Ultrasonic modeling of borehole seismic surveys

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ABSTRACT

Ultrasonic physical model data were acquired in simulated vertical seismic profile (VSP) and crosswell (XT) geometries. Various targets (teflon and aluminum cylinders, plexiglas and anisotropic phenolic sheets) have been used. Preliminary identification of wavetypes show direct arrivals, primary and multiple reflections, and mode conversions. These physical model data are useful for testing processing and numerical modeling algorithms.

INTRODUCTION

Physical and numerical modeling are useful in simulating the events which would be recorded in an actual field experiment. The ability to conduct many different types of experiment in the laboratory or on a computer, as opposed to the field, makes modeling an attractive precursor or adjunct to field studies. Numerical seismic modeling is usually based upon some approximation to the wave equation and assumptions about the media through which waves propagate. The question will always arise as to the validity of the approximations or the significance of the results.

Physical modeling uses real propagating waves and actual media and so avoids the limitations of numerical theory. The technique is necessarily constrained by the scaling of the model with respect to the elements of the modeling system, including the source and receiver dimensions and bandwidth, the geometry of the experiment and the characteristics of the model media. Nonetheless, kinematic (traveltime) information is reliable and the relative amplitudes (the dynamics) of many events provide a measure of the properties of the media (Lo et al., 1988).

Two seismic borehole geometries are explored in this set of physical experiments: vertical seismic profiling (VSP) and crosswell tomography (XT). The intention of the experiments is to produce sets of seismograms for event interpretation and the testing of processing and modeling algorithms in both isotropic and orthorhombically anisotropic media.

All measurements were made in the seismic modeling tank operated by the CREWES project at the University of Calgary. The experiments are conducted with the model and ultrasonic source and receiver transducers submerged in water. The tank measures 4 m x 3 m x 2 m, and for these experiments the water depth was 1 m. The main components of the signal generation and acquisition system are outlined schematically in Figure 1. Carriages move along tracks on two orthogonal beams to carry the source (S) and receiver (R1) transducers during an experiment. More than one receiver (or source) can be used to simulate the desired geometry. A photograph of the modeling system during a crosswell experiment is shown in Figure 2.

The piezoelectric hydrophones used in this study are International Transducer Corp. 1089c transducers. These are spherical omnidirectional elements with a diameter of 1 cm., and produce a broad band wavelet with a centre frequency of 240 Khz. The data were recorded with a Nicolet digital storage oscilloscope, using time sample rates of between 50

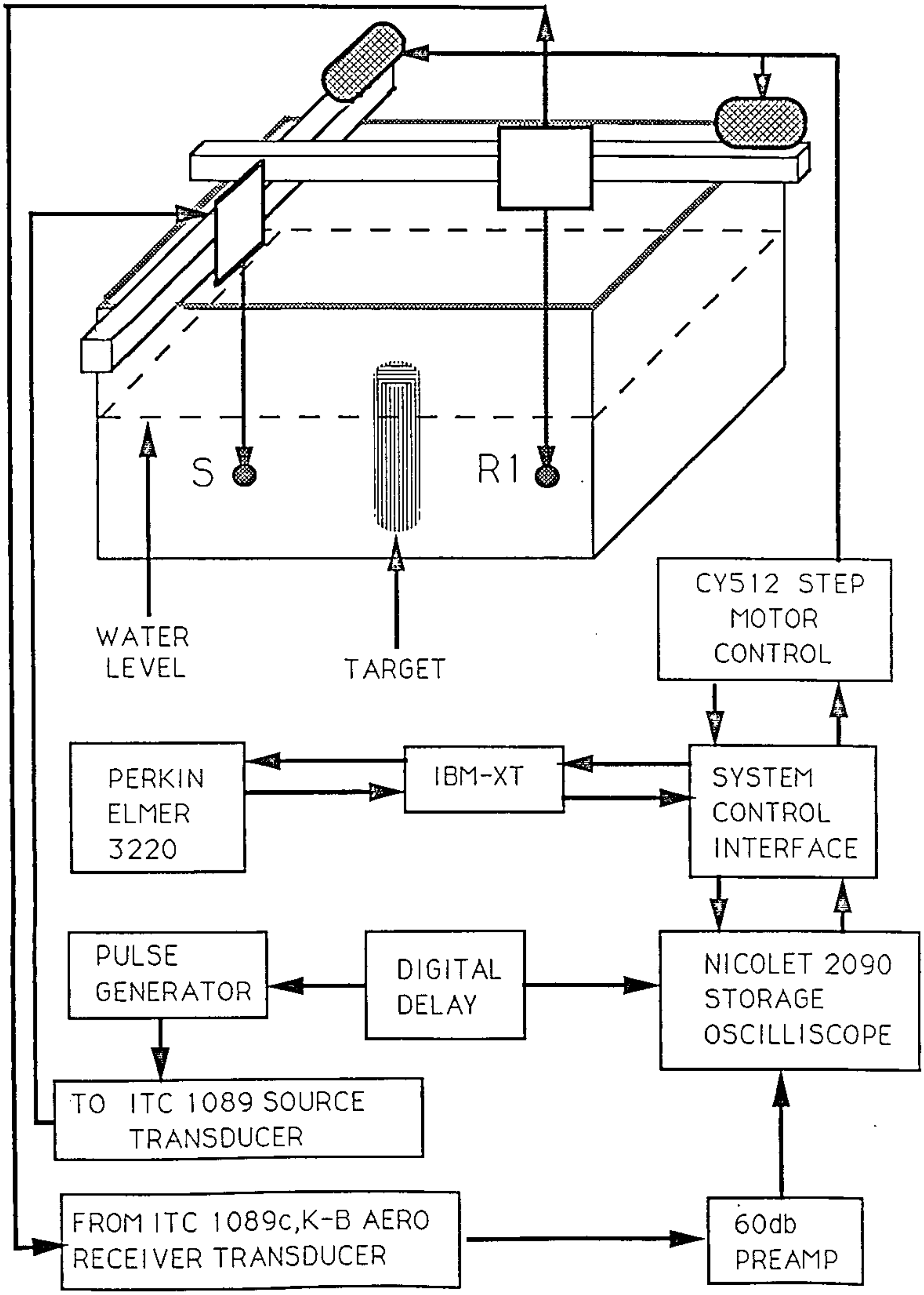

FIG. 1. A schematic flowchart of the CREWES physical modeling system.

