Analysis of direct wave arrivals in a shallow multi-offset reverse VSP

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ABSTRACT

A shallow, multi-offset, multi-azimuth reverse vertical seismic profile was recorded using three-component geophones. The borehole used was 30 m deep and penetrated four distinct velocity horizons. The upper layer is 3 m thick with $V_P \approx 300$ m/s, the second is 11 m thick with $V_P \approx 650$ m/s and $V_S \approx 340$ m/s, the third is 9 m thick with $V_P \approx 2\ 660$ m/s, and the lowest is at least 7 m thick with $V_P \approx 1\ 500$ m/s. The source used in the experiment was a 50 gm booster which provided substantial compressional wave energy. Converted shear wave energy was also recorded by the surface geophones.

INTRODUCTION

Near-surface characterization can be accomplished using the spectrum of seismic techniques in addition to other geophysical tools. Resolution is one of the critical factors in such a study. Reverse vertical seismic profiles (RVSP's) provide an opportunity to investigate the earth's composition and structure in fine detail (Jones, 1991;Hu, 1991).

When combined with three-component recording, an RVSP can yield increased amounts of information. Anisotropy may be identified using velocity information from direct arriving waves, or from observations of shear wave splitting (Douma et al, 1990). Critical to such a study is a determination of the nature of the shear wave source. Shear waves may be generated at the point of P-wave generation, may be converted from P at the wellbore, or may be converted from tube-waves at the top of the fluid column. In addition, shear waves are converted from P-waves at non-normal incidence at acoustic impedance boundaries.

DATA ACQUISITION

A shallow RVSP was acquired in August of 1993 during the University of Calgary Geophysics Field School. Three-component geophones were laid out in two orthogonal lines: one running north-south and one east-west. Both were centred on a 30 m deep borehole (Figure 1). Eight three-component OYO geophones were used on each of the four limbs radiating from the borehole. The near offset to the borehole was 2 m for each limb, with the remaining receivers placed at 2 m intervals. All receivers were planted with positive east and positive north orientations. Horizontal components in-line with their limb are referred to as radial, those orthogonal to their limb are transverse. Shots were suspended in the borehole at one metre intervals from 1 to 30 m

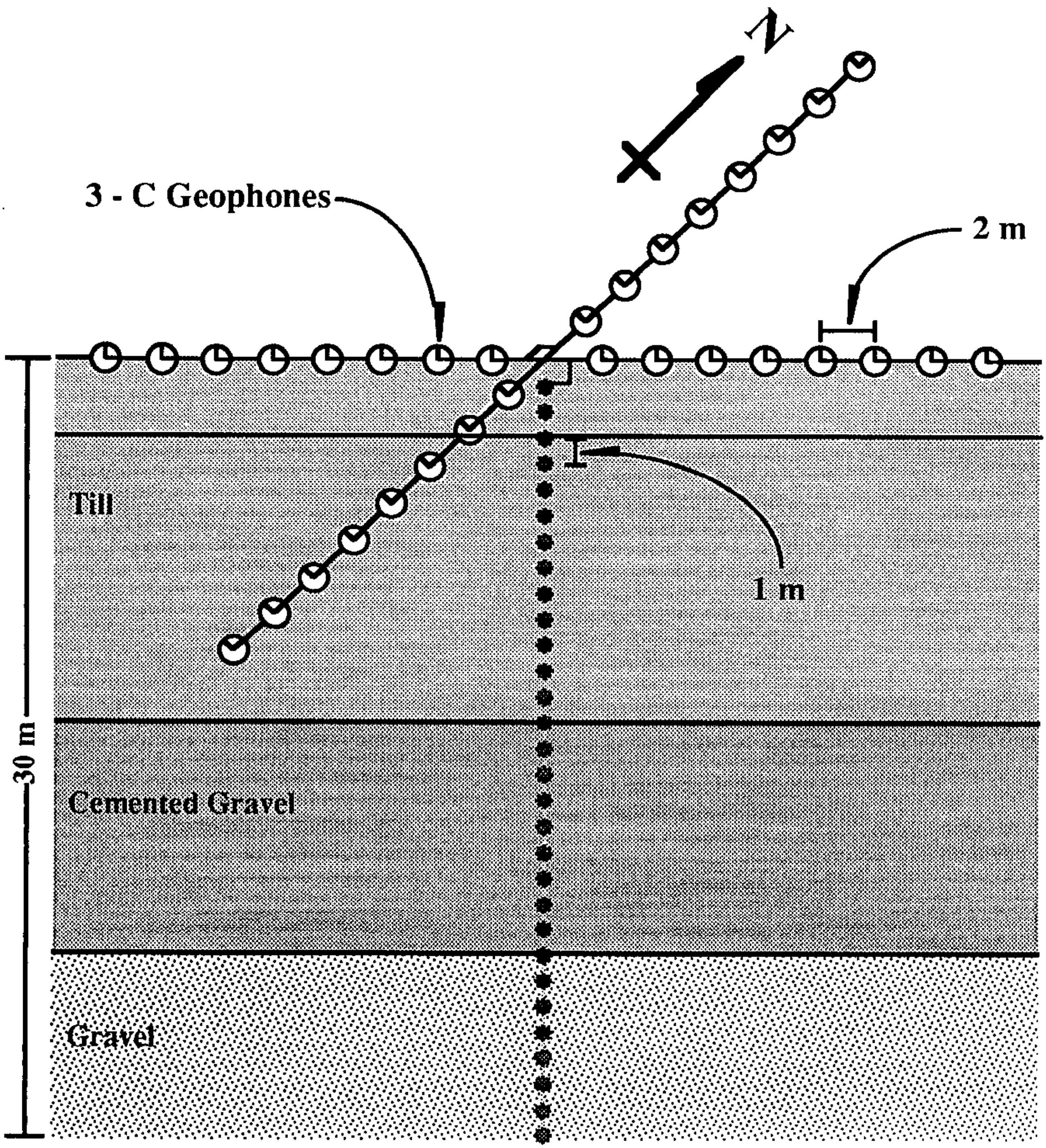

FIG. 1. Survey geometry and geological interpretation.

depth. The source employed was a 50 gm booster loaded in a cylindrical shell oriented vertically.

Each shot produced three records. For these records, trace 1 is the most northerly receiver, trace 16 the southernmost, trace 17 is westernmost, and trace 32 the furthest east. Data were recorded to 1 s using a 2 ms sample interval. No data were acquired at depths of 4, 12, and 29 m due to shot misfires.

Once the original string of shots had been fired, an extra charge was prepared and fired at about 5 m depth. The record thus acquired is a very close match for the original 5m deep record, except that it appears to contain less high frequencies.

