Reflection imaging for crosswell seismic data: Friendswood, Texas

Guoping Li and Robert R. Stewart

ABSTRACT

This paper outlines a processing flow for extracting reflections from crosswell seismic data and using them to construct an image. This flow is applied to a field data set acquired by Exxon Production Research Company in two 1000-ft boreholes separated by 600 ft near Friendswood, Texas. The crosswell seismic data consisted of 98 shot gathers each having 96 traces. The data are part of a combined seismic experiment which also collected reversed vertical seismic profiling (RVSP) and surface seismic CDP data at the same site. The source was shot from the source well between 30 ft and 1000 ft (spacing at 10 ft) into the receiver well where hydrophones, placed from 10 ft to 960 ft in depth at 10 ft intervals, recorded the data. The seismic traces were sampled at 1/4 ms with a record length of 1.0 second. The Friendswood crosswell data are dominated by strong low frequency tube waves, which obscure the reflections. Because these tube waves have a linear nature in common source gathers, a 9-trace median filter is used to eliminate them. A 70-620 Hz bandpass filter is applied to suppress low-frequency and high-frequency noise. Strong direct arrivals are removed in common interval gathers by running a 9-trace median filter. An f-k filter is applied in common source gathers to separate up- and down-going reflected waves. Velocity information, used for moveout corrections, is derived from velocity scanning in a zero-interval gather, which collects traces with zero interval between the source and receiver depths. Reflection data are sorted into common reflection point (CRP) gathers where both horizontal and vertical moveout are corrected. Stacked sections are generated by summing the moveout-corrected CRP gathers. Following that, an up- and down-going wavefield combination and a time-depth conversion are performed to produce a depth section. The stacked sections obtained show high-resolution imaging of subsurface layers, with a resolution of about 10 ft. A comparison of the crosswell reflection imaging results with the RVSP and CDP stacked sections processed by Chen et al. (1990) is made. This case study shows that the crosswell reflection imaging procedure presented here is an effective means of imaging.

INTRODUCTION

The value of crosswell seismic data has been increasingly recognized because of its potentially high resolution. In the last decade, there has been considerable interest in processing crosswell seismic data. The commonly used techniques include tomographic inversion (Peterson et al., 1985; Bregman et al., 1989; Lines and LaFehr, 1989; Lines and Tan, 1990; and Abdalla et al., 1990), prestack migration (Hu et al., 1988; Qin and Schuster, 1993; Zhou and Qin, 1993) and the well-known crosswell-CDP mapping technique (Abdalla et al., 1990; Lazaratos et al., 1991; Lazaratos et al., 1992; Khalil et al., 1993).

Recently, a few efforts have been made to produce a stacked section, similar to the surface CDP case, from crosswell seismic data of multi-fold coverage. In a physical modeling study, Stewart et al.(1991) and Stewart and Marchisio (1991) proposed processing crosswell seismic data like CDP reflection seismic data. Some of these concepts have been expanded by Li and Stewart (1992a, b). This CDP-based crosswell reflection imaging method is composed of several major processing steps (Li and Stewart, 1992b), including: 1) removing direct arrivals in *common interval* (CI) gathers, 2) separating up- and down-going reflections in *common source* (CS) gathers, 3) deriving velocity information in a zero-interval CI gather, 4) applying vertical and horizontal moveout corrections in *common mid-depth* (CMD) gathers, and 5) stacking traces in *common reflection bin* (CRB) gathers to obtain the final stacked section.

However, we can directly sort up- and down-going reflection wavefields into CRB gathers before VMO and HMO corrections, without using the CMD gathers. This analysis leads to a new crosswell reflection imaging technique, the common reflection point (CRP) stacking method.

In this paper, we will present a case study of crosswell reflection imaging. A complete processing flow, developed by Li and Stewart (1993), will be applied to a field data set. The crosswell seismic data we use in this case study are from a combined surface and borehole seismic experiment conducted by Exxon Production Company at a Friendswood, Texas site. The results of prestack processing the same data set up to wavefield separation were published by Cai and Schuster (1993), but no stacked section, produced from a field crosswell seismic data set, using these methods has been published before to our knowledge.

FRIENDSWOOD SURVEY

Survey geometry and field parameters

A combined seismic experiment consisting of crosswell, VSP, reversed VSP, and surface CDP seismic data was performed by Exxon Production Research Company at a test site located near Friendswood, Texas (Chen et al., 1990). Two 1000-ft cased wells, separated by 600 ft, were used as a source and receiver well respectively. The maximum deviation in both wells is found to be less than 7 ft. A surface seismic line recording the CDP data runs across the location of the two wells.

The borehole recording geometry used in this experiment is shown in Figure 1. Three groups of data were recorded: (1) sources located in one well shot into receivers located in the other well (crosswell data); (2) sources located in one well shot into receivers located on the surface line going across the two wells (RVSP); and (3) sources located on the surface line shot into receivers located in a well (VSP).

In the crosswell seismic case, downhole explosive sources of 10g charges were fired at 10 ft intervals from a depth of 1000 ft to 30 ft in the source well. The 10 g charge provided high-quality data and did not damage to the well (Chen and Eriksen, 1989; Chen et al., 1990). A 24-channel hydrophone streamer served as the downhole receiver. The space between receiver stations was 10 ft. Each station consisted of ten hydrophones for improved sensitivity. Four streamer positions were needed to cover the receiver well from depths of 960 ft to 10 ft. The analog signals from all 24 stations were transmitted uphole simultaneously through tow leaders. The digitizer has 16 bits of dynamic range. In this experiment, the data were recorded at a 1/4 ms sampling rate for 4000 points. The digitized data are written on tape in SEG-D format. Only first 0.5 second of data for the first 95 shot gathers are processed here.

Data examples and wavefield analysis

An example of the field data is illustrated by a common source gather (source depth 330 ft) and a common receiver gather (receiver depth 460 ft) displayed in Figures 2 and 3. The interpretation of wavefields contained in the crosswell data is given by Chen et al. (1990). The following wave identification is based on their analysis. In the common source gather, a number of events can be identified. The strong hyperbolic wave labeled as *D* is the direct P wave from the source well to the receiver well. *SR* is the downgoing P-wave reflection. This wave is radiated from the source well upwards to the surface and reflected into receivers in the receiver well. Events like *DR* are P-wave reflections generated from layers between the two boreholes. A few upgoing reflections such as *UR* are weak but still can be seen. In addition to high-amplitude 60 Hz noise, data in the common source gather are dominated by strong low-frequency tube waves such as *T1* and *T2*. These two tube waves have a similar generation mechanism, but have different propagation directions. Tube wave *T1* is a P wave radiated from the source well to the bottom of the receiver well, converted into a tube wave, and transmitted uphole. The tube wave *T2*, however, is a P wave radiated from the source well to the top of the receiver well, converted into a tube wave, and transmitted downhole. Reflections can also be converted into tube waves. For example, the tube wave *T3* is converted from the downgoing reflection *SR* at the bottom of the receiver well, and then travels uphole. Tube waves are usually undesirable but, because of their linear nature in common source gathers, they can be suppressed by velocity filters.

Some of the reflections that can be seen in the shot gather are generated from layers with obvious velocity changes, as indicated by the sonic log (from Zhou and Qin, 1993) in Figure 1. For example, the layer at 650 ft has a large velocity increase on the sonic log and it is a good reflector that generates reflections, seen in the shot gather.

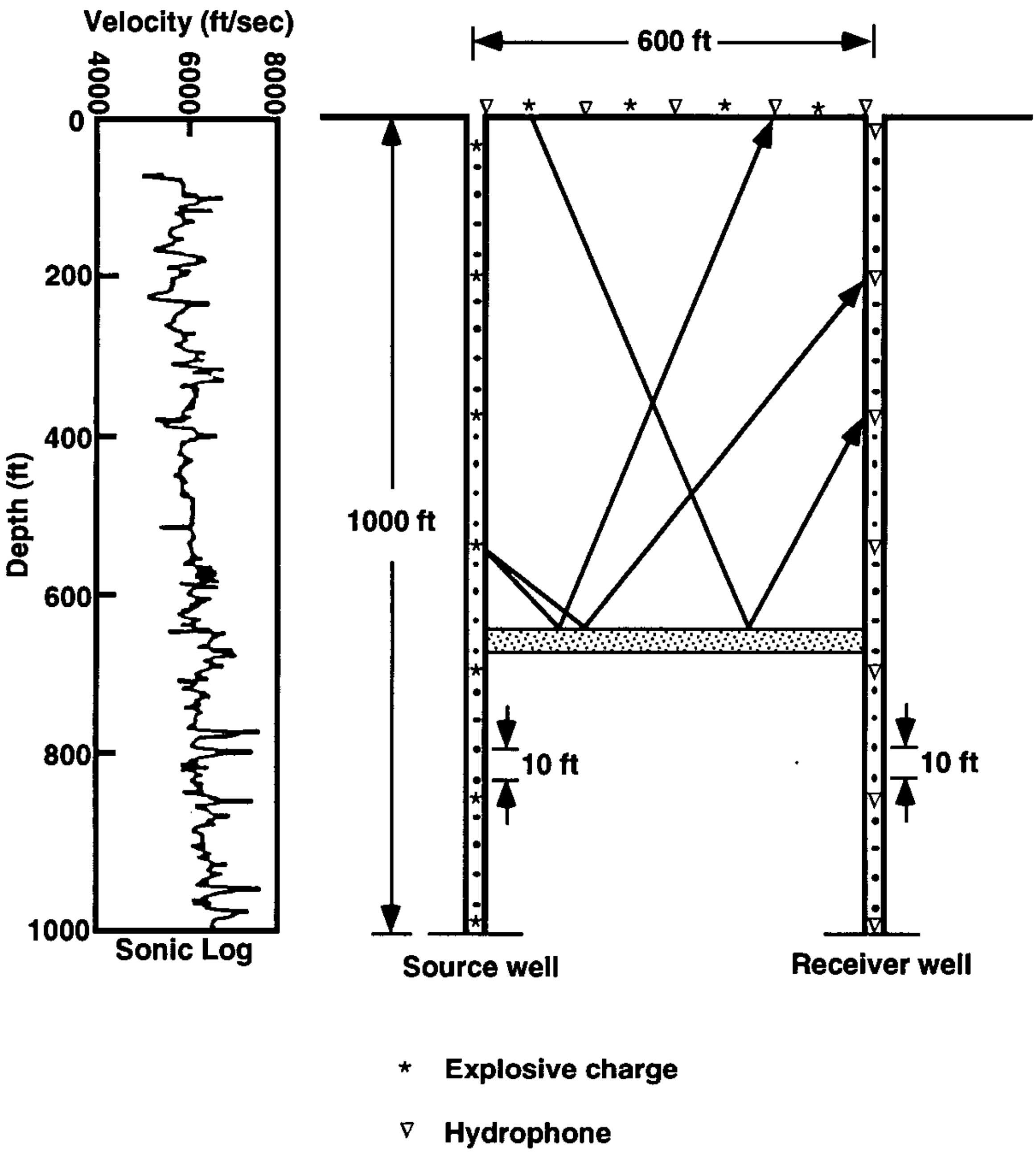

FIG. 1. Schematic diagram of the Friendswood combined seismic experiment and a sonic log. In this experiment, crosswell seismic data, VSP, and reversed VSP data were recorded. A surface seismic line across the two wells recorded CDP seismic data.