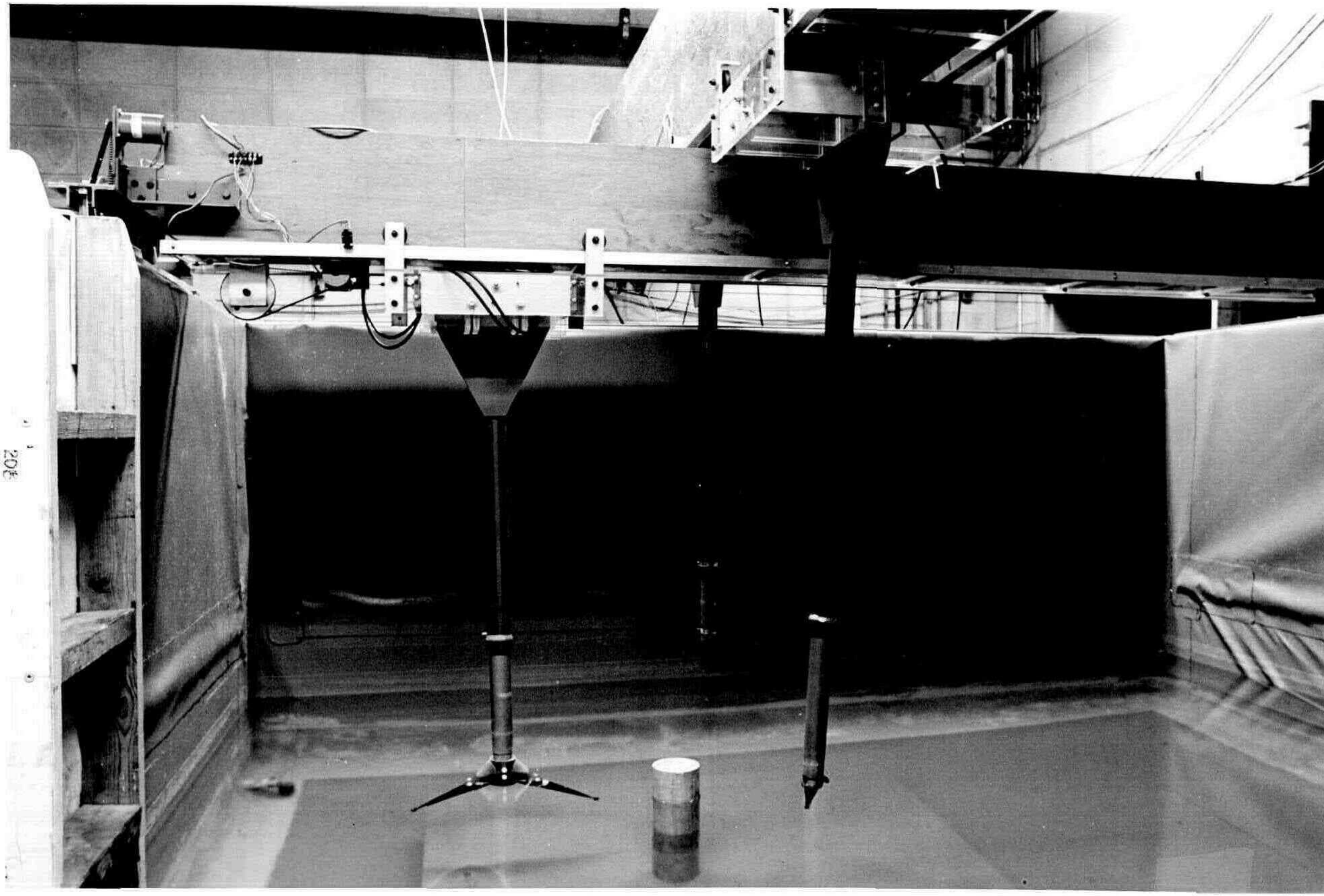

FIG. 2. The modeling tank is shown during the execution of a crosswell experiment using an aluminum cylinder target.

ns (0.25 ms) and 200 ns (1.0 ms). The experiments are controlled from an IBM-XT computer, which transfers the data to magnetic tape or disc storage in standard SEG-Y format.

VSP MEASUREMENTS

For these experiments, the water formed an isotropic host medium while an acrylic plexiglas sheet measuring 1.2 m x 1.2 m and 1.9 cm thick stood vertically in the tank. The P-wave velocity in the sheet is 2750 m/s and the shear wave velocity is 1380 m/s. The velocity in water is 1495 m/s. Horizontal movement of the source and receivers was used to simulate the VSP geometry. A scaling factor of 1:5000 was used for both distance and time, with the velocity scaled at 1:1.

The geometry for the first experiment is shown in Figure 3. The target sheet was perpendicular to the receiver line, simulating a vertical borehole and a horizontal reflecting layer at a depth of 1000 m. The source was 20 cm from the sheet, and 40 receiver stations, 20 on either side of the sheet, were occupied at 1 cm intervals. The initial source-receiver offset distance was 10 cm, or a scaled distance of 500 m.

The results from this experiment are shown in Figure 4. The data are displayed as two separate groups, twenty traces each from receivers on either side of the sheet. The gap between the records is due to the inability of the receivers to occupy space within the 1.9 cm thickness of the sheet. Traces were recorded with a 200 ns (1 ms) sample rate from receiver positions which increase in depth at 50 m intervals from right to left on the display. The data are plotted in true relative amplitude. The direct P-wave arrival and three reflection events are labelled. P-wave reflections from the top and bottom of the sheet are separated by 69 ms, while a mode-converted P-SV reflection arrives 103 ms later than the top reflection.

The geometry of the second experiment is shown in Figure 5. The target sheet was tilted with respect to the receiver line or "borehole", to simulate a layer dipping at 11° with the receivers downdip from the source. The source was 18 cm (900 m) from the target sheet, while the initial receiver position was 20 cm (1000 m) from the sheet and 10 cm (500 m) from the source. All other parameters were unchanged from the first experiment. The results from the downdipping experiment are shown in Figure 6. The data are displayed in true relative amplitude, and direct P, reflected P and mode-converted arrivals are labelled.

The geometry of the third VSP experiment is shown in Figure 7, and differs from the second experiment only in the direction of dip of the sheet. In this case, the source was 22 cm (1100 m) from the sheet, while the initial receiver position was 20 cm (1000 m) from the sheet and 10 cm (500 m) from the source. This arrangement simulates a target layer dipping at 11° with the receivers updip with respect to the source. All other parameters were unchanged from the other experiments. The recorded data from the updip experiment are shown in Figure 8.

CROSSWELL MEASUREMENTS

Crosswell experiments have been conducted with both isotropic and anisotropic media. The first series involved collecting shot records from different locations with respect to the target or velocity anomaly situated between the source and receiver "borehole" lines. The targets were aluminum or teflon cylinders which stood vertically in the water tank, equidistant between the source and receiver transducers, which move horizontally. The crosswell geometry then illuminates a circular crossection perpendicular to the long axes of

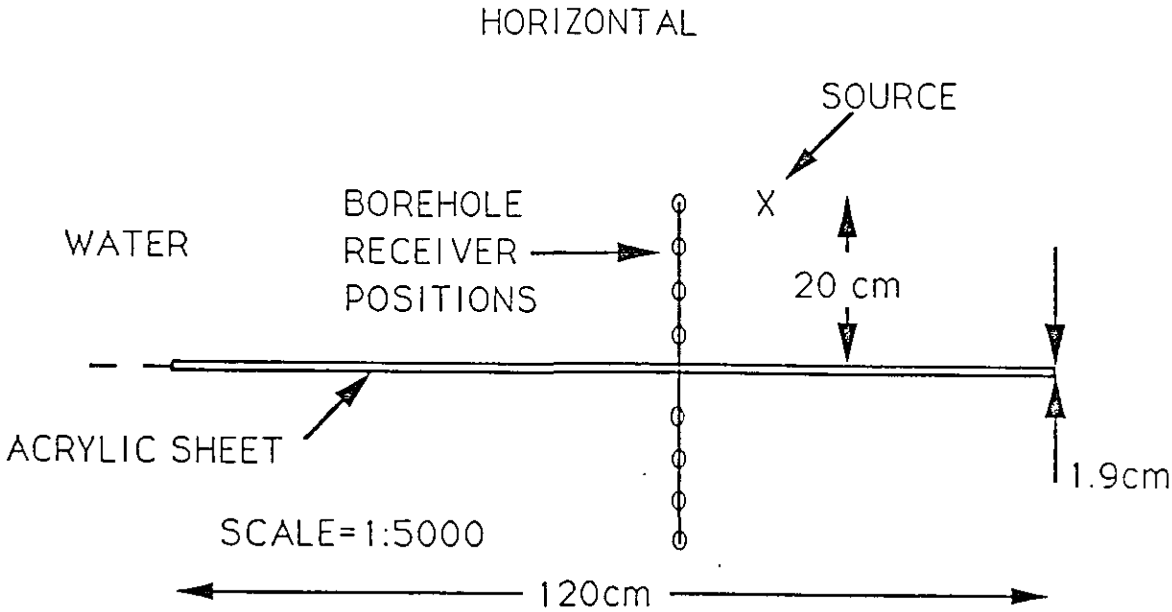

FIG. 3. The geometry for the flat layer VSP experiment. The distances were scaled 1:5000 (1 cm = 50 m) for these experiments.