The survey was acquired at the University of Calgary Farm in Northwest Calgary (Twp. 25, R. 2 W5M). The near-surface here is comprised of glacial till on gravel on bedrock. The bedrock - Porcupine Hills Fm. - consists of flat lying sandstones, siltstones, and shale and is Paleocene in age. Resting directly atop the Porcupine Hills Fm. is a Pleistocene braid-plain gravel deposit. Pleistocene Cordilleran and Laurentide tills cap the sequence (Moran, 1987). Both the tills and the gravel contain high volumes of carbonate locally, and can be well indurated (Osborn et al, 1991).

DATA PROCESSING

Minimal processing was required for the present analysis as this paper is concerned primarily with the direct arriving energy. IT&A's Insight software was used to pick the direct arrival times and to apply a 125 ms agc and a 5/10-120/180 Hz bandpass filter to the plotted records. The records were also sifted to produce common receiver gathers.

RESULTS AND DISCUSSION

Figure 2 is a shot gather for shot 27. Figure 3 and 4 are plots of the early time (first 200 ms) for shot 27 and 16 respectively. The shot numbers equate to depth in metres. Direct arriving P-waves are well defined and clear on the vertical component records. The horizontal components present more difficulty.

Radially oriented components record first arrivals that appear to be reasonably easy to identify. The shear wave first arrivals are not, however the first signals recorded on the transverse component. They are somewhat obscured by P-wave "noise" leaking through to the horizontal. This is especially true for the shallow shots at near offsets, making first arrival picking difficult (and sometimes impossible). The apparent polarity of these traces flips by 180° across the borehole.

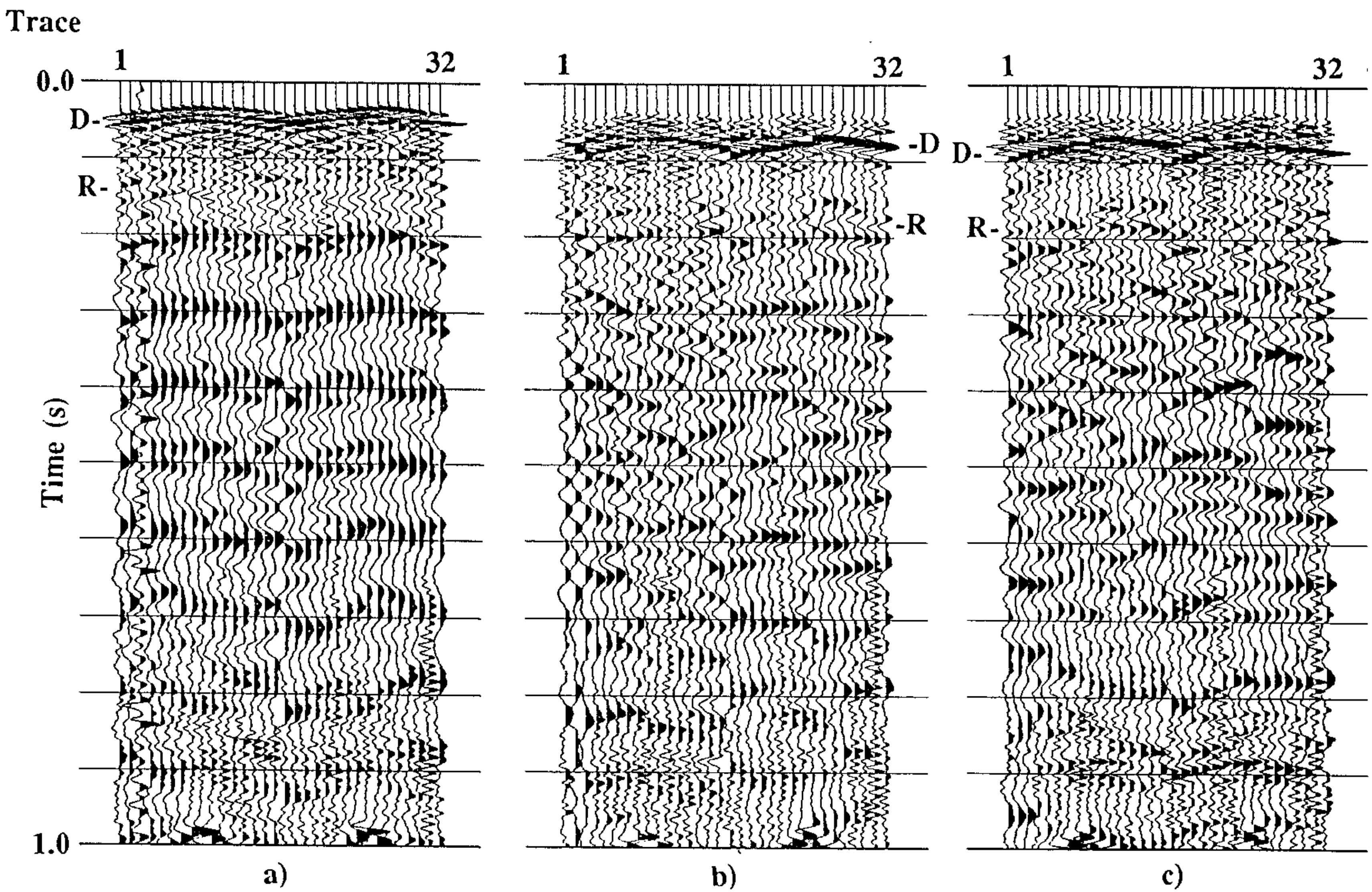

FIG. 2. Shot gathers for a) vertical, b) east-west, and c) north-south oriented components. Shot at 16 m depth. Traces 17-32 of b) and 1-16 of c) are radial. Direct arrivals - D, Reflections - R.