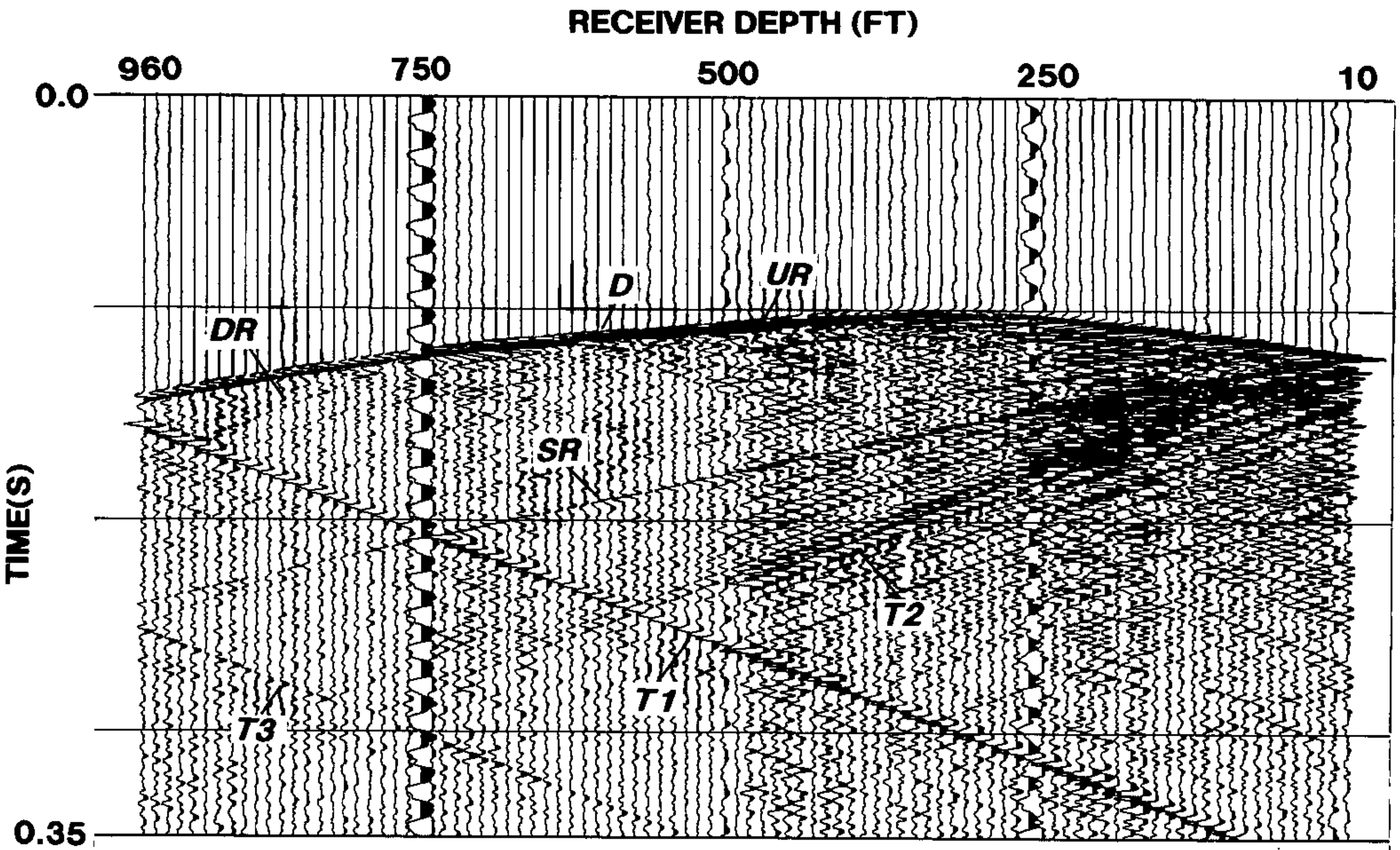

FIG. 2. Common source gather of the Friendswood crosswell seismic data. The source depth is 330 ft. Receivers are positioned between 10 ft and 960 ft, spaced at 10 ft. According to Chen et al. (1990), a number of events are identified and labeled. *D* - The direct P wave from the source well to the receiver well; *SR* - A P-wave radiated from the source well up to the surface and reflected into receivers in the receiver well;*DR* -A downgoing P-wave reflection generated from subsurface layers between the wells; *UR* - An upgoing P-wave reflection from layers between the wells; *T1* - A P-wave radiated from the source well to the bottom of the receiver well, converted into a tube wave, and traveled uphole; *T2* - A P-wave radiated from the source well to the top of the receiver well, converted into a tube wave, and traveled downhole; and, *T3* - Downgoing reflection *SR* converted into a tube wave at the bottom of the receiver well, and transmitted uphole.

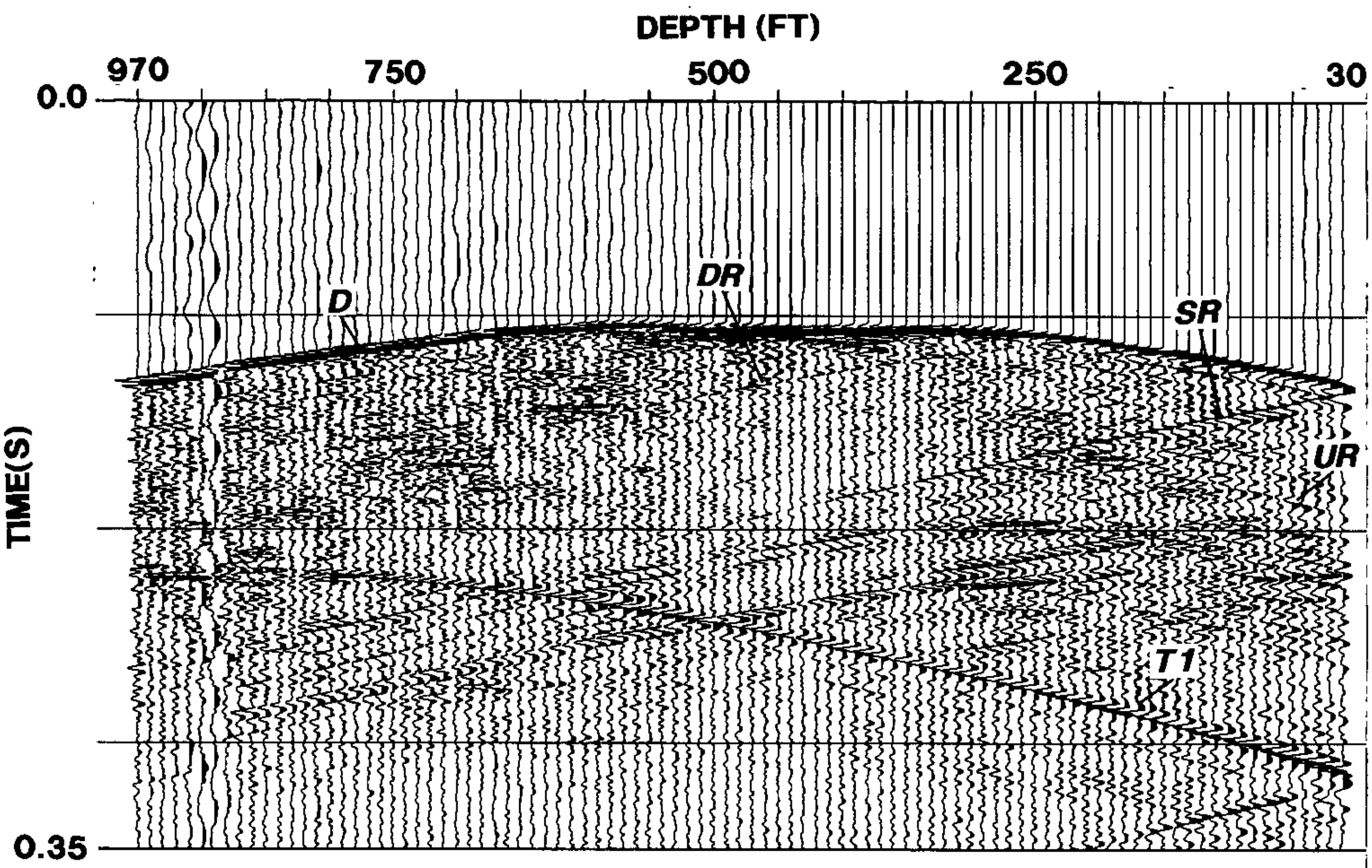

FIG. 3. Common receiver gather of the Friendswood crosswell seismic data. The receiver depth is 460 ft. Sources are shot in the source well between 30 ft and 1000 ft, spaced at 10 ft (The last three traces are not used here). According to Chen et al. (1990), a number of events are identified and labeled. *D* - The direct P wave from the source well to the receiver well; *SR* - A P-wave radiated from the source well up to the surface and reflected into receivers in the receiver well;*DR* -A down-going P-wave reflection generated from subsurface layers between the wells; *UR* - An upgoing P-wave reflection from layers between the wells;and *T1* - A P-wave radiated from the source well to the bottom of the receiver well, converted into a tube wave.

The crosswell seismic data have a more complicated wavefield in the common receiver gather (Figure 3). Although direct P wave, *D*, downgoing reflection from the surface, *SR*, downgoing reflections from layers, *DR*, and upgoing reflections, *UR*, are still identifiable in this gather, tube waves become more difficult to trace. These tube waves are not linear any more.

A spectral analysis for the shot gather in Figure 2 was performed and an average amplitude spectrum of 96 traces in a 500 ms window is shown in Figure 4. The frequency band in the spectrum is quite wide, and the central frequency is at about 250 Hz. Notice the high-energy 60 Hz noise in the spectrum. The distribution of relatively high energy in a frequency band from 20 Hz to 60 Hz may be due to low-frequency components of various tube waves and other noise. A useful bandwidth for the reflection signals may be located between 70 Hz and 650 Hz. In the processing discussed next, a frequency band of 70 - 620 Hz is used.

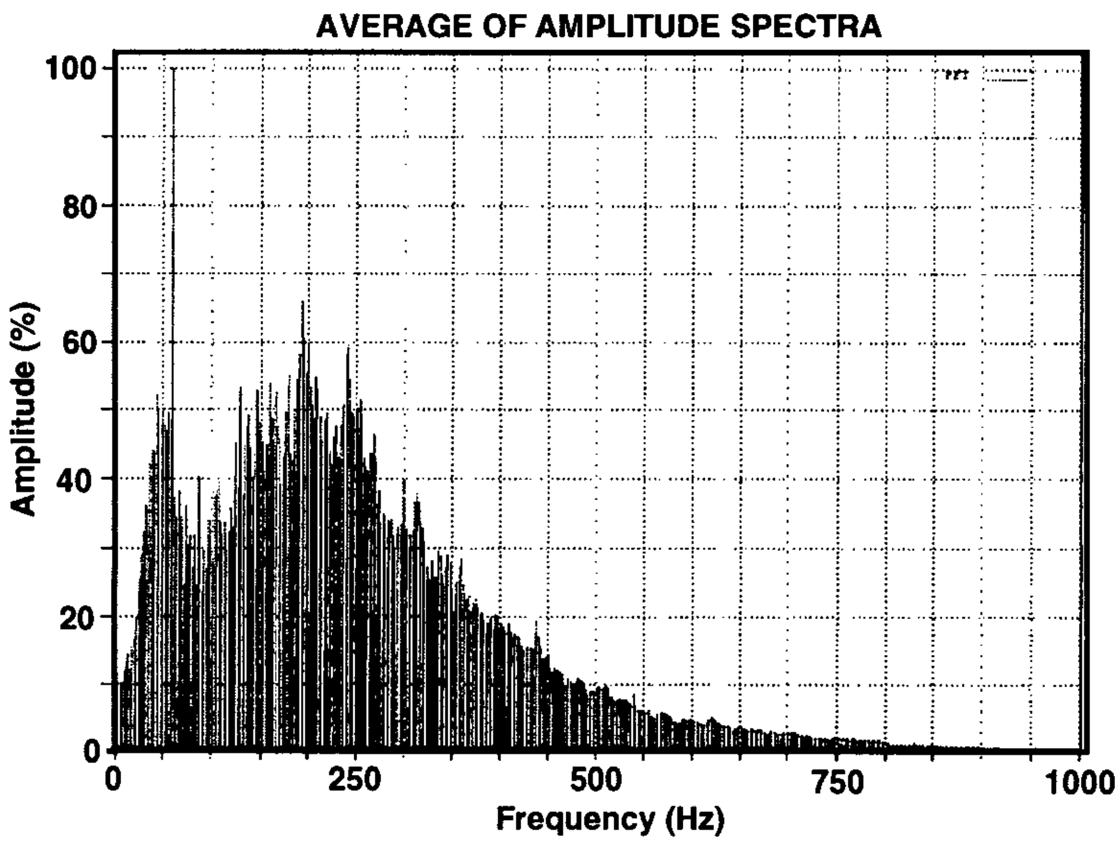

FIG. 4. Amplitude spectra for raw data of the shot gather in Figure 2. The spectra are calculated for 96 traces in a time window of 500 ms.

CROSSWELL DATA PROCESSING

The objectives of initial data processing are to extract reflection wavefields and to reduce noise in the data. The procedure of processing prior to reflection imaging consists of preprocessing, tube wave suppression, direct wave removal, and reflection wavefield separation. This procedure is similar to those of Stewart and Marchisio (1991) and Cai and Schuster (1993).

