Seismic wavefields recorded at near-vertical incidence from a counterphase source

Zandong Sun and Michael J. Jones*

ABSTRACT

To acquire direct shear-wave data without a shear-wave vibrator we have tested a different type of shear-wave source – the counterphase source (two P-wave vibrators running 180° out of phase) in VSP experiments. Although the data were acquired in the deepest parts of wells (at near-vertical incidence), they allow us to compare counterphase shear waves, direct shear waves, and converted shear waves. It has been observed that a significant amount of shear-wave energy propagates in the vertical direction, which indicates a good potential for the counterphase source to be applied to VSP area. A comparison between counterphase shear waves and direct shear waves indicates the particle-displacement direction of counterphase shear is in, or close to, the direction of the line joining the two P-wave vibrators. Shear-wave velocities inverted from counterphase shear waves and converted shear waves are comparable.

INTRODUCTION

In the summer of 1993, two datasets were acquired in the deepest parts of wells from VSP counterphase tests run by PanCanadian Petroleum Ltd. (to be called dataset A) and Conwest Exploration Company Ltd. (to be called dataset B) in Alberta. By counterphase source we mean two P-wave vibrators running in counterphase, that is 180° out of phase from each other. Edelmann's (1981) field experiments indicate the existence of significant shear wave energy generated by two vertical surface sources. Dankbaar's (1983) theory fail to explain the existence of the normal incident shear wave energy. The double-couple representation of this source has been successfully applied by Easley (1992). In fact, this is a more general term for such sources. Two coupled mixed-phase P-wave vibrators is one possible such double-couple source (Easley, 1993).

This paper, as an initial study, concerns the following aspects: 1) it describes and examines, in the vertical or near-vertical direction, the radiation pattern and characteristics of a counterphase source; 2) by using available direct shear-wave data it compares some characteristics of shear-wave data from counterphase sources, direct shear sources, and converted from P waves.

DATA ACQUISITION

Dataset A was acquired with VSP counterphase tests and direct shear-wave data. Figure 1 shows the survey geometry for the data acquired by PanCanadian Petroleum Ltd. The line connecting two P-wave vibrators is parallel to the displacement

* Schlumberger of Canada

direction of one shear-wave vibrator (located on the left, called crossline shear vibrator). The offset for both direct shear-source and counterphase P-wave vibrators is about 50 m. The ground-level and zero-offset elevations are both about 1034 m. The acquisition parameters are listed in Table 1.

Table 1. Acquisition parameters

Frequency:	P-wave 8–100 Hz
	S-wave 6–40 Hz
Record length:	6000 ms
Sample rate:	2 ms
Receiver:	Schlumberger ASI, 3-component

Counterphase test geometry information of Conwest Exploration Company Ltd. is not available.

COMPARISON AMONG COUNTERPHASE, DIRECT-SHEAR, AND CONVERTED SHEAR-WAVE SOURCES

Theoretically, in the full-space case, the radiation characteristics of a counterphase source have been described by Aki and Richards (1980) (Figure 2a). Although this development is not at the free surface, the most interesting feature is the shear-wave lobe in the vertical direction. According to the theory, most shear-wave energy can be observed propagating in or near the vertical direction from such a source. This may provide a good explanation for Edelmann's (1981) shot record. It is predicted that the shear-wave particle displacement falls into the plane containing the particle motions of the two P-wave vibrators (vertically, see Figure 2b).

Realistically, the theory of double-couple source to the free surface is needed for half space. Some theoretical work have been done for the two P wave vibrators on the free surface. Previously, Easley (1992) worked out theoretical aspect for two P-wave vibrators in counterphase, and recently (1993), he has done theoretical work for more general case which is for two P wave vibrators in mixed phase.

The theory states the magnitude of shear wave energy and the phase of shear-wave polarization are the functions of altitude angle. By altitude angle, we mean the angle between vertical direction (facing down) and raypath deviated from vertical direction (see Figure 2b). In the vertical direction of counterphase source (altitude angle = 0°, see Figure 2b), compared with other directions, maximum shear wave energy should be observed and no polarization phase change can be observed. As altitude angle increases, shear-wave energy decrease and shear-wave polarization is subjected to phase change. Datasets to be presented in following are recorded near vertical direction of the counterphase source.

Counterphase and direct shear-waves

The counterphase data acquired by PanCanadian Petroleum Ltd. have, for comparison, direct shear-wave data over the same depth interval (1914–2050 m). The altitude angles over this interval are from 1.5° to 1.4°. With such a small altitude angle (almost vertical) we do not expect any shear-wave polarization phase changes. Also, we expect to observe maximum shear-wave energy.

Figure 3 shows the horizontal components from different sources (a counterphase source, an inline shear source and a crossline shear source). Similarities can be found between the counterphase data (a) and the data from the crossline shear-wave vibrator (b). The bandwith of the counterphase data extend higher than that of the shear-wave vibrator data (Figure 4). The frequency bandwith of the spectra shows a notch at 25 Hz which suggests that there may be a coupling effect in this source system.