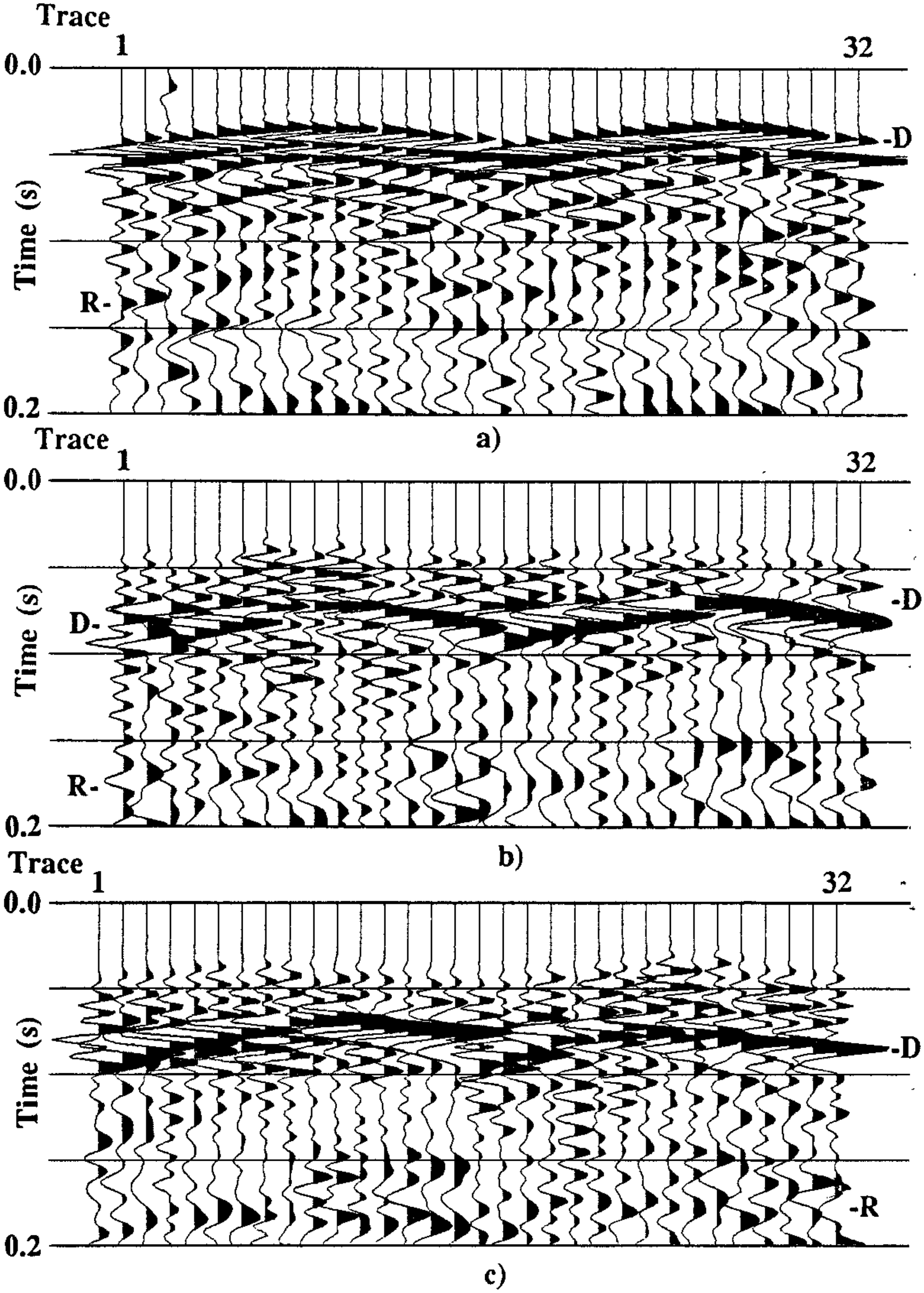

FIG. 3. Shot gathers for a) vertical, b) east-west, and c) north-south oriented components. Shot at 16 m depth. Traces 17-32 of b) and 1-16 of c) are radial. Direct arrivals - D.

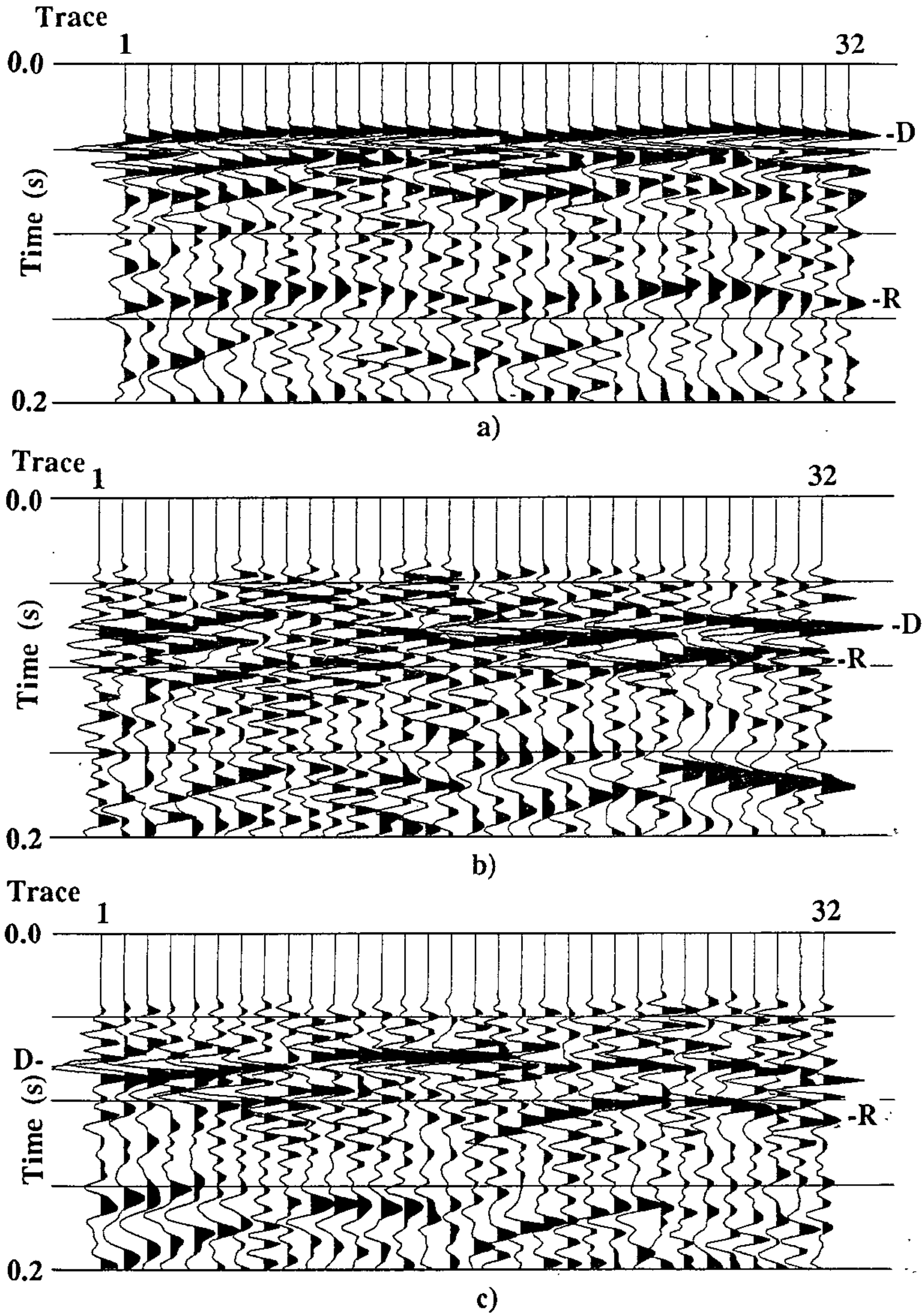

FIG. 4. Shot gathers for a) vertical, b) east-west, and c) north-south oriented components. Shot at 21 m depth. Traces 17-32 of b) and 1-16 of c) are radial. Direct arrivals - D.