Preprocessing

Preprocessing is composed of geometry loading, trace editing, spectral analysis, bandpass filtering and trace balancing. Bad traces may be edited and energy bursts may be surgically muted. Spectral analysis of the data as in Figure 4 is useful to determine filter parameters. A bandpass filter of 70-620 Hz is applied to common source gathers in order to filter out low-frequency and high-frequency noise. Following the bandpass filter, a trace balancing is performed to equalize the different amplitude energy in traces.

Tube wave suppression

Tube waves are suppressed in common source gathers. As has been noticed before, the tube waves that are present in the data are linear in these gathers. In this study, we use a median filter to suppress the tube waves. Since the tube waves in common source gathers exhibit two opposite apparent dips, the median filter is run twice (Hardage, 1983; Stewart, 1985). Short filter operators suppress tube waves more effectively than longer ones, but they may distort the reflection data more severely. A longer operator preserves reflections, but leaves some tube waves unfiltered out. So different operators were tested. The operator length of 9 traces is used. After median filtering, a bandpass filter (70-620 Hz) is applied to eliminate high-frequency glitch noise caused by median filtering (Stewart, 1985).

Figure 5 shows the same common source gather as in Figure 2, after tube waves are removed. A 500 ms AGC was applied for display. Both downgoing and upgoing reflected waves now become clearer.

Direct wave removal

Li and Stewart (1993) show using synthetic data that applying a velocity filter to common source gathers to remove direct waves may possibly damage the reflection wavefield, as the reflections can have similar moveout to that of the direct waves. They suggest using common interval gathers to achieve direct wave removal. We follow this strategy here.

A common interval gather is a group of traces with the vertical distance (interval) between source and receiver constant. Ideally, in a constant velocity medium,

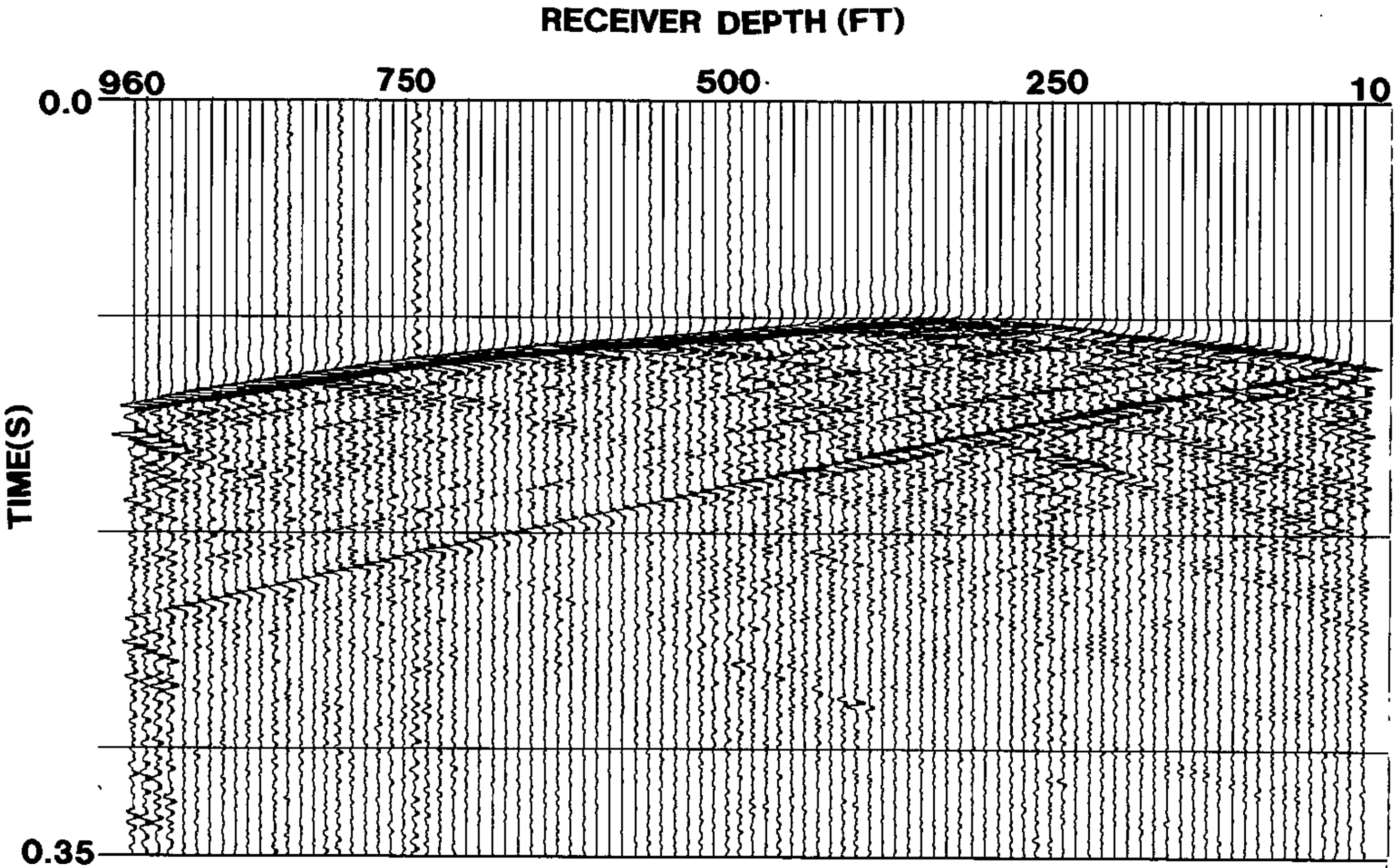

FIG. 5. Common source gather of the Friendswood crosswell seismic data, after tube waves are removed by median filtering. The filter operator length is 9 traces. An AGC of 500 ms was used for display.

the direct wave should be flat, as they travel the same amount of distance from the source to the receiver. However, the real earth is rarely constant-velocity. Instead, a velocity variation with depth is expected. In some cases, anisotropy of the velocity may also be present. This introduces some complexity into methods of removing direct arrivals. Figure 6 shows a common interval gather of the Friendswood crosswell data. It has 77 traces, each having a constant interval of 200 ft between the source and receiver. A few events such as a direct wave, a downgoing reflection, and an upgoing reflections, are marked. Form the figure, it can be seen that, although the direct wave is close to be flat and does not have dramatic change in its shape, there is some difference in traveltime, indicating that the velocity varies with depth.

Note that, in the gather, a relationship of sharp termination of both upgoing and downgoing reflections against the direct wave above them is clear. This sharp termination relationship is an important characteristic of the CI gather that makes possible removing effectively direct waves via velocity filters without damage to the reflected wavefield. Also note that as in common source gathers, upgoing and downgoing reflections have opposite dips.

A median filter of 9 traces is used to remove the direct wave in the CI gather. Before median filtering, the direct wave is aligned by applying a bulk shift. Figure 7 displays the result after applying the median filter. The direct wave has been removed nicely, and the reflections keep a good shape at the positions of their contact with the direct wave. The data delineated by the rectangles in Figures 6 and 7 is shown in Figure 8.

Reflection wavefield separation

Wavefields for upgoing and downgoing reflections are separated in the f-k domain. Upgoing and downgoing reflections occupy different quadrants in the f-k domain. The area to pass reflections is selected for either upgoing or downgoing waves. The separated upgoing and downgoing reflections in a common source gather are respectively displayed in Figures 9 and 10. Despite some smearing, the f-k filter performed well. After reflection wavefield separation, we see that the Friendswood crosswell seismic data contain good reflections. These reflections are generated from layers at various depths, as indicated by the shot gathers in Figures 9 and 10.

CROSSWELL REFLECTION IMAGING

For imaging, we use the common reflection point stacking method, developed by Li and Stewart (1993). The imaging part involves a few steps: zero-interval gather velocity analysis, CRP gathering, moveout corrections, and CRP stacking.

Velocity analysis

The zero-interval CI gather provides a data domain for velocity analysis. For a constant-velocity case, a zero-interval gather is a true CRP gather, since all reflections contained in this gather are from the same subsurface location. The horizontal moveout existing in each trace of the gather is constant, while vertical moveout caused by the vertical distance difference between traces is a function of velocity. Therefore, if the correct velocity is used, the same reflection events should be flat after the moveout corrections.

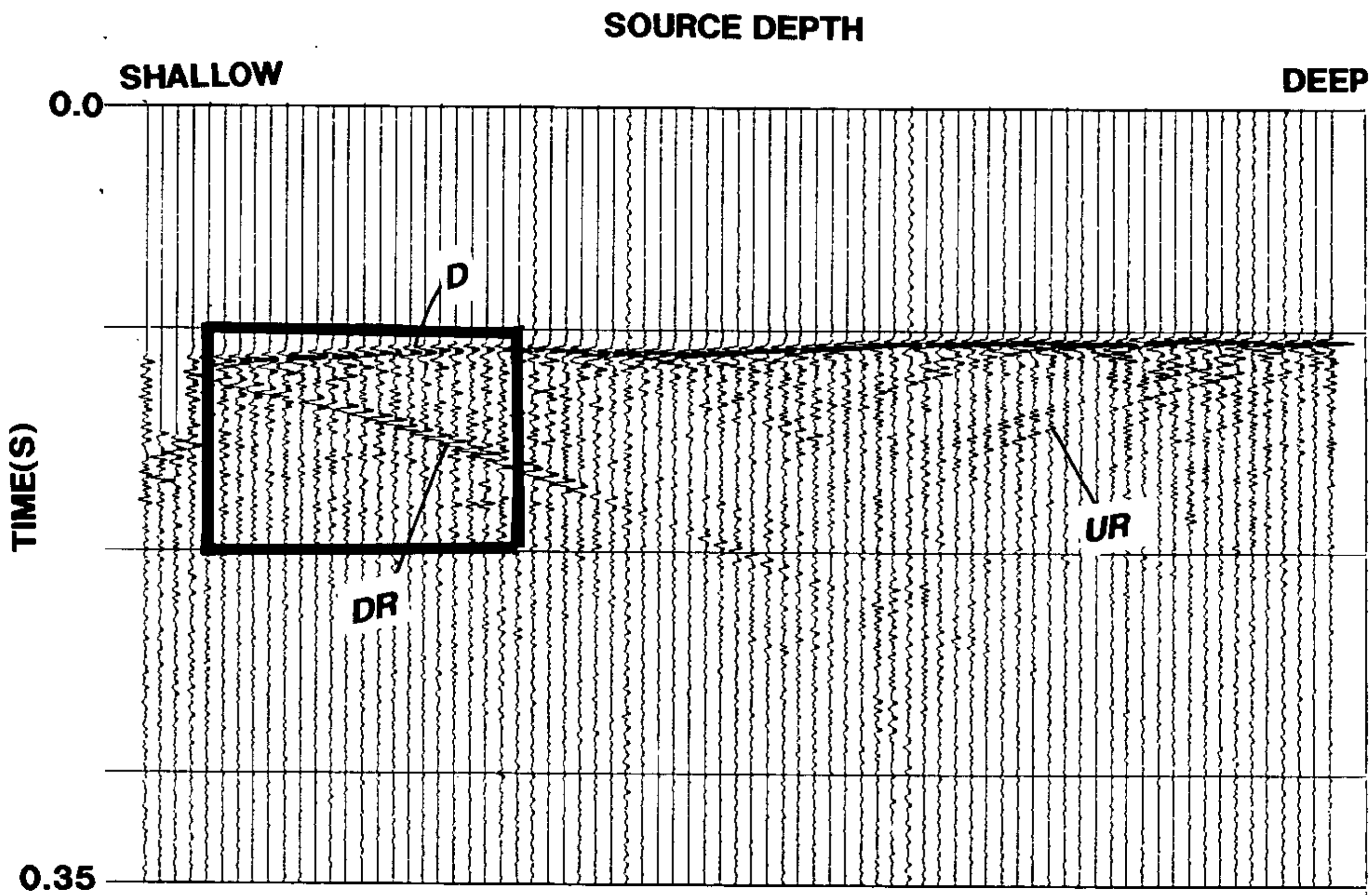

FIG. 6. Common interval gather before removing the direct wave *D*. The other events marked are downgoing reflections, DR, and upgoing reflections, UR. The interval between the source and the receiver for this gather is 200 ft. An AGC of 500 ms was used for display.