Counterphase and converted shear wave

The second counterphase dataset was acquired by Conwest Exploration Company Ltd. (dataset B). We do not know of any existing direct shear-wave data to compare with the counterphase data. The offset of the counterphase P-wave vibrators was about 50.m and recording depth was from 1969 to 2300 m, from which the altitude angles were calculated at 1.45° to 1.2° (from shallow to deep). Figure 5 shows the two horizontal components. A significant time shift can be seen between the first arrivals of the two horizontal components. To see that the time shift is caused by a local anisotropic medium or is accumulated through the top anisotropic layers, a local parametric inversion algorithm (Esmersoy, 1990) has been applied to the data. The results of this (Figure 6) indicate some local anisotropy effects over the interval. We do not have any geological information to confirm what this means to the real world about this anisotropic effect. But we have applied the same algorithm to the converted shear-wave data (Figure 7). Comparing the inversion results from counterphase and converted shear-wave data, we find that the shear-wave velocities show the same pattern.

One should be aware that the inverted velocities from converted wave are apparent velocities, and are subject to a conversion to true velocities that depend on incident angle. This is why the inverted velocities from the converted-wave data are higher than those from the counterphase shear-wave data. Also converted shear waves are subject to near surface TI medium containmination which suggests anisotropic information extracted from converted wave is different from direct shear wave. We do not expect the azimuthal angles from direct shear wave and converted shear wave to agree with each other because, relative to the VSP wellbore, the P-wave vibrator for offset-VSP (for converted waves) and the two P-wave vibrators for counterphase will not necessarily stay on the same line.

DISCUSSION

The results of these tests of the counterphase source at near the vertical incidence can be summarized as follows:

1) a significant amount of shear-wave energy propagates to great depth in the wells (2000–2300 m) in or near the vertical direction (altitude angle around 1.2° to 1.5°);
2) similarities have been found between the counterphase shear waves and the direct shear waves from the crossline shear-wave vibrator which indicates that the particle displacement direction of the counterphase shear waves is in, or close to, the inline direction of the two P-wave vibrators;
3) shear-wave anisotropy information (velocities) provided by counterphase shear waves is comparable to that provided by converted shear waves.

FUTURE WORK

We are planning to do more counterphase tests to acquire three–component data from deep to shallow to study the radiation pattern and other features.

ACKNOWLEDGMENTS

We wish to thank Don Easley for many discussions on the theoretical aspects. We acknowledge PanCanadian Petroleum Ltd. and Conwest Exploration Co. Ltd. for the donation of the data. Also, we appreciate the help of Dr. R. James Brown and Mr. Richard Pearcy for proofreading this paper.

REFERENCES

Aki, K. and Richards, P.G., 1980, Quantitative seismology: 1. Theory and methods: W.H. Freeman and Co.

Dankbaar, J.W.M., 1983, The wave-field generated by two vertical vibrators in phase and in counterphase: Geophysical prosp., 31, 873-887.

Easley, D.T., 1992, Alternate description of wavefields generated by two vertical vibrators in counterphase: CREWES Res. Rep., **4**, 2, 1-10

Easley, D.T., 1993, Mixed-phase coupled vibrators: CREWES Res. Rep., **5**, 17, 1-16.

Edelmann, H.A.K., 1981, SHOVER, shear-wave generation by vibration orthogonal to the polarization: Geophys. Prosp., **29**, 541-549.

Esmersoy, C., 1990, Split-shear wave inversion for fracture evaluation: 60th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 1400-1403.

