Elastic physical seismic modeling

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ABSTRACT

A physical seismic modeling system for studying elastic waves in solid models has been established. Compressional and shear transducers are used to acquire multi-component shot gathers over models of interest. Split shear waves were observed in initial experiments over a layer of phenolic CE, which displays orthorhombic anisotropy. Moveout velocities of P-P and SH-SH reflections from the base of the phenolic layer are offset-dependent and are complex functions of the vertical and horizontal P-wave and SH-wave velocities.

INTRODUCTION

The CREWES project has expanded the physical seismic modeling laboratory at the University of Calgary to include capabilities for elastic physical modeling. Previously, only acoustic modeling had been undertaken (Cheadle et. al., 1985). Elastic modeling now enables the complete vector wavefield to be recorded at the surface of solid models. Future plans in the CREWES project are to include both surface-to-borehole and borehole-to-borehole elastic measurements.

Seismic data obtained from physical elastic modeling makes an important contribution to the CREWES project for several reasons. Firstly, it serves to 'ground-truth' observations made in actual multi-component seismic data. Secondly, it provides a quantitative comparison to numerically modelled data. Thirdly, the data are very useful for testing algorithms which are being developed in the CREWES project for processing multi-component data, such as converted-wave gathering and mapping, and wavefield separation.

The acquisition of multi-component reflection seismic data enables shear waves to be recorded, and the extraction of shear-wave velocity information from VSP or surface seismic data has the potential of providing important information about lithology (Tatham, 1982). Furthermore, shear-wave birefringence (shear-wave splitting), which is caused by shear-wave anisotropy, has been shown to be able to detect the occurrence and orientation of fractures in the subsurface (Crampin, 1985).

In this study, physical modeling is used to demonstrate shear-wave splitting in an anisotropic medium, and multi-component shot gathers have been collected to examine moveout velocities of reflections from material which exhibits orthorhombic anisotropy. This paper describes the initial experimental results, and the analysis of the data will proceed over the next few months.

LABORATORY APPARATUS

The elastic modeling system is an extension of the water-tank physical seismic modeling system described by Cheadle et. al., (1985). Separate flat-faced, cylindrical transducers are used for source and receiver for seismic experiments over solid models. The transducers are manufactured by Panametrics Ltd and both compressional and shear types are used. They are 1 cm in diameter and are nominally rated at 1 MHz. Coupling between the face of the transducers and the surface of the model is achieved through a viscous coupling agent, although pharmaceutical wax has been found to be just as effective and considerably less expensive.

To record shot gathers across the surface of a solid model, an aluminum frame was constructed which contains sliding carriages into which the appropriate transducers are positioned. The carriages can be moved relative to each other by independent, threaded drives which are turned with hand cranks. A photograph of the system is shown in Figure 1, and more detailed upper and lower views of the carriages containing the transducers are shown in Figures 2 and 3 respectively. In the upper view (Figure 2), the millimetre scale enables the source-receiver offset distance to be monitored.

During experiments, the aluminum frame is clamped rigidly to the model, and the receiver transducer is moved with respect to the source transducer, creating an end-on record. Because of the physical size of the transducers, the minimum near-offset distance is 1 cm, or 50 m for a typical distance scaling factor of 1:5000.

ISOTROPIC MODEL RESULTS

Shot gathers were acquired initially over an isotropic layer to confirm the integrity of the elastic modeling system, in terms of geometry, traveltime and moveout velocity. The material used for this test was plexiglas, which has a P-wave velocity of 2740 m/s and S wave velocity of 1385 m/s. The parameters for the data acquisition were:

Distance scale factor	=	1:5000
Time scale factor	=	1:5000
Velocity scale factor	=	1:1
Modeling material	=	Plexiglas
Layer thickness	=	5.2 cm (260 m scaled), underlain by air
Near offset	=	1 cm (50 m scaled)
Trace spacing	=	0.2 cm (10 m scaled)
Far offset	=	12.8 cm (640 m scaled)
Number of traces	=	60
Sample interval	=	50 ns (0.25 ms scaled)
Record length	=	0.2 ms (1 s scaled)

Shot gathers acquired using P and SH source transducers are shown in Figure 4 and the receiver orientation is described as transverse (shear), radial (shear) or vertical (compressional), as indicated in Figure 4. The records have been displayed with an a.g.c. window 300 ms long (scaled). Data recorded with the P source show primary P reflections from the base of the plexiglas (air contact), as well as significant mode-converted energy and numerous multiples of these events. Data recorded with the SH source and receiver transducers show clear primary and multiple SH reflections. Primary and first-order mode-converted events are labelled on Figure 4.

Figure 5 shows the same records as those in Figure 4 after hyperbolic NMO corrections had been applied to the data. Moveout velocities of 2740 m/s and 1385 m/s were used for the P-P and SH-SH events respectively (plexiglas velocities). The onsets of the P and SH event have been flattened correctly, thus confirming the robustness of the modeling system. The moveout velocity used for the P-SV event was the square root of the product of the P and S velocities, as reported by Iverson et. al. (1989).

ANISOTROPIC MODEL RESULTS AND SHEAR WAVE SPLITTING

A modeling material known as Phenolic CE was used to study moveout velocities over as anisotropic medium. The elastic properties of this material are described fully elsewhere (Cheadle and Lawton, this volume; Brown, this volume) and these show that the anisotropic behaviour of this material can be described as being approximately orthorhombic. This classification can be viewed as a combination of transverse isotropy (hexagonal symmetry about a vertical axis) and azimuthal anisotropy.

In these experiments, multi-component shot gathers were collected on Face 1 of the phenolic sheet. The acquisition geometry and recording parameters for all of the experiments were the same as those listed for the isotropic experiment above, except that the scaled thickness of the slab is 522 m. The slab is underlain by air. Figure 6 shows records obtained with the P source transducer and the vertical-component receiver, with no a.g.c or trace balancing applied to the data, for 3 azimuths across Face 1 of the slab. Zero and 90 degree azimuths coincide with the principal symmetry axes of the orthorhombic phenolic modeling material. The records show a strong P event from the base of the slab and a weak vertical-component of mode-converted energy. A strong surface wave and weak direct P-wave arrivals can also be seen.

Figure 7 shows records obtained with the P source transducer but now with the radial component receiver. Some P-wave energy leaks onto the radial channel because the upcoming energy raypath is not vertical. There is a significant amount of P-SV energy, particularly at near offset. These data also show that the P source generates some SV energy as the SV-SV event has a rather large amplitude. Shear-wave splitting is observed from this reflection. The moveout of the fast SV event (0 degree azimuth) is similar to that of the slow SV event (90 degree azimuth), resulting in the delay between the components of the split shear wave (45 degree azimuth) being observable at all offsets. As expected, the delay between the split shear wave P-SV event is approximately half that of the SV-SV event.