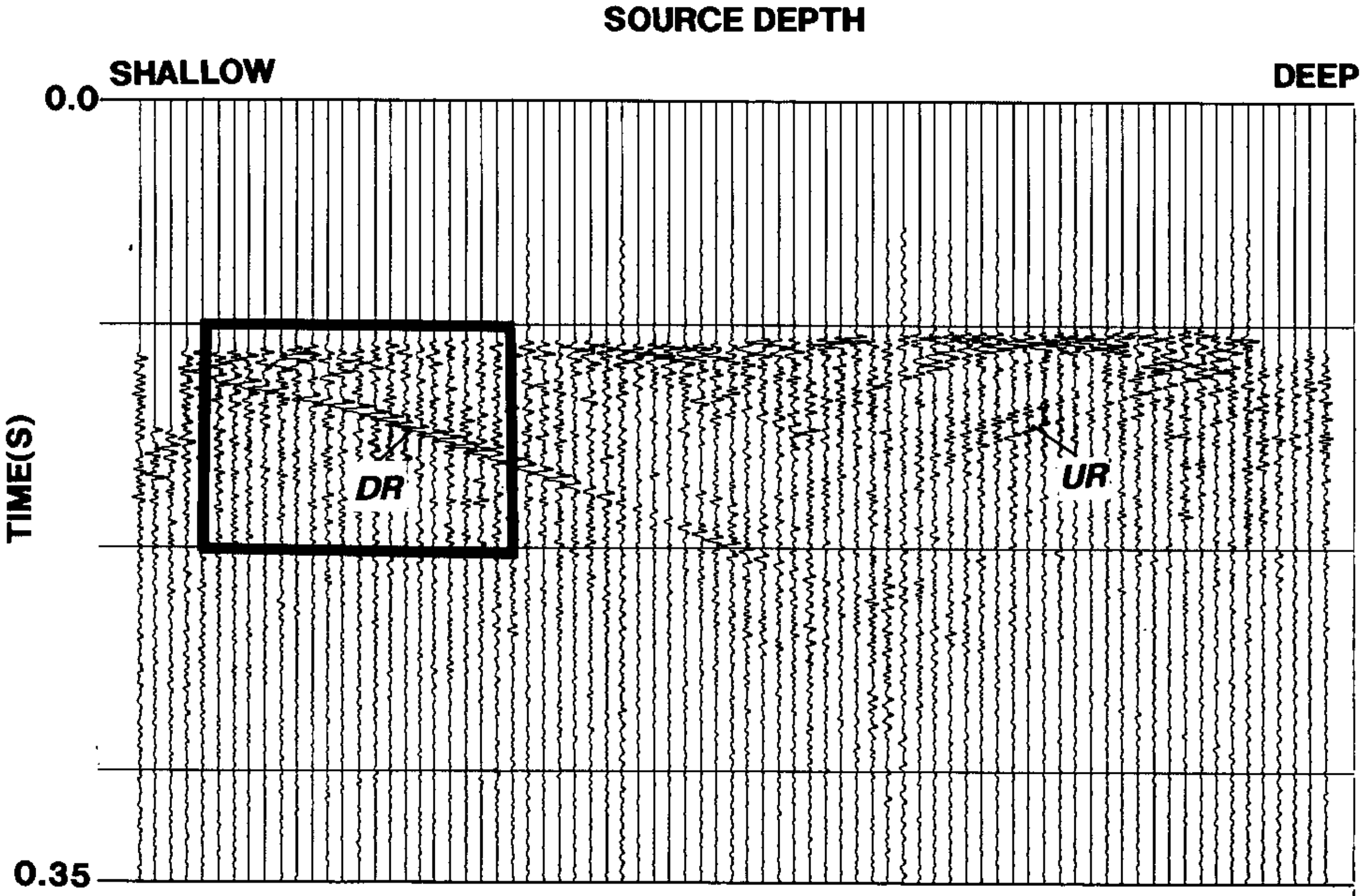

FIG. 7. Common interval gather after removing the direct wave. The events marked are downgoing reflections, DR, and upgoing reflections, UR. The interval between the source and the receiver for this gather is 200 ft. An AGC of 500 ms was used for display.

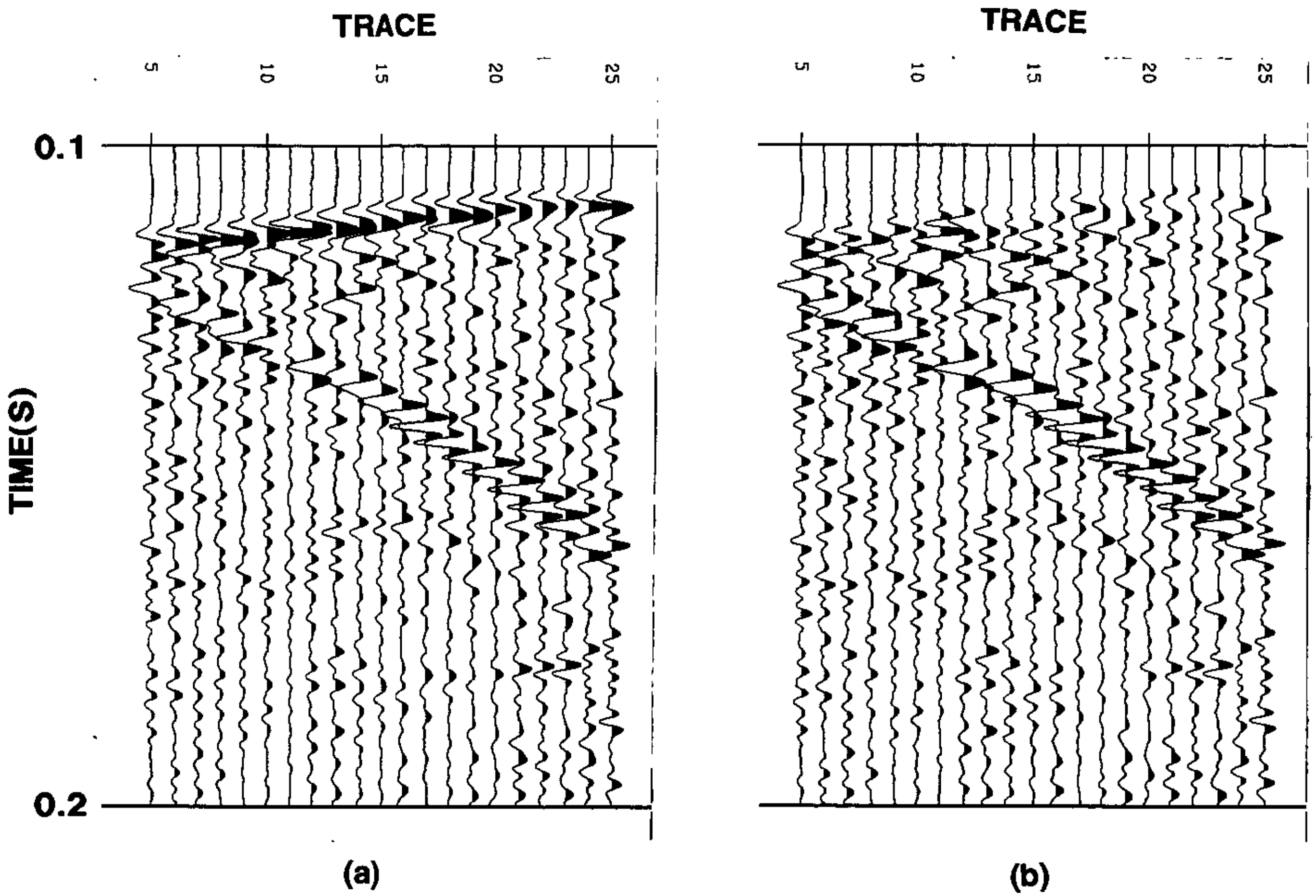

FIG. 8. Expanded portion of the common interval gather marked with a rectangular frame in Figures 6 and 7. (a) is before removing the direct wave and (b) is after removing the direct wave. An AGC of 500 ms was used for display.

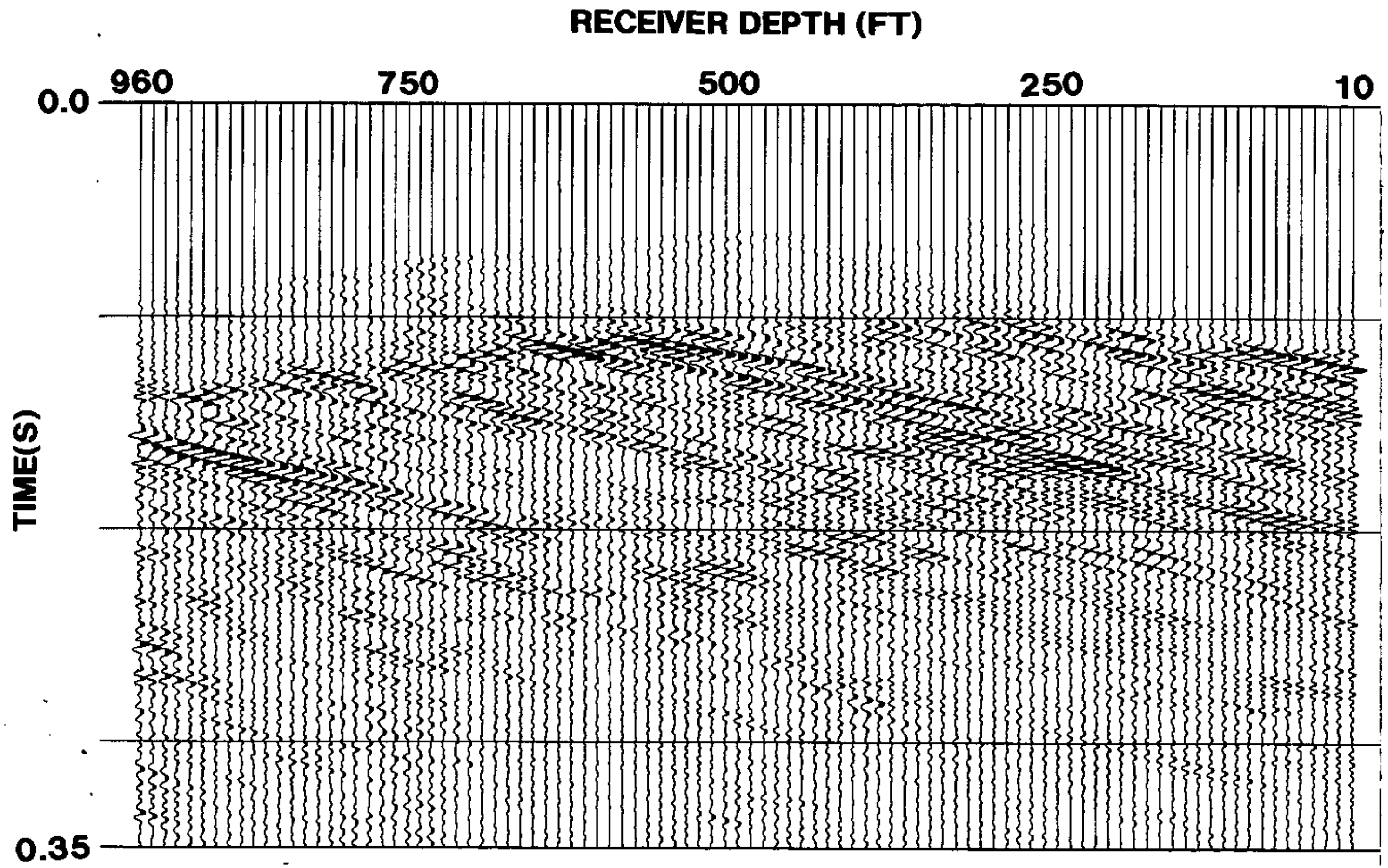

FIG. 9. Upgoing reflections in the common source gather with source depth of 330 ft. An AGC of 500 ms was used for display.