Transverse components record even lower signal to noise ratios (S/N) than do the radial components. This likely results from the cylindrical shape of the source and borehole - less transverse oriented shear is generated than is radial shear. The deeper shots provide the lowest S/N for transverse components, with an improvement for shots further uphole. The polarity of first arriving shear on the transverse component is less predictable than that for the radial component. No analysis of the transverse direct arrivals has yet been performed as the quality of picks is too poor.

Velocities

A *t-x* velocity analysis has been performed for each of the near offset (2 m) receivers (Figure 5). This was performed by plotting shot depth versus direct arrival time. In much the same manner as a refraction survey, velocity is determined as the inverse of the slope of such a graph. This analysis only applies, strictly speaking, to a zero offset receiver. Compensation for offset was performed by assuming a straight raypath and reducing recorded traveltimes by the factor cos α, where α is the angle between the borehole and a straight line drawn from shot to receiver. There is little appreciable time compensation for shot depths greater than 5 m at 2 m offset.

The velocities thus derived are presented in Table 1. The compressional wave velocities (V_P) appear well behaved for intervals 1, 2, and 4. Interval 3 is substantially higher velocity, but the scatter in values is much greater. The shear wave velocities are interpretable for layer 2 only. The slopes for layers 3 and 4 of the radially directed arrivals match quite closely with those for the vertical component. This suggests that the direct arrivals from the deeper shots at the near offset travel as compressional waves below 14 m depth. They are converted to shear at this level. No shear wave velocity was obtainable, therefore, for layers 3 and 4.

Layer		North	South	West	East	Average	Error
1	Vertical	280	280	340	290	300	±25
2	Vertical	680	650	630	650	650	±20
	Radial	350	400	270	320	340	±35
3	Vertical	2860	3310	2060	2390	2660	±330
4	Vertical	1390	1510	1540	1540	1500	±200

TABLE 1. Interval velocities from *t-x* analysis (m/s).

The velocities reported are consistent with the following stratigraphy: 1) basal, uncemented gravel (layer 4), 2) highly cemented gravel (layer 3), 3) unweathered till (layer 2), and 4) weathered till/soil horizon (layer 1). This is consistent with the expected geology and drilling rates provided by the driller. The interval boundaries are defined by the points at which the *t-x* slope changes. At the wellbore then, layer 1 is 3 m thick, layer 2 is 11 m, layer 3 is 9 m, and layer 4 at least 7 m thick.

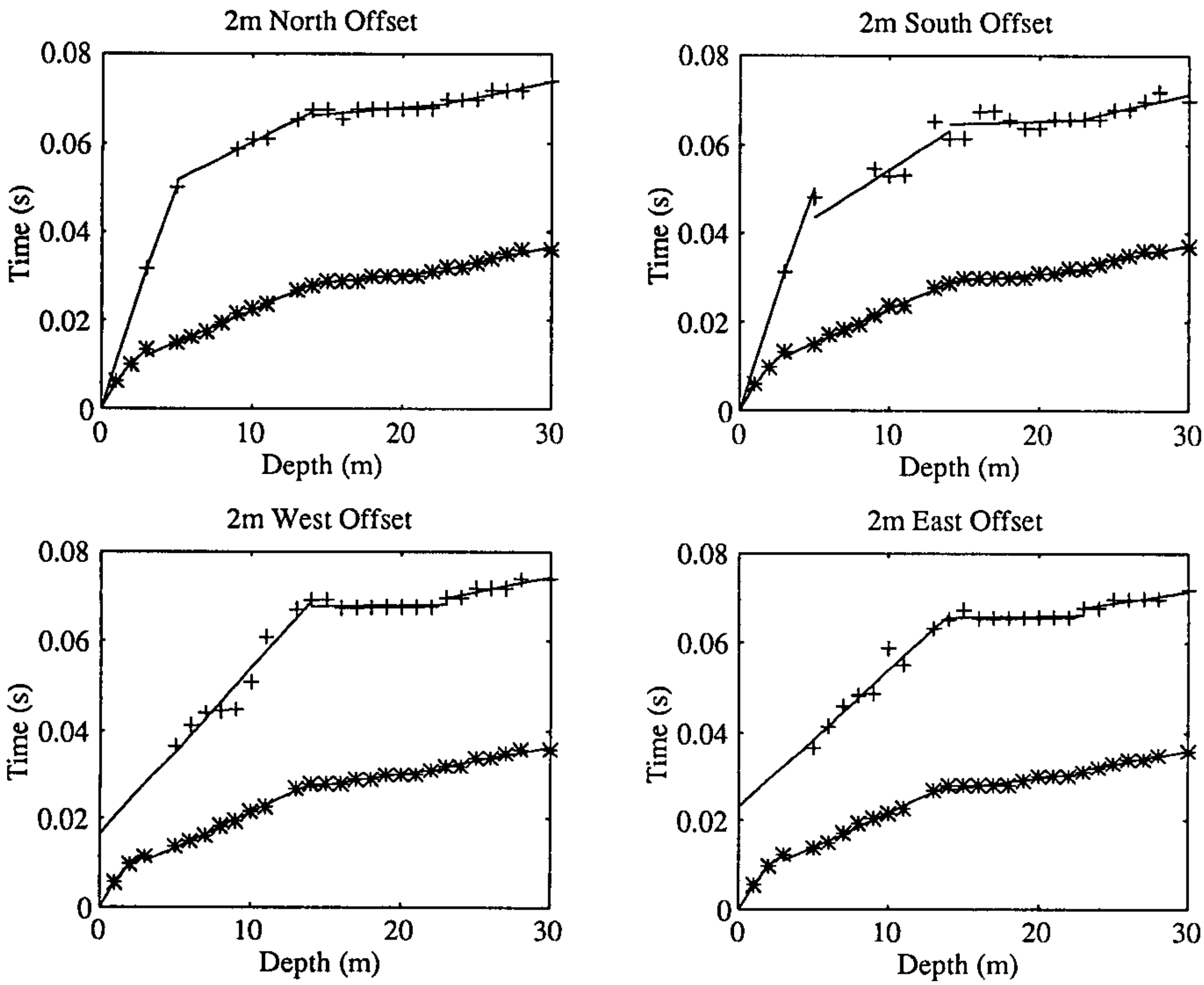

FIG. 5. Time/depth curves for the near offset (2m) receivers (+ = radial component, * = vertical component).

