PAPER G

ANALYSIS AND ATTENUATION OF TUBE WAVES: IN CROSSWELL SEISMIC SURVEYS

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ABSTRACT

Seismic data collected in a crosswell survey often contain strong tube waves that have parts of their travel paths along wells where the sources and receivers are positioned. Tube waves can be excited by the source and propagate along the source well, and then radiate as body waves propagating to the receiver well to be recorded. This is called the source well tube wave. Tube waves can also be excited by passing body waves and propagate along the receiver well, and are recorded. This is called the receiver well tube wave. By the principle of reciprocity, source and receiver well tube waves have similar characteristics and can be analyzed by the same method. Owing to the slow propagation velocity of the tube waves, they are usually spatially aliased in practical records in either common shot gathers (CSG) or common receiver gathers (CRG). While receiver well tube waves are aliased in CSG, they are well sampled and predictable in CRG, and vice versa for source well tube waves. Tube waves that have travel paths in both the source and receiver wells are also predictable. I predict and attenuate source well tube waves in CSG, and predict and attenuate receiver well tube waves in CRG.

INTRODUCTION

Seismic data recorded in a crosswell survey often contain strong tube waves. These tube waves can be stronger than any body waves being recorded. Most explorationists view the tube waves as undesirable coherent noise because they are superimposed on reflection signals and prevent optimum imaging of stratigraphic and structural conditions in the subsurface. Thus, attenuation of tube waves has been the topic of extensive current research. One method to attenuate tube waves is to apply special equipment in field data recording (Pham et al., 1993). Even though tube waves are attenuated in field data recording, tube waves are still recorded, and then one has to resort to numerical processing techniques. Cai and Schuster (1993) aligned tube waves along their traveltime picks in common shot gathers and common receiver gathers and applied a median filter to predict tube waves. Finally, the predicted tube waves are subtracted from the field data. In this method, tube wave traveltimes must be picked precisely and upgoing and downgoing tube waves are processed separately. A serious problem with this method is to deal with the data within a polygonal shape after the tube waves are aligned. These are the factors that limit the effectiveness of this method.

In this paper, I first analyze the generation and propagation of tube waves in a crosswell experiment. Then I predict and attenuate source well tube waves in CSG, and predict and attenuate receiver well tube waves in CRG. My method is shown to be effective in attenuating tube waves in a field dataset.

ANALYSIS OF CROSSWELL TUBE WAVES

In crosswell seismic surveying using a downhole source, the source excites body waves, and it also excites a tube wave propagating along the borehole fluid called the source well tube wave. When the tube wave passes through an impedance contrast in the source well, it excites body waves that propagate to the receiver well to be recorded. Common impedance contrasts in a borehole are radius changes, junction points between casing and noncasing, perforation, and the top and bottom of the borehole. And according to numerical calculations and field data, body waves excited by tube waves at these impedance contrasts can often be stronger than the body waves directly excited by the source (Balch and Lee, 1984).

When body waves from the source well impinge the receiver well, they are recorded by the receivers. At the same time, strong tube waves are excited at impedance contrasts to propagate along the receiver well. The excitation and propagation of various waves in a crosswell experiment is schematically illustrated in Figure 1 for the recording of a common shot gather. Figure 2 is a synthetic CSG obtained by ray tracing with the experimental geometry of Figure 1(a).

Figure 3 schematically illustrates the wave propagation and the traveltime trajectories within a common receiver gather. By the principle of reciprocity, a common receiver gather can be considered as a common shot gather. And this can be realized by reversing the wave propagation directions (the directions the arrows point) in Figure 3(a). Thus, source and receiver well tube waves have similar characteristics and can be analyzed by the same method. Figure 4 is a synthetic CSG with the experimental geometry of Figure 3(a).

Owing to the slow propagation velocity of the tube waves, the receiver (source) well tube waves have steep slopes in the common shot (receiver) gathers. In discretely sampled field data, these steep events are usually spatially aliased. However, in the other domain, they are well sampled and predictable. For the source (receiver) well tube waves in a CSG (CRG), they are well sampled and predictable. For those tube waves that have propagation paths in both the source and receiver wells, even though they are aliased, they are also predictable.