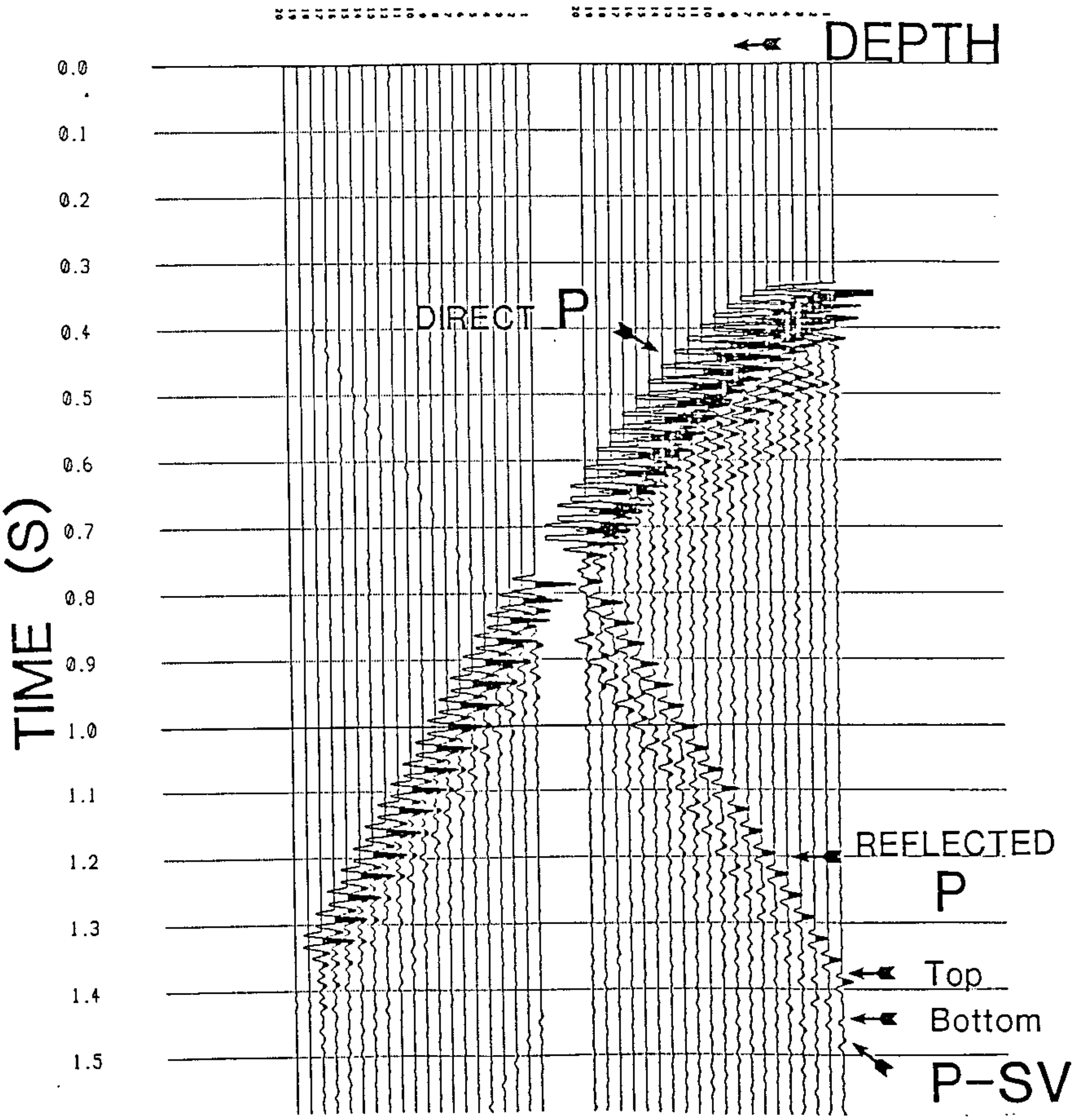

FIG. 4. The record from the flat layer VSP experiment is shown as two groups of traces recorded on either side of the plexiglas target sheet. The gap indicates the approximate positions the transducers could not occupy within the target sheet of plexiglas.

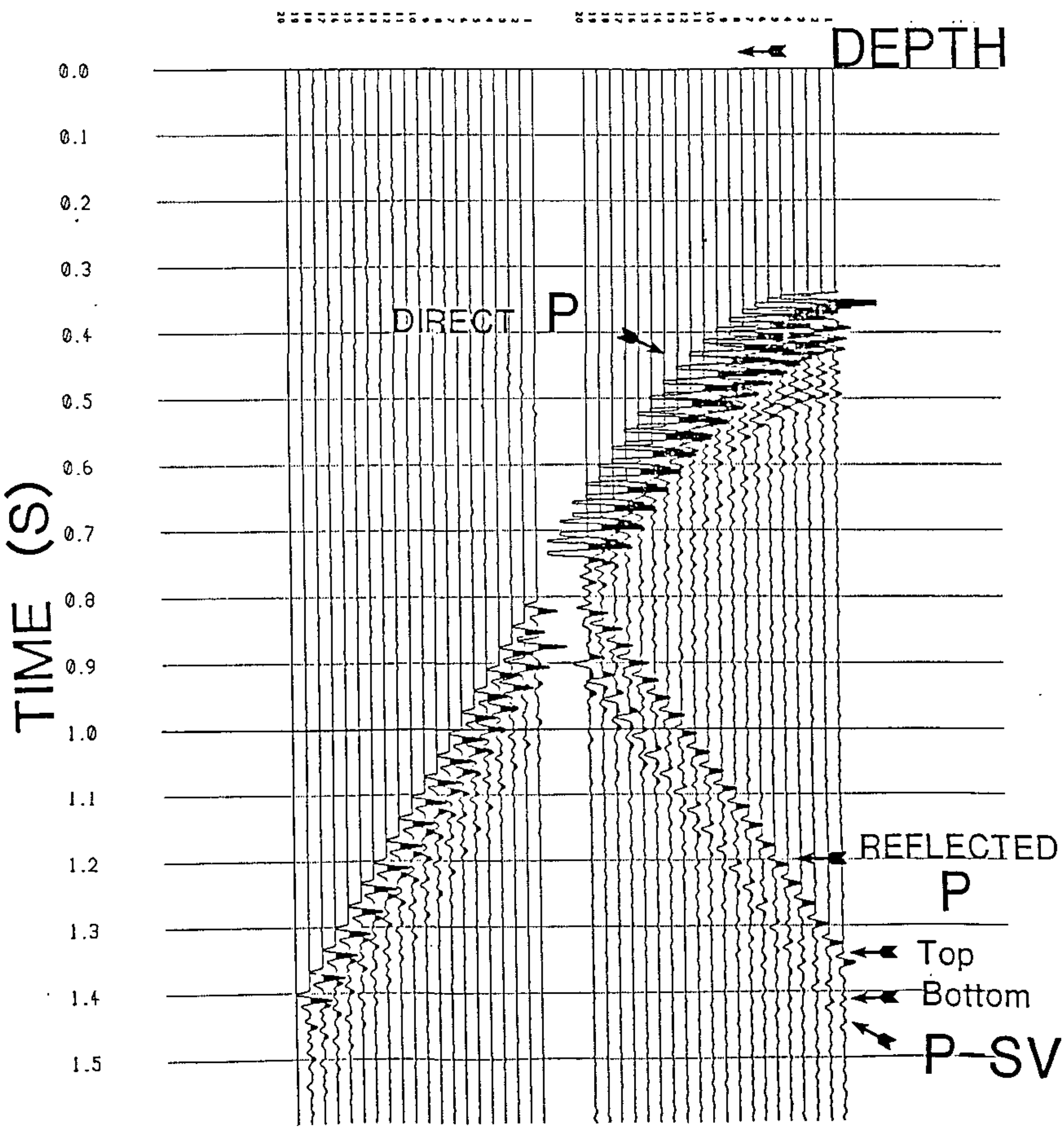

FIG. 6. The record from the downdip VSP experiment. The direct P-wave and reflections from the top and bottom of the sheet as well as the P-SV mode conversion from within the sheet are identified.