It is not reasonable to apply the *t-x* analysis to receivers at increased offset as the raypaths to these receivers deviate even further from the straight ray assumption than do the 2 m offset receivers. Average velocity plots are, however, instructive. Figures 6 and 7 are such plots for the vertical and radial components at geophones which are at 2, 6, 12, and 16 m offset. Figures 8 and 9 are average velocity plots for varying offset receivers for shots 2, 10, 20, and 30. These velocities are computed simply by dividing the straight line source/receiver distance (from the borehole) by the recorded direct arrival time. The figures show an overall increase in average velocity with offset. This is anticipated as the farther offset rays will travel farther within high velocity material.

There is also a distinct partitioning of velocities at longer offset. The northward travelling rays appear slower and the southward faster for the radial receivers. The north and west travelling rays appear slower than the south and east for the vertical receivers. This effect may possibly be the result of a slight deviation in the borehole toward the southeast.

Shear Wave Source

One of the potential difficulties in this type of survey is characterization of the shear wave source. It is possible that shear is being converted from tube wave energy at the top of the fluid column. If this is the case, the shear wave moveout will be constant for all records obtained from shots below the top of this column. Stacking velocities were determined for direct arrivals for all shots after bulk shifting each record so that t_0 was equal for each shot depth (Figure 10.). These stacking velocities generally increase with depth, suggesting that P-wave to S-wave conversion is occurring on transmission through layer 3. The *t-x* velocity analysis, however, suggests that the near offset receivers record shear wave energy generated from compressional waves below 14 m depth.

Common Receiver Gather

Figure 11 is a common receiver gather for receiver 10 (4 m south of the borehole). This gather presents the data in such a way that it may be interpreted in a similar fashion as may a VSP. Both reflections and multiples from below the depth of the borehole can be observed on these gathers. Analysis of the common receiver gathers is currently in progress.

CONCLUSIONS

Compressional and shear wave direct arrivals suggest a velocity structure in the vicinity of the borehole of: 0-3 m $V_P \approx 300$ m/s; 3-14 m $V_P \approx 650$ m/s $V_S \approx 340$ m/s; 14-23 m $V_P \approx 2\,660$ m/s; and 23-30 m $V_P \approx 1500$ m/s. This is consistent with the anticipated geological composition at this location.

No shear wave velocities were obtained for the lower two zones as the *t-x* plots suggest that the direct arrivals at the near offsets travel solely as compressional waves in these intervals.

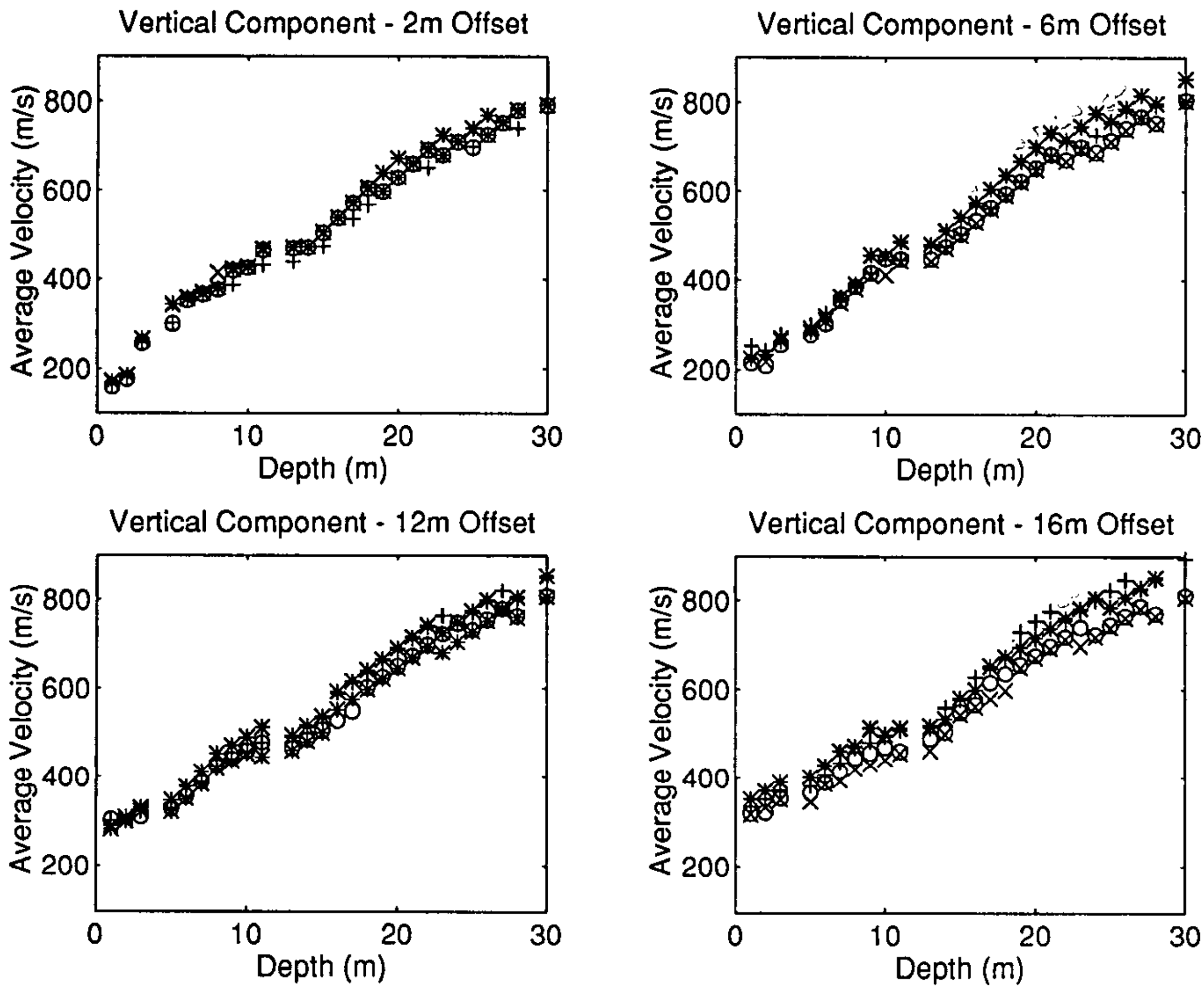

FIG. 6. Average velocities vs. depth - vertical components (o = north limb; + = south limb; x = west limb; * = east limb).