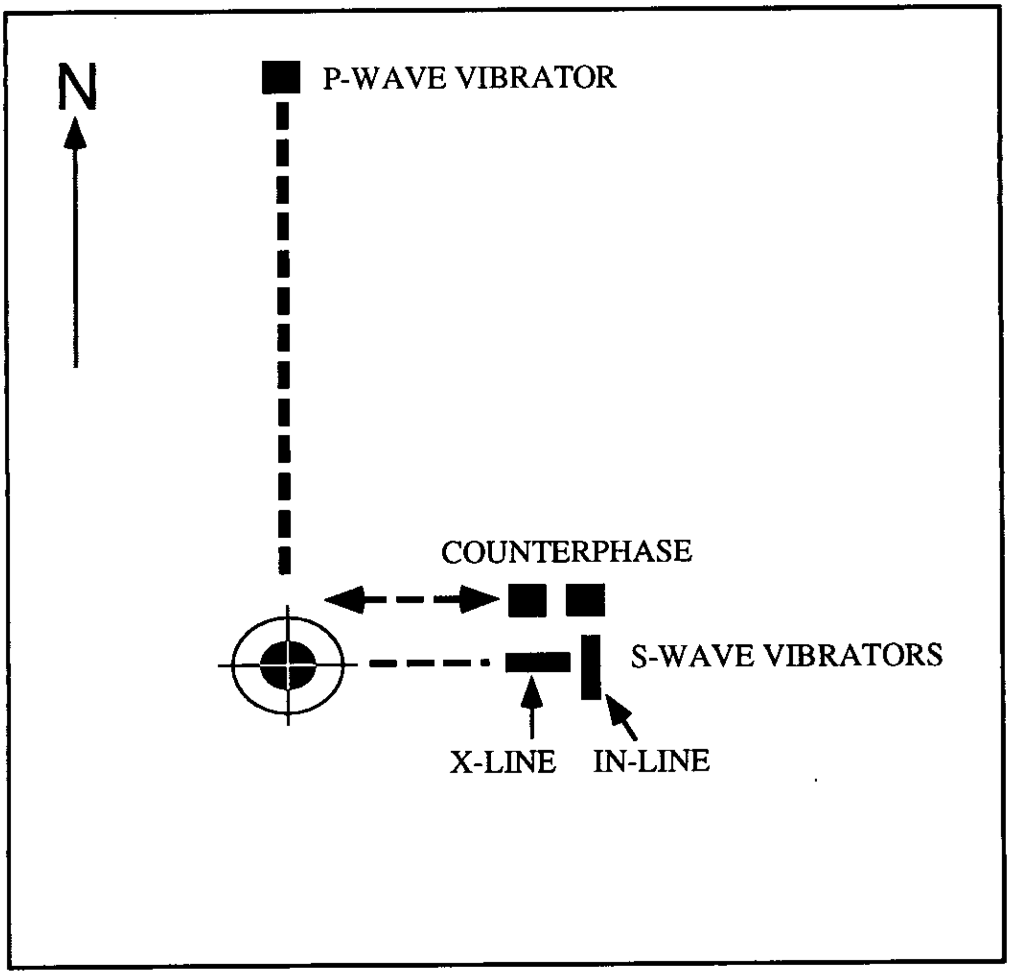

FIG. 1. Schematic geometry of PanCanadian VSP survey (for dataset A)

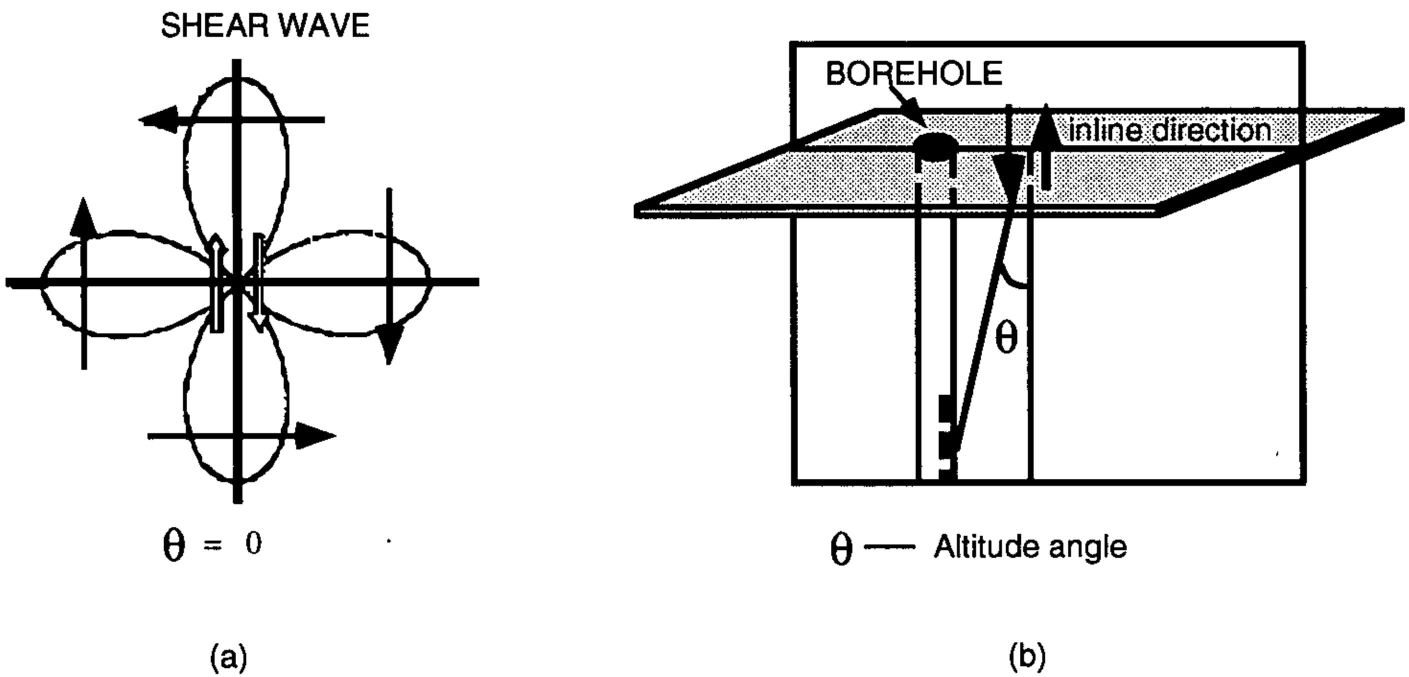

FIG. 2. Radiation pattern for a counterphase source (a) for a full space (after Aki and Richards, 1980), and schematic diagram for particle displacement, and altitude angle.