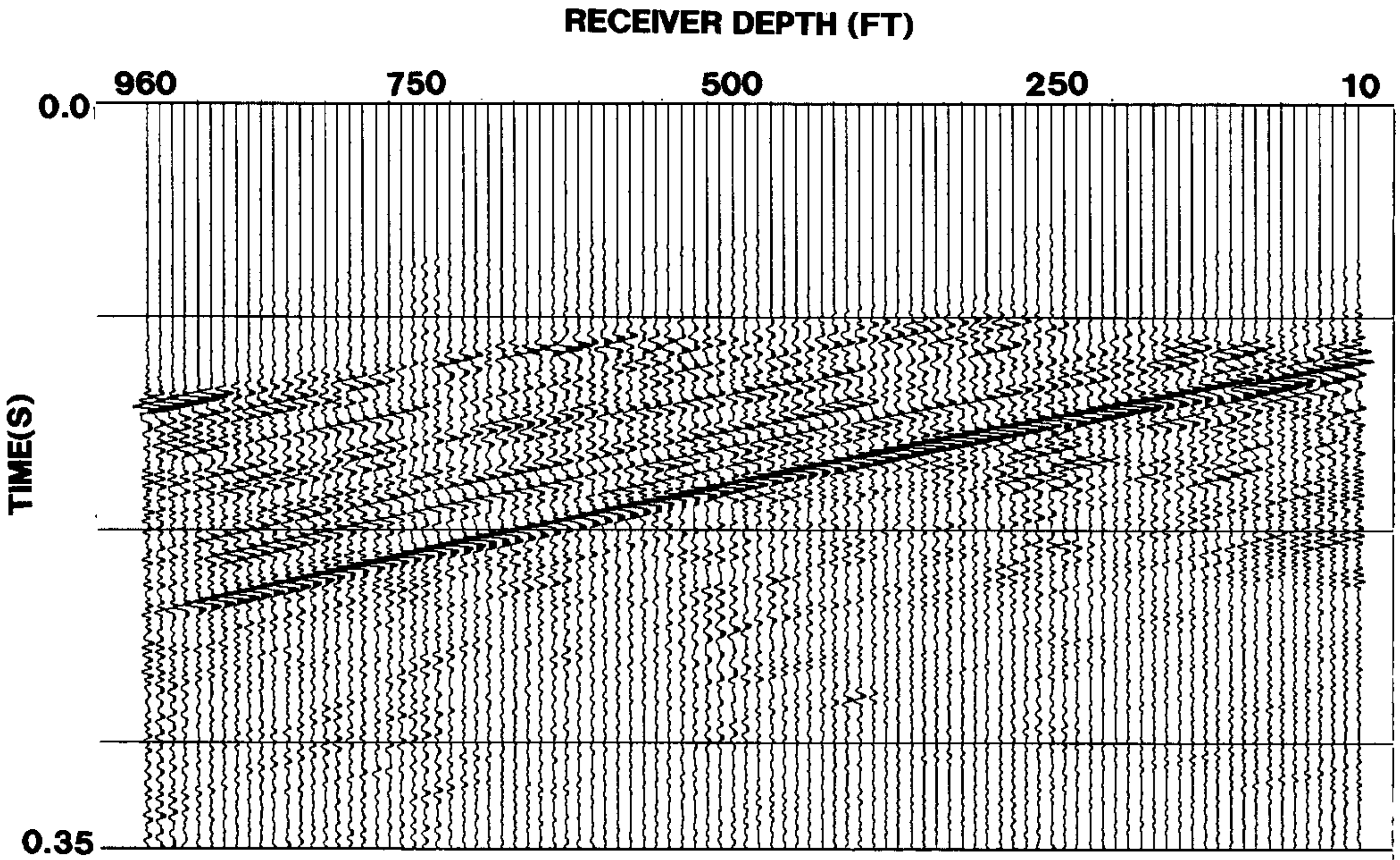

FIG. 10. Downgoing reflections in the common source gather with source depth of 330 ft. An AGC of 500 ms was used for display.

Figure 11 shows a zero-interval gather of upgoing reflection data. There are a number of reflection events that can be seen. Each of these events exhibits a hyperbolic shape and has a different moveout. Correcting for the moveout with different velocities should give rise to different effects on these events. We use velocity scanning method in this gather to find the best velocity. This velocity analysis method has been discussed by Li and Stewart (1992b; 1993). For the CRP stacking method, we focus on only one reflection event to which the best velocity applies. In this case, we are focusing on the event at 0.25 second on the shallowest trace on the left side of the section, indicated by an arrow. A velocity range from 4000 ft/sec to 8000 ft/sec with an interval of 50 ft/sec is scanned. A few of them are displayed in Figure 12.

The zero-interval gather is affected differently by the scanned velocities, as indicated in Figure 12. The velocity of 5100 ft/sec gives the best moveout correction of the event indicated by the arrow (Figure 12b). Velocities below 5100 ft/sec cause an under-correction to happen to the same event (Figure 12a). On the other hand, however, velocities higher than 5100 ft/sec make the event over-corrected (Figure 12c and d). So for the event of interest, 5100 ft/sec is the best velocity for moveout corrections. Actually, we are able to extend the velocity to a variable velocity, as the zero-interval gather velocity analysis is sensitive to depths. For example, for events above the zone of interest but below 0.2 second, a higher velocity of 5800 ft/sec would be the best velocity. For very deep reflections, a velocity higher than 7400 ft/sec would be required. In short, this velocity analysis method provides a useful tool to quickly extract velocity information from crosswell reflection seismic data.

CRP gathering

A CRP gather is shown in Figure 13 (a). When gathering, a reflector depth of 650 ft was used. The reflection point bin is 3 ft. The fold in CRP gathers varies. For this gather, the fold is 14. The maximum fold achieved is 74. This gather contains upgoing reflections. Although hyperbolic shapes of these reflections are difficult to observe, they do have moveouts.

Moveout corrections

The moveout corrections include two parts: one for horizontal moveout, and the other for vertical moveout. The horizontal moveout correction is to remove the moveout caused by the horizontal distance between two boreholes, which is constant for each trace, while the vertical moveout correction is to eliminate the moveout due to the difference in vertical distance (form the source to the receiver) for each trace. The mathematical basis of these corrections can be found in the paper by Li and Stewart (1992b).

To correct for these two types of moveouts, a velocity of 5100 ft /sec is used, which is from the above velocity analysis. Figures 13 (b) and (c) show the same CRP gather as in Figure 13(a), after HMO and VMO corrections. After the moveout corrections, the events are flattened. Note that the traveltime now is in two-way *vertical* time.

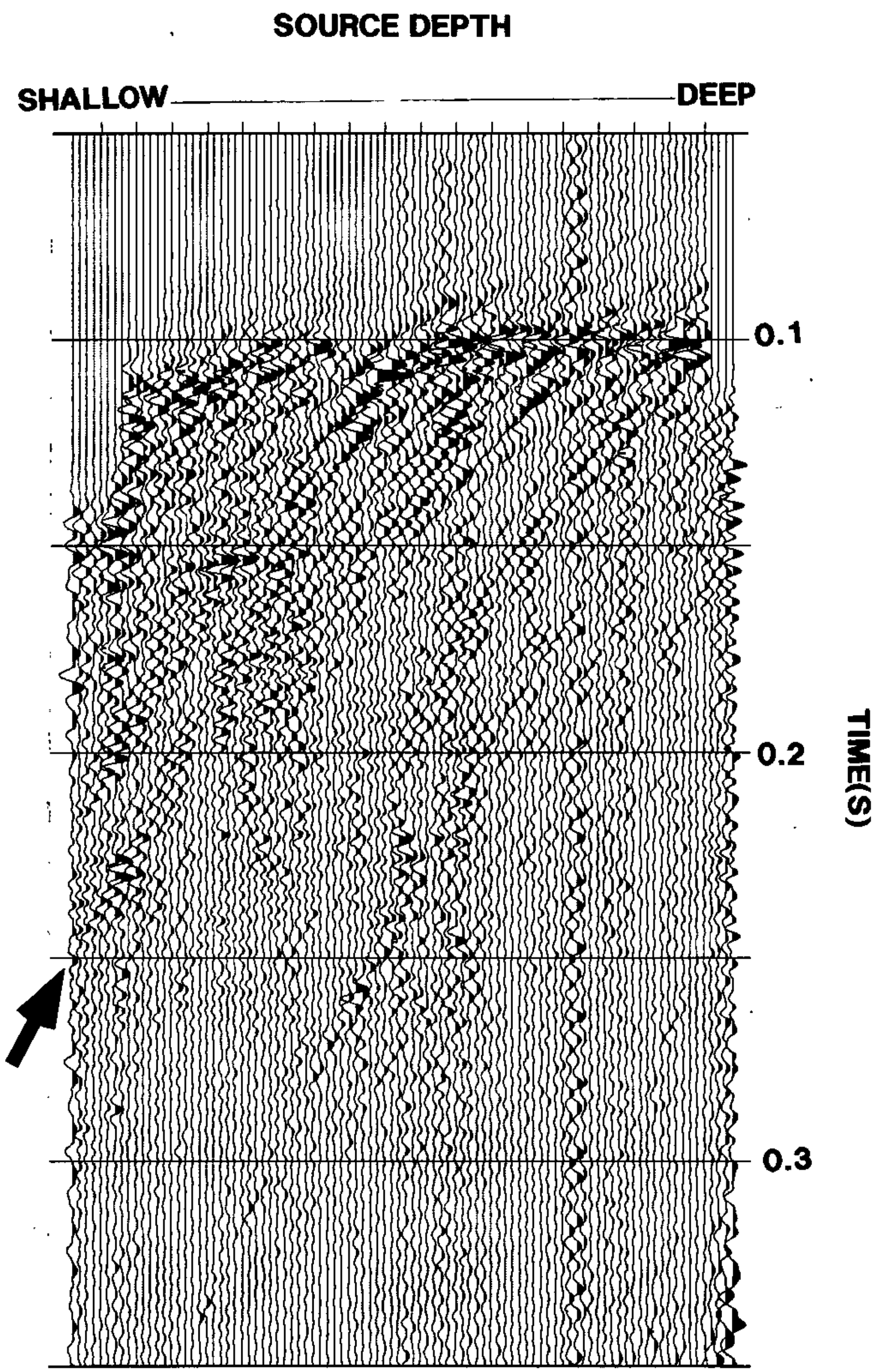

FIG. 11. Upgoing reflections in a zero-interval gather. This gather will be used for velocity analysis.

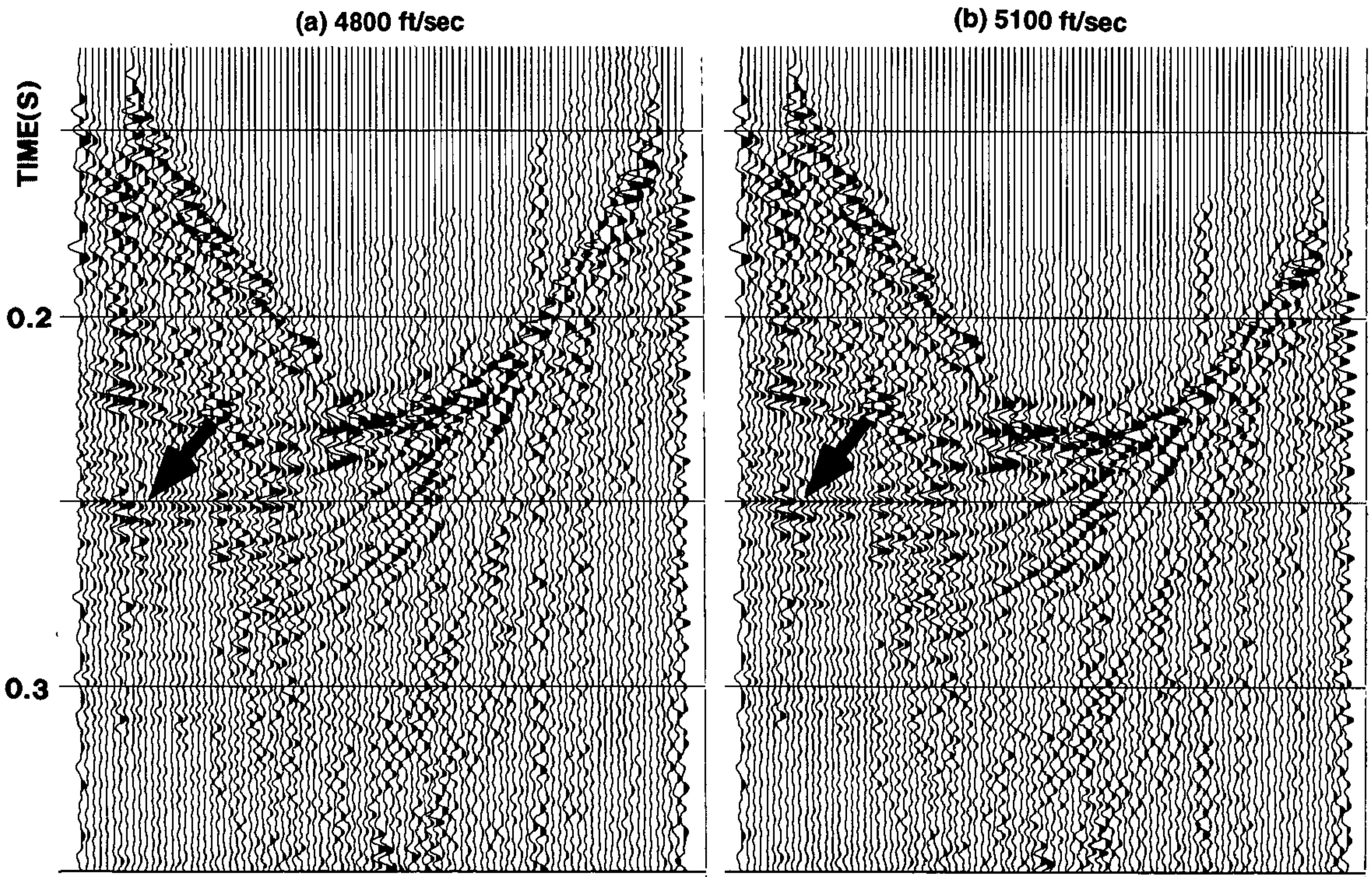

FIG. 12. Results of velcity scanning in a zero-interval gather. (a) 4800 ft/sec; (b) 5100 ft/sec. (This figure is continued on next page).