Records obtained with an SH source and transverse receiver are shown in Figure 8, and as expected, no P-wave or converted-wave energy is recorded on the transverse channel. The SH-SH event has a high amplitude and shear-wave splitting is again observed when the line azimuth does not coincide with a principal symmetry axis. However, the slow SH wave exhibits less moveout than the fast SH wave, resulting in offset-dependent tuning of the radial components for the record along the 45 degree azimuth.

A 3-component survey along the 45 degree azimuth is illustrated by the records in Figure 9. Shear-wave splitting is observed on all components and these data will be used to test wavefield-separation algorithms currently under development.

MOVEOUT VELOCITIES

The moveout velocities of reflections from anisotropic layers are poorly understood and may, in certain circumstances, be greater or less then either the horizontal or vertical velocities (Thomsen, 1986; 1988; Winterstein, 1986). To investigate the orthorhombic model further, moveout corrections were applied to some of the data, assuming hyperbolic trajectories. Initially, tests were undertaken on the P-P events from records shown in Figure 6. Figure 10 shows the records with NMO corrections applied using velocities of 2850 m/s and 3480 m/s; these are the vertical and horizontal P-wave velocities in the phenolic in the 0 degree principle plane. The P-P event is overcorrected at far offsets when the vertical P-wave velocity is used, and is undercorrected at near offsets when the horizontal P-wave velocity is used. Using semblance, the optimum P-wave moveout velocity as a function of offset was determined and the results are shown in Figure 11.

These results show that the moveout velocity is greater than vertical velocity and that it approximately equals the horizontal velocity when the offset to depth ratio exceeds about 1.5.

Similar tests were performed for the SH-SH event. Figure 12 shows that this event is clearly non-hyperbolic, being undercorrected at near offsets and overcorrected at far offsets when the vertical velocity is used. If the medium had been transversely isotropic, the moveout velocity of the SH-SH event would then be expected to be the vertical velocity (Levin, 1980). When the fast SH (horizontal) velocity is used, the data are undercorrected at all offsets.

DISCUSSION

The results presented here are preliminary and work is currently in progress to quantify the observed moveout velocities for all wave modes. An important objective is to determine whether the class of anisotropy of the subsurface medium can be determined from surface seismic measurements.

CONCLUSIONS

1. A reliable laboratory apparatus has been constructed for collecting multi-component reflection seismic data over solid models.
2. Split shear waves have been observed on reflection seismic data collected over a medium which has orthorhombic anisotropy.
3. Experimentally determined moveout velocities of reflections from an isotropic layer agree closely with the actual velocities of the medium.
4. Moveout velocities of reflections from a layer with orthorhombic anisotropy are complex functions of the vertical and horizontal velocities in the principal planes.

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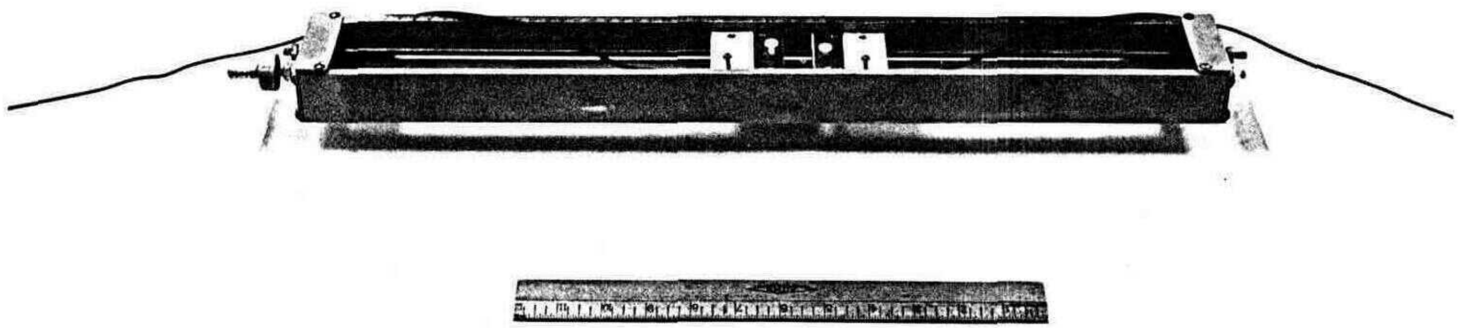

FIG. 1. View of the elastic modelling data acquisition apparatus.

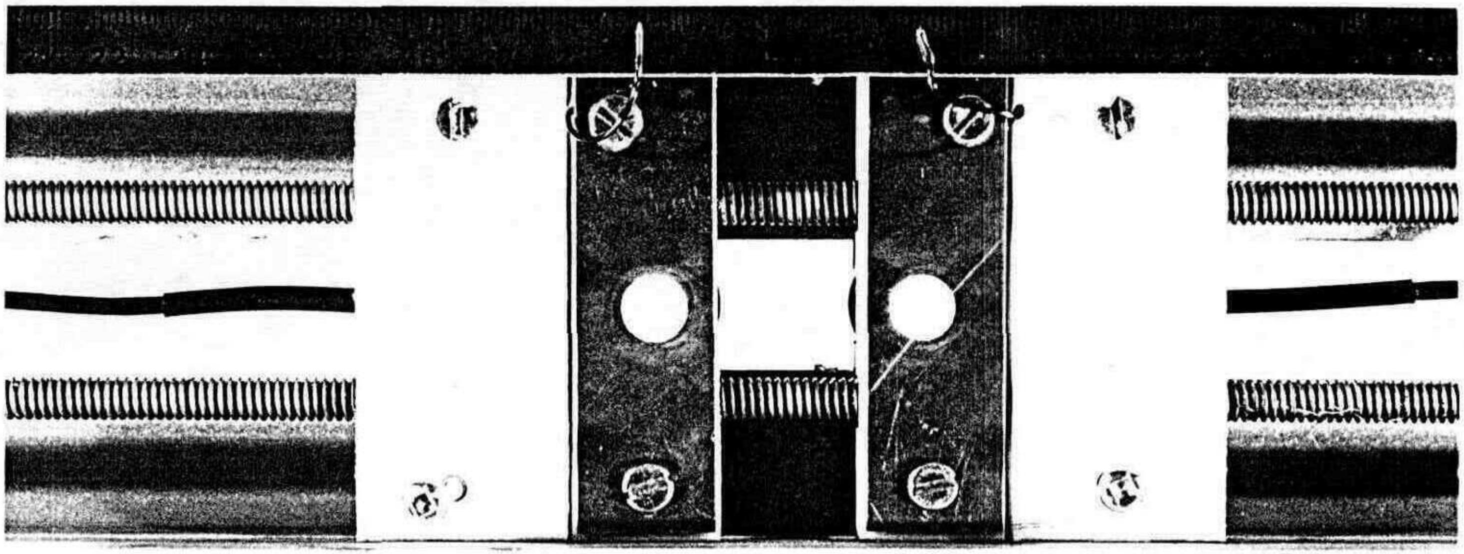

FIG. 2. Detailed view of the top of the transducer carriages, with the millimetre rule for position. Note the threaded rods which drives the carriages.