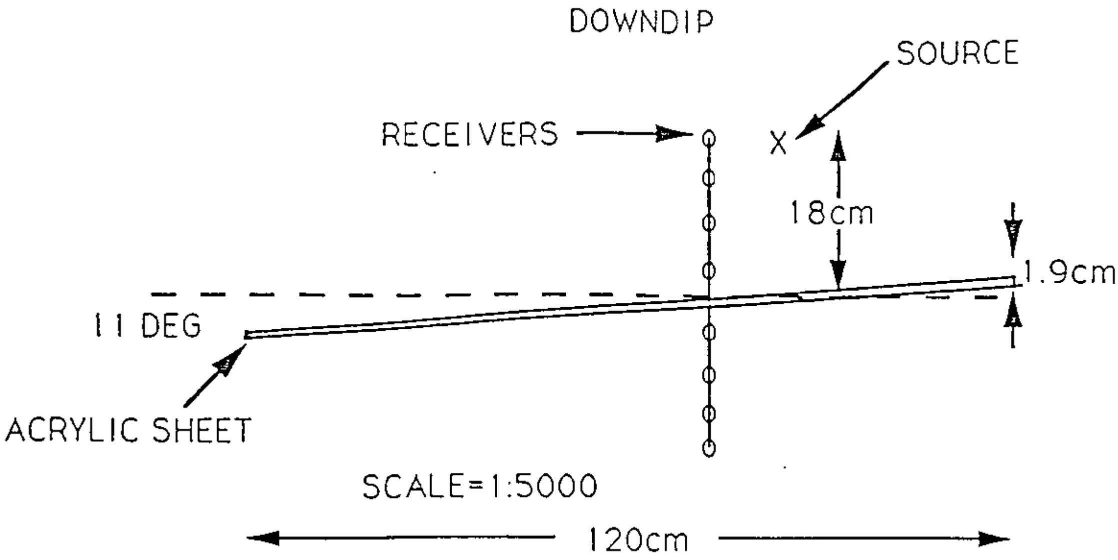

FIG. 5. The geometry for the downdip VSP experiment.

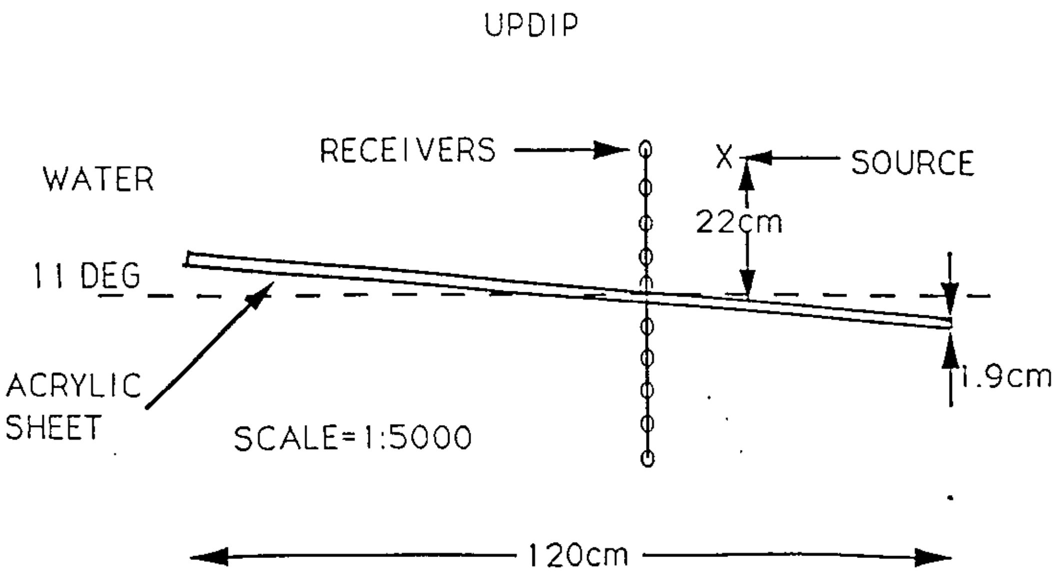

FIG. 7. The geometry for the updip VSP experiment.

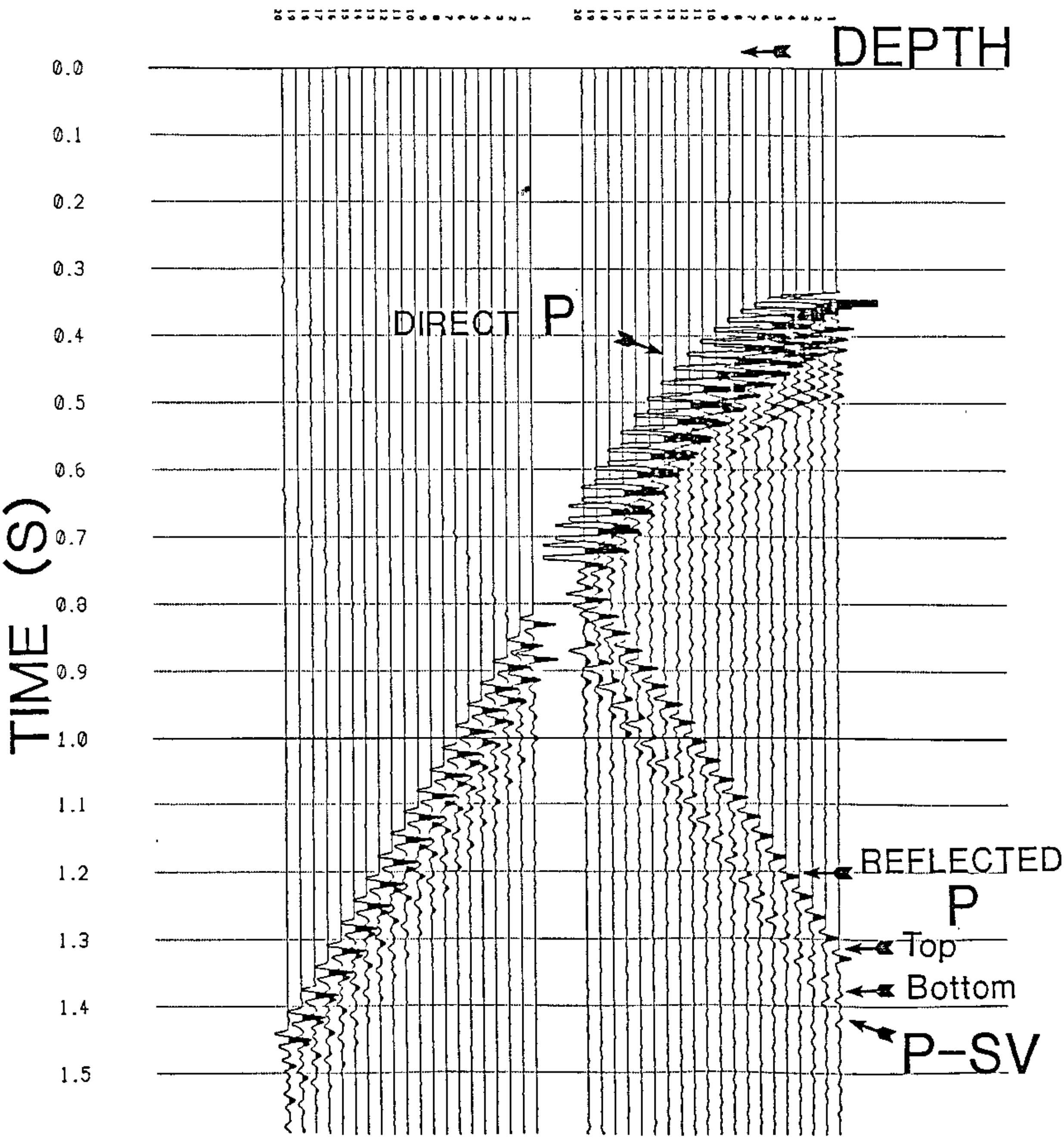

FIG. 8. The record from the updip VSP experiment.

the target cylinders. The general experimental geometry is shown in the photo of Figure 2. For a particular shot record, the source on one side of the target stayed stationary while the receiver occupied multiple positions along a line on the opposite side.

The geometry for the first crosswell experiment is shown in Figure 9. An aluminum cylinder 10 cm (500 m) in diamter was equidistant between the source and receiver lines which were 20 cm (1000 m) apart. The P-wave velocity of the aluminum is 6200 m/s, more than 4 times the velocity of the water. The shear wave velocity in aluminum is 3280 m/s. Forty shot records with 40 traces per shot were recorded at 1 cm (50 m) intervals. Two shot records from this experiment are shown in Figure 10. The data are displayed in true relative amplitude, and direct, reflected and transmitted P-wave arrivals are labelled.

Three sets of shot records were collected using a 3.8 cm (190 m) diameter teflon cylinder. The teflon has a lower P-wave velocity than water, (1300 m/s) but because of its high density (2200 kg/m 3), produces a positive polarity reflection. These experiments used the same geometry as the previous aluminum case, but the source-receiver line separations were 8 cm (400 m), 12 cm (600 m) and 20 cm (1000 m). The geometries for these three experiments are summarized on Figures 11a,b and c, and 3 shot records, one from approximately the middle of each of the shot lines, are shown in Figures 12 a,b and c. The data are displayed in true relative amplitude.