In neighboring CSG's, the source well tube waves 2 and 22 in Figure 1 and Figure 2 vary by a time delay, the time that the source well tube wave propagates between neighboring source positions. Likewise, in neighboring CRGs, the receiver well tube waves 12 and 22 in Figure 3 and Figure 4 vary by a time delay, the time that the receiver well tube wave propagates between neighboring receiver positions.

ATTENUATION OF CROSSWELL TUBE WAVES

When the source is at a location that excites source well tube waves, the source direct arrival and source well tube waves are time coincident. For a source located away from the location that excites source well tube waves, there is a time delay that the tube wave takes to propagate from the source location to the source well tube wave excitation point. Since one can predict the time trajectory of source well tube waves in CSG's, one can use the relationship between neighboring CSG's to estimate the arrivals of source well tube waves. When the estimated source well tube waves are subtracted from the original CSG's data, source well tube waves are then attenuated.

A CSG data can be modeled as

$$D_i = S_i + T(t - t_0) \qquad (1)$$

where i is the index of the CSG, D_i are the whole CSG data, T is source well tube wave (events 2 and 22 in Figure 1 and Figure 2), t is recording time, t_0 is the first break time trajectory by this analysis, S_i is the portion of the data other than T. A neighboring CSG can be modeled as

$$D_j = S_j + T(t - t_0 + \delta t) \qquad (2)$$

where T is the same as in equation (1) except a time shift δt. Cross-correlation D_i with D_j around t_0 and picking the maximum correlation value can determine the time shift δt. Cross-correlation can be carried out for the whole CSG, or for individual traces.When the source well is straight and vertical, the tube wave time delay δt is trivial to predict geometrically, but when the well deviates or curves,one has to resort to a cross-correlation procedure to estimate it.

Then neighboring CSG's are shifted to place the source well tube waves in phase and are stacked to estimate the source well tube waves.

$$\hat{T} = \frac{1}{2n+1} \sum_{i=-n}^{n} D_i(t - \delta t) \qquad (3)$$

where n is the number of chosen CSG's on each side of the designated CSG. In the following field data example, I choose n to be 5 so that the events other than the tube waves to be estimated are attenuated by an order of magnitude in the stacking. The estimated source well tube wave $\hat{T}$ is then subtracted from the CSG data.

In practice, source well tube waves are excited at an identifiable finite number of points of impedance contrasts. Source well tube waves excited at these points are each estimated and attenuated. Finally, the data are sorted into CRG's, and estimation and attenuation of receiver well tube waves (events 12 and 22 in Figure 3 and Figure 4) are carried out by the same method as outlined above, invoking the principle of reciprocity.

EXAMPLES

I apply the above method to a field crosswell dataset, which has 201 CSG's and 203 CRG's. Figure 5 is an unprocessed CSG, Figure 6 an unprocessed CRG (Depth 0 in the following Figures refers to the top of the survey, instead of the Earth surface). The borehole source excites both compressional (P-) and shear (S-) waves, as does the source well tube wave. In this dataset, both the source and receiver well tube waves are much stronger than the body waves. Figure 7 is the estimated source well tube wave on the CSG data in Figure 5. Figure 8 is the result after subtracting the source well tube wave in Figure 7 from Figure 5. After all the CSG's are processed, the data are sorted into CRG's.

Figure 9 is the new CRG of the CRG in Figure 6. Figure 10 is the estimated receiver tube wave on the CRG data in Figure 9. Figure 11 is the result after subtracting the receiver well tube wave in Figure 10 from Figure 9. After all the CRG's have been processed, Figure 12 is the new CSG of the CSG in Figure 8. Comparing data in Figure 5 and 6 to the processed data in Figure 11 and 12, it is obvious that after attenuation of crosswell tube waves, the direct arrival and reflection of body waves stand out clearly.

CONCLUSIONS

The linear time delay relationship of tube wave excited body waves in neighboring data gathers has been used to estimate and attenuate tube waves. I predict and attenuate source well tube waves in common shot gathers, and then predict and attenuate receiver well tube waves in common receiver gathers. Application of the method has shown that it is effective in attenuating tube waves in a crosswell seismic experiment. After attenuation of tube waves, body waves stand out clear, otherwise difficult to identify.