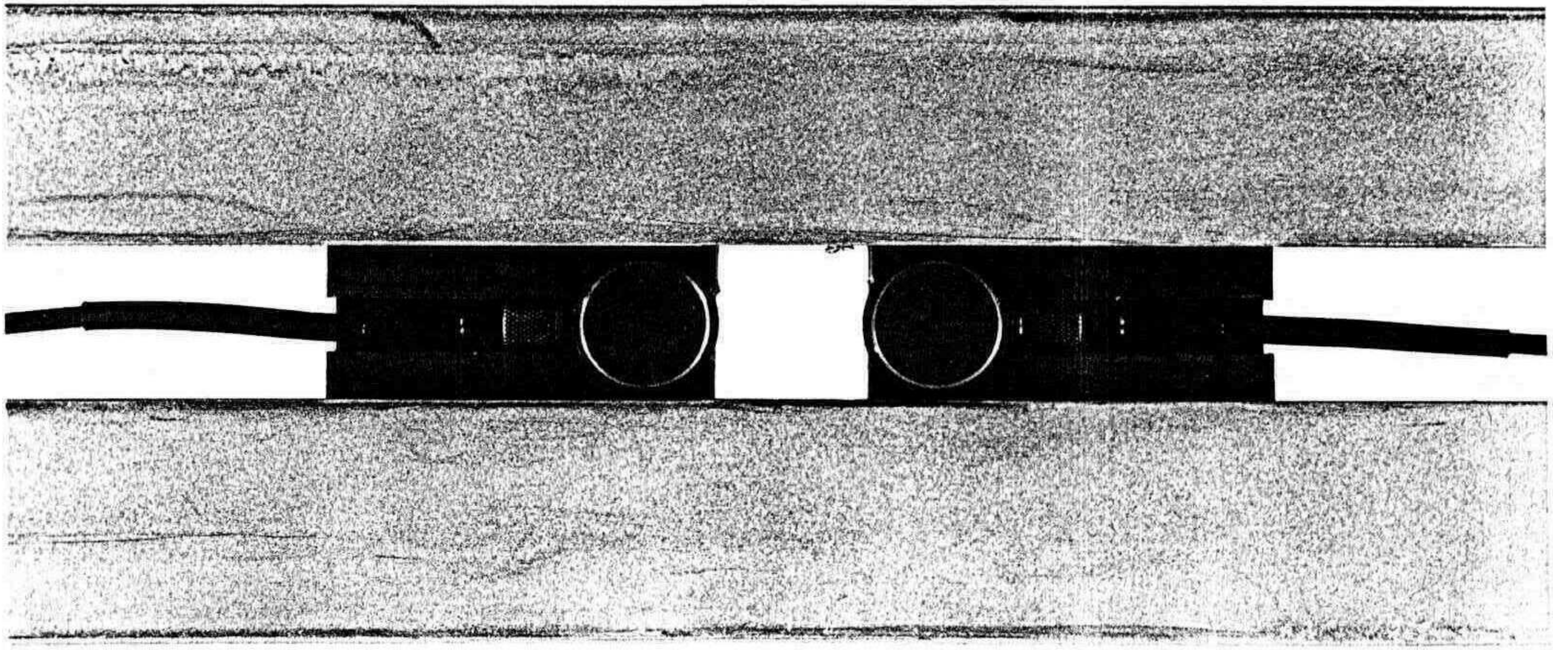

FIG. 3. Detailed view of the base of the transducer carriages, showing the faces of the transducers.

