. To make the algorithm applicable to realistic reservoir environment having changes in fracture orientation with depth, Winterstein and Meadows (1991a, b) introduce the layer-stripping concept to quantify subsurface shear-wave birefringence (natural polarization direction and time delay) by using this algorithm.

Figure 2 shows a 2-by-2 shear-wave data matrix. The vertical axis is considered as the source axis and the horizontal axis is considered as the receiver axis. The XY data component, for example, is from the X source on the Y receiver, where X indicates inline, and Y indicates crossline. XY and YX are two off-diagonal components. Alford rotation was implemented by choosing time windows that included only the leading portions of the first-arrival shear waves and then calculating energy (sums of squares of amplitudes) on the off-diagonal components at rotation angle increments of one degree. The angle which minimizes off-diagonal energy is the fast shear-wave polarization direction (natural coordinate for fracture strike orientation). Figure 3, shows a plot of the sums of the off-diagonal-component energy from real seismic data. The period of scanning rotation is 90°, described by equation (1).

$$E = U_{XY}^2 + U_{YX}^2$$

$$= A\ \mathrm{Sin}^2 2\theta + B\ \mathrm{Sin}\ 4\theta + C \quad (1)$$

where A, B, C are constants related to the amplitudes of the four shear-wave components. Therefore, the scanning range of the angle from -45° to 45° is good enough.

We use the same procedure for layer stripping as Winterstein and Meadows (1991) did. Figure 4 shows the results after the first layer stripping, from which we can see that off-diagonal components have been well minimized. A polarization angle of 15° has been found. As we have seen in the VSP model, those traces minimized are not in the fracture zone. The polarization angle of 15° is the residual effect from the top fracture zone, which is supported by the fact that there is no time shift between diagonalized components over the interval. We repeat the same procedure for a second layer stripping. A polarization angle of 45° relative to the previous 15° has been found, which indicates the polarization direction for the second fracture zone is 60°. After layer stripping twice, a final shear-wave data matrix is plotted in Figure 5, where we can see that the off-diagonal components have been well minimized, except for a little edge effect on the top of the second fracture zone. As a summary of final results, polarization direction and waveform are plotted in Figure 6.

One should note that in Alford rotation top-layer polarization information is needed before a local polarization and time lag can be quantified; otherwise, Alford rotation is subject to distortion of signal on the off-diagonal components of the 2-by-2 shear-wave data matrix. This means that a whole dataset from surface to the zone of interest is needed. This is not a problem for surface seismic data. It is more expensive to acquire the VSP data from the zone of interest to the surface than just to do the zone of interest.

Single-source polarization analysis - crosscorrelation modelling

As discussed by Thomsen (1988), Alford rotation does not work for the data acquired with a single source polarization, such as converted shear-wave data. Most VSP data available are data acquired with a single source (usually a P-wave source) and three-component receivers. In other words, converted shear-wave data are the most popular shear-wave data; and in this type only two shear-wave components are available.

Harrison (1992) developed a crosscorrelation modelling algorithm that has been successfully applied to converted-wave surface data. The algorithm is based on a modelling of the crosscorrelation function between rotated radial and transverse field components. For example, we have radial and transverse components (two traces) recorded after shear waves propagate through an azimuthally anisotropic medium with polarization angle of -30° and a time lag of 10 ms (Figure 7a). First, we generate an autocorrelation of the data within the analysis time window and a set of crosscorrelations by rotating the field data in fixed increments of 15° sweeping the range of -90° to 90°. Second, we crosscorrelate the rotated radial and transverse components at each angle by changing the time lag. Thirdly, we generate an energy-normalized crosscorrelation sum and calculate the signal-to-noise variance ratio (S/N). Finally, we plot S/N versus rotation angle and time lag. The contour plot of these synthetic two traces is shown in Figure 7b. As is expected, the result gives -30° for polarization angle and 10 ms for time lag (centre of the contour). In the isotropic case or on the symmetry axes the contour does not concentrate on the 2-D plot (see Figure 8).

In order to understand if the algorithm is applicable to VSP data and to see if the layer stripping concept can be extended to the data of single source polarization, a synthetic converted-wave dataset was generated from the VSP model described above (see Figure 9). It is shown in Figure 9 that there are two dominant downgoing converted-wave events. The event converted from the top is used for crosscorrelation modelling analysis because it contains anisotropic information of the top fracture zone and second fracture zone. After the first layer stripping, the results of crosscorrelation analysis from the top of the second fractured zone to the bottom of the VSP model are shown in Figure 10.

This analysis has shown that the layer stripping concept can be extended to the converted-wave data (single source polarization). But anisotropy information above the interest zone is required before local anisotropy information can be precisely extracted. Also, in the VSP wavefield when this algorithm is applied, the downgoing wavefield should be separated from the upgoing wavefield; or CCP stack sections should be used (only containing the upgoing wavefield). The time window around the converted wave event should be picked appropriately so that no other converted waveform (for example, a converted wave from the top of the second fractured zone, see Figure 9) is covered by the window.

Single source polarization analysis – local parametric inversion

As demonstrated above, both Alford rotation and crosscorrelation modelling can be applied for VSP birefringence-analysis purposes. For the layer stripping to be effective, starting at the surface, birefringence effects must be removed as soon as they occur. This requires that the VSP data be recorded from the zone of interest to the surface. Moreover, multiple conversions and splitting at shallow layers (for example, TI-medium contamination) can complicate the polarizations of shear waves before they reach the depths of interest. An alternative method for measuring local shear-wave birefringence has been developed by Esmersoy (1990), called local parametric inversion. Assuming that the medium is locally homogeneous (i.e. at several neighboring depth spacings – two or more) and waves have locally planar wavefronts, local vector wavefield decomposition is carried out by a robust least-squares inversion algorithm. In modelling split shear waves, we first establish a parametric model for the local wavefield, such that we can choose to model up- and/or down-going waves, trace spacing window. Then the parameters are estimated by minimizing the squared error between the model data and the observed data.

The local-wavefield inversion technique is tested on both the synthetic four-component (vertically incident) shear-wave VSP data (direct shear-wave data) and the synthetic converted-shear-wave VSP data that were analyzed previously with Alford rotation and crosscorrelation modelling.

Figure 11 shows with nine-level inversion (four depth spacings) wave velocities (fast and slow), polarization angle of the fast shear wave (relative to the XX component, counterclockwise) as a function of depth. One of four shear-wave components is also plotted showing the zone of interest. The result, 60° of fractured zone, indicates that parametric inversion gives accurate results. Applying the algorithm to the direct shear-wave data from the crossline source, we have obtained the same results, for the fractured zone. For the unfractured zone (isotropic) we obtained the same velocity as from shear-wave data of the inline source. But polarization angle for the unfractured zone is very scattered.

Figure 12 shows, with seven-level inversion (three depth spacings), the inverted shear-wave velocities (fast and slow), polarization angle of the fast shear wave (relative to the radial component, counterclockwise, the same direction as the XX component) as a function of depth. Comparing Figure 12 with the results from crosscorrelation modelling, we can see that the two algorithms give similar results; but the edge effect of the crosscorrelation modelling algorithm is stronger than that of local parametric inversion.

From the analysis of three different algorithms, the advantages of local parametric inversion in VSP data can be summarized: a) it is local in space, therefore local fractured zones can be detected and analyzed without requiring shallower information and layer stripping; b) velocities of split shear waves and polarization angles can be obtained by fully employing all available data simultaneously – therefore it is robust and optimal; c) near-surface effects (multiples, TI-medium contamination etc.) can be overcome.

CASE STUDY

A 9-component survey was conducted by PanCanadian Petroleum Ltd. in May 1993. Recording was accomplished through Schlumberger's five shuttle magnetically clamping sonde and Maxis recording system. An additional monitor geophone was placed on the surface near wellbore. Record length was six seconds at a 2 ms sampling rate. Two AMOCO Mertz rotating-baseplate shear vibrators polarized radially and transversely (see Figure 13).

The offset P-wave VSP was used for tool orientation. Followed tool orientation, all 4-component shear wave data were rotated to get shear wave data matrix. XX component was rotated to the true north.