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Cai, W., and Schuster, G. T., 1993,Processing Friendswood cross-well seismic data for reflection imaging: 63rd Ann. Internat. Mig., Soc. Expl. Geophys., Expanded Abstracts,92-94.

Pham, L. D., Krohn, C. E., Murray, T. J., and Chen, S. T., 1993, A tube wave suppression devices for cross-well application: 63rd Ann. Internat. Mig., Soc. Expl. Geophys., Expanded Abstracts,17-20.

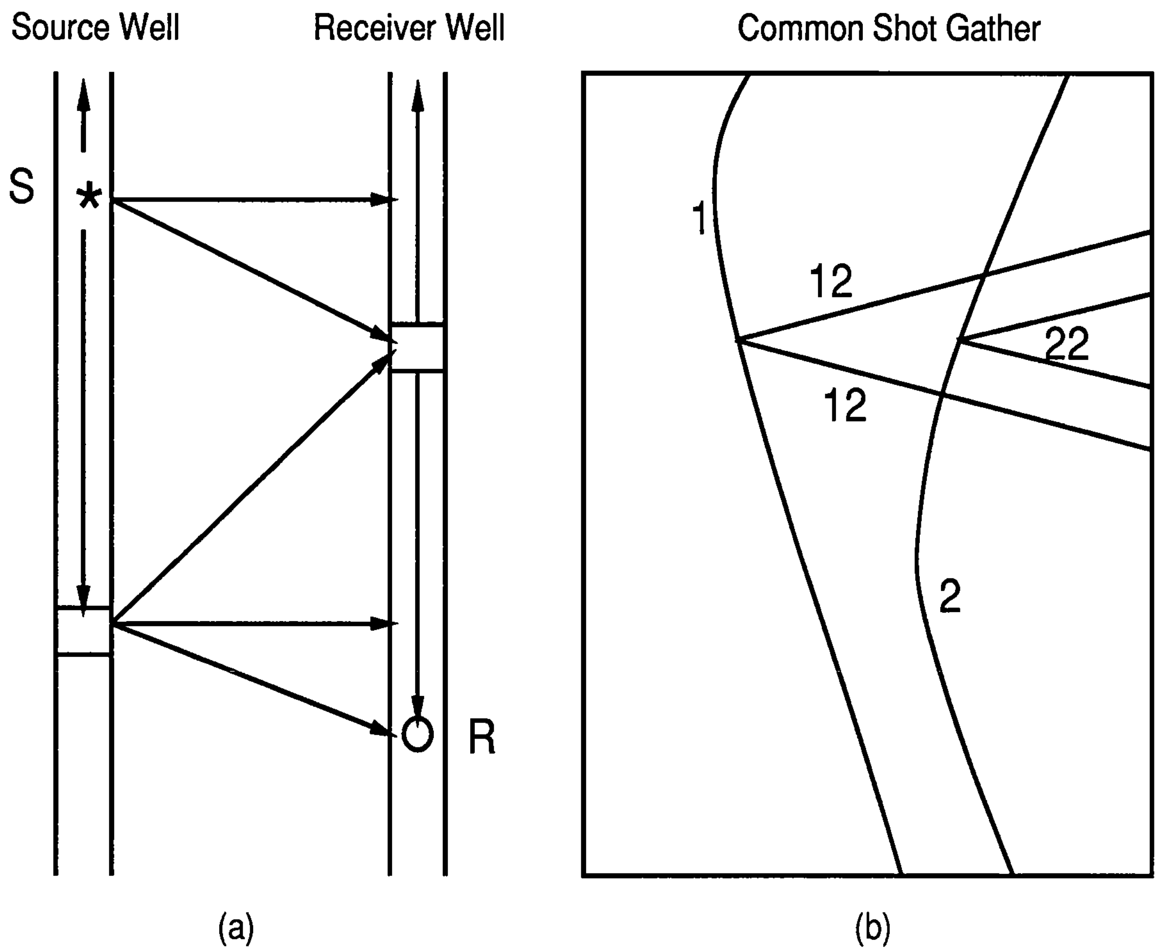

Figure 1 (a) is the crosswell experimentsetup. (b) is the traveltime trajectory of a common shot gather. In (b), 1 is the direct arrival, 2 is the body wave excited by the source well tube wave, 12 (22) is the receiver well tube wave excited by 1 (2).