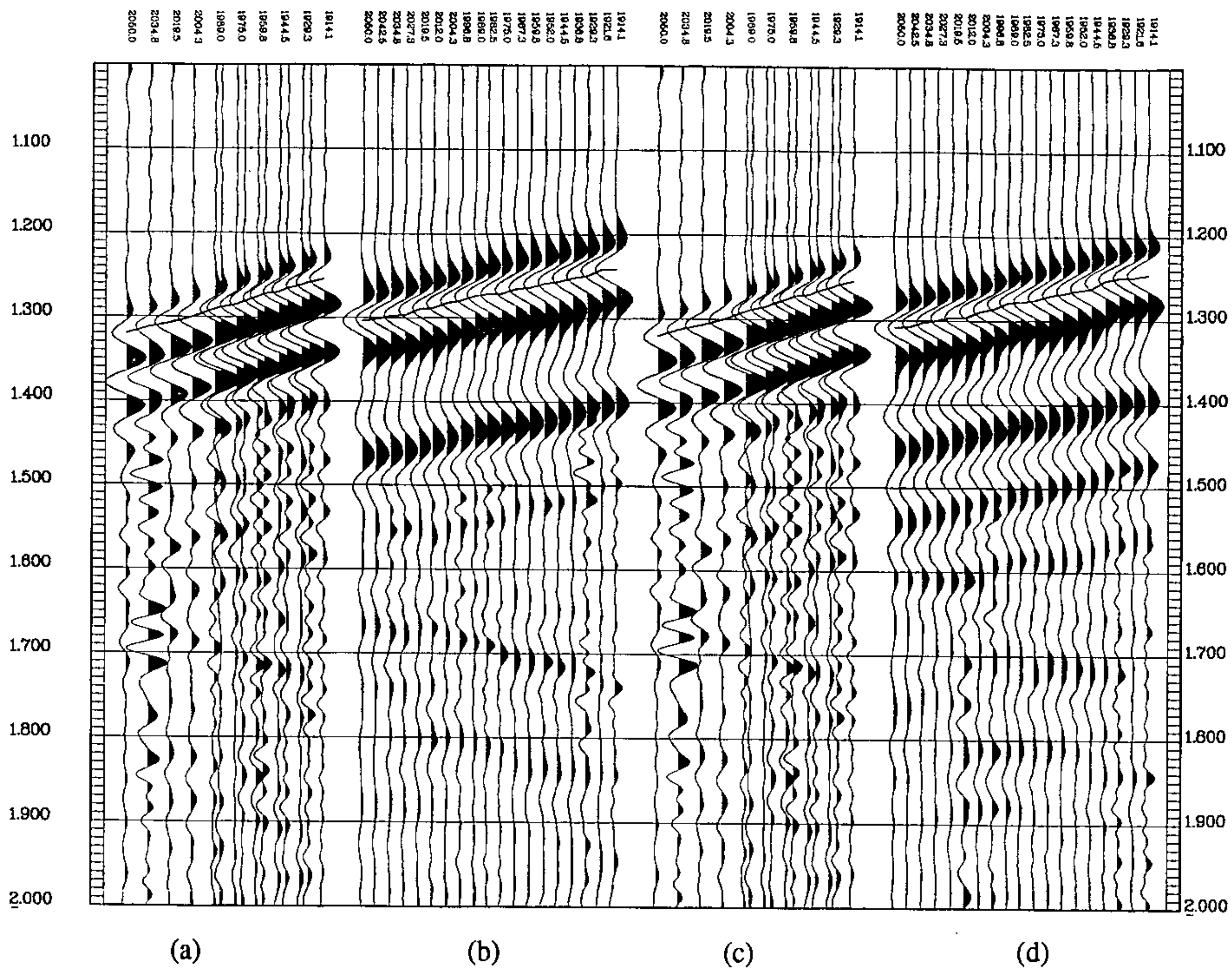

FIG. 3. Comparison of counterphase and direct shear-wave data (recorded near the vertical). (a) quasi-inline component from counterphase source; (b) inline component from crossline shear vibrator; (c) same as (a); (d) inline component from inline shear vibrator.