The data have been analyzed with Alford rotation and Local Parametric Inversion. A 9-trace spacing window was used for local parametric inversion around first arrival time for both inline source and crossline source data. Figure 14 shows the inverted shear wave velocities and polarization angle for both sources. The results of two sources agree with each other, which indicate local parametric inversion is a good approach. Also, the results indicate, in the work area, no anisotropic effects shown above Lea Park (most of them are under 5%). It is seen from the first arrival time difference between diagonalized components that there are three anisotropic zones within these shale formations. Within Lea Park and Colorado formation most inverted azimuthal angle are 0° which indicates sources polarizations fall into symmetry axes. It is supported by the fact that Alford rotation does not change the first arrival time difference between diagonalized components (see Figure 15). The amount of anisotropy within this shale zones are less than 10%.

CONCLUSIONS

This study has shown that three different algorithms corroborated each other. Local wave field parametric inversion is a reliable, quick approach for detection of vertical shear wave birefringence while other algorithms need layer stripping procedure. In the work area some anisotropic effect is shown in Lea Park and Colorado shale.

ACKNOWLEDGMENTS

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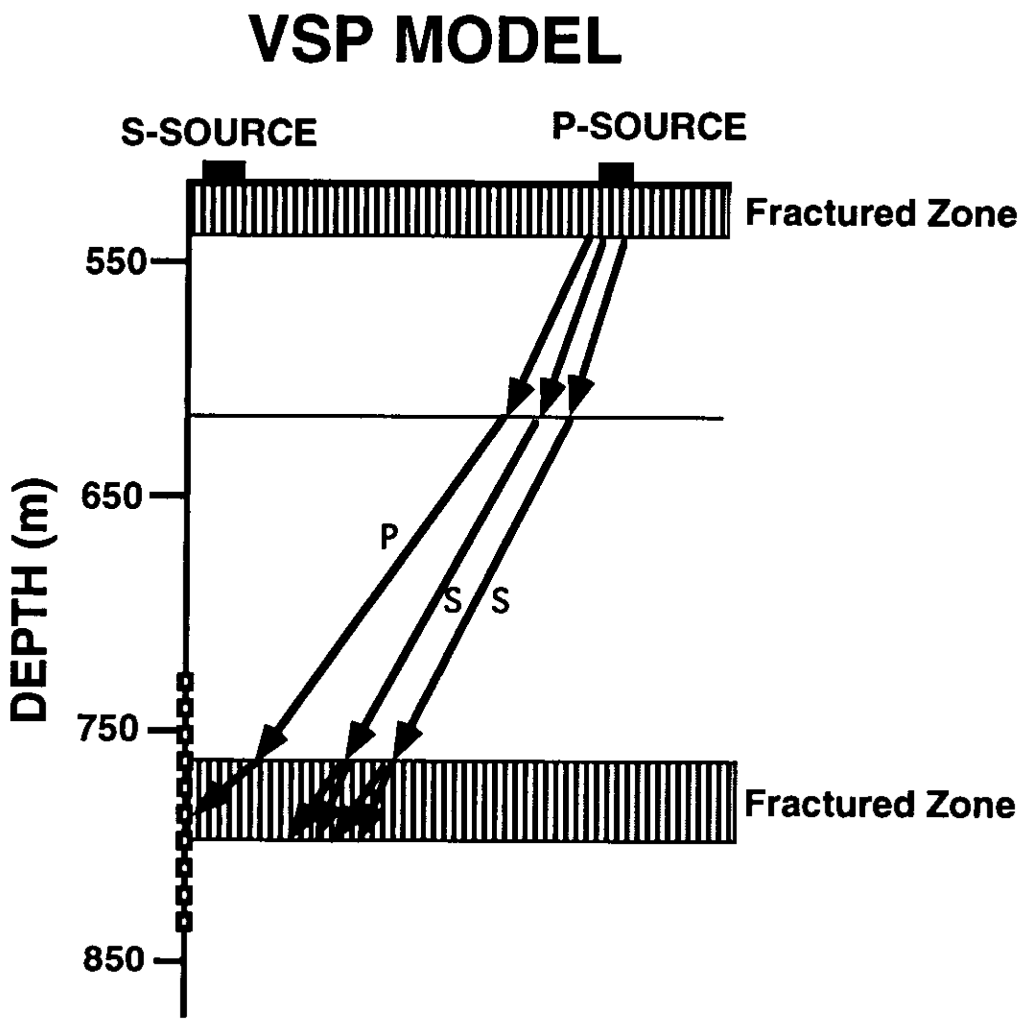


FIG. 1. VSP model with two fracture zones, top layer is near surface with a strike of 15°, and the bottom layer is within receivers with strike of 60°.

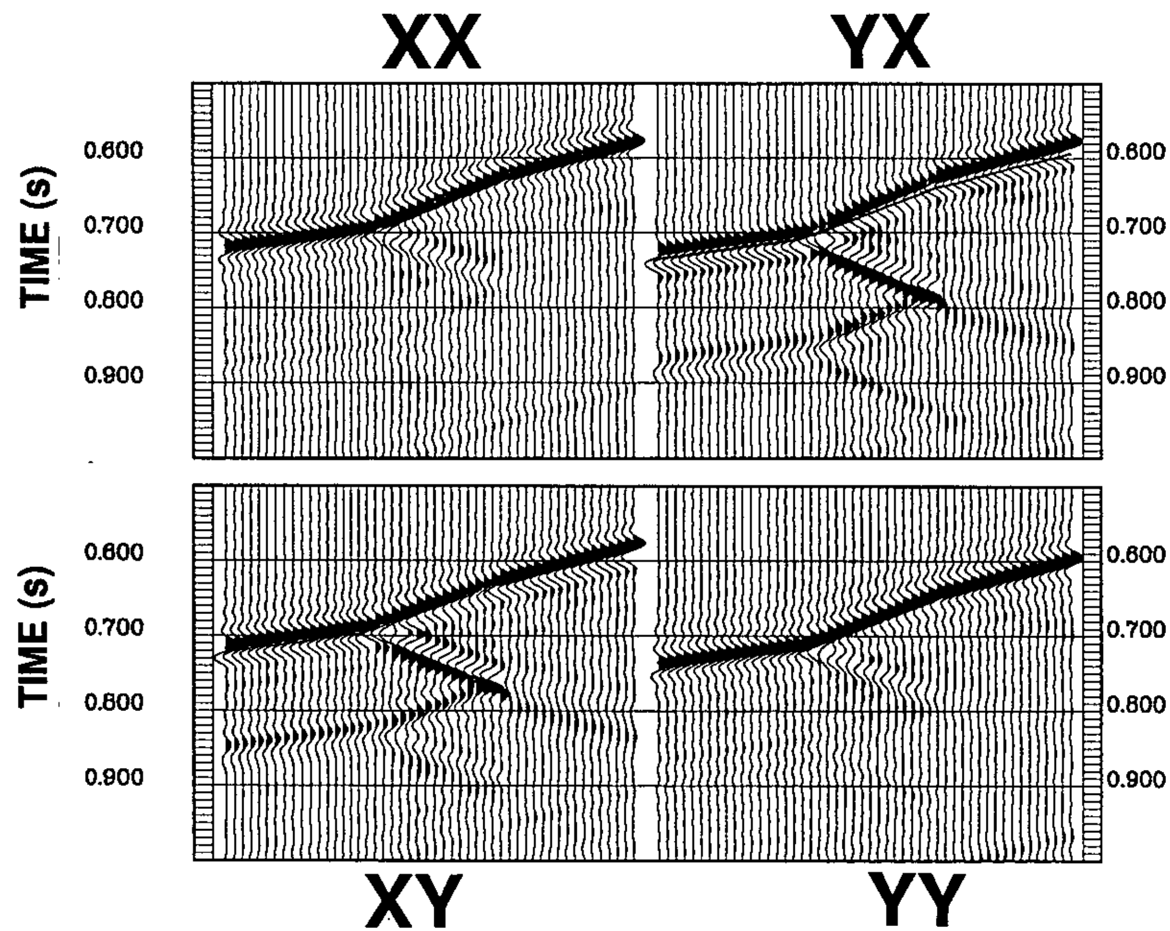


FIG. 2. Synthetic 4-component shear wave data matrix:
XX – inline source inline receiver; YY – crossline source crossline receiver;
YX – crossline source inline receiver; XY – inline source crossline receiver.