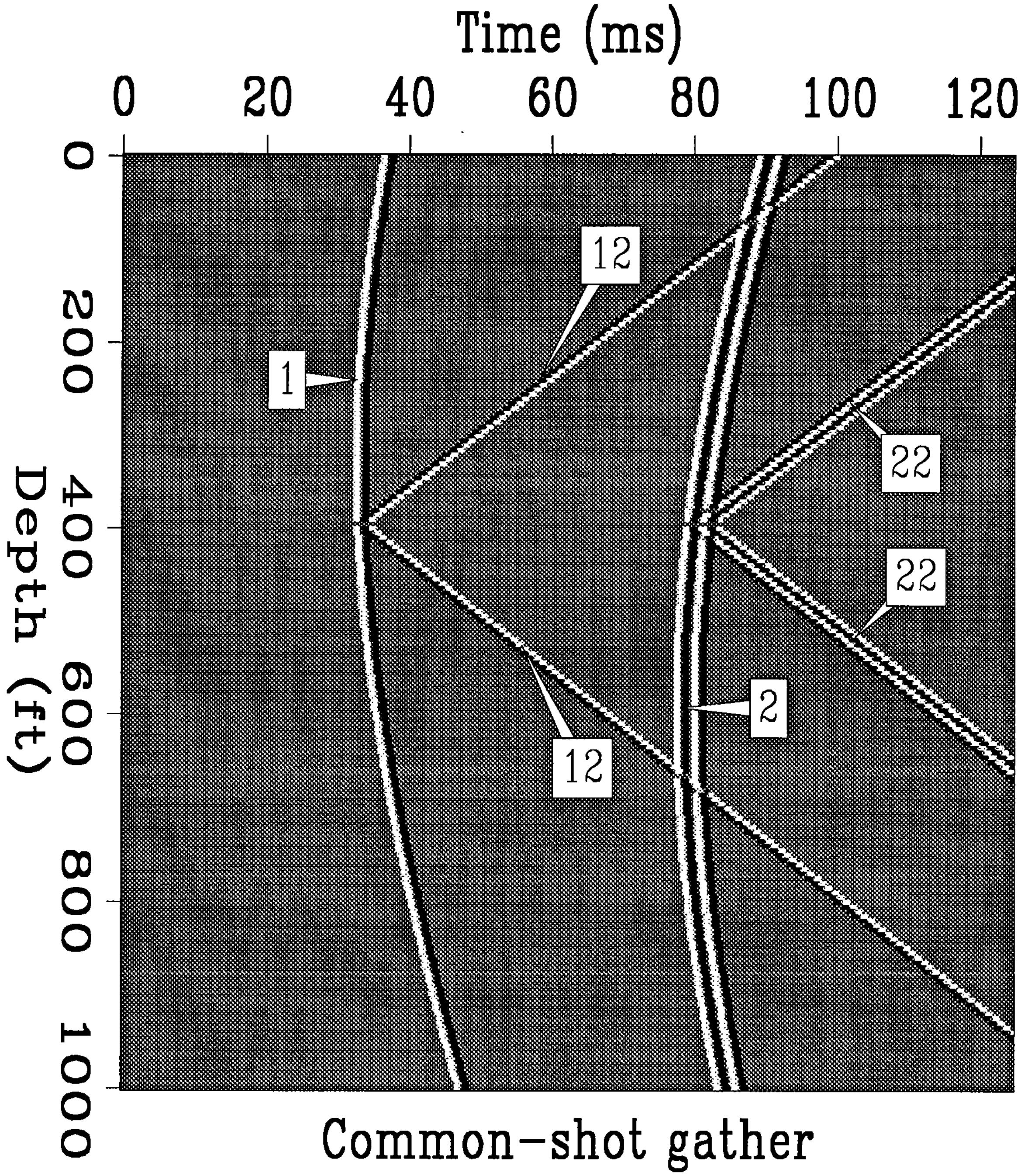

Figure 2 A synthetic common shot gather. Events 1, 2, 12, and 22 have the same descriptions as in Figure 1(b).