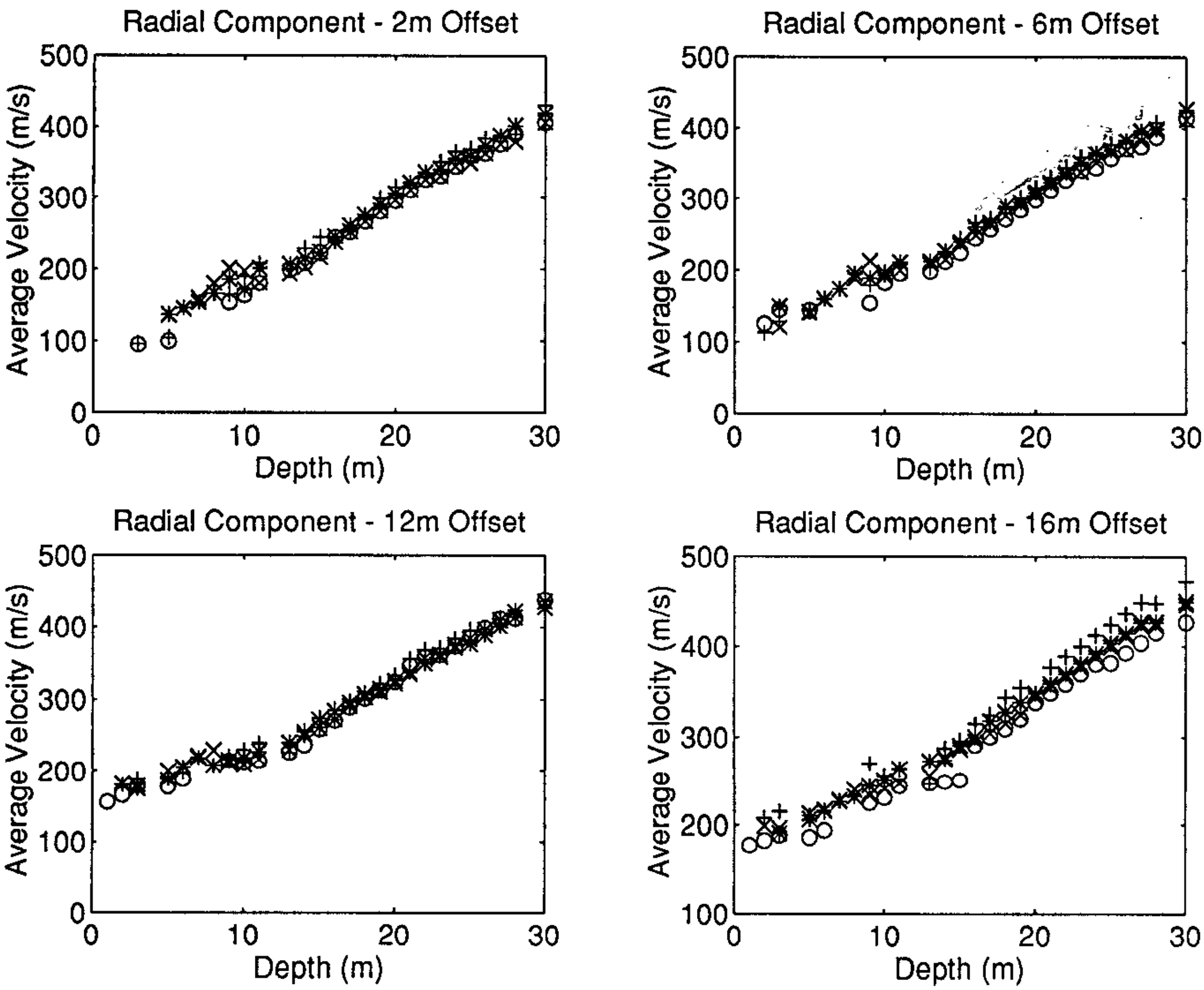

FIG. 7. Average velocities vs. depth- radial components (o = north limb; + = south limb; x = west limb; * = east limb).

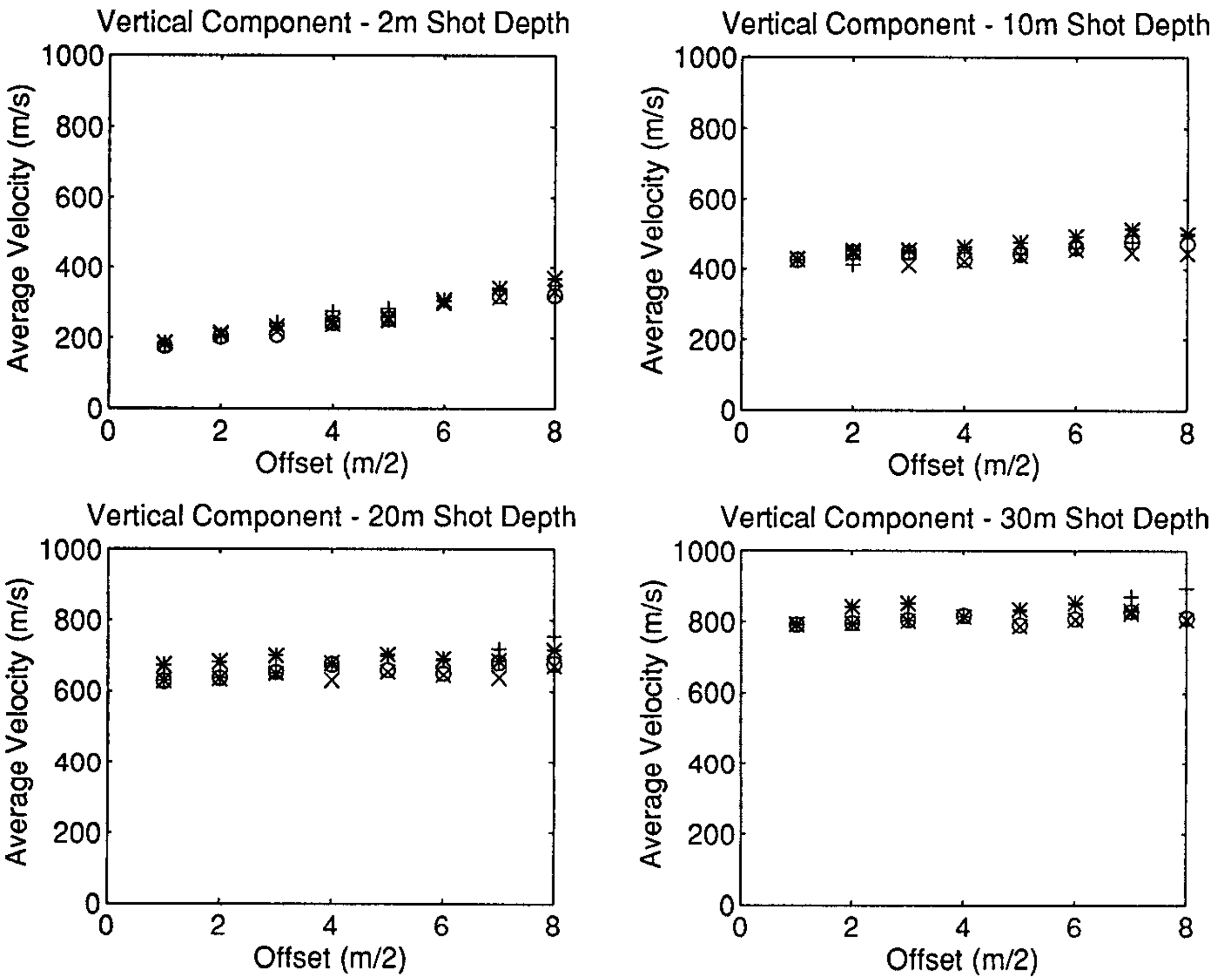

FIG. 8. Average velocities vs. depth - vertical components (o = north limb; + = south limb; x = west limb; * = east limb).