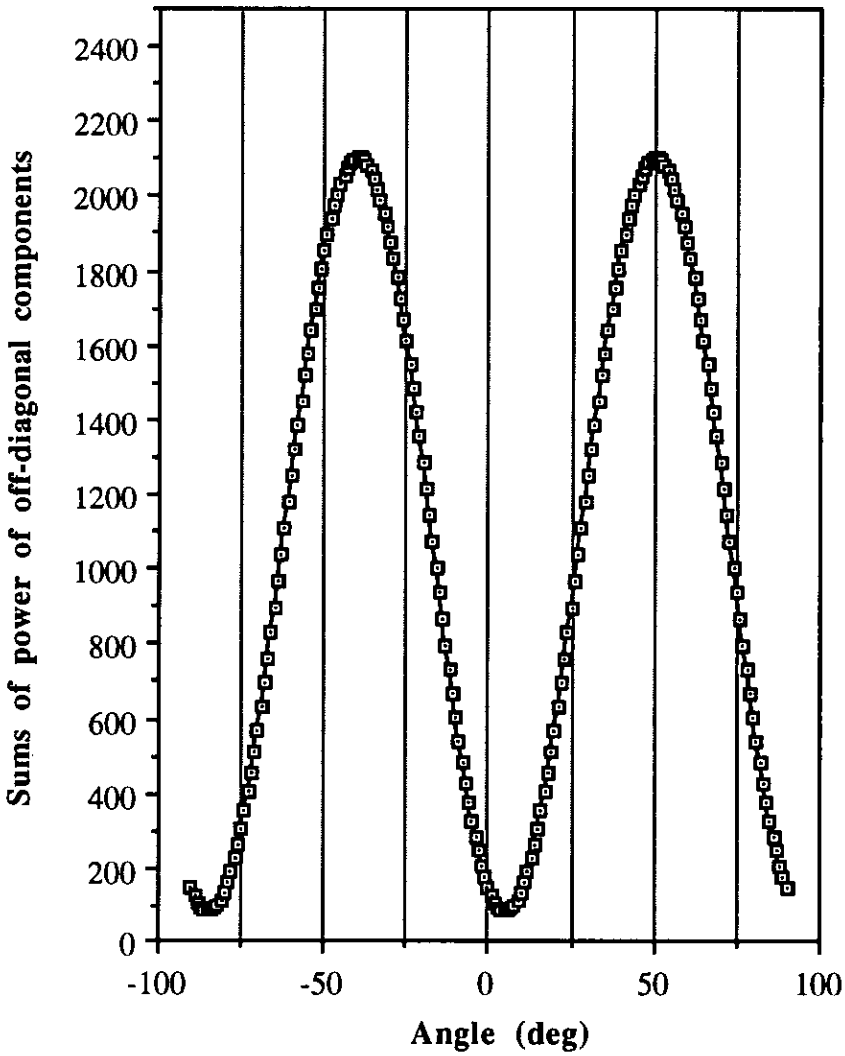


FIG. 3. Sums of power of off-diagonal components versus scanning angle, showing period of Alford rotation.

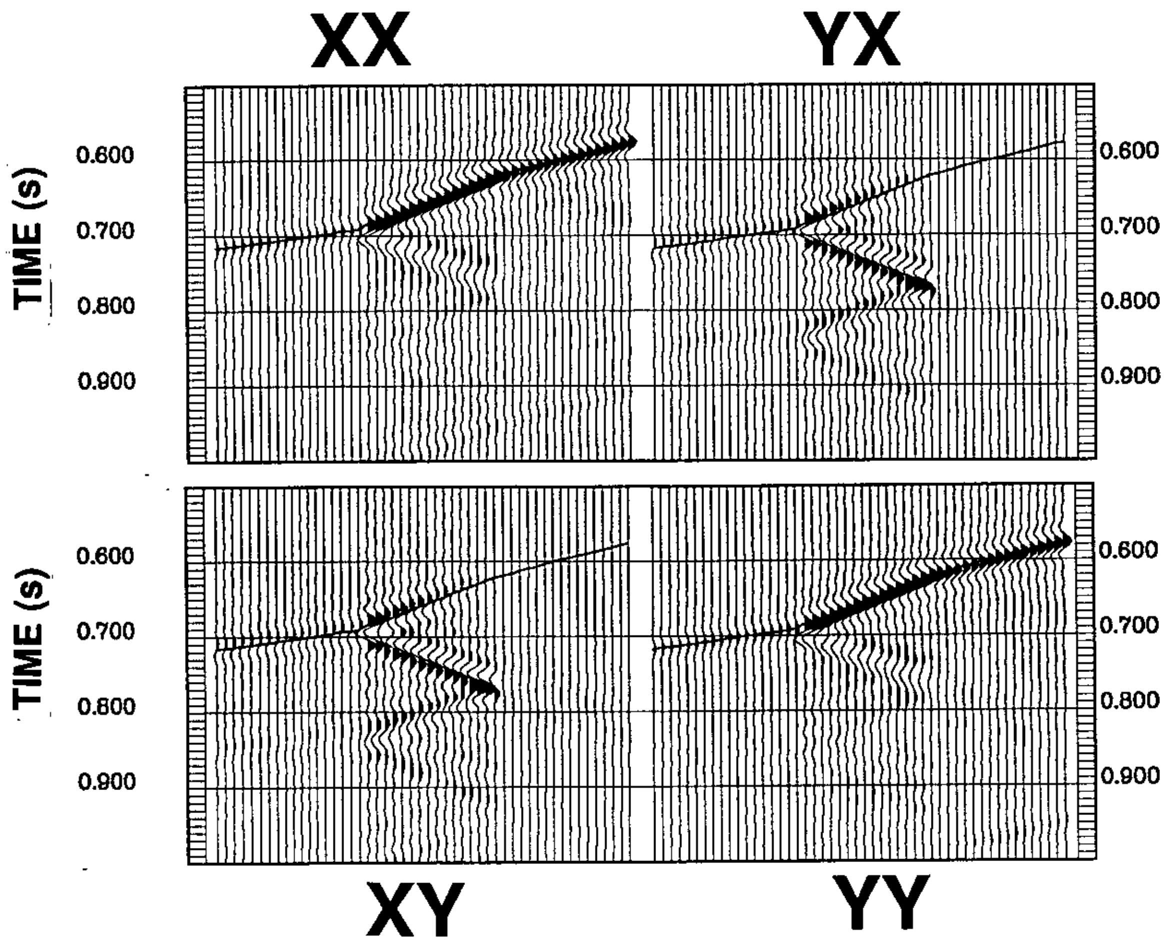


FIG. 4. Synthetic shear wave data matrix after first layer stripping.