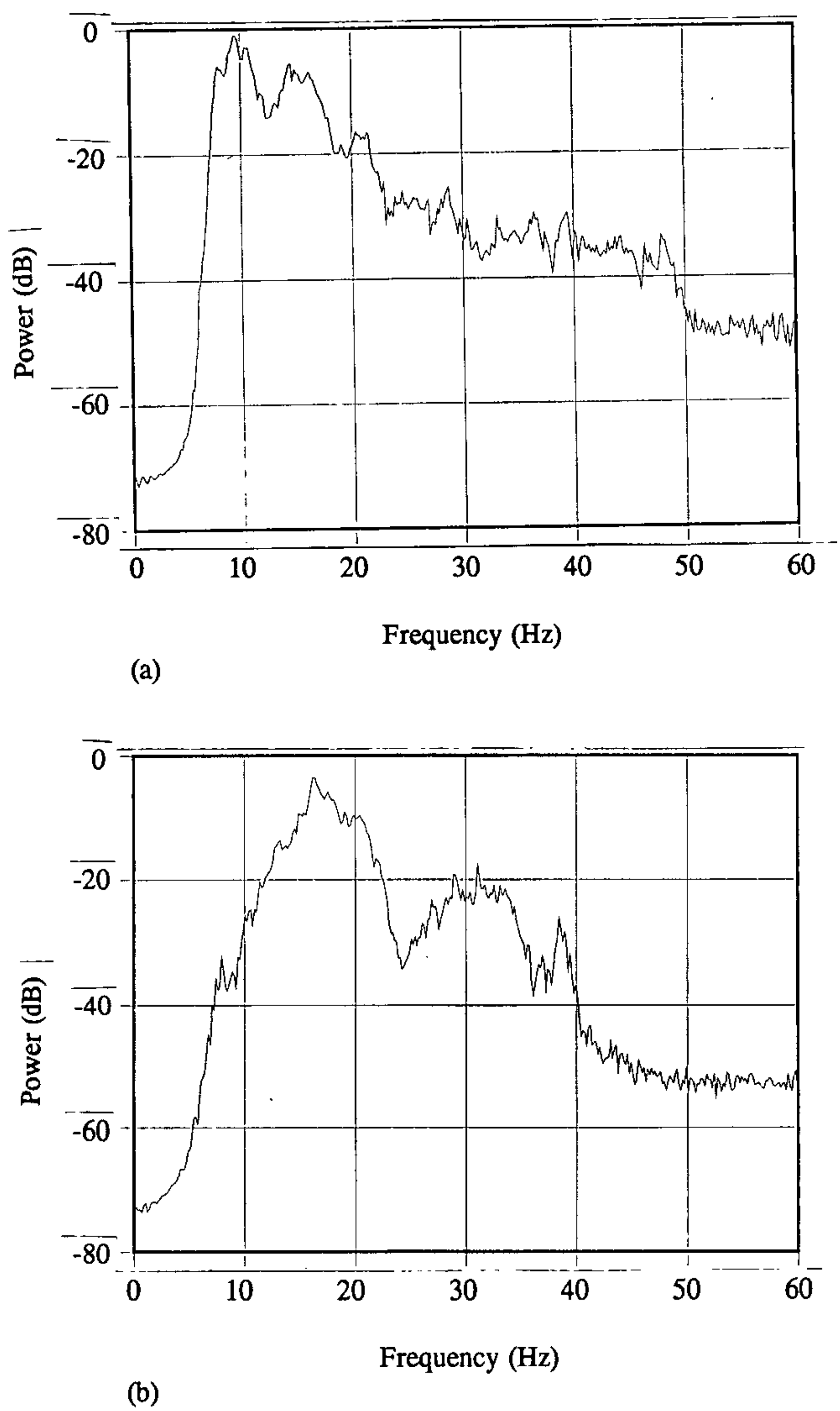

FIG. 4. Amplitude-frequency spectra of direct shear waves (a) and counterphase shear waves (b)