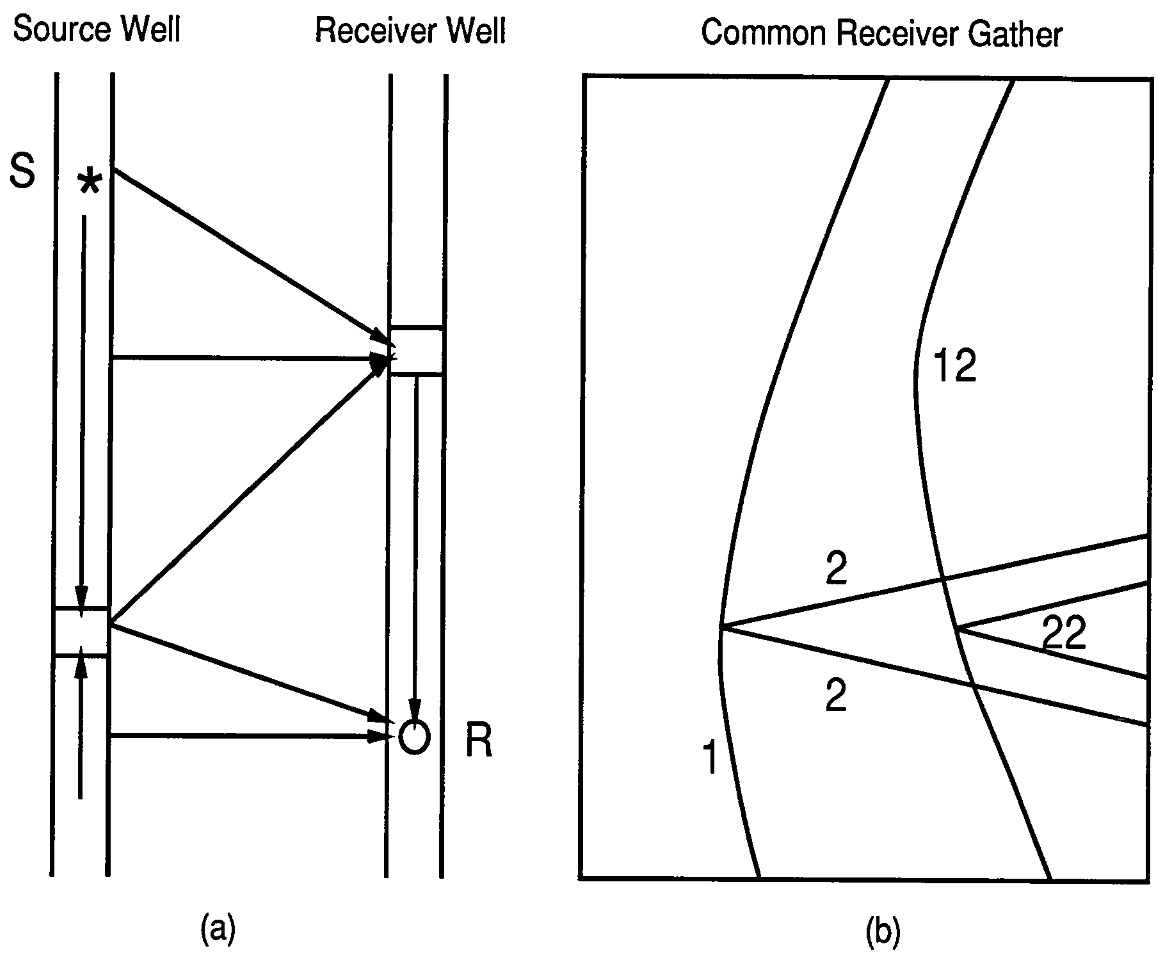

Figure 3 (a) is the crosswell experimentsetup. (b) is the traveltime trajectory of a common receiver gather. In (b), 1 is the direct arrival, 2 is the body wave excited by the source well tube wave, 12 (22) is the receiver well tube wave of 1 (2), as in Figure 1.By the principle of reciprocity, 1 can be considered as the first arrival excited by the receiver, 12 is the body wave excited by tube wave in the receiver well, 2 (22) is the source well tube wave excited by 1 (12).