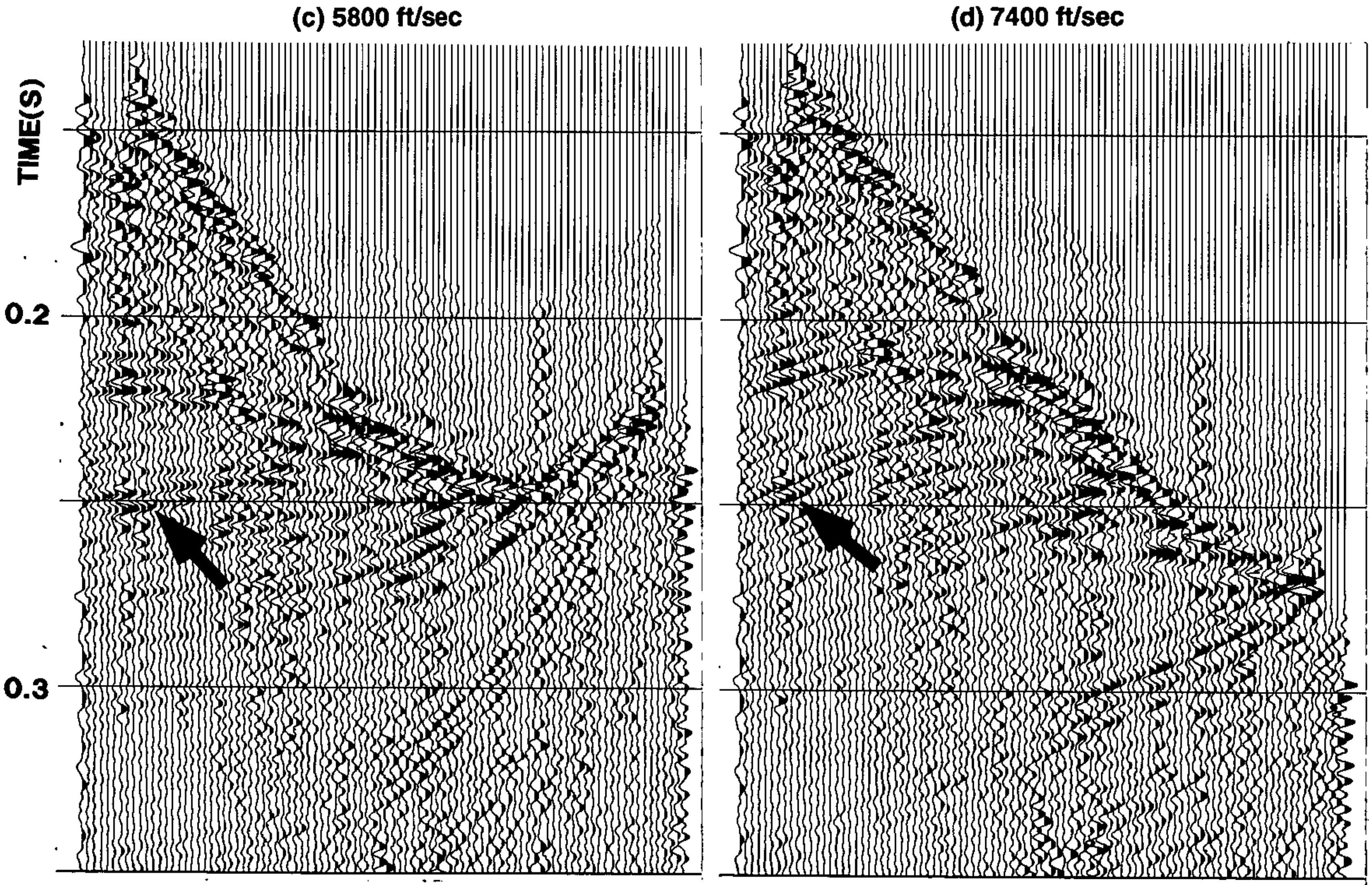

FIG. 12. (Continued from last page). Velcocity scanning results: (c) 5800 ft/sec; (d) 7400 ft/sec.

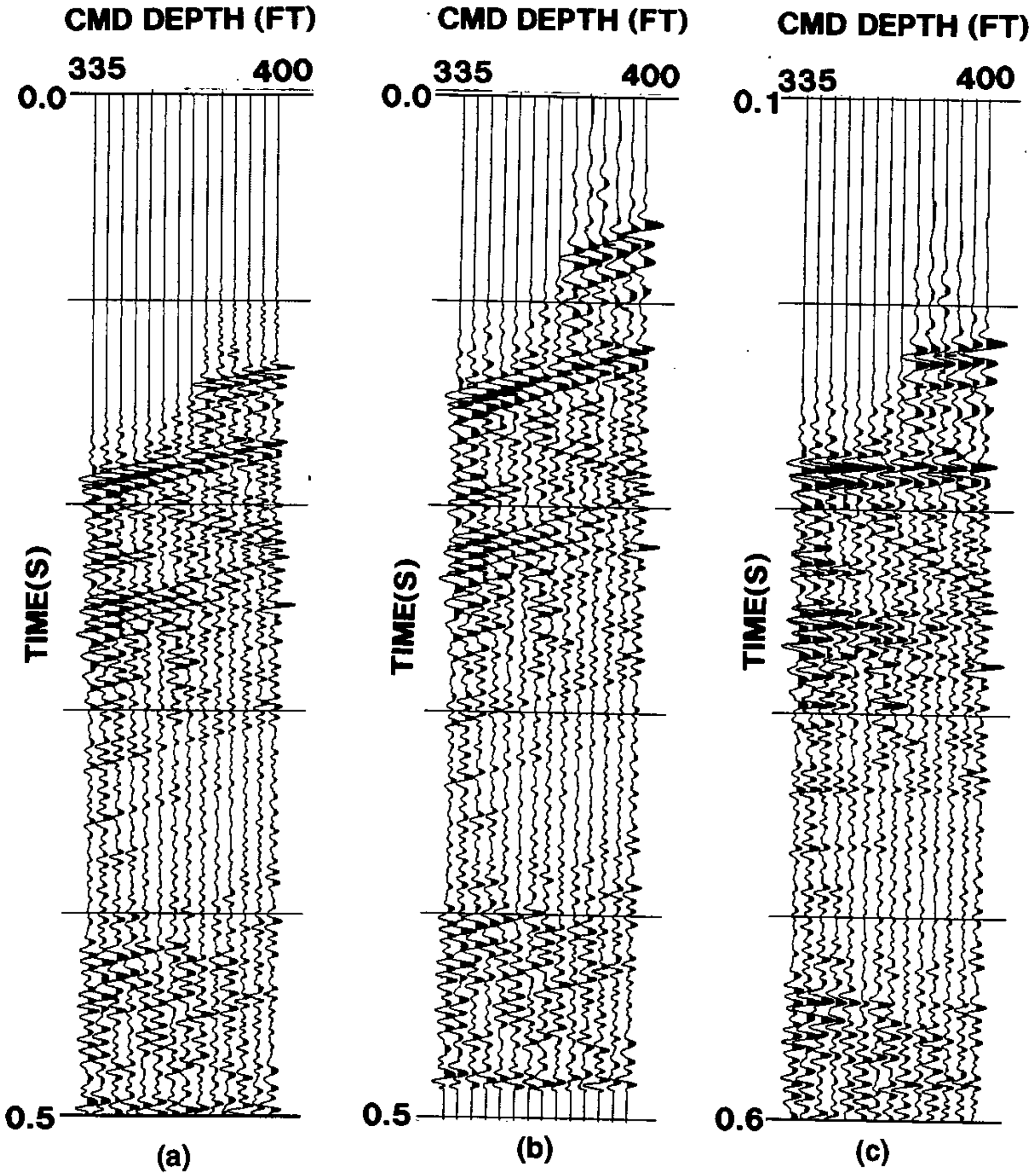

FIG. 13. (a) Upgoing reflections in a CRP gather; (b) after HMO correction; and (c) after VMO correction. The CRP bin is 3 ft, and the reflector depth used is 650 ft. The horizontal axis is mid-depths.

CRP stacking

A stacked time section for upgoing reflections is given in Figure 14. A 50 ms AGC was applied. This section contains rich reflection information which represents the subsurface reflectors. Note that, in the shallow part of the section, there is a strong dipping event, which is stretch caused by moveout corrections. This stretch needs to be muted. A section with muting applied is shown in Figure 15. After muting, the shallow reflections become clearer and more consistent. An analysis of the results obtained from crosswell reflection imaging of the Friendswood data will be given in the next section.

RESULTS

The upgoing reflection stacked section shown in Figure 15 contains many reflections. Shallow reflection events are stronger than deeper reflections, possibly because of the difference in S/N ratio. A small fault in the middle of the section between times 0.25 second and 0.3 second can be clearly identified. The interwell zone is nicely imaged by the upgoing crosswell reflections.

A stacked section combining upgoing and downgoing reflections is displayed in Figure 16, and compared with the RVSP and surface seismic stacked sections published by Chen et al. (1990). It is obvious that the crosswell section provides much higher resolution than the RVSP and CDP stacked sections. Major reflection events contained in the RVSP and surface sections are imaged in the crosswell section. Moreover, the crosswell section has resolved thin layers which the RVSP and surface stacks have not. Like the RVSP section, the crosswell stacked section has some structures, which do not show in the surface stacked section, where reflections are almost flat. The crosswell section provides a number of very good shallow reflections.

A time-to-depth conversion using a 5100 ft/sec velocity is conducted to generate a depth section, which is shown in Figure 17. A portion of the section above the depth of 1000 ft, as indicated by the rectangular frame, is enlarged and displayed in Figure 18. A depth CDP stacked section between 0 ft and 1000 ft is also plotted for comparison. As can be seen, the crosswell data provide much better resolution either in shallow or deep section.

Notice that a dipping event appearing in the RVSP section also appears in the crosswell section between times 0.375 second and 0.45 second (Figure 16). The same event shows in the depth section (Figure 17) below the depth of 950 ft. Clearly, this event occurs near the bottom of the source well. As explained by Chen et al. (1990), this artifact may be caused by the conversion of tube waves to P waves at the bottom of the source hole. Other factors causing this artifact are being investigated.