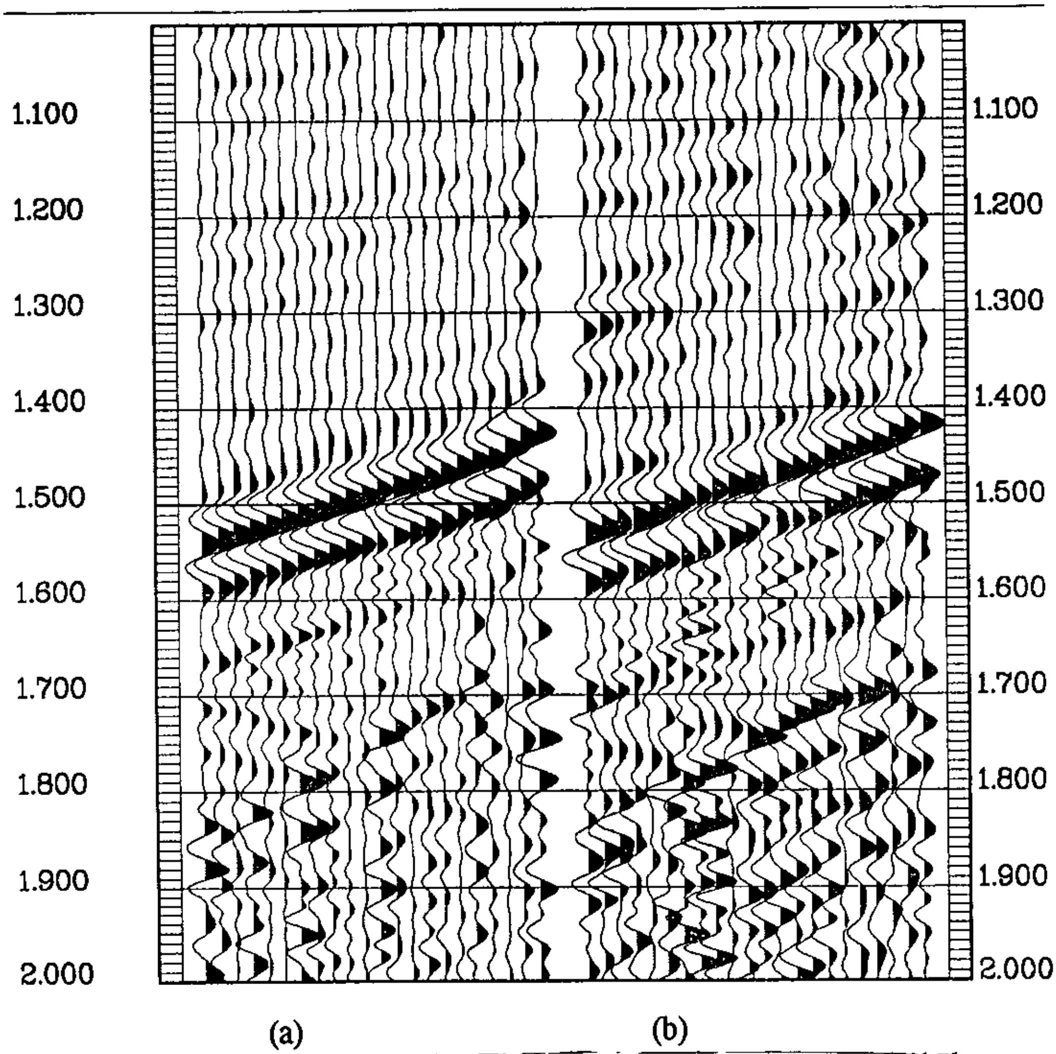

FIG. 5. Inline component (a) and crossline component (b) recorded near the vertical from a counterphase source.