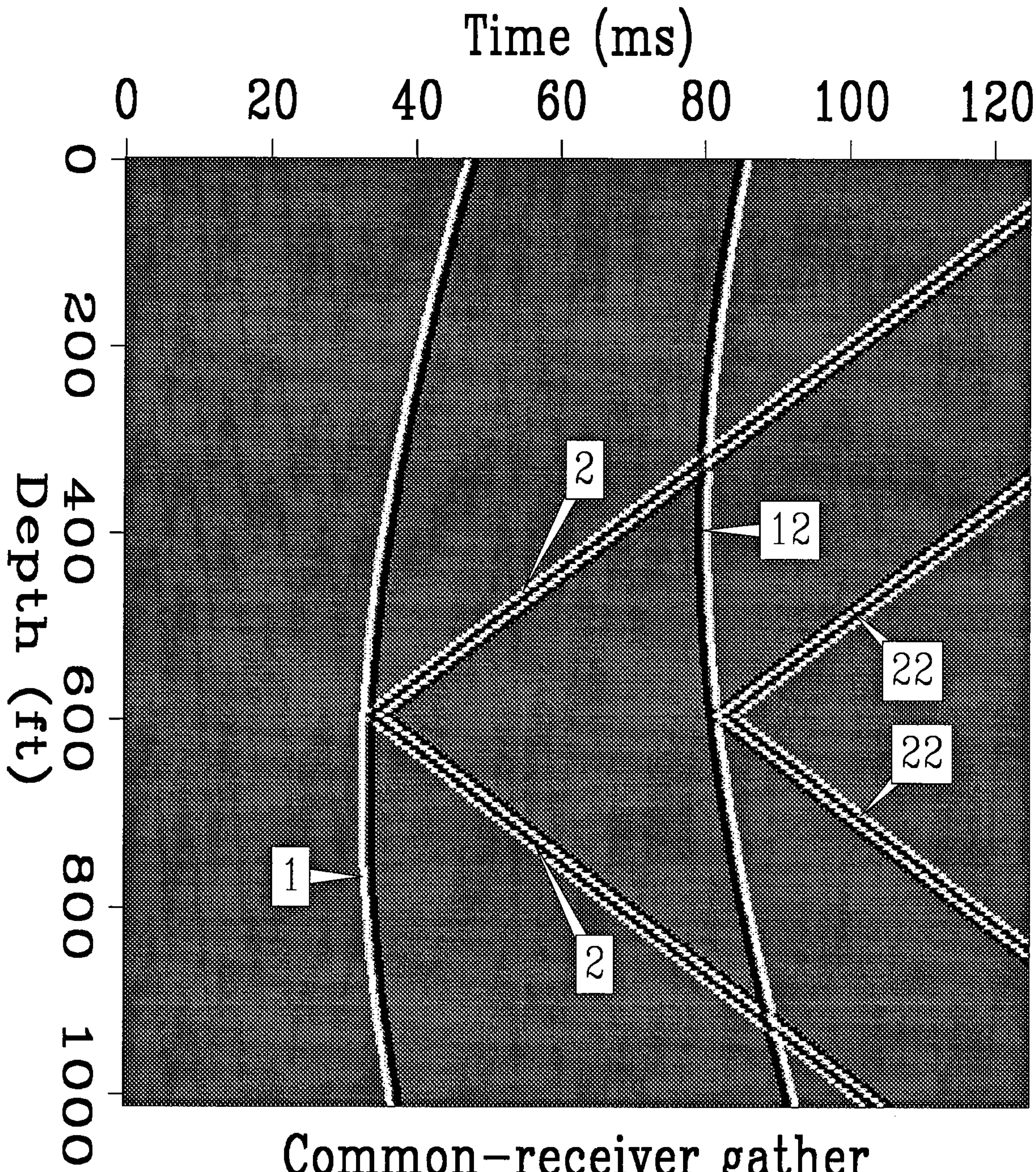

Figure 4 A synthetic common receiver gather. Events 1, 2, 12, and 22 have the same descriptions as in Figure 3. Polarities help to identify the corresponding events between Figure 2 and Figure 4.