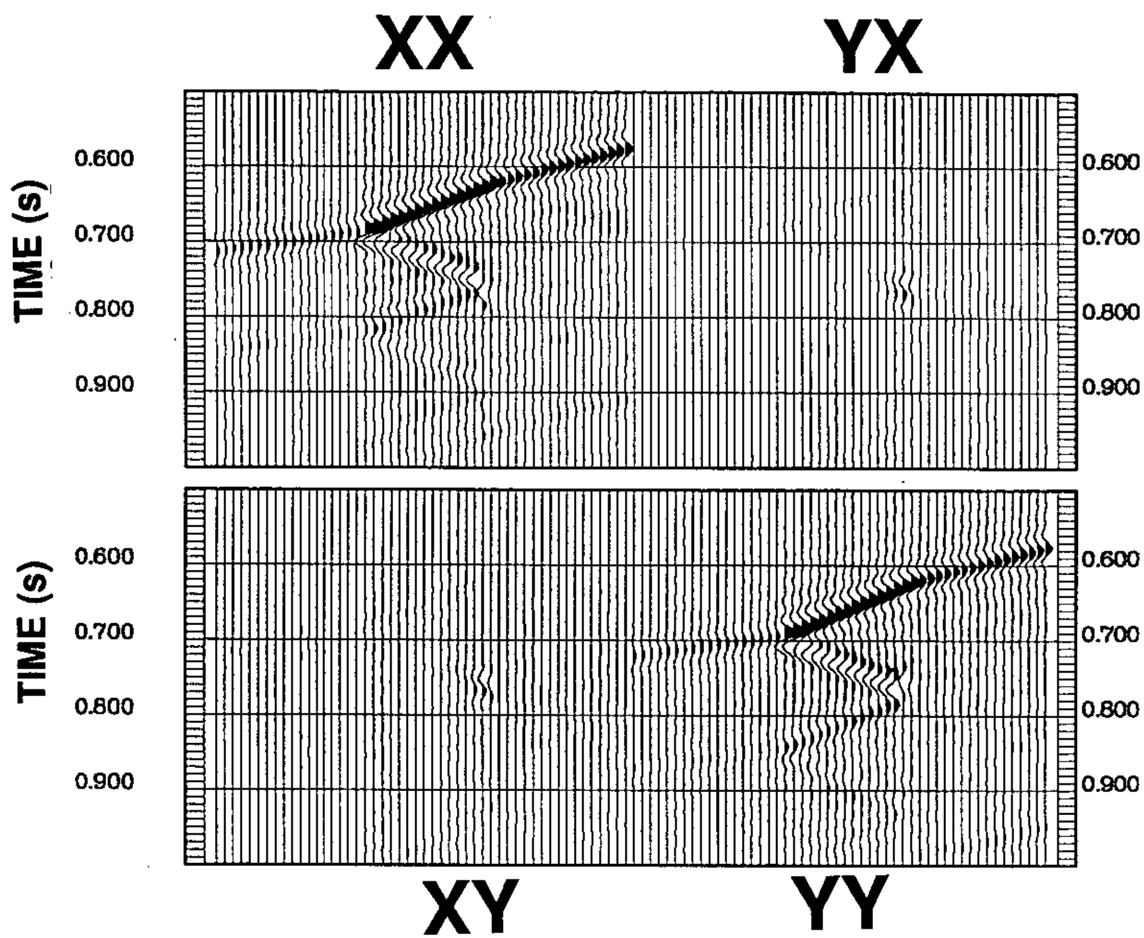


FIG. 5. Final waveform of Alford rotation after two layer stripping on shear wave data matrix (see Figure 2).

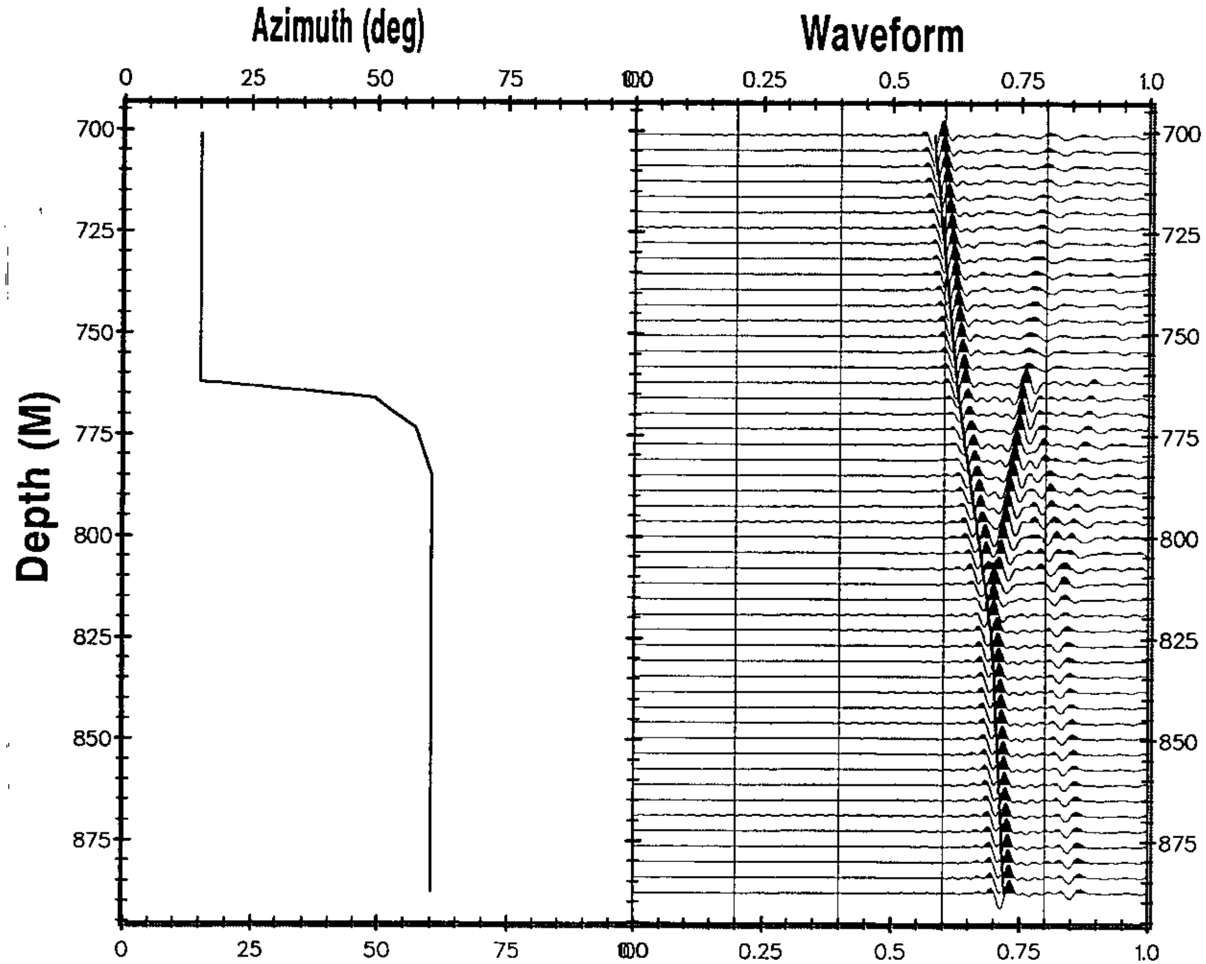
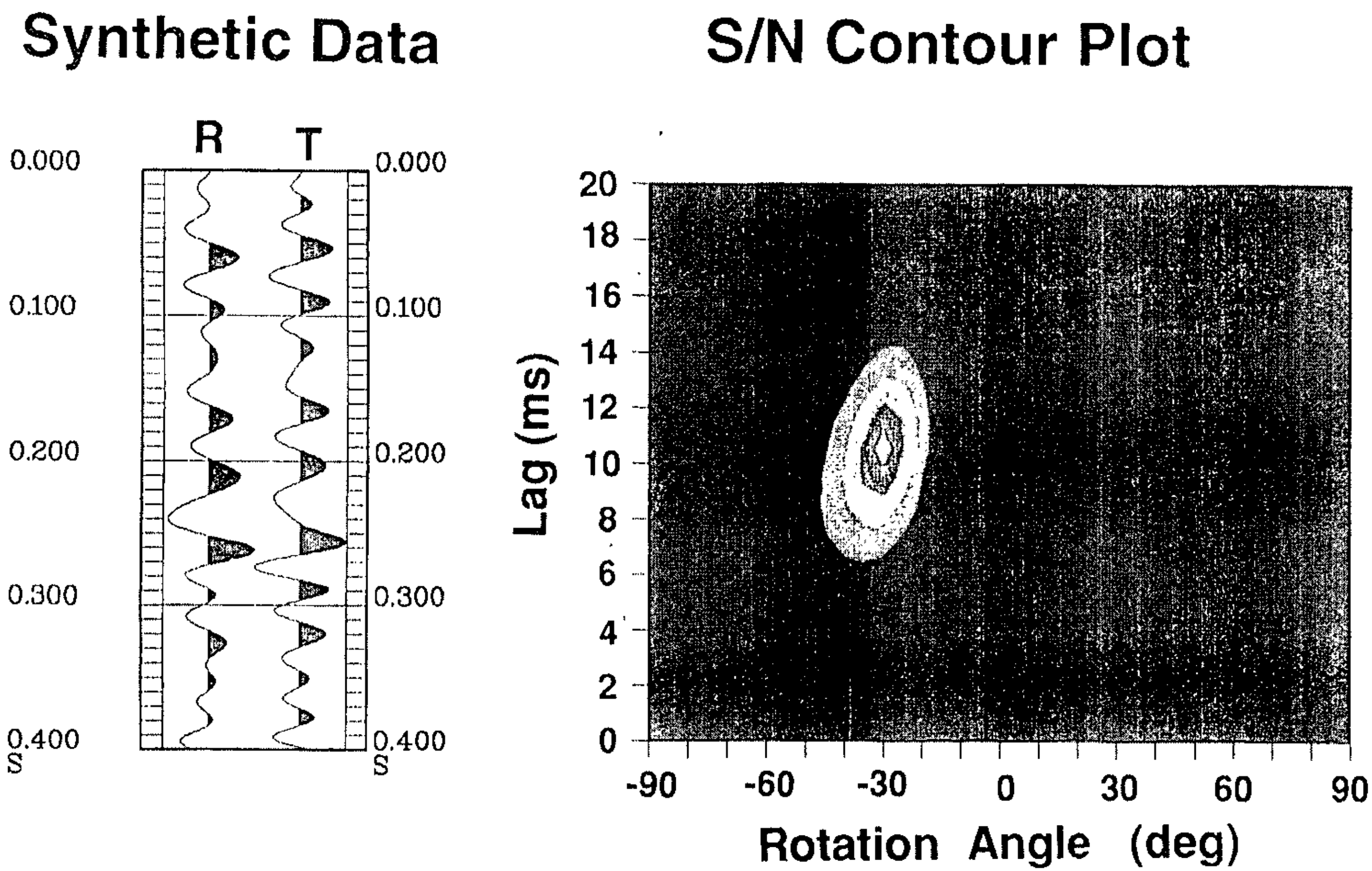