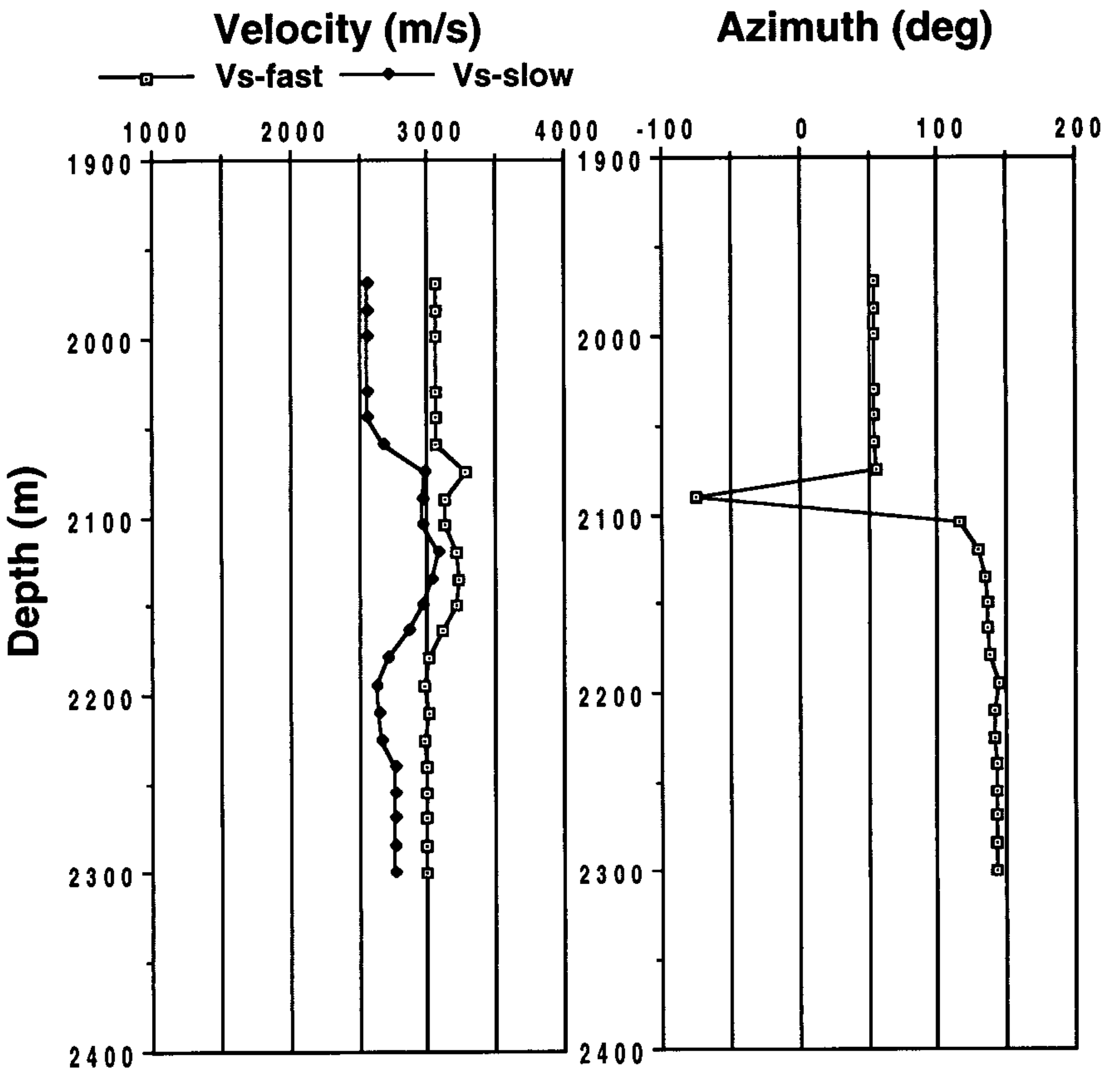

FIG. 6. Parametric inversion results of counterphase shear-wave data (dataset B).