A crosswell geometry was also used to record data from a sheet of anisotropic material. A 10.5 cm (525 m) thick sheet of Phenolic CE laminate, which exhibits orthorhombic anisotropy (Cheadle and Lawton, 1989; in this volume), was placed on edge between the source and receiver lines, which were 17.5 cm (875 m) apart. This simulates the crosswell experiment through a vertically fractured media. The source was stationary opposite the centre of the sheet, while 101 traces were recorded at 0.5 cm (25 m) intervals as a symmetric spread along a line on the other side of the sheet from the source. A 50 ns (0.25 ms) sample rate was used. The geometry of this experiment is outlined in Figure 13.

The P-wave and S-wave velocities through the sheet are dependent on both the raypath angle and the azimuth of the source-receiver plane with respect to the three mutually perpendicular axes of symetry that characterize the anisotropy of the phenolic. The data from the source-receiver azimuth parallel to the fast direction (0°) through the sheet are shown in Figure 14, and the record from the source-receiver azimuth parallel to the medium speed direction (90°) is shown in Figure 15. On both records, the slow direction through the material corresponds to raypaths normal to the surface of the sheet, i.e. the centre traces. The moveout of the P-wave arrival on the record from the 90° azimuth clearly lags that observed for the same event on the record at a 0° azimuth.

The second event observed on the records of Figures 14 and 15 is the wave that propagated through the water as a P-wave, but was mode converted to a shear wave through the solid sheet. Again, the moveout for the mode-converted event at the 90° azimuth lags that seen at the 0° azimuth. The converted events are characterized on the split spread data by the low amplitudes at near zero offset distances due to low angles of incidence of the source P-wave at the surface of the sheet of phenolic.

A third record with the same geometry as the previous two experiments was conducted with the azimuth of the source-receiver line at 45° to the two principal axes on the face of the sheet. Tests with a cube of equal thickness to the sheet suggested a split mode-converted shear wave might be recorded with this geometry. The results can be seen in Figure 16. The split mode-converted event does not appear, but the moveout is intermediate between the same events on the 0° and 90° records. Direct tests on the sheet with shear wave contact transducers, which do not rely on mode-conversion to generate the shear wave, clearly showed split events at near vertical incidence that merge into an apparent single event at broader ray path angles.

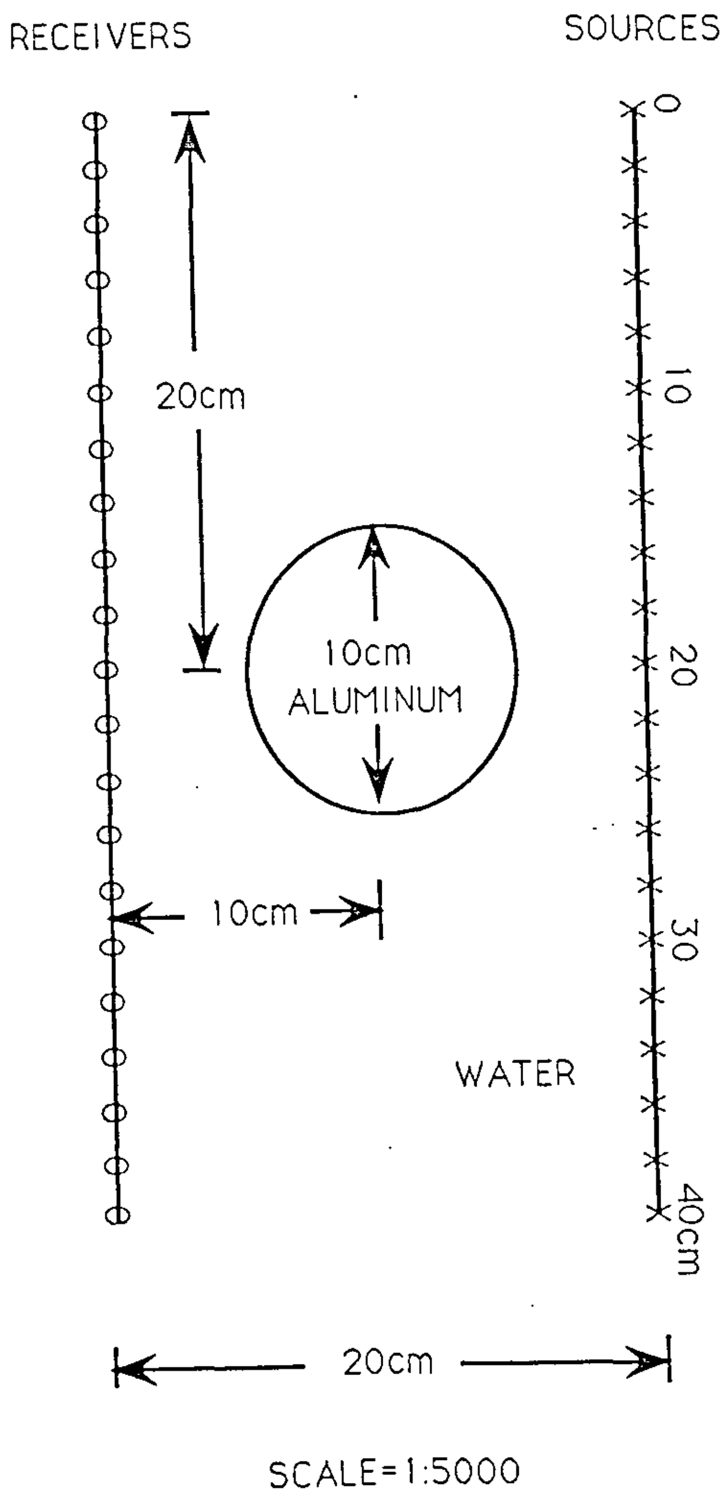

FIG. 9. The geometry of the crosswell experiment using an aluminum cylinder 10 cm in diameter equidistant between source and receiver lines 20 cm apart.