FIG. 6. Polarization angle calculated through Alford rotation and waveform, showing zone of interest.



(a) (b)

FIG. 7. Synthetic traces of radial (R) and transverse (T) components (a), and plot of crosscorrelation modeling analysis: rotation angle and time-lag (b)

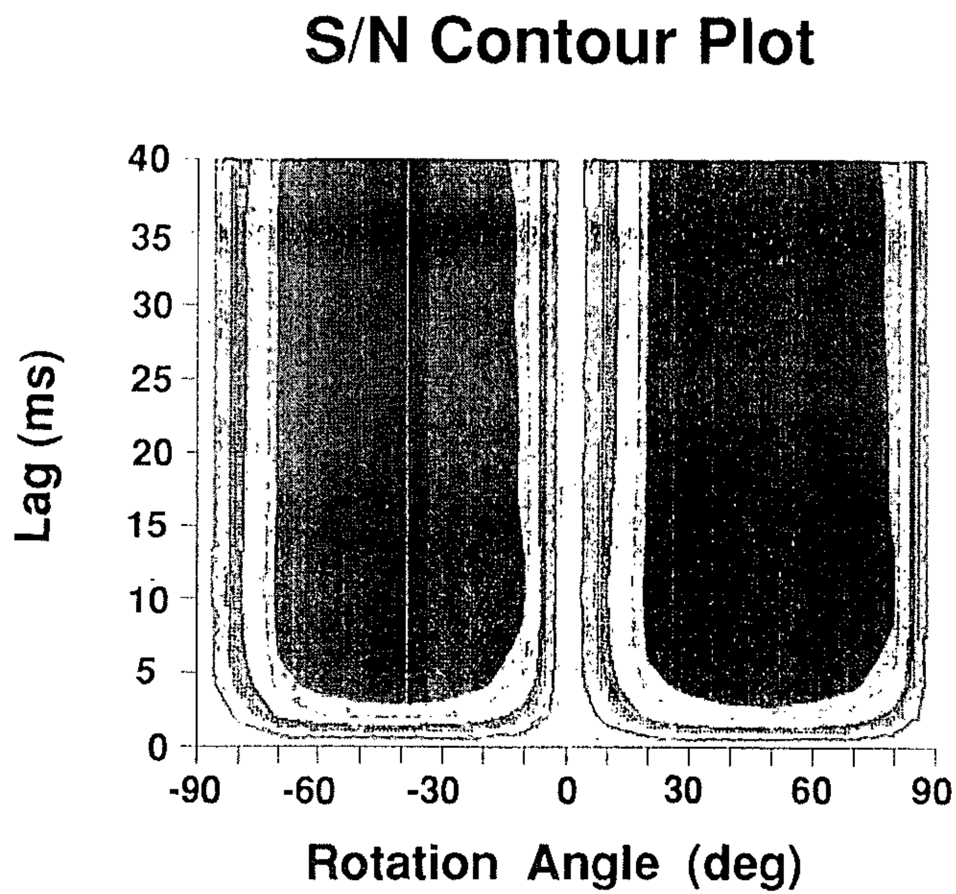
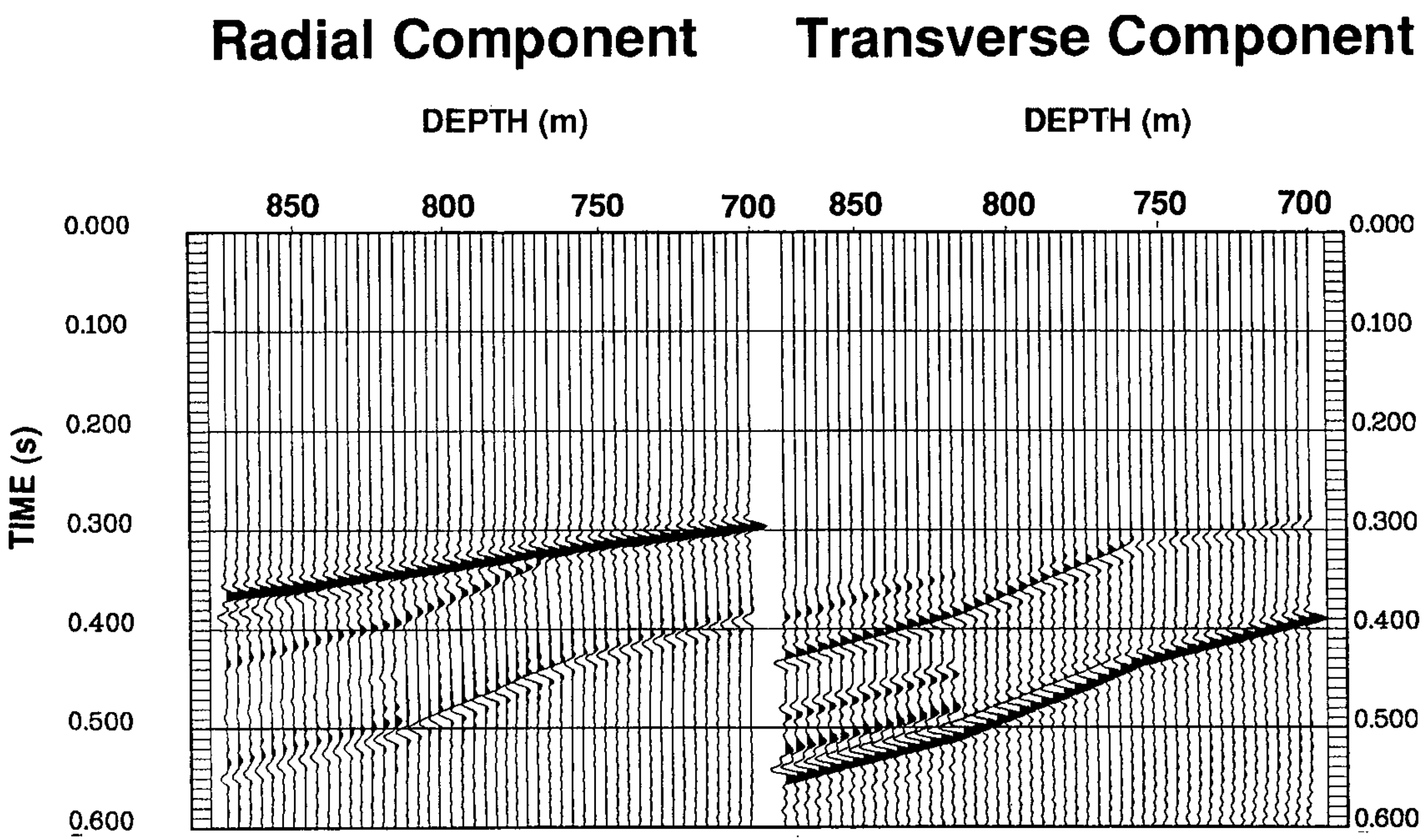


FIG. 8. Typical plot of crosscorrelation modeling analysis on the data from isotropic media or falling into symmetry axes.