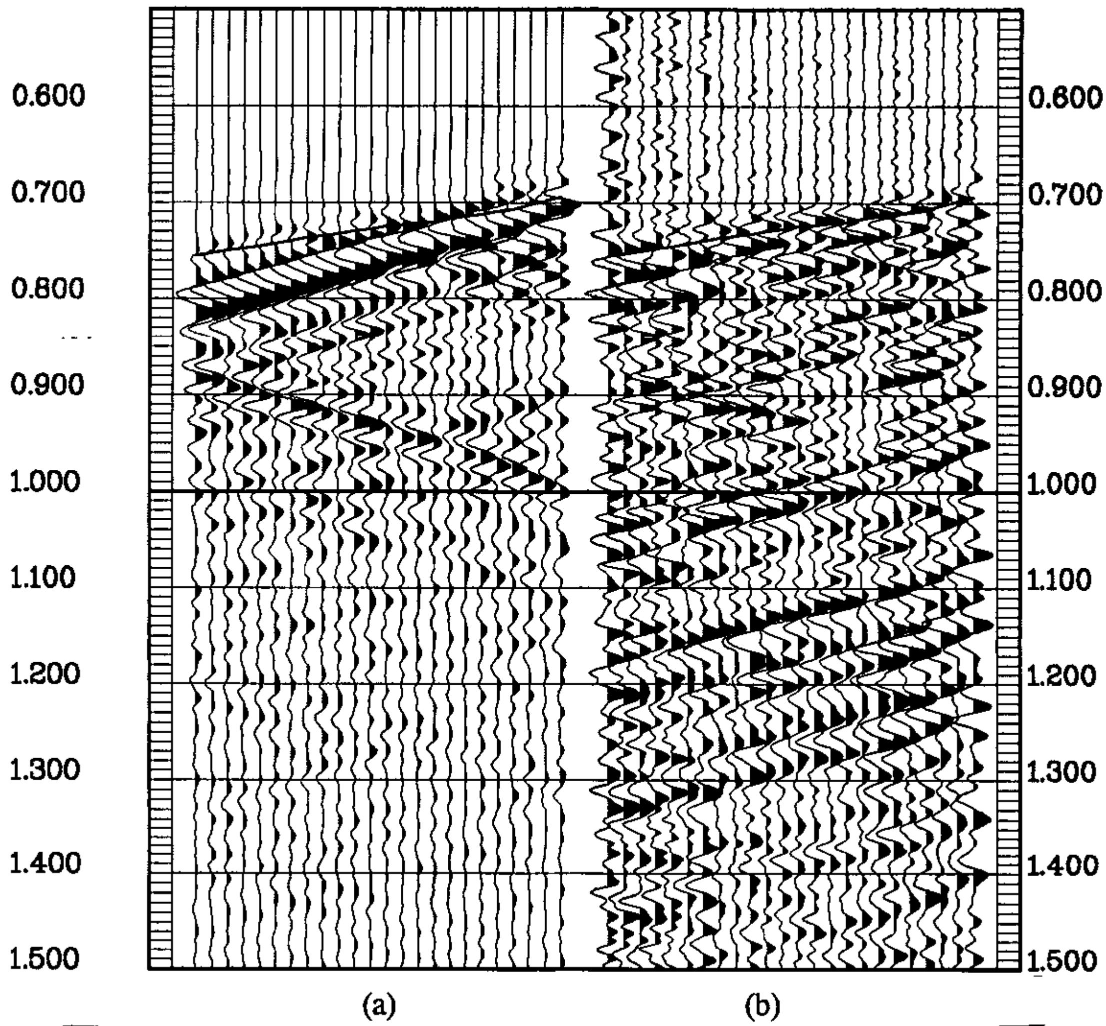

FIG. 7. Reconstructed radial component (a) and transverse component (b) of converted shear-wave data over the same interval as the counterphase data (see Figure 5).

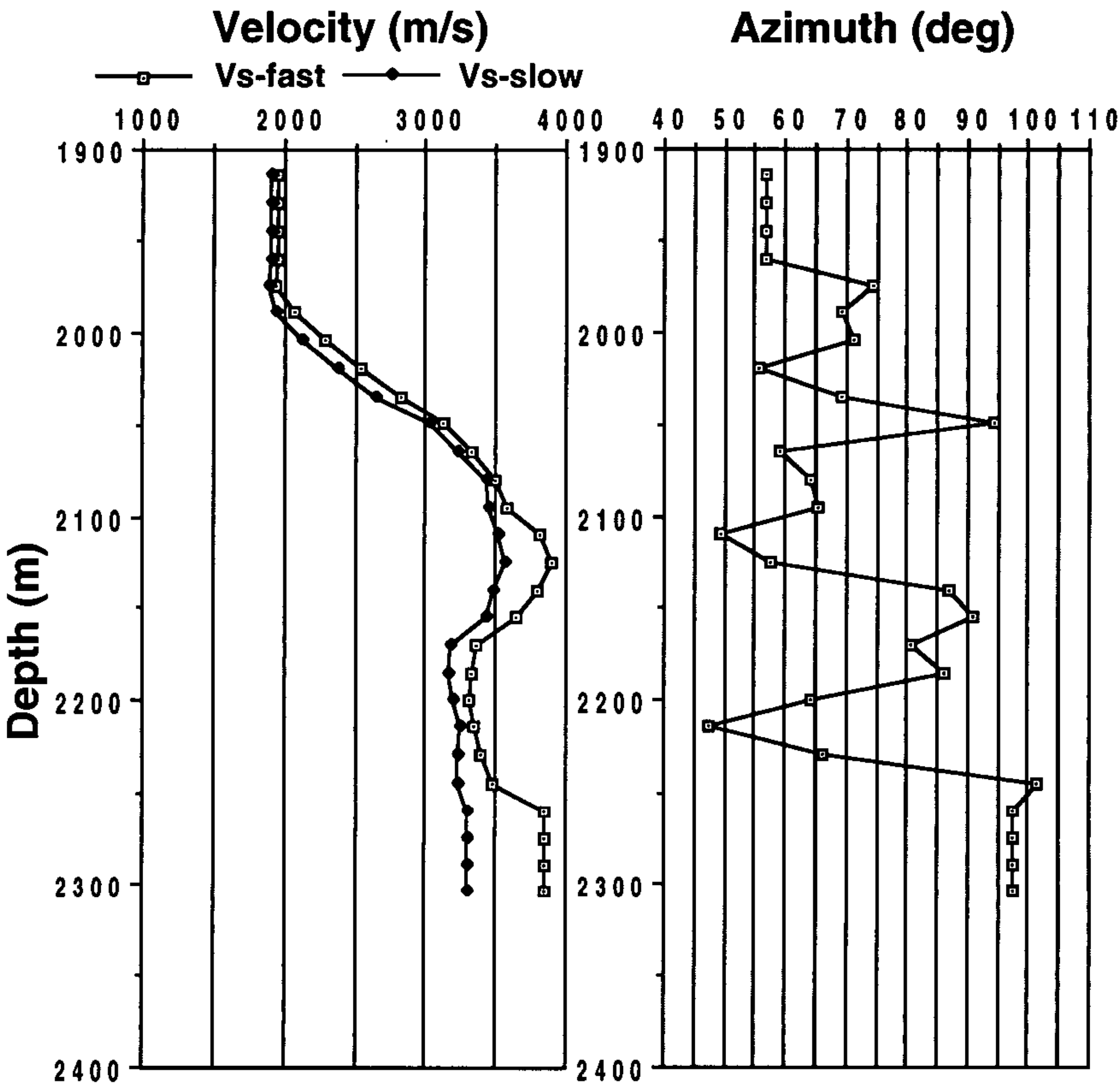

FIG. 8. Parametric inversion results of converted shear-wave data., (dataset B).