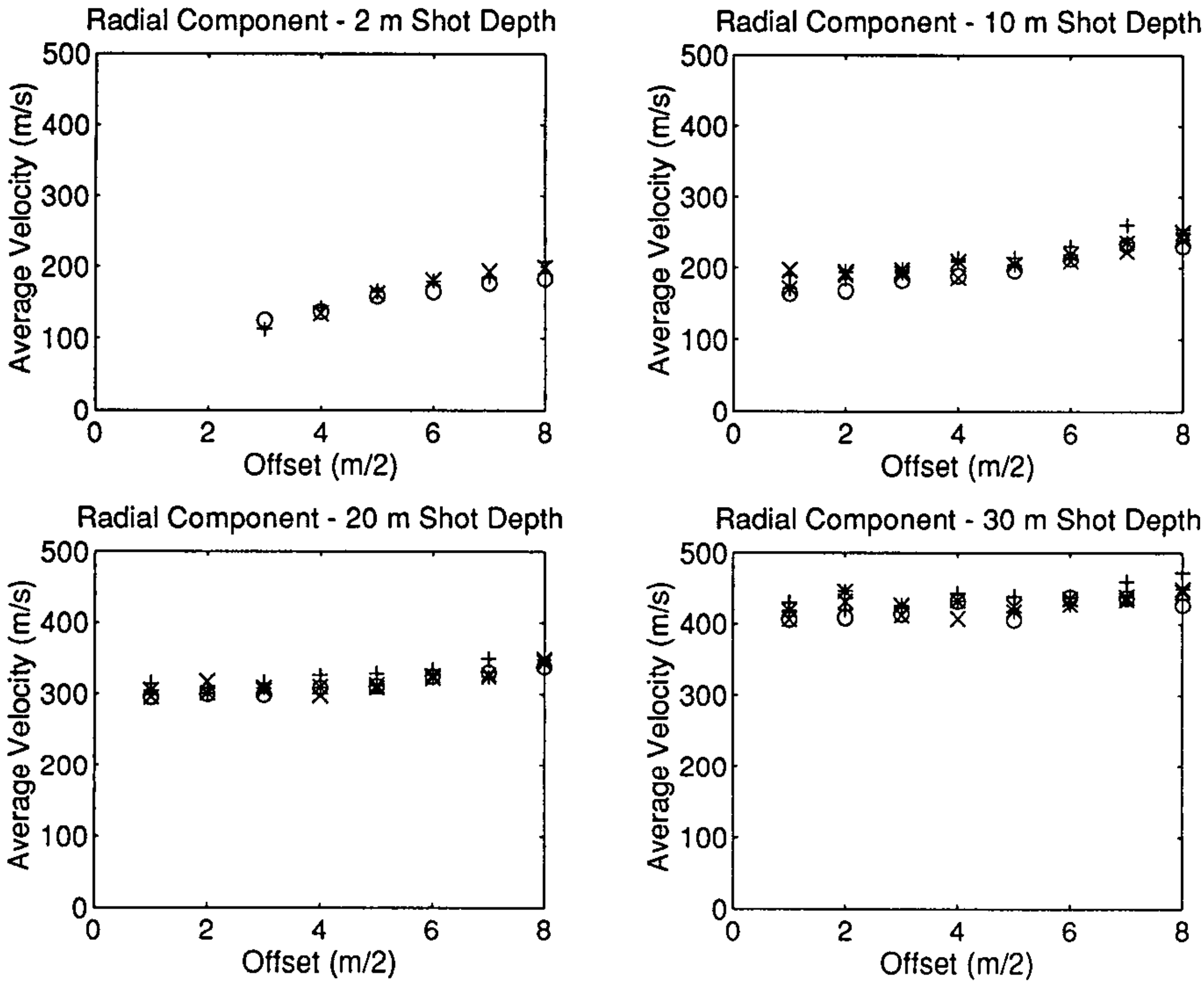

FIG. 9. Average velocities vs. depth - radial components (o = north limb; + = south limb; x = west limb; * = east limb).