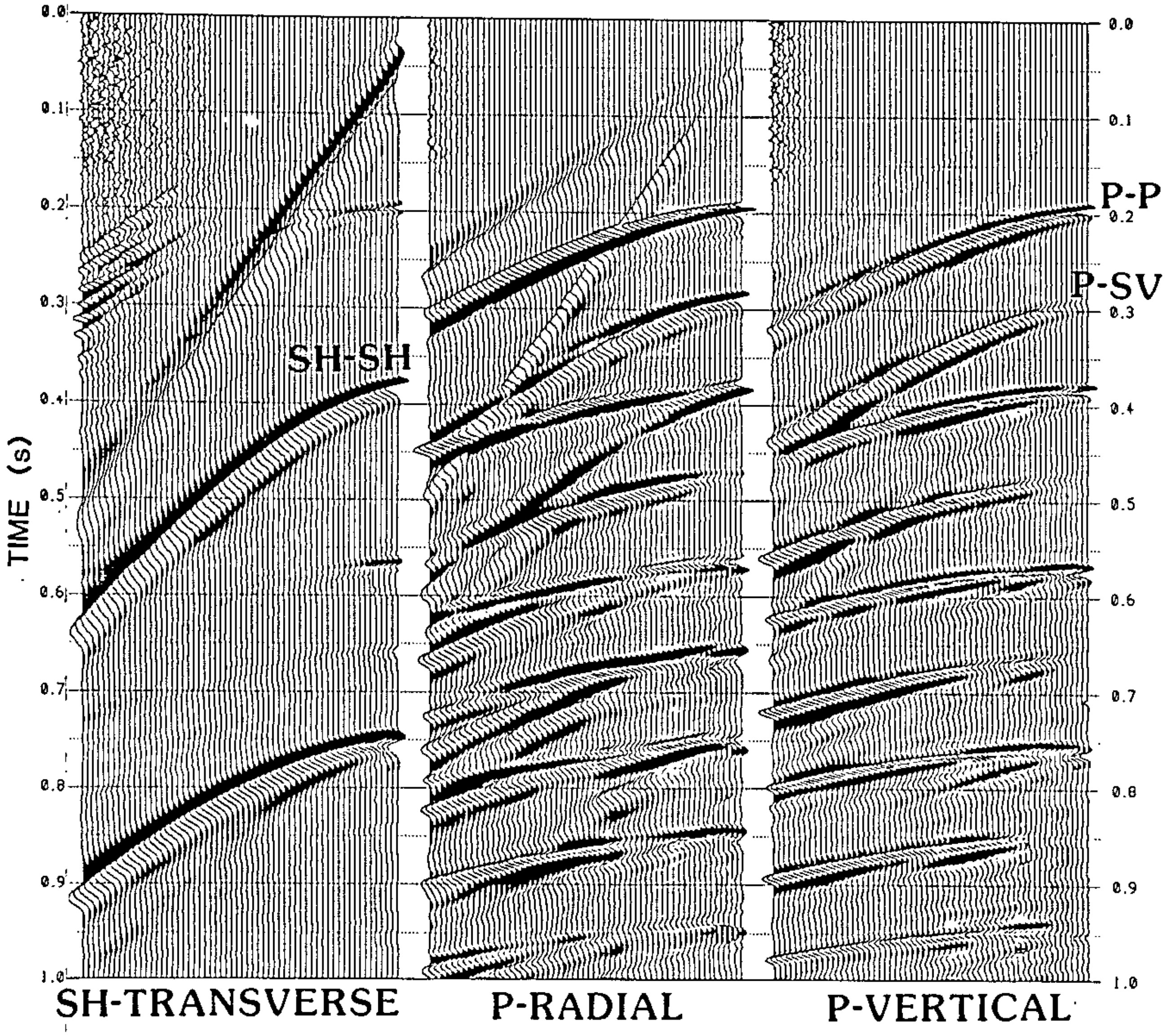

FIG. 4. Multi-component record obtained over an isotropic layer of plexiglas.

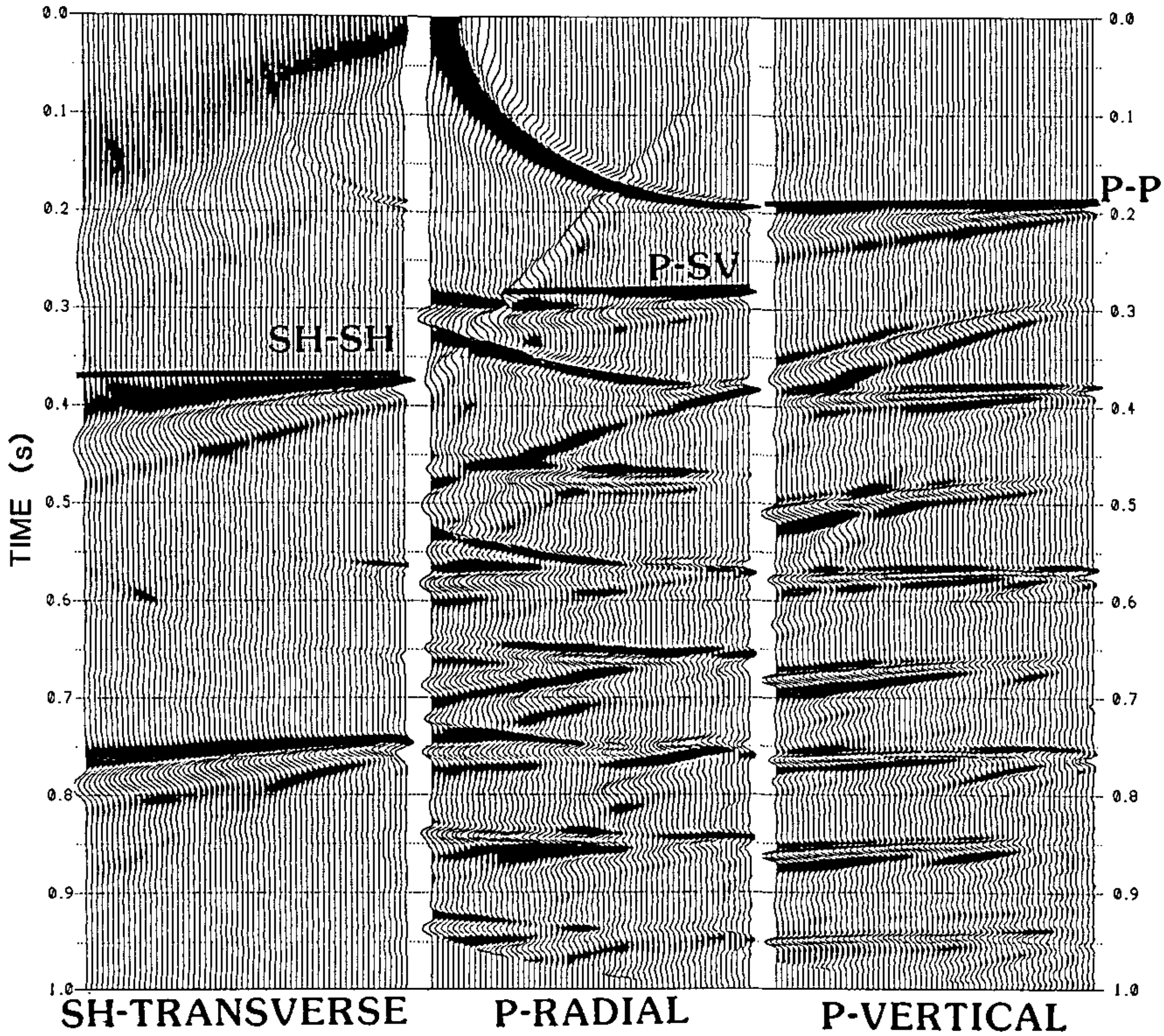

FIG. 5. The same records as shown in Figure 4 but after correction for normal moveout, using the known plexiglas velocities. The primary events on all components have been flattened correctly.