(a) (b)

FIG. 9. Synthetic converted wave data from VSP model: radial component (a) and transverse component (b)

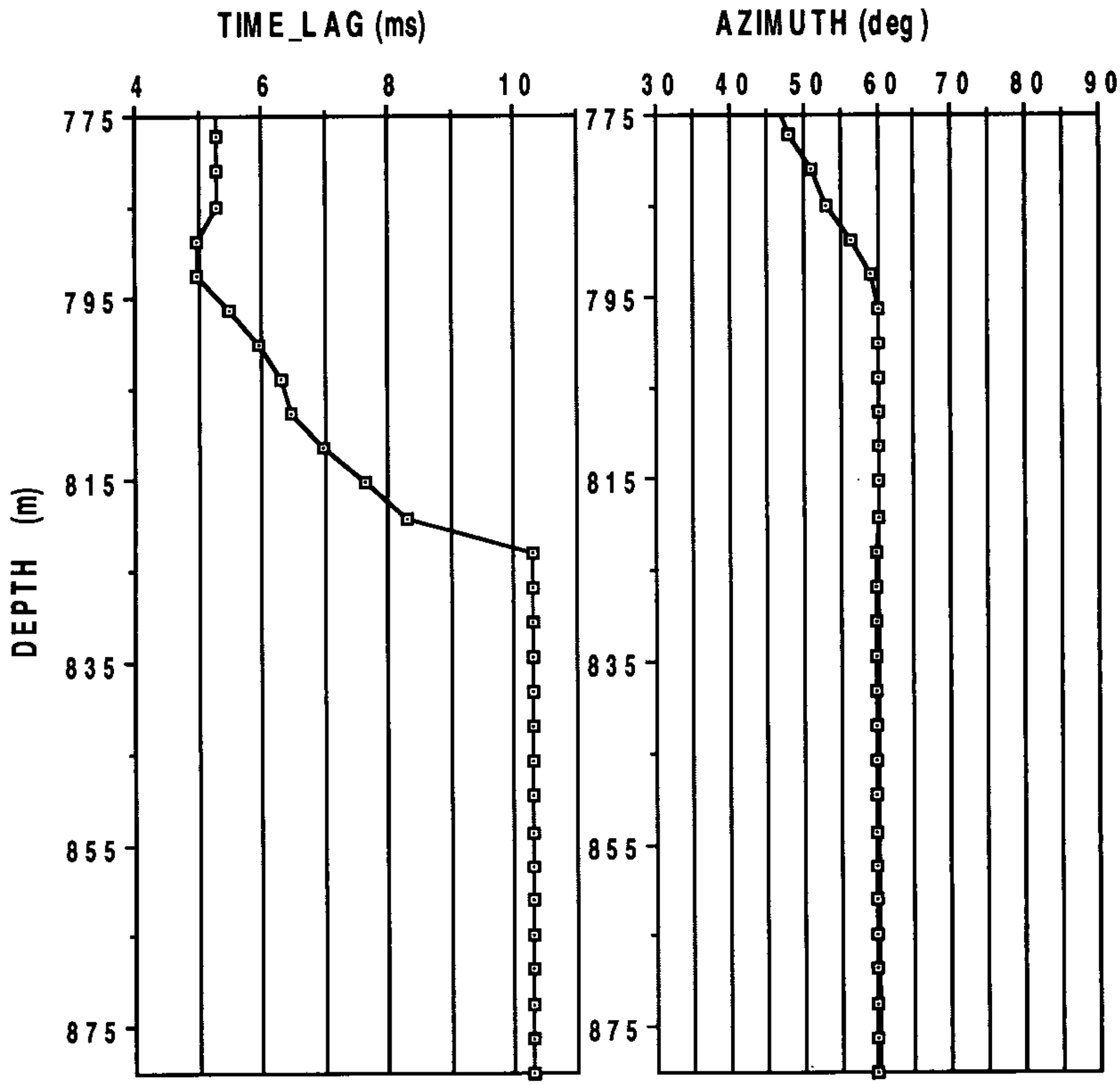


FIG. 10. The time-lag and azimuth angle for second fracture zone analyzed from crosscorrelation modeling.

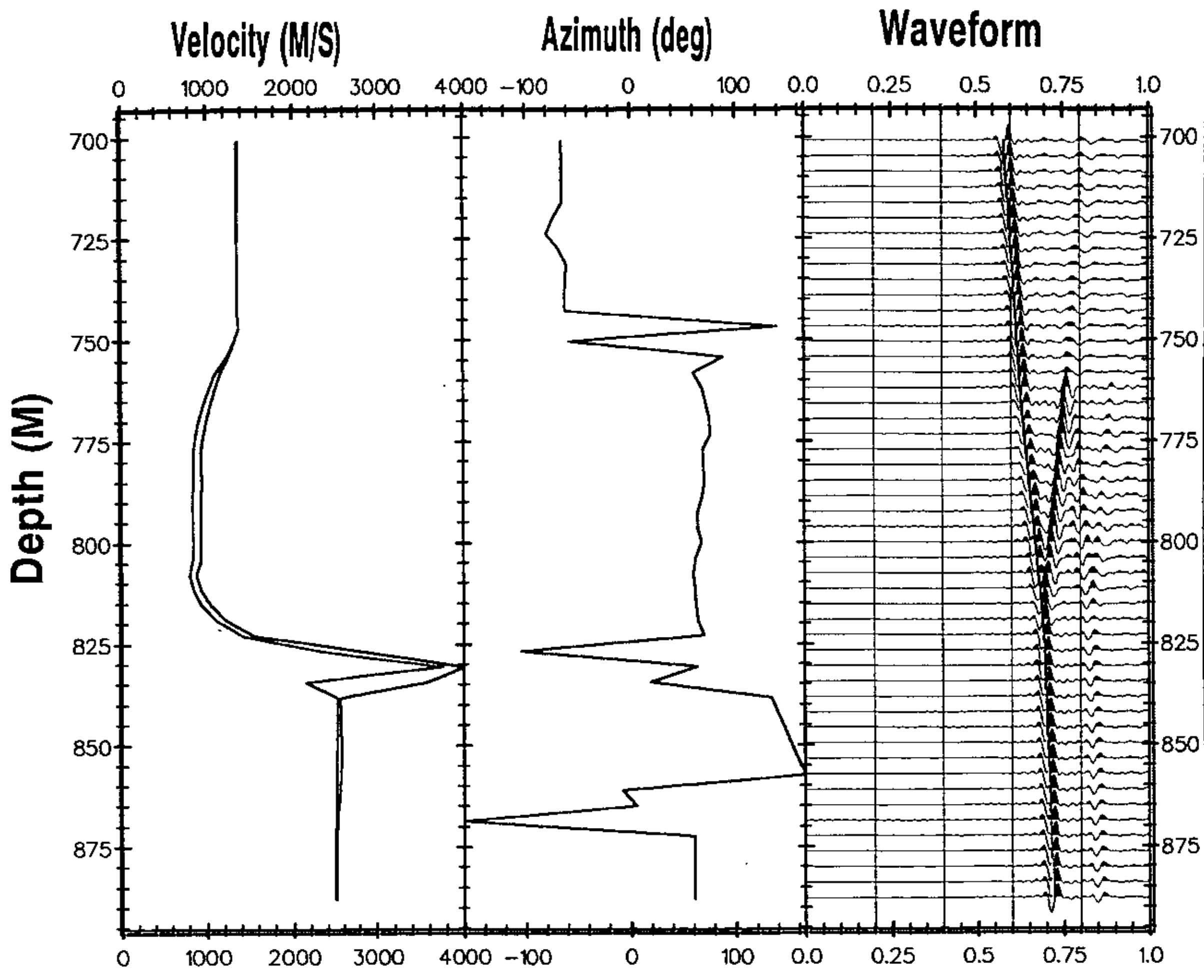


FIG. 11. Parametric inversion results of two horizontal components (XX, XY, see Figure 44) from inline shear source.
(a) fast and slow shear wave velocities; (b) inverted polarization angle of fast shear wave;
(c) waveform of one horizontal component, showing zone of interest.