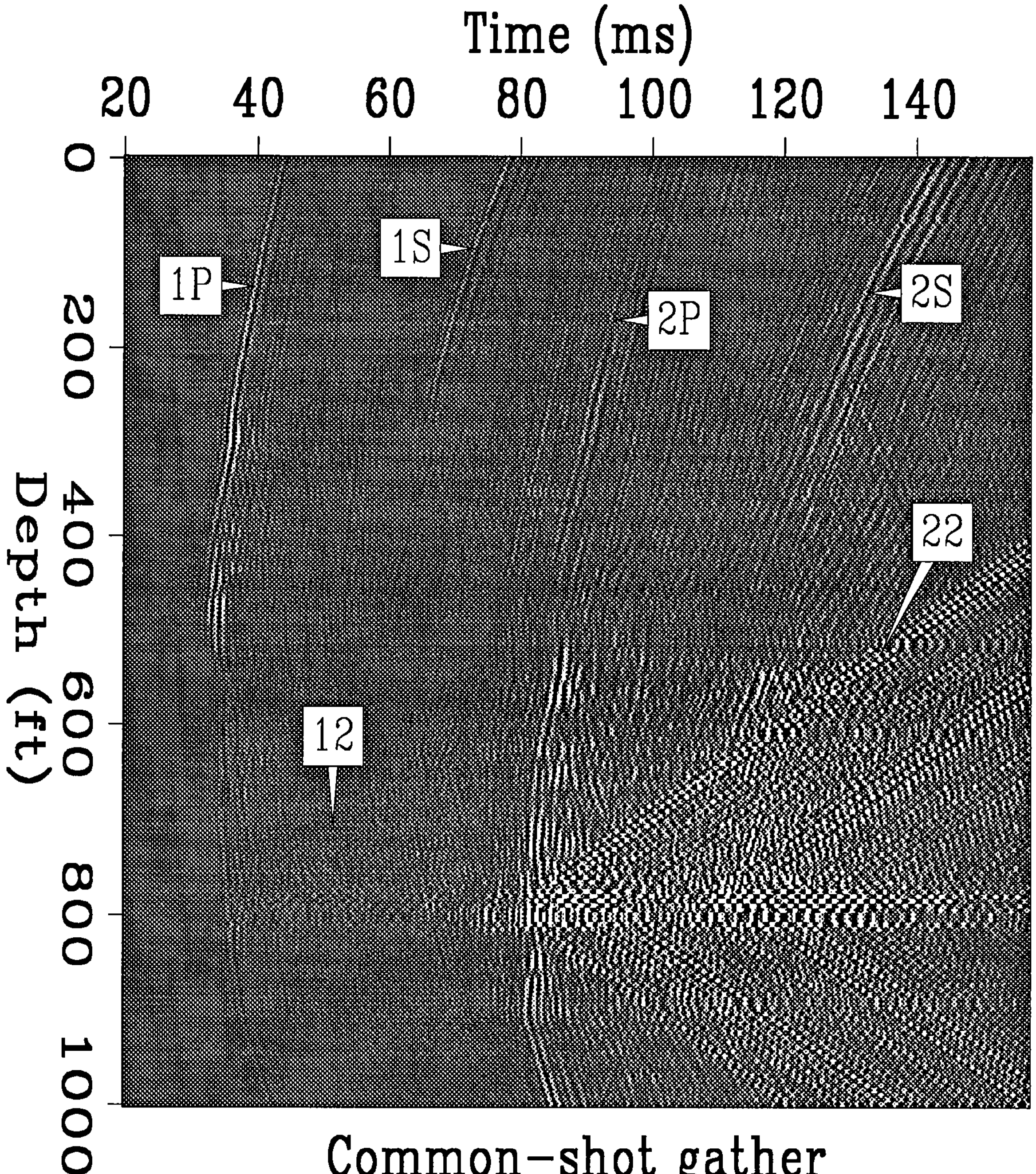

Figure 5 An unprocessedcommon-shot gather. Events 1, 2, 12, and 22 have the same descriptions as in Figure 1 and Figure 2. P (S) stands for P-wave (S-wave). Strong source well tube waves (events 2 and 22) are excited at the depth of 800 ft.