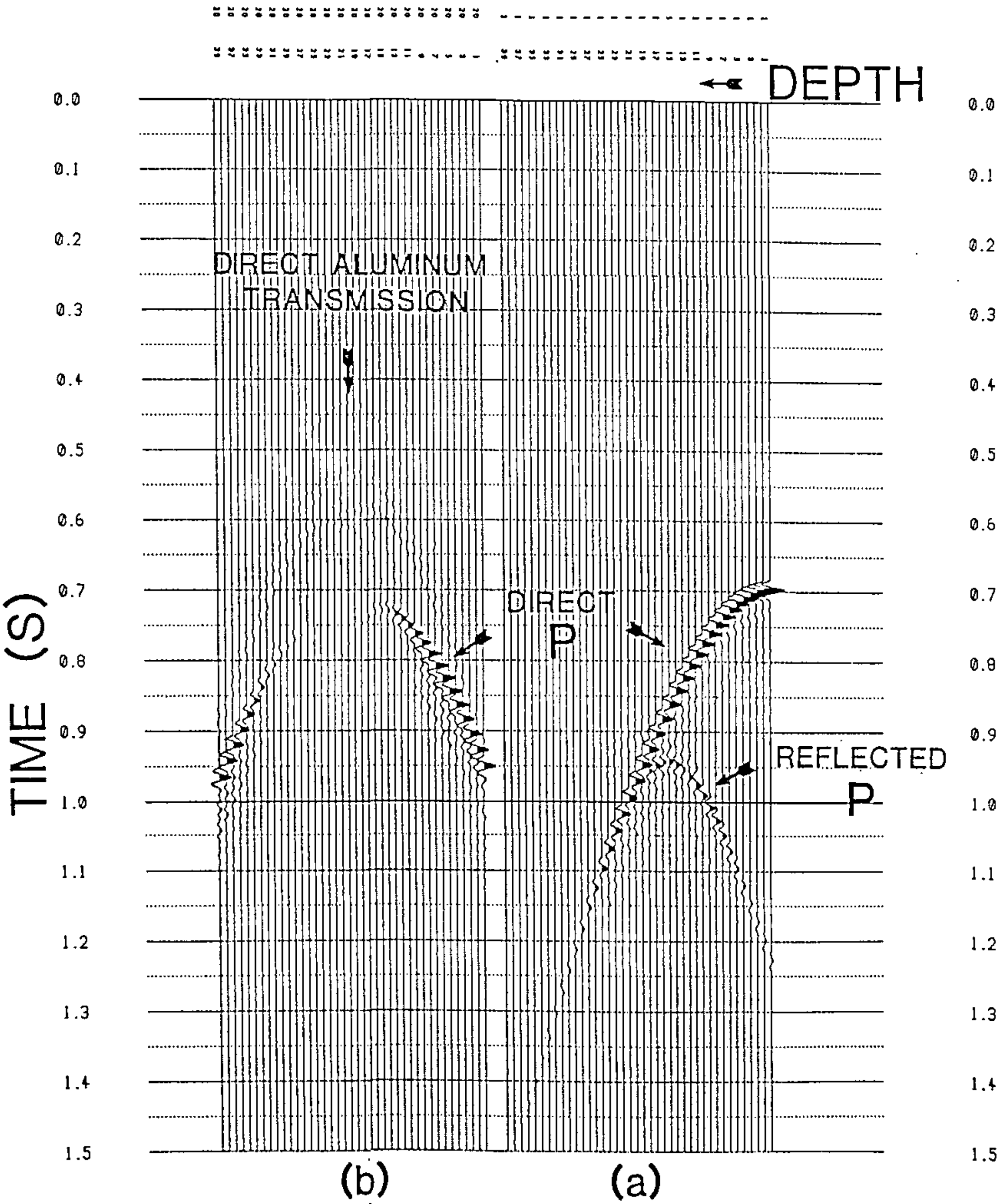

FIG. 10. Two shot gathers, from one end (a) and from the middle (b) of the source line. Direct and reflected P-waves, as well as P-waves transmitted through the high velocity aluminum are identified.

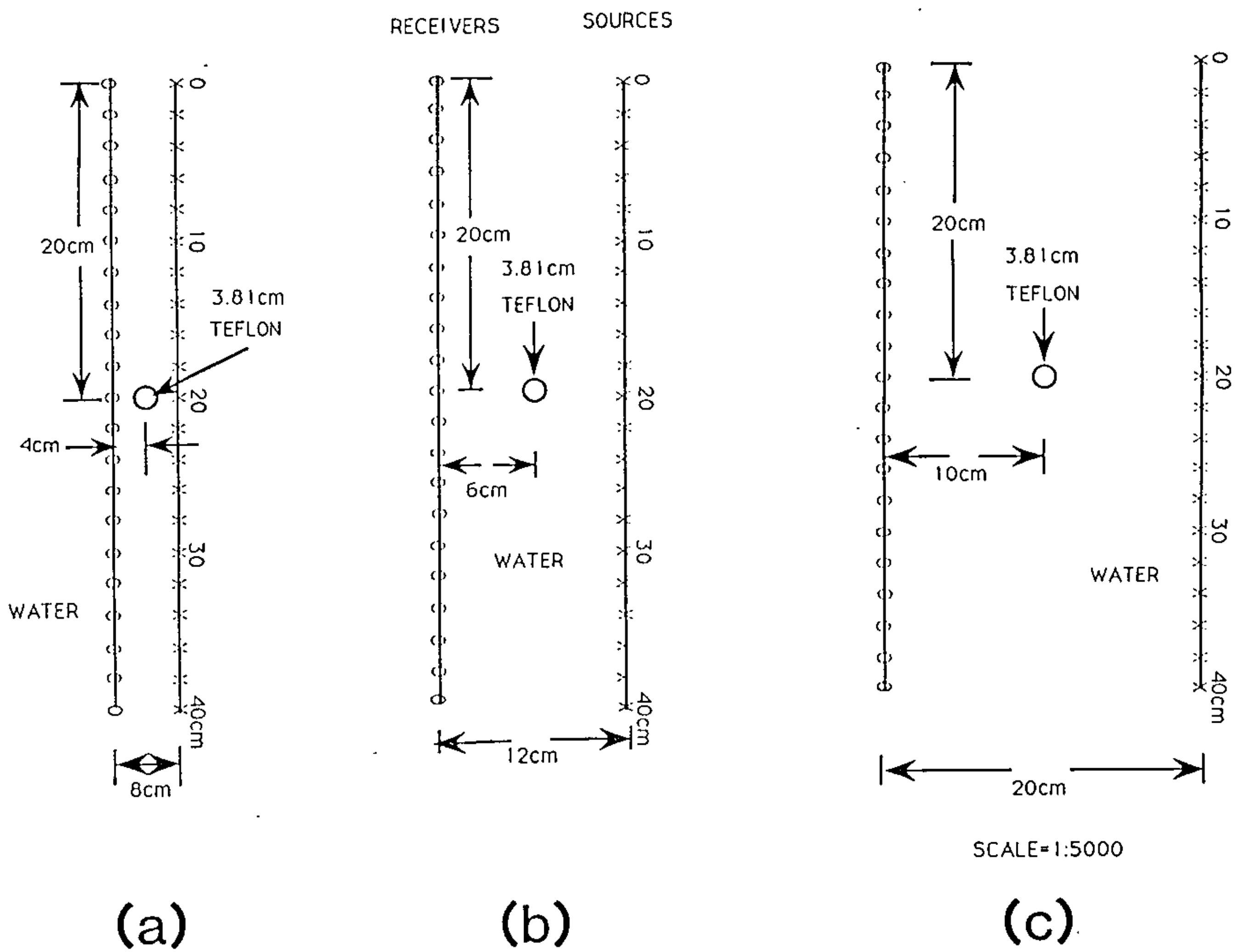

FIG. 11. The geometries of the three crosswell experiments using a teflon cylinder 3.8 cm in diameter equidistant between source and receiver lines that were 8 cm (a), 12 cm (b) and 20 cm (c) apart.