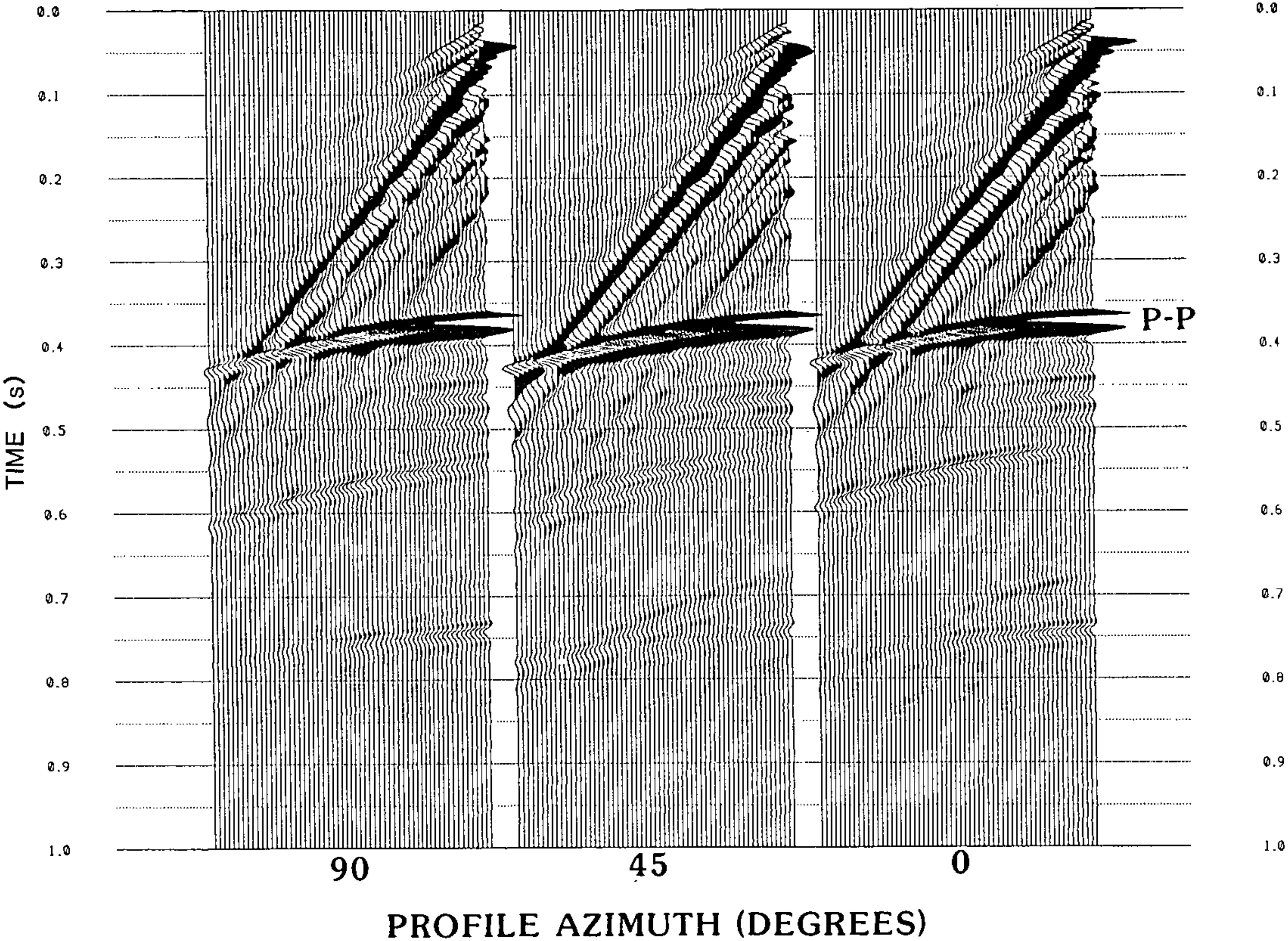

FIG. 6. P-vertical component shot gathers collected along azimuths of 0, 45 and 90 degrees on Face 1 of the phenolic layer.

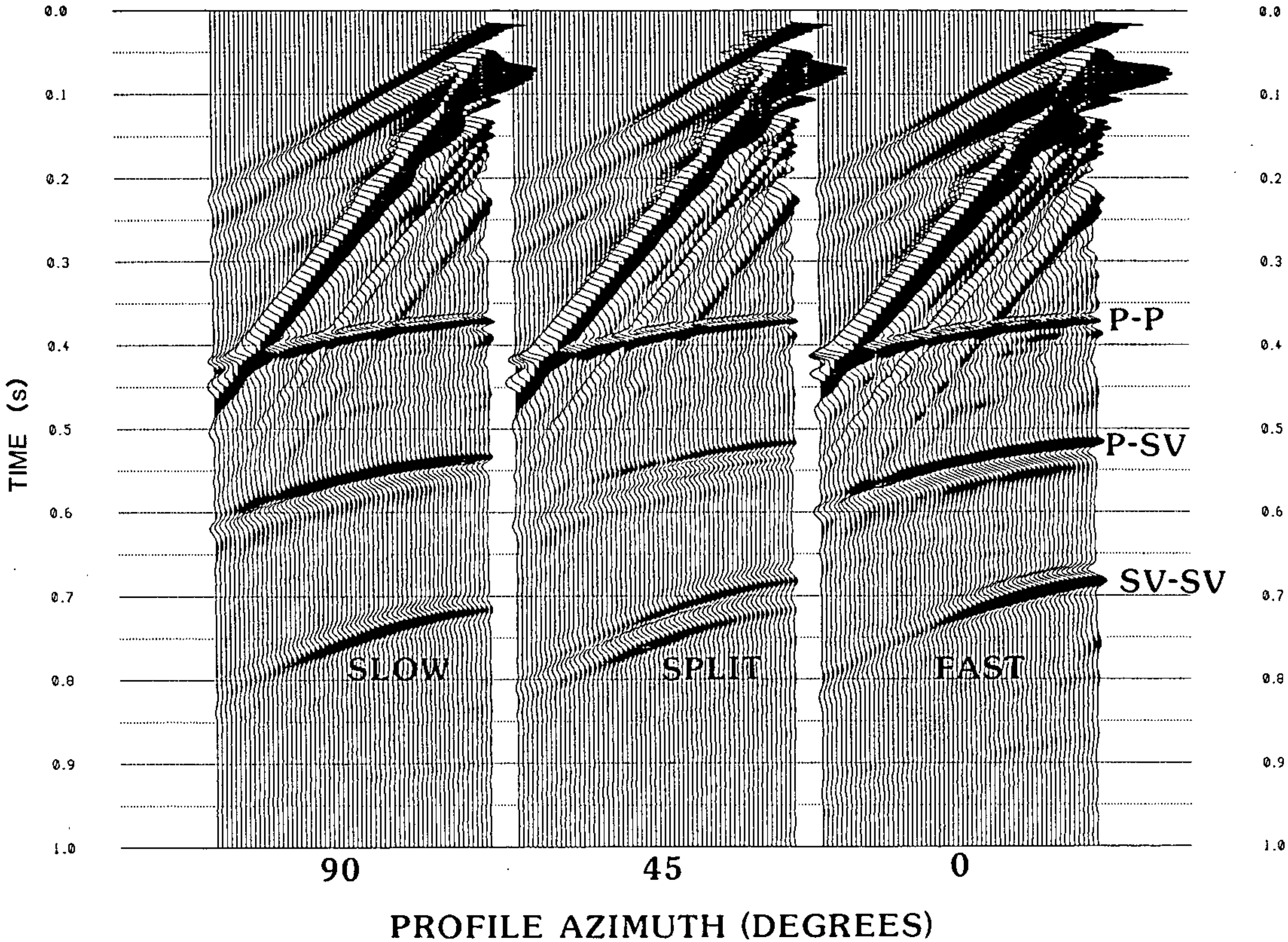

FIG.7. P-radial component shot gathers collected along azimuths of 0, 45 and 90 degrees on Face 1 of the phenolic layer.