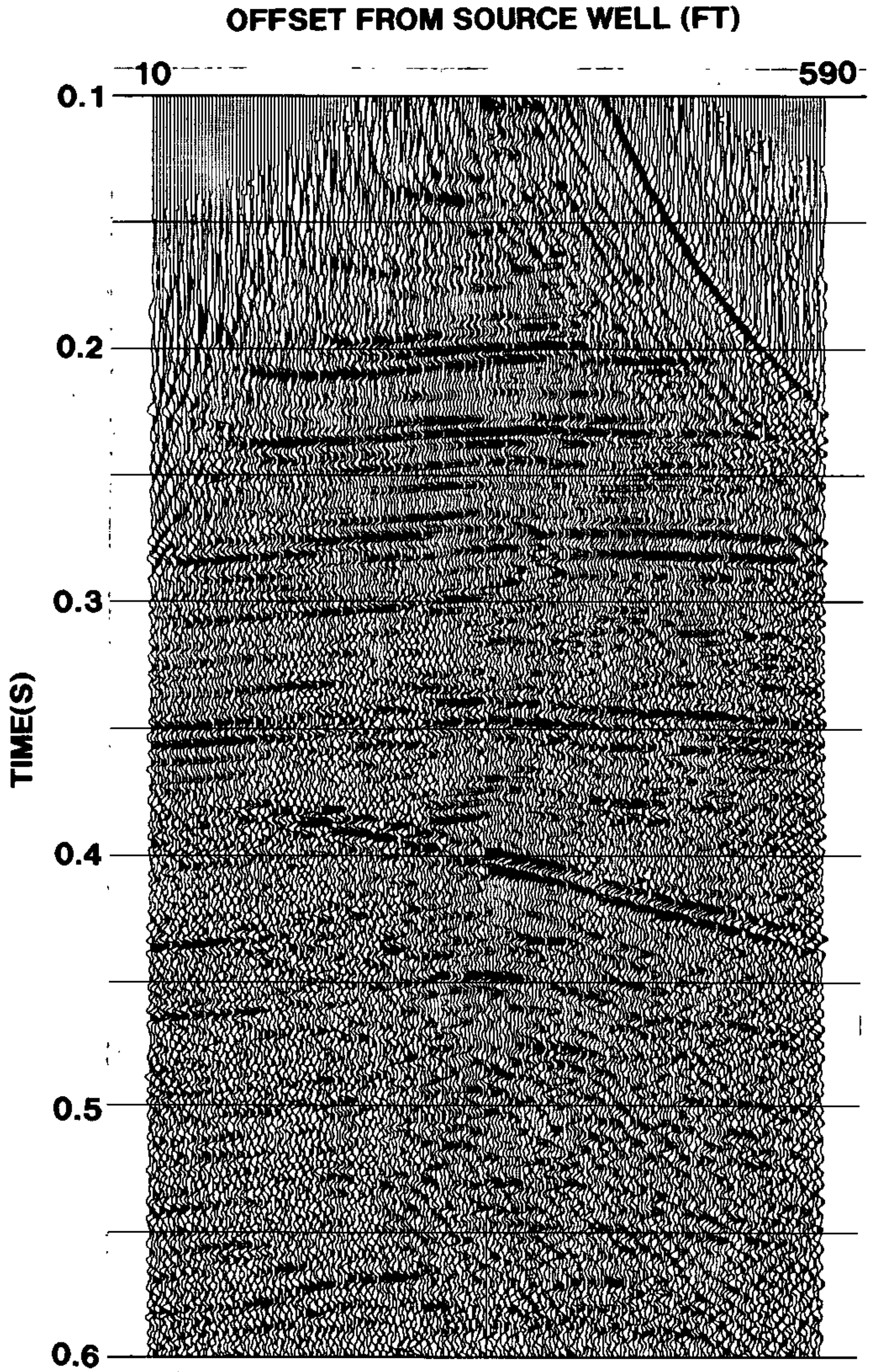

FIG. 14. Stacked section of upgoing reflection data. The horizontal axis is offset distance from the source well, while the vertical is in two-way vertical time. An AGC of 50 ms was applied.

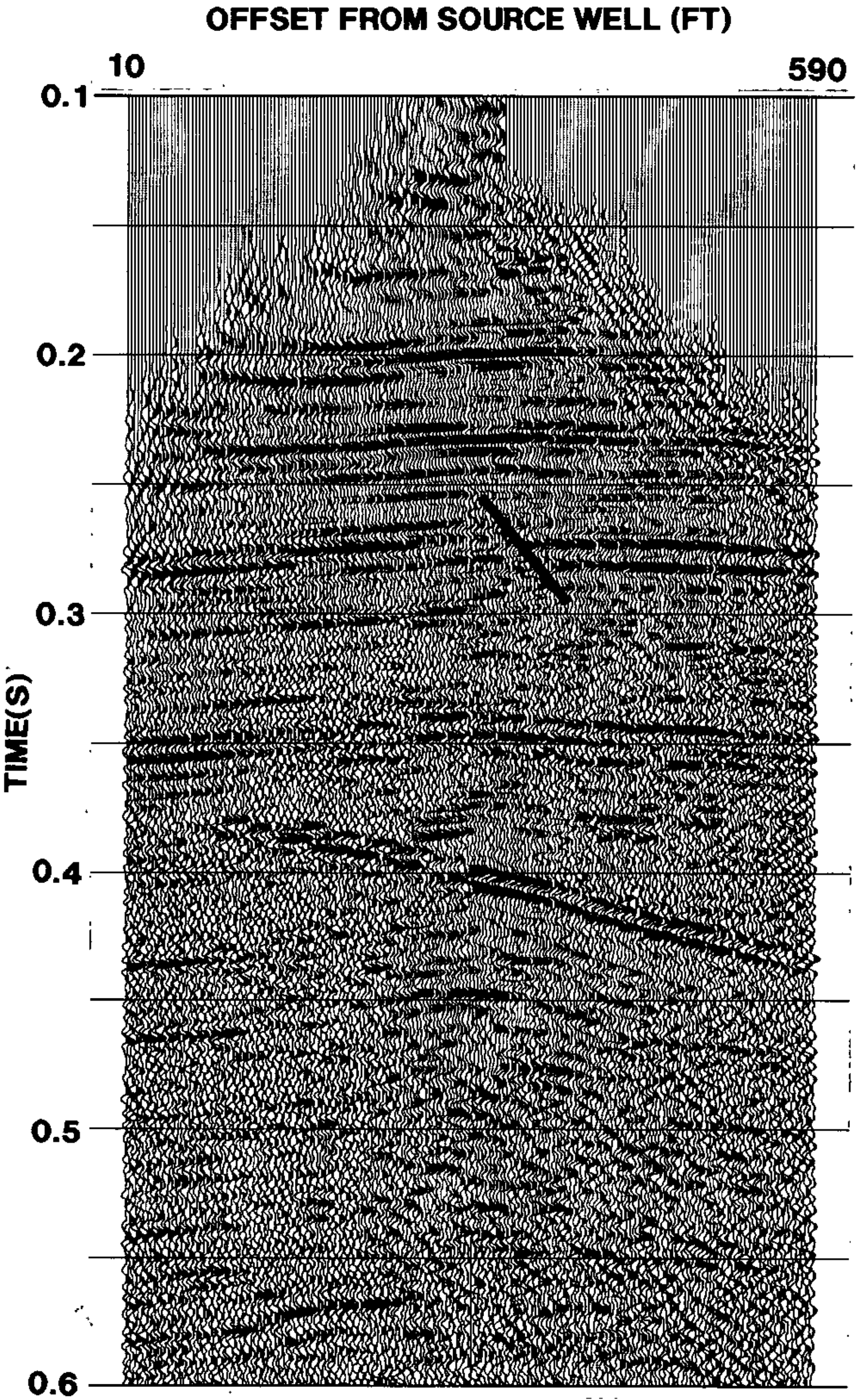

FIG. 15. Stacked section of upgoing reflection data, with shallow moveout stretches muted.

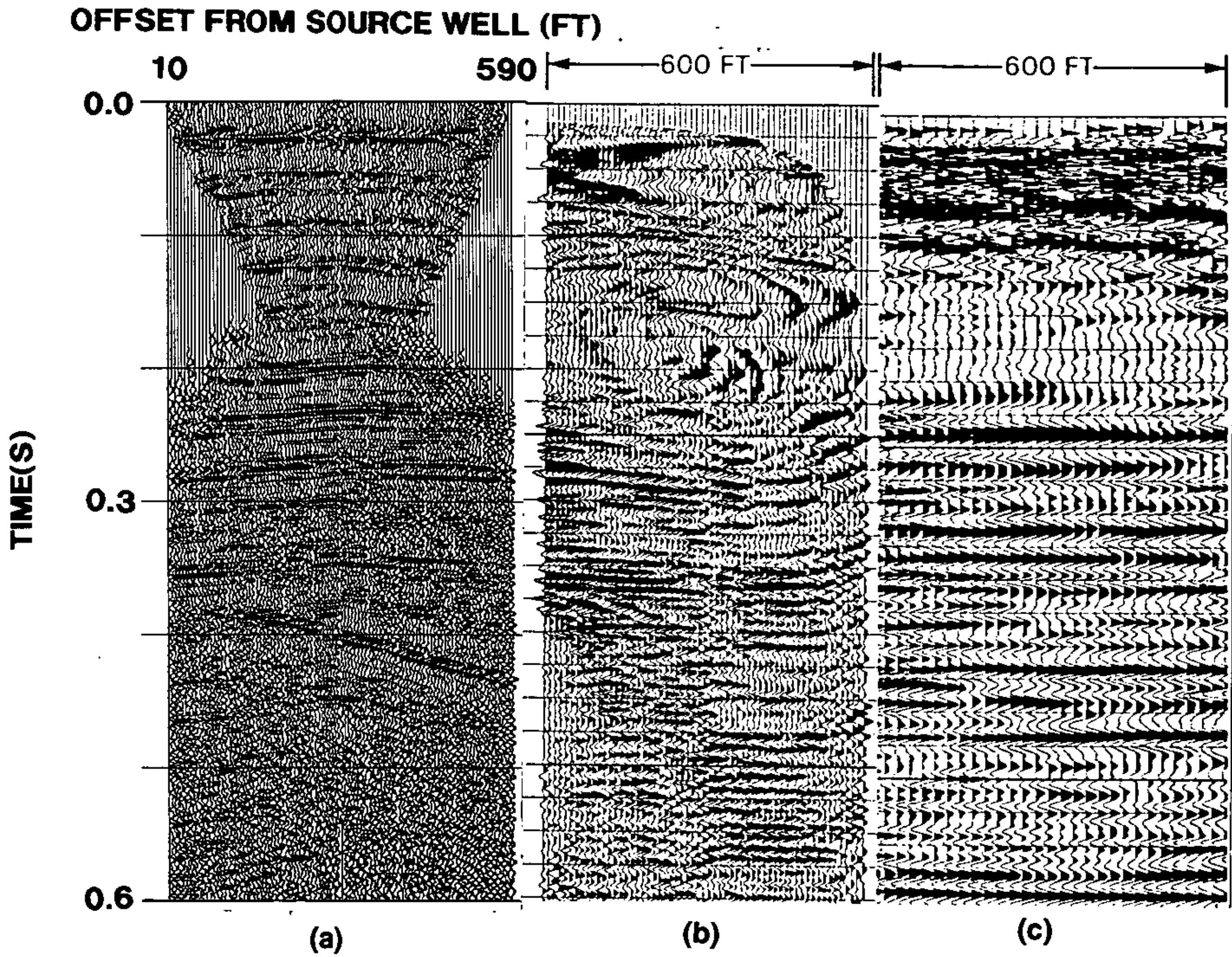

FIG. 16. Comparison of (a) crosswell, (b) RVSP, and (c) surface seismic stacked sections.