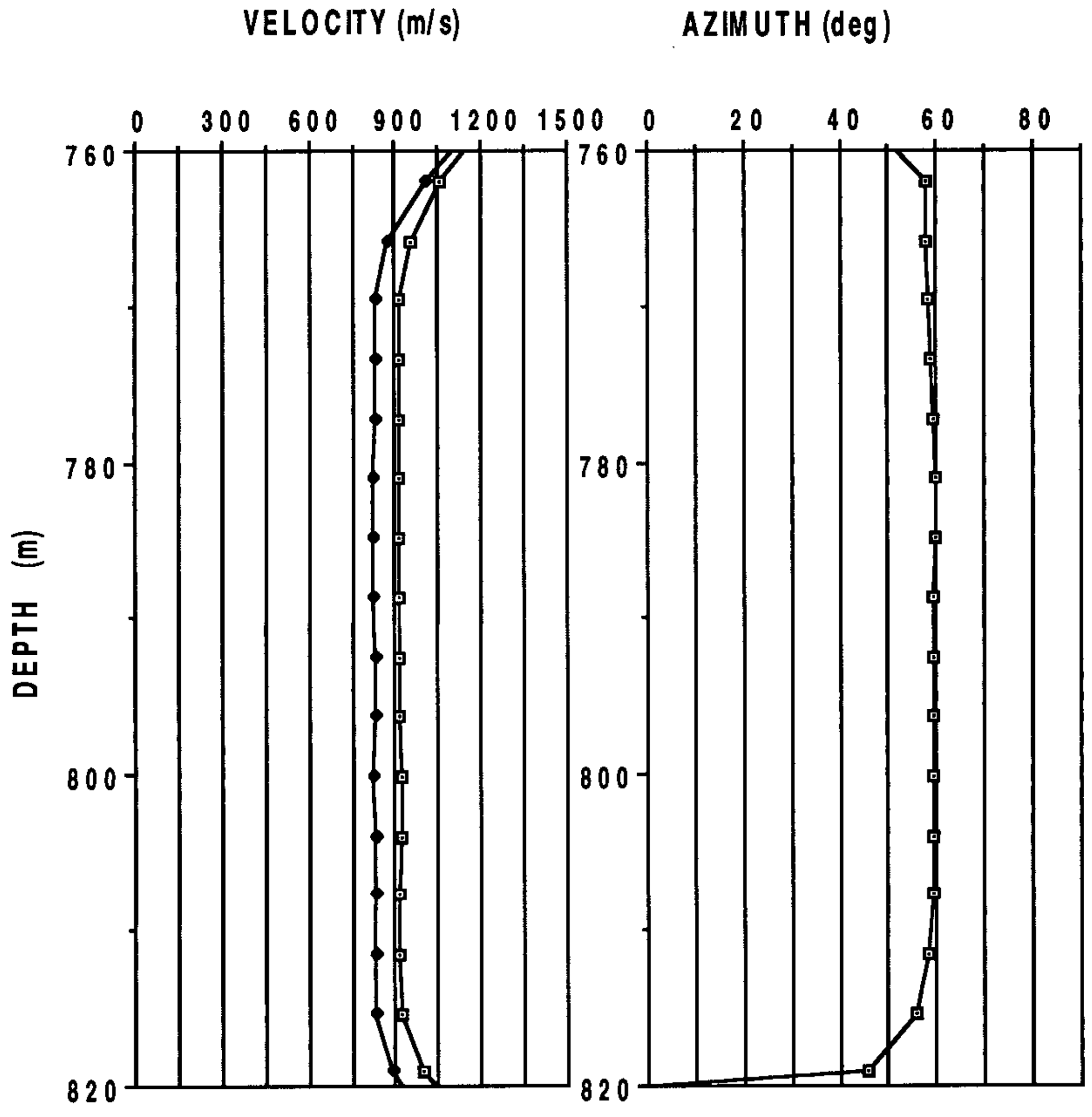


FIG. 12. Parametric inversion result of synthetic converted shear wave data, showing inverted fast and slow shear wave velocities (left) and polarization of fast shear wave (right).

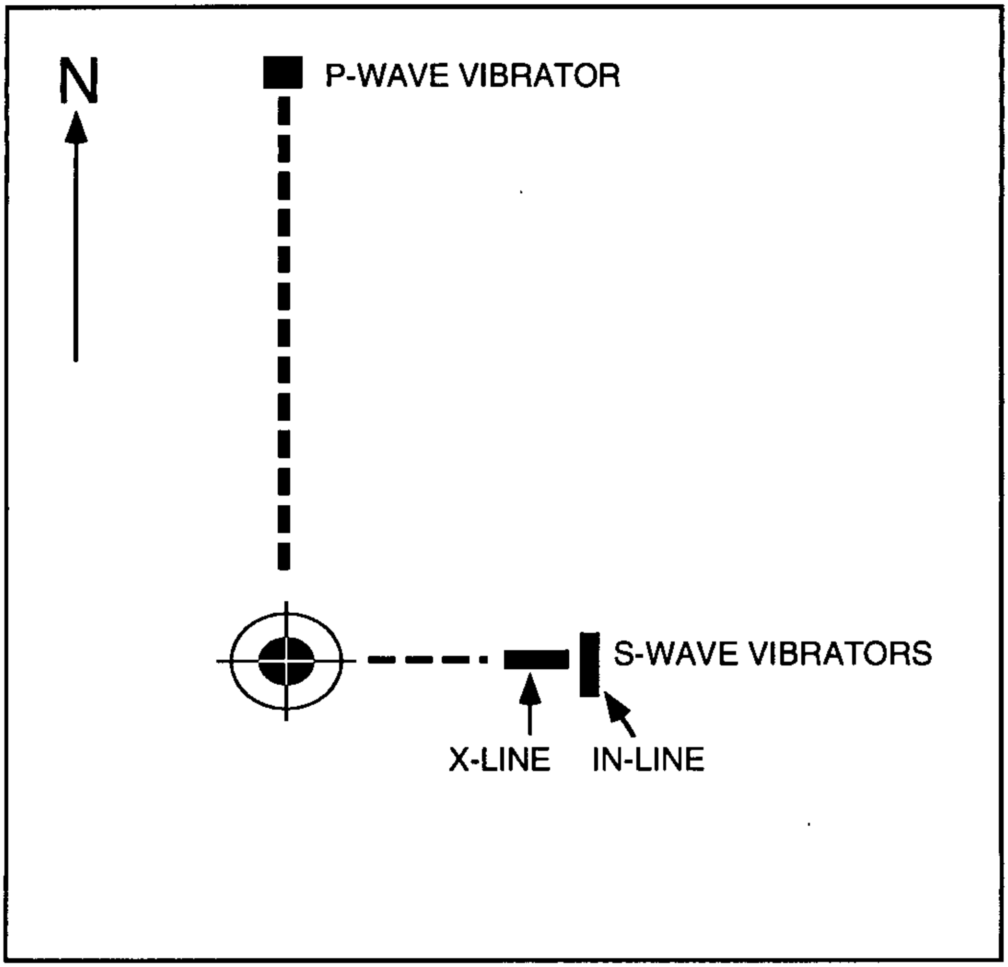


FIG. 13. Schematic geometry of nine-component VSP experiment.