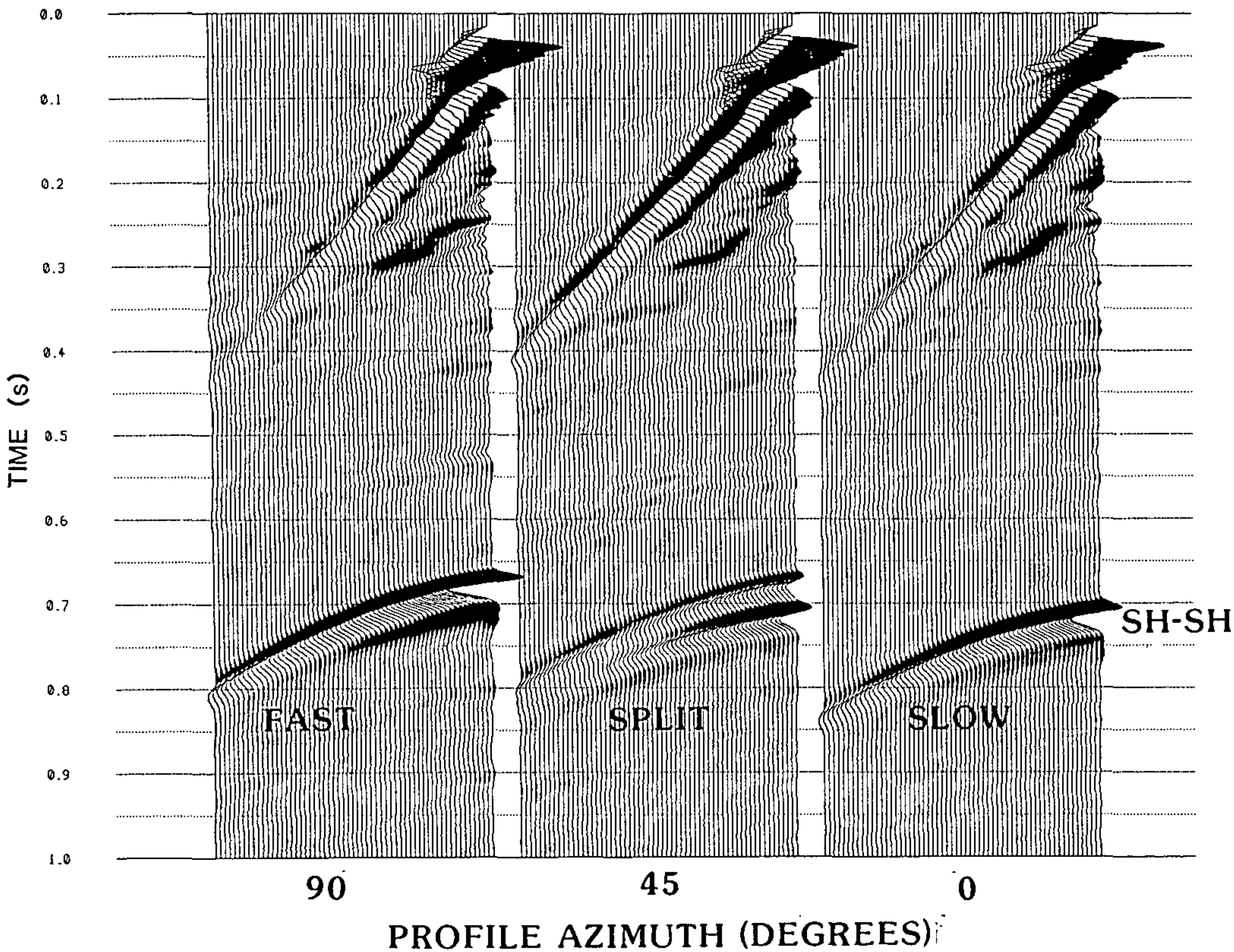

FIG. 8. SH-transverse component shot gathers collected along azimuths of 0, 45 and 90 degrees on Face 1 of the phenolic layer.