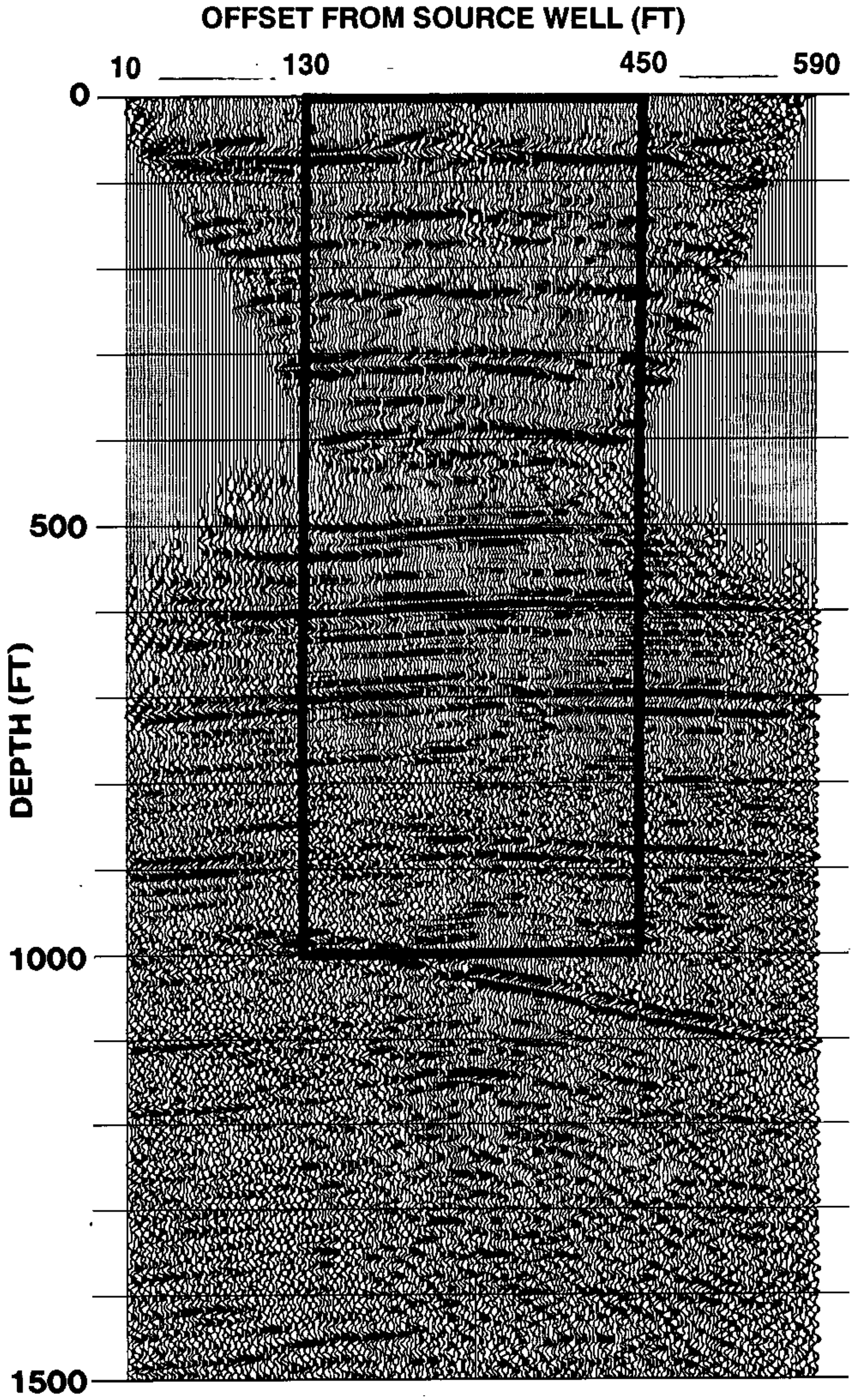

FIG. 17. Crosswell stacked depth section.

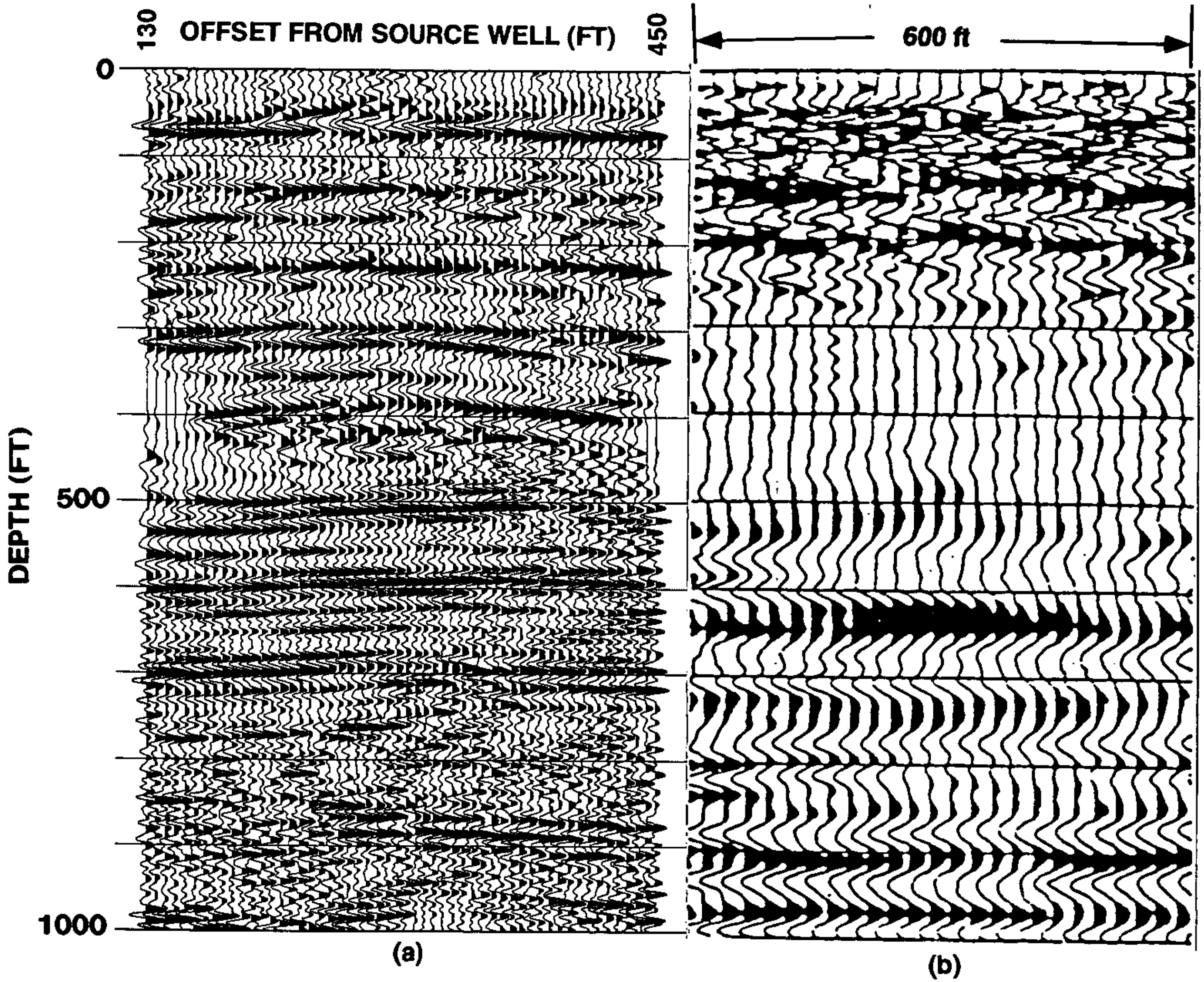

FIG. 18. Comparison of (a) crosswell and (b) surface seismic stacked depth sections.

LIMITATIONS

A few limitations of the reflection imaging procedure based on the common reflection point stacking method exist. So far, we are assuming a constant-velocity background. This may have caused some artifacts in the stacked section. The zero-interval gather velocity analysis method provides a simple tool to get velocity information, and a velocity function of depth can also be derived from this velocity analysis. However, a reference time pointing to a known reflection event that has to be provided to the velocity analysis limits its universality. Imaging provided by the method discussed here is dependent on reflector depths. As can be seen in Figure 17, a limited coverage of subsurface reflectors exists in the shallow part of the section, due to this depth dependence. To overcome these limitations, further research work needs to be conducted.

CONCLUSIONS

We have processed a field crosswell seismic data set collected near Friendswood, Texas. From reflection imaging, we have generated stacked sections in time and depth. A complete processing procedure including a common reflection point stacking method has been tested. The sections contain high-resolution reflection information that is not available in reversed VSP or surface seismic data acquired at the same experimental site. The crosswell reflection imaging of the Friendswood data provides a vertical seismic resolution on the order of 10 ft. This case study has shown that the imaging method we presented in this paper provides a novel and effective way to process a large crosswell seismic data set.

ACKNOWLEDGMENTS

This work is supported by the Consortium for Research in Elastic Wave Exploration Seismology (CREWES) Project at The University of Calgary. The authors would like to thank Exxon Production Research Company for donating their Friendswood crosswell seismic data and Imperial Oil Resources Ltd. for donating their Cold Lake crosswell seismic data to the CREWES Project. The authors are also very grateful for the continuous support of the sponsors of the CREWES Project.

REFERENCES

Abdalla, A. A., Stewart, R. R., and Henley, D. C., 1990, Traveltime inversion and reflection processing of cross-hole seismic data: presented at the 60th Ann. Internat. Mtg., Soc. Expl. Geophys.

Bregman, N. D., Bailey, R. C., and Chapman, C. H., 1989, Crosshole seismic tomography: Geophysics, **54**, 200-215.

Cai, W., and Schuster, G. T., Processing Friendswood cross-well seismic data for reflection imaging: Presented at the 63th SEG Ann. Intern. Mtg., Expanded Abstracts, Washington, D. C.

Chen, S. T., and Eriksen, E. A., 1989, Experimental studies on downhole seismic sources: Presented at the 59th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 62-64.

Chen, S. T., Zimmerman, L. J., and Tugnait, J. K., 1990, Subsurface imaging using reversed vertical seismic profiling and crosshole tomographic methods: Geophysics, **55**, 1478-1487.

Hardage, B. A., 1983, Vertical Seismic Profiling, Part A: Principles, Geophysical Press, Amsterdam.

Hu, L., McMechan, G. A. , and Harris, J. M., 1988, Acoustic prestack migration of cross-hole data: Geophysics, **53**, 1015-1023.

Khalil, A. A., Stewart, R. R., and Henley, D. C., 1993, Full-waveform processing and interpretation of kilohertz cross-well seismic data: Geophysics, **58**, 1248-1256.

Lazaratos, S. K., Rector, J. W., Harris, J. M., and Van Schaack, M., 1991, High-resolution imaging with cross-well reflection data: Presented at the 61st SEG Intern. Ann. Mtg., Houston.

Lazaratos, S. K., Rector, J. W., Harris, J. M., and Van Schaack, M., 1992, High resolution crosswell imaging of a west Texas carbonate reservoir: part 4: reflection imaging: Presented at the 62nd SEG Intern. Ann. Mtg., New Orleans.

Li, G., and Stewart, R. R., 1992 a, Imaging the subsurface using crosswell seismic reflection data: A synthetic study: Presented at the 1992 CSEG Convention, Calgary, Alberta.

Li, G., and Stewart, R. R., 1992 b, Crosswell reflection imaging: CREWES Project Research Report, Vol. 4, The University of Calgary.

Li, G., and Stewart, R. R., 1993, Reflection imaging for synthetic crosswell seismic data: CREWES Project Research Report, Vol. 5, University of Calgary.

Lines, L. R., and LaFehr, E. D., 1989, Tomographic modeling of a cross-borehole data set: Geophysics, **54**, 1249-1257.

Lines, L. R., and Tan, H., 1990, Cross-borehole analysis of velocity and density: presented at the 60th Ann. Internat. Mtg., Soc. Expl. Geophys.

Peterson, J. E., Paulsson, B. N. P., and McEvilly, T. V., 1985, Applications of algebraic reconstruction techniques to crosshole seismic data: Geophysics, **50**, 1566-1580.

Qin F., and Schuster, G. T., 1993, Constrained Kirchhoff migration of cross-well seismic data: Presented at the 63th SEG Ann. Intern. Mtg., Expanded Abstracts, Washington, D. C.

Stewart, R. R., 1985, Median filtering: review and a new F/K analogue design: J. Can. Soc. Expl. Geophys., **21**, 54-63.

Stewart., R. R., Marchisio, G., and Li, G., 1991, Crosswell seismic imaging: Fundamentals and a physical modeling study: Presented at the 1991 CSEG Convention, Calgary, Alberta

Stewart, R.R., and Marchisio, G., 1991, Cross-well seismic imaging using reflections: Presented at the 61st SEG Intern. Ann. Mtg., Houston.

Zhou, C., and Qin F., 1993, Real data crosshole reverse-time migration: Presented at the 63th SEG Ann. Intern. Mtg., Expanded Abstracts, Washington, D. C.