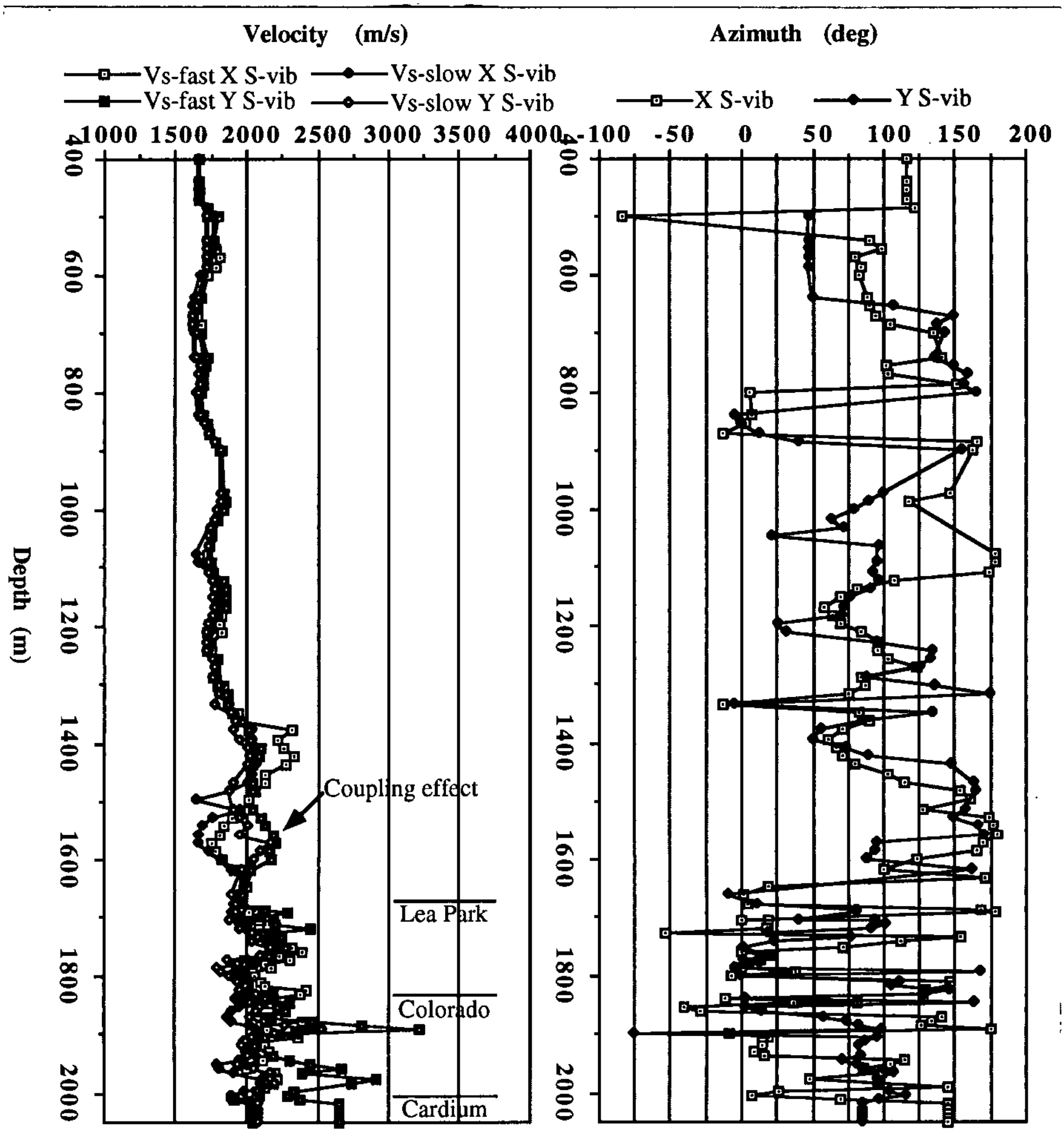


FIG. 14. Parametric inversion result of 4-component shear wave data, showing local parametric inversion applied to multi-source polarization data, the agreement of shear velocities and polarization angles between two shear sources.

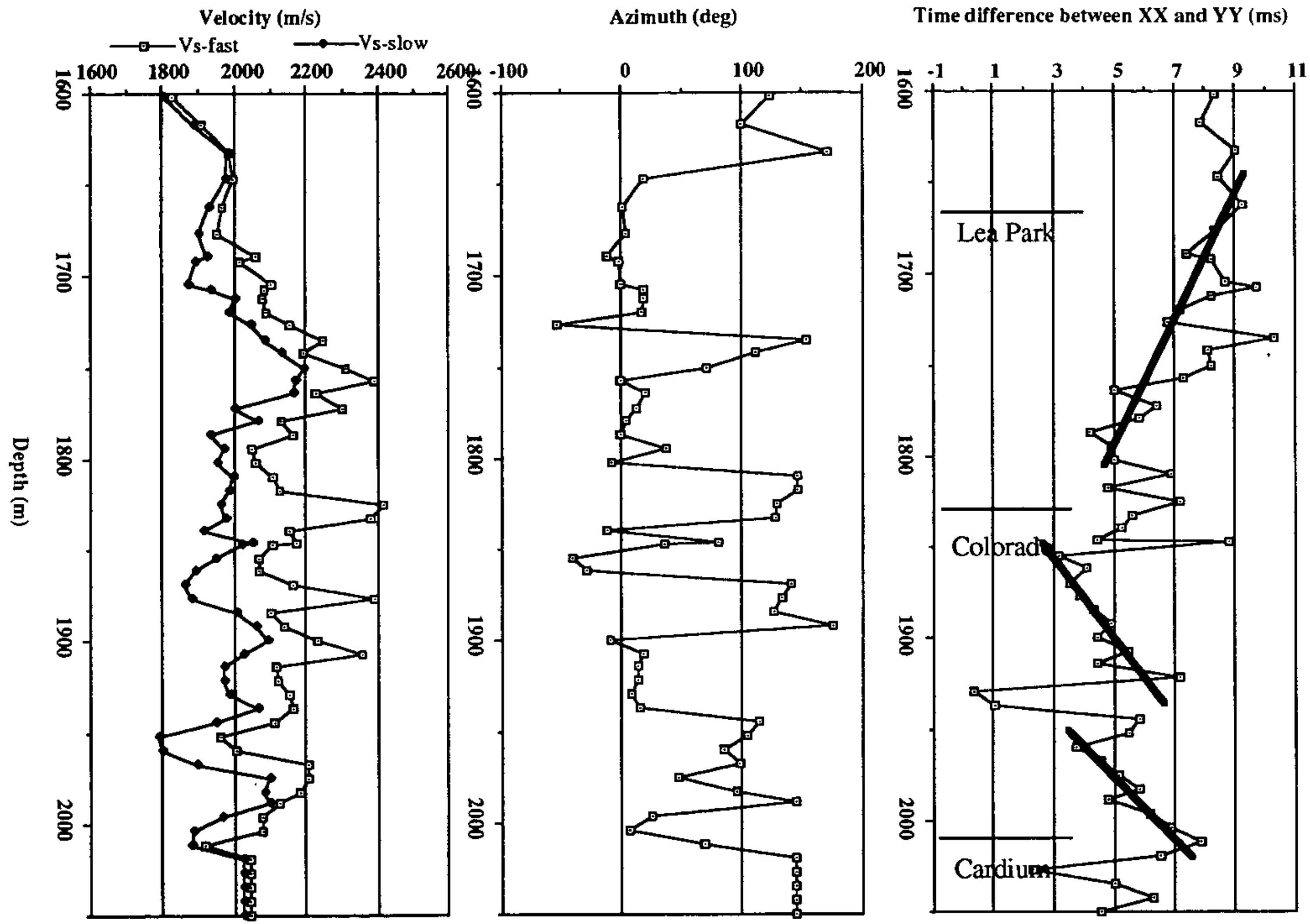


FIG. 15. Comparison between local parametric inversion results and time difference of diagonalized components, showing vertical shear wave birefringence in Lea Park and Colorado shale.