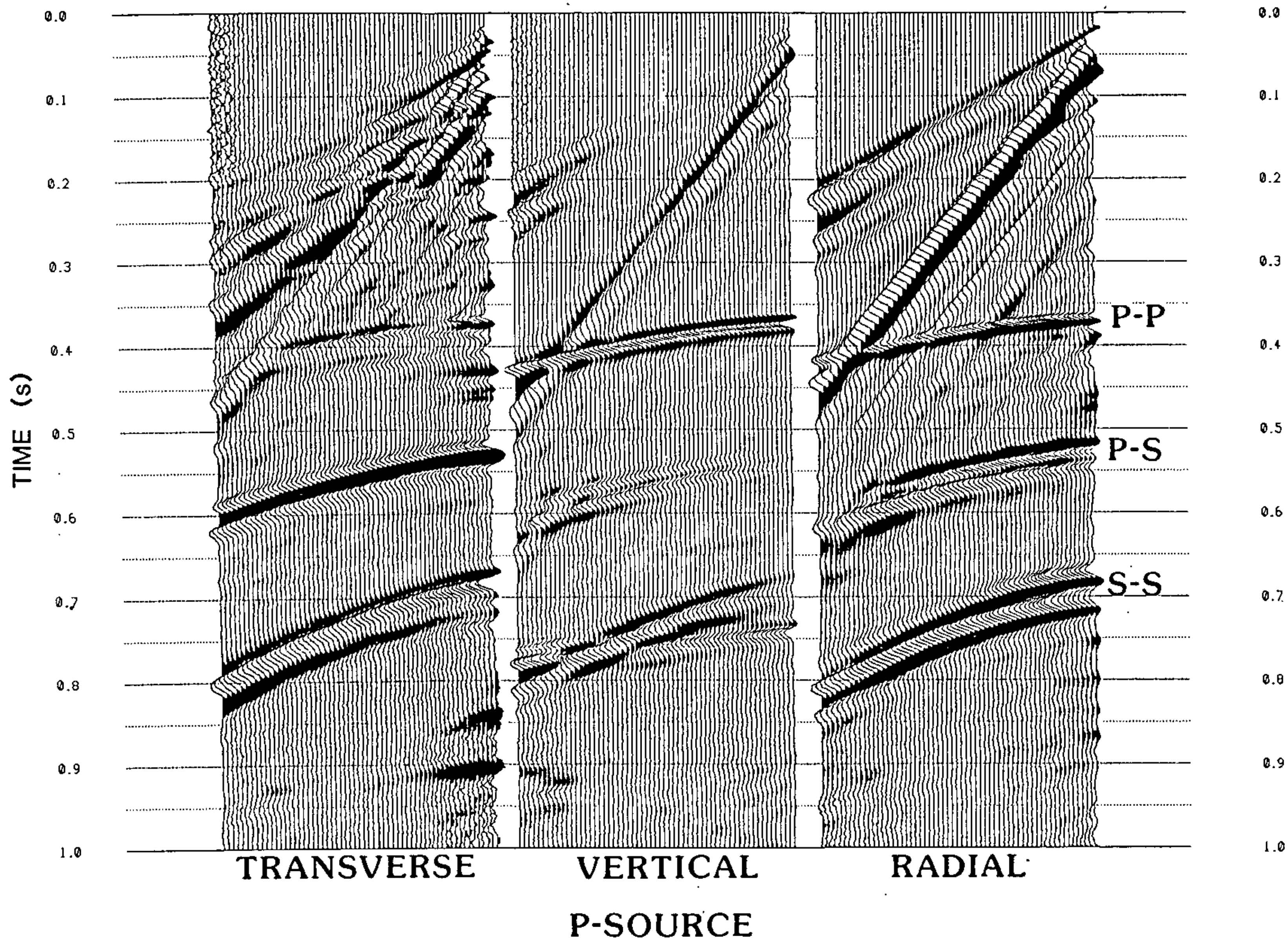

FIG. 9. A 3-component shot gather, acquired using a P-source, collected along an azimuth of 45 degrees on Face 1 of the phenolic layer.

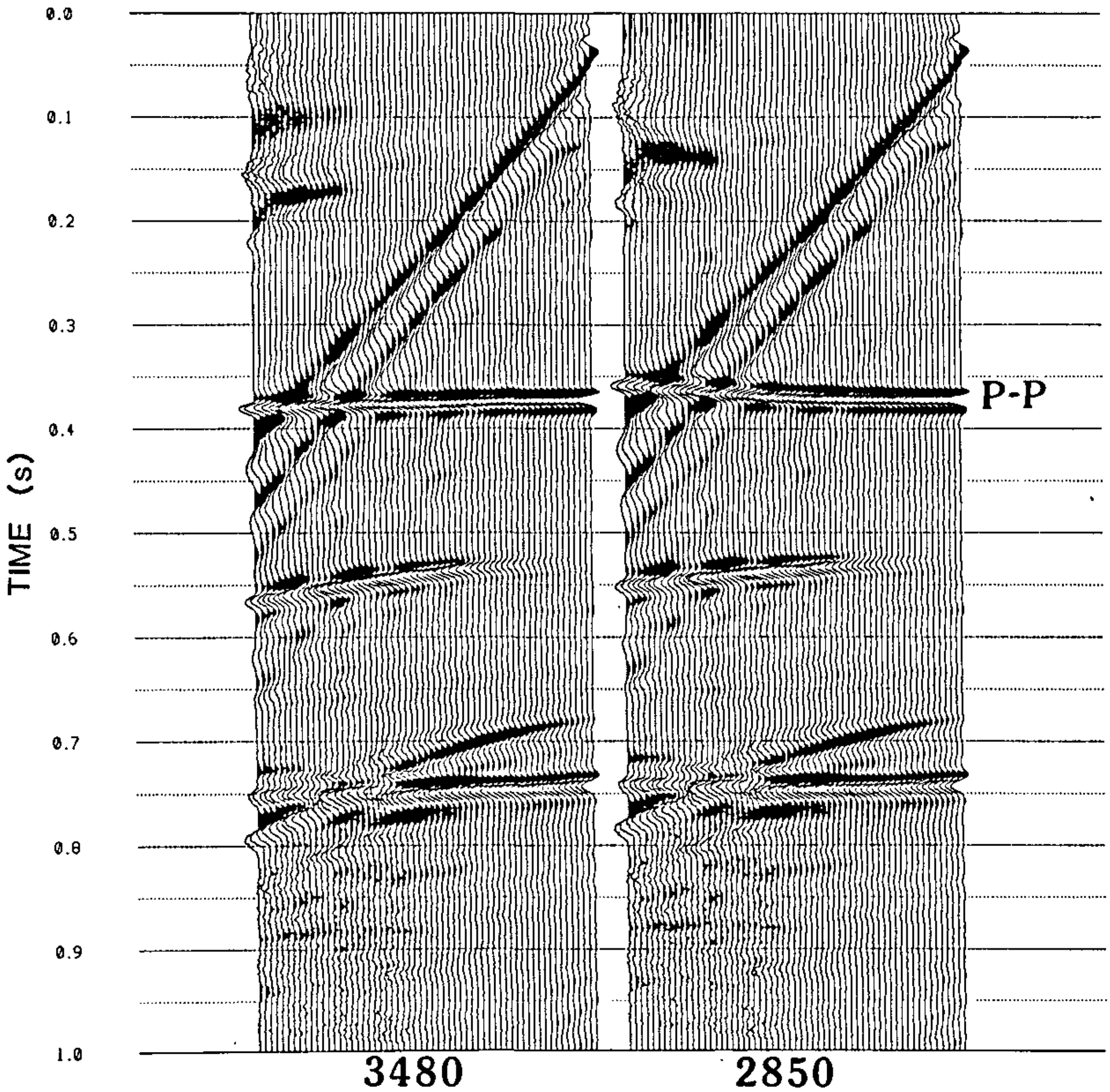

FIG. 10. NMO-corrected P-vertical component gathers at an azimuth of 0 degrees. The moveout velocities shown below each panel correspond to the vertical and horizontal P-wave velocities in the 0 degree principal plane of the phenolic layer.