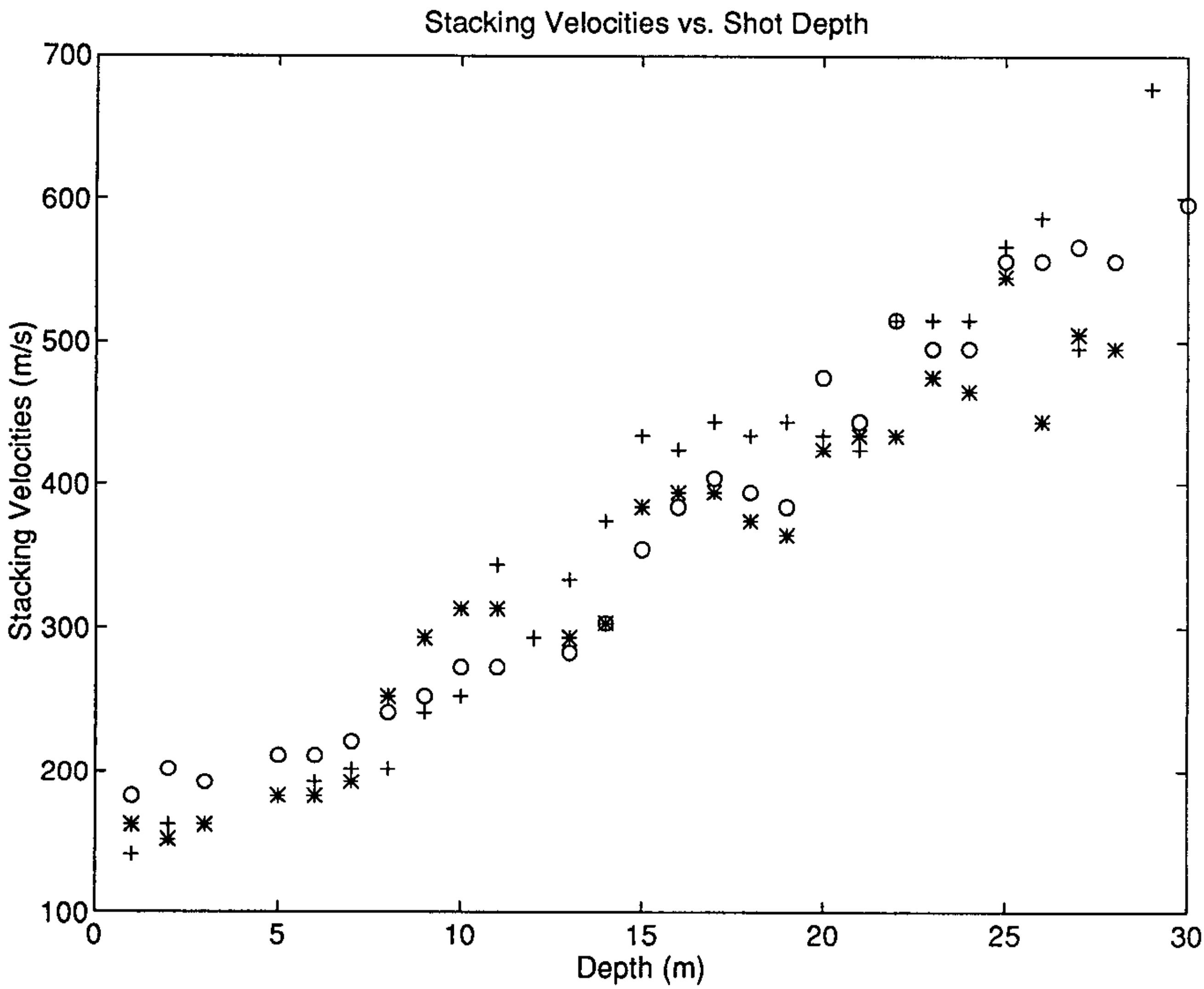

FIG. 10. Stacking velocities for radial records. NMO in the direct arrivals will be compensated for by these velocities (o = vertical component, + = east-west component, * = north-south component).

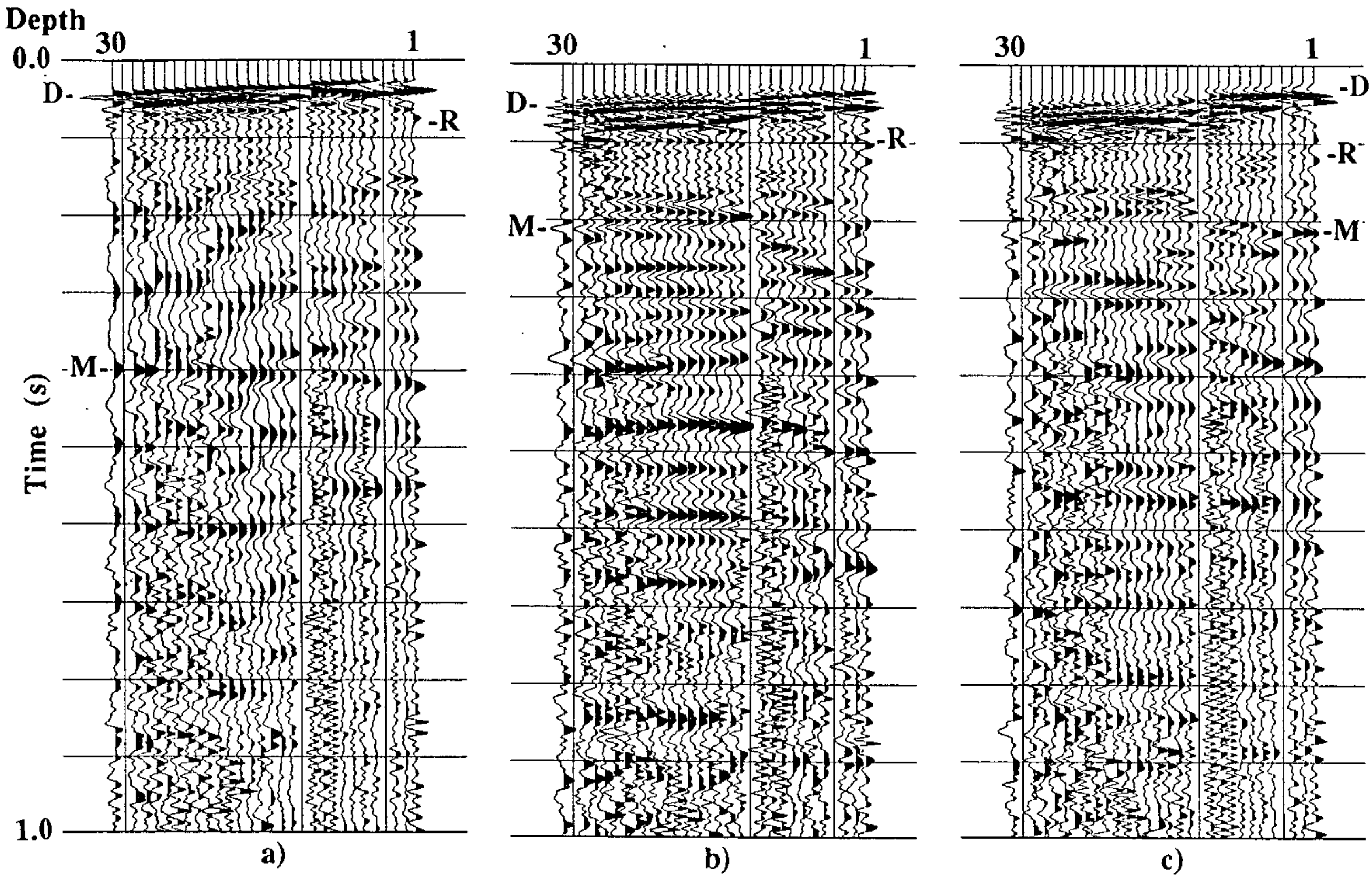

FIG. 11. Common receiver gathers for receiver 10 (4 m south of borehole). a) vertical, b) radial, and c) transverse. Direct arrivals (D), Reflections (R), Multiples (M). 125 ms agc applied. Bandpass filtered at 5/10-120/180 Hz.

REFERENCES

Douma, J., Den Rooijen, H., and Schokking, F., 1990, Anisotropy detected in shallow clays using shear-wave splitting in a VSP survey: Geophysical Prospecting, **38**, 983-998.

Hu, L. Z., 1991, Wavefield processing of reverse VSP data: Society of Exploration Geophysicists, Sixty-first annual international meeting and exposition; expanded abstracts with biographics, 78-81.

Jones, M. J., 1991, On the analysis of a reverse VSP data set using a core-gun source: Society of Exploration Geophysicists, Sixty-first annual international meeting and exposition; expanded abstracts with biographics, 73-77.

Moran, S.R., 1987, Surficial geology of the Calgary urban area: Alberta Research Council, Bulletin 53.

Osborn, G., Thomas, R., McCoy, W., Miller, B., and Smith, A., 1991, Significance of a molluscan fauna to the physiographic history of the Calgary area, Alberta: Canadian Journal of Earth Sciences, **28**, 1948-1955.