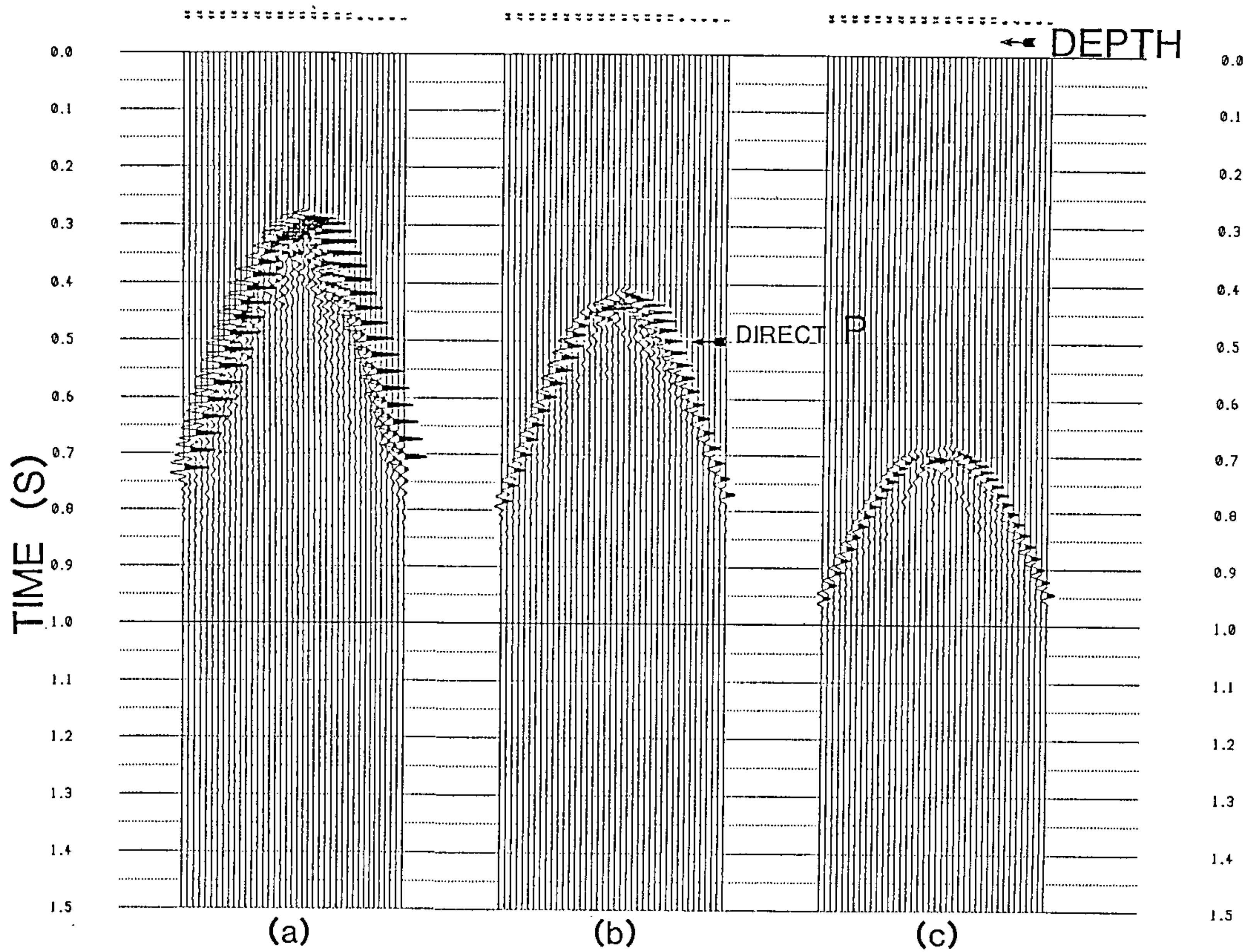

FIG. 12. Shot gathers from the middle of the source lines for the three geometries outlined in Figure 11. The source-receiver line separations were 8 cm (a), 12 cm (b) and 20 cm (c).

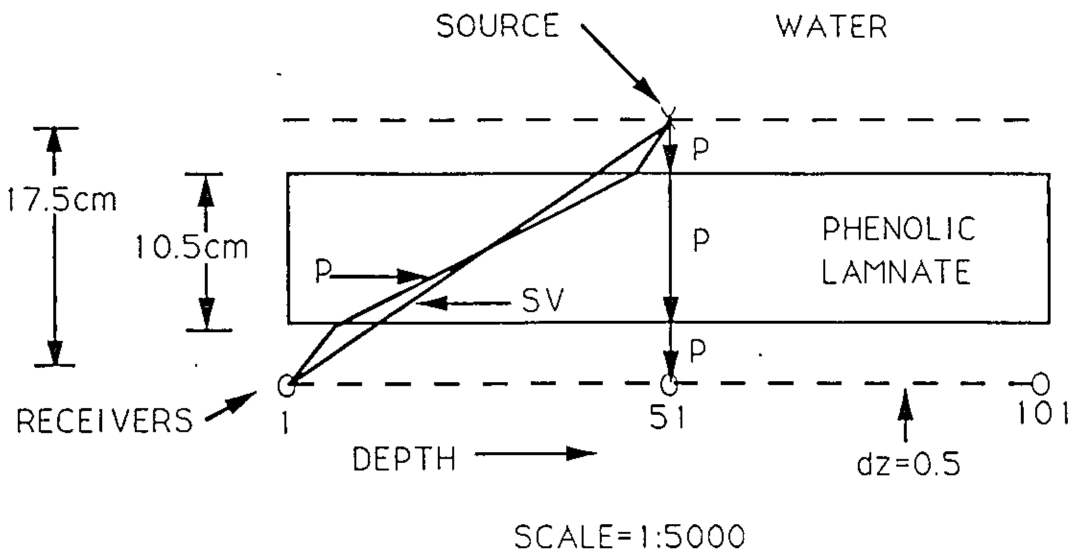

FIG. 13. The geometry for the anisotropic crosswell experiment using a 10.5 cm thick sheet of Phenolic CE laminate equidistant between a source and receiver line 17.5 cm apart.

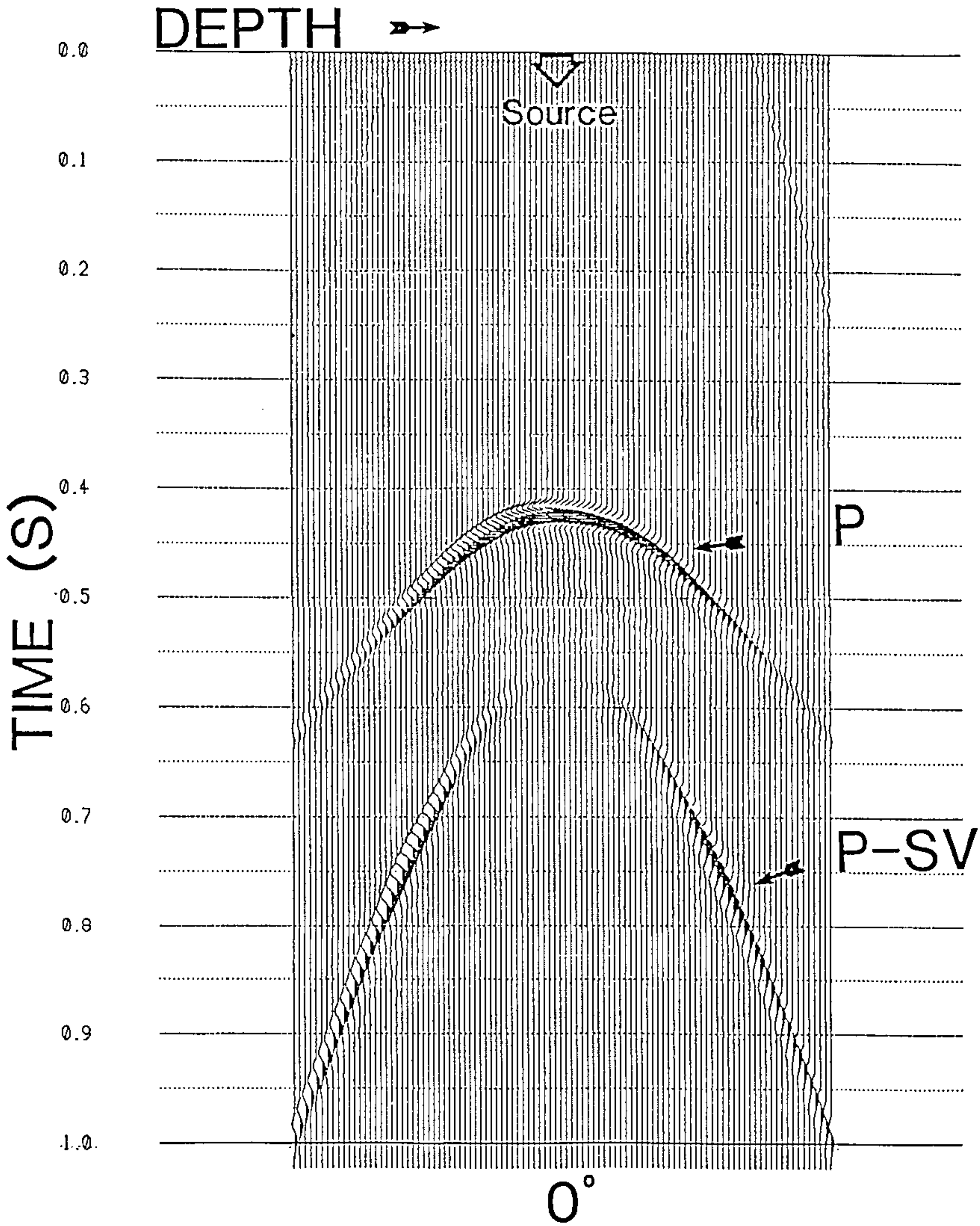

FIG. 14. The crosswell record from a source-receiver azimuth of 0°, parallel to the fast principal axis direction across the sheet of phenolic. The event labelled P-SV was mode converted from a P-wave in the water to a shear wave within the phenolic sheet.