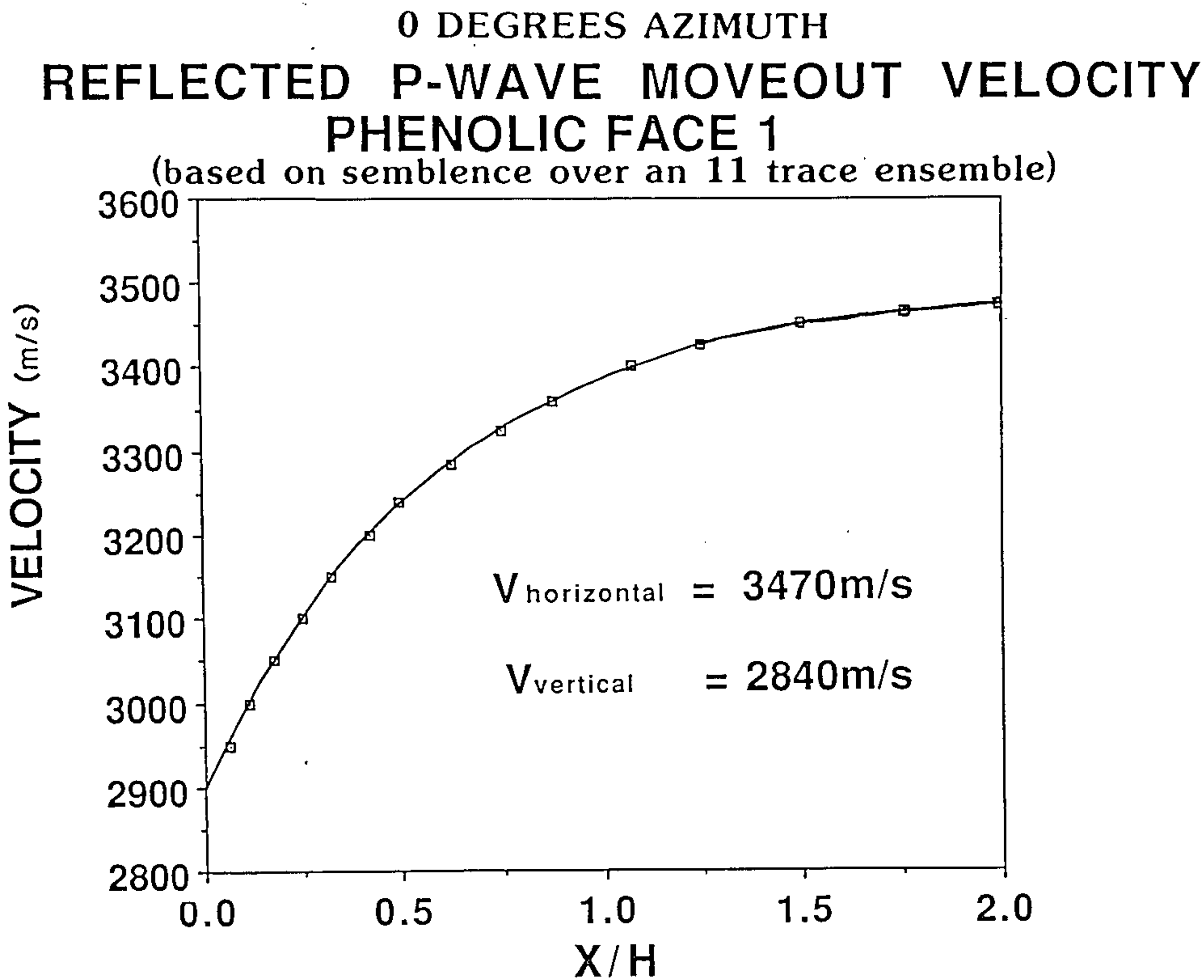

FIG. 11. A graph of 'stacking velocity' versus offset for P-vertical component data in the 0 degree principal plane of the phenolic layer.

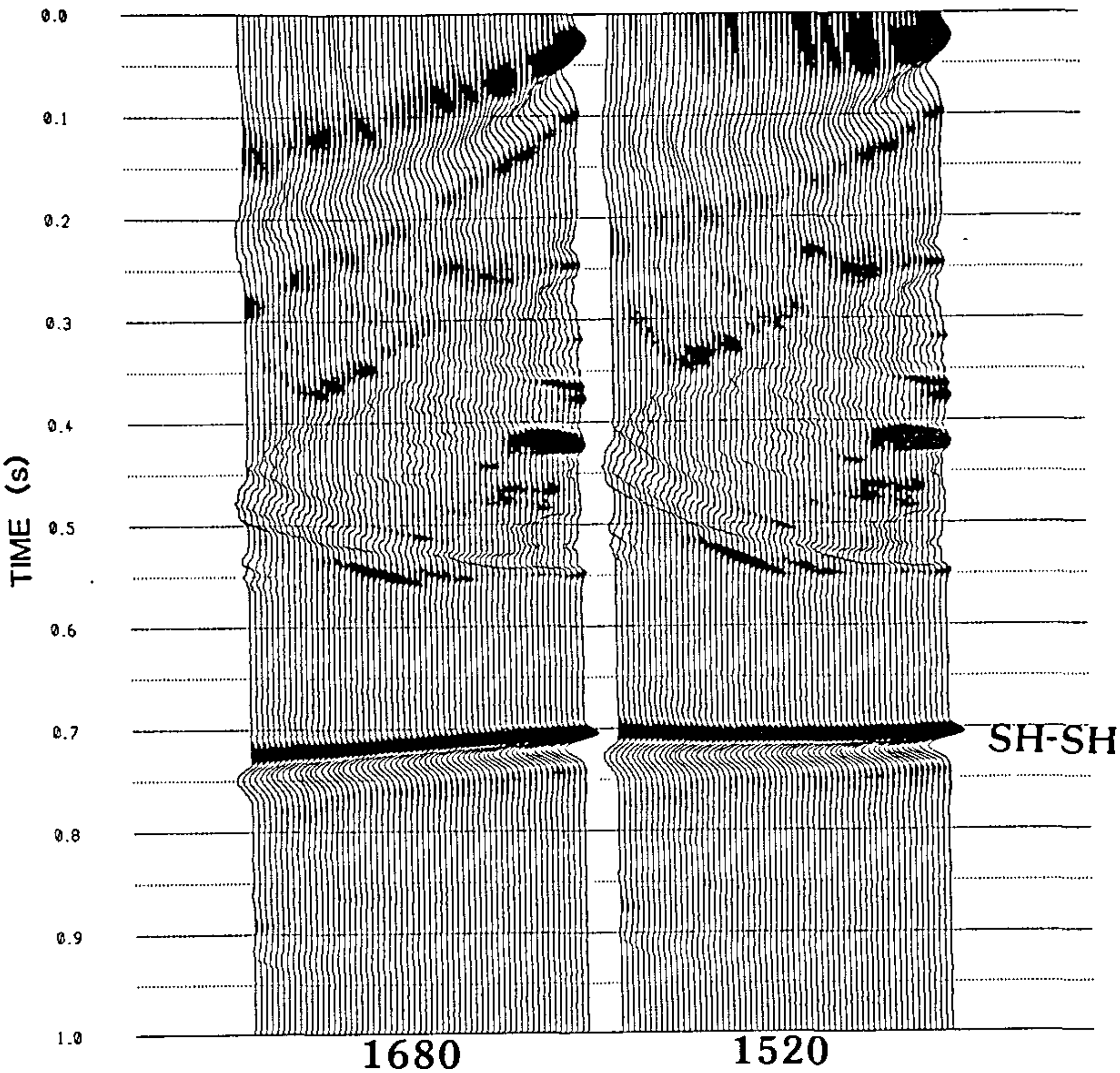

FIG. 12. NMO-corrected SH-transverse component gathers at an azimuth of 0 degrees. The moveout velocities shown below each panel correspond to the vertical and horizontal SH-wave velocities in the 0 degree prinicipal plane of the phenolic layer.