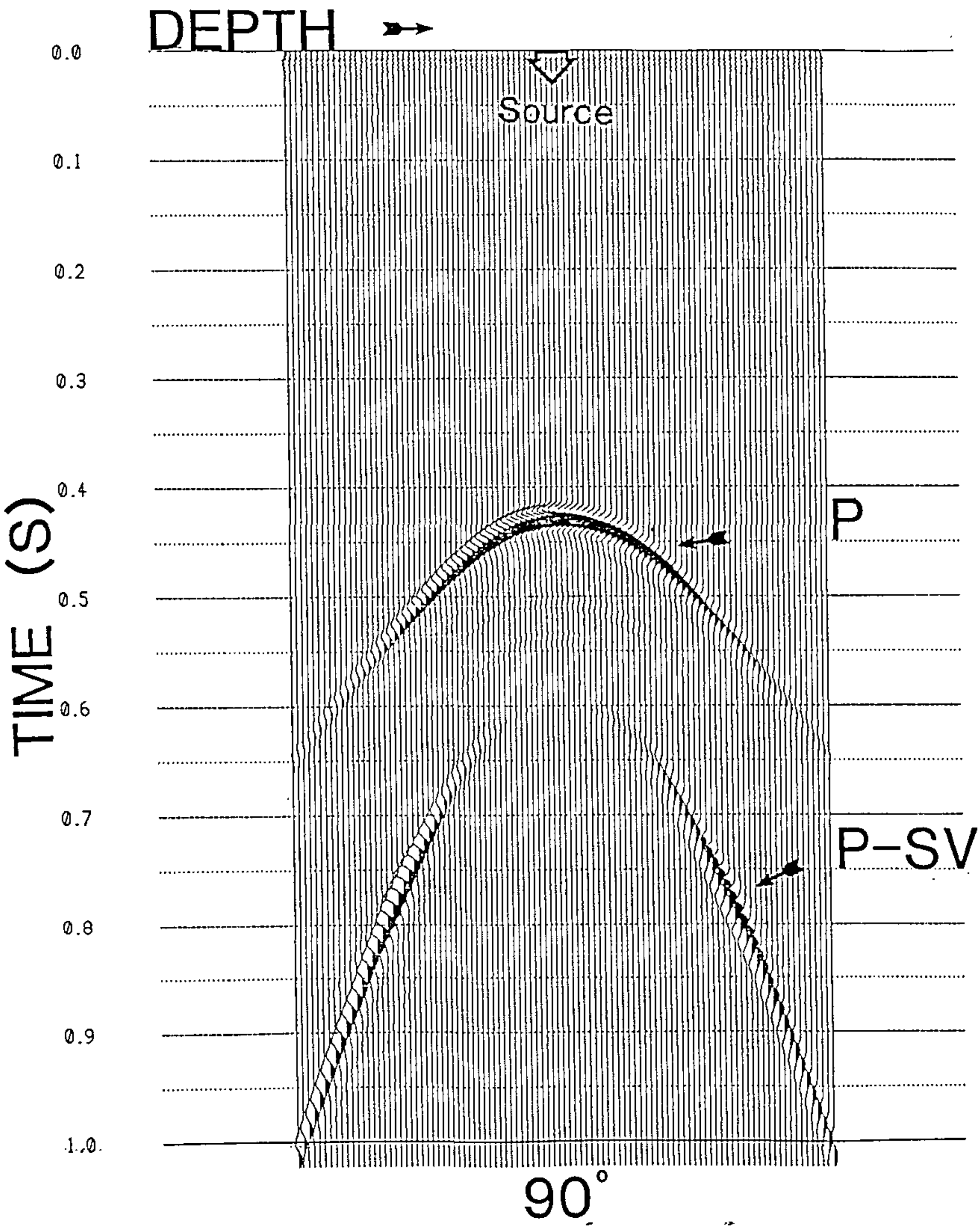

FIG. 15. The crosswell record from a source-receiver azimuth of 90°, parallel to the slower principal axis across the phenolic sheet. The gap near normal incidence for the P-SV event is due to weak mode conversion at small angles of incidence.

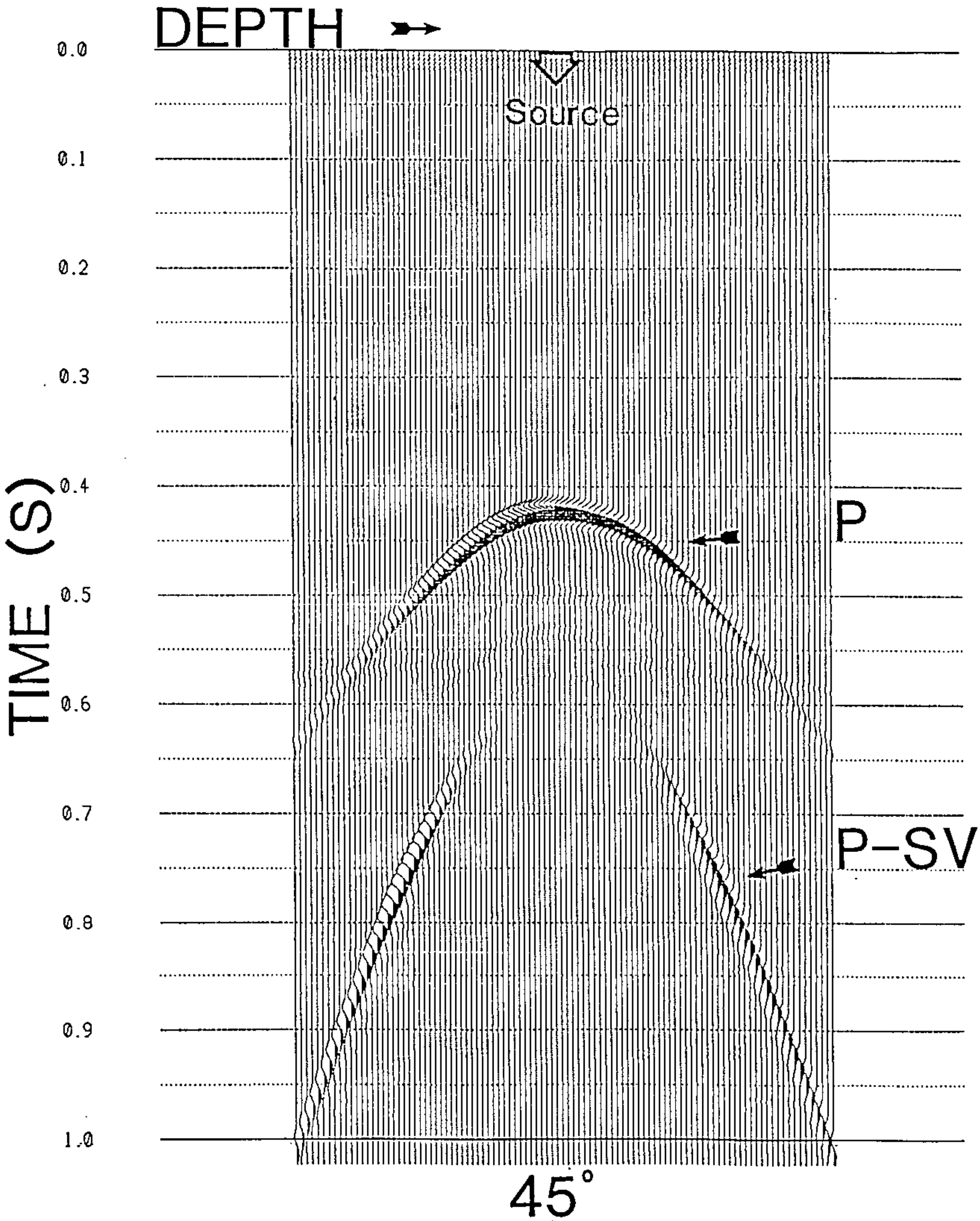

FIG. 16. The crosswell record from a source-receiver azimuth of 45°, intermediate between the principal axes across the face of the phenolic sheet. The expected split shear wave event does not appear at the wide angles of incidence that produce the strongest mode conversion.

CONCLUSIONS

VSP and XT geometries have been simulated in ultrasonic physical model experiments for both isotropic and anisotropic media. The records provide test data for processing and numerical modeling algorithms, as well as basic interpretive examples for a variety of cases. Some limitations of the current modeling system were encountered, particularly the inability to simulate multilayered VSP models effectively. As part of the ongoing study of elastic wave modeling, a "downhole" transducer 0.5 cm in diameter is currentlty being developed that will enable these geometries to be more realistically simulated for multilayered and dipping layer models.

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