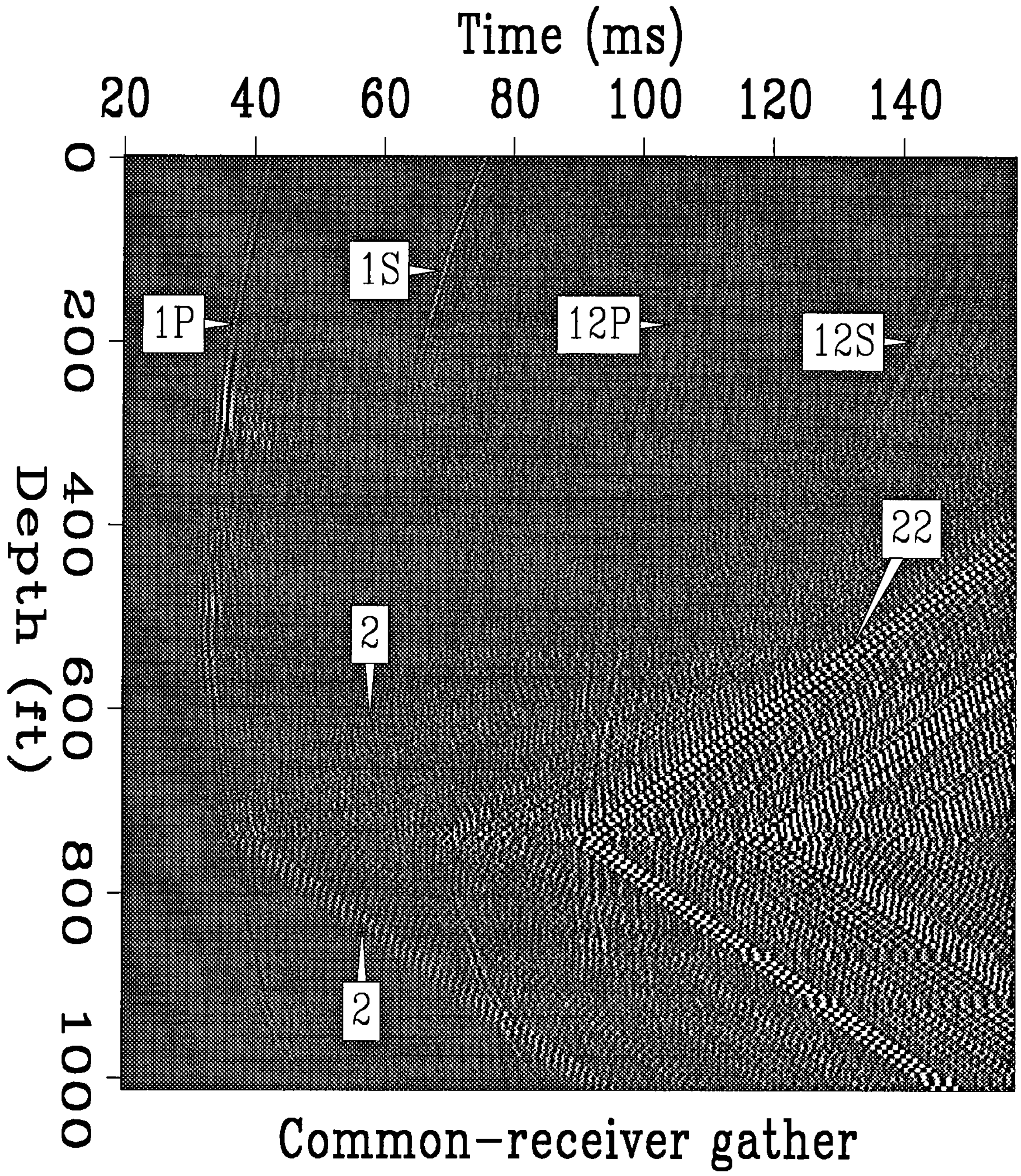

Figure 6 An unprocessedcommon-receiver gather. Events 1, 2, 12, and 22 have the same descriptionsas in Figure 3 and Figure 4. P (S) stands for P-wave (S-wave).Strong receiver well tube waves (events 12 and 22)are excited at the depth of 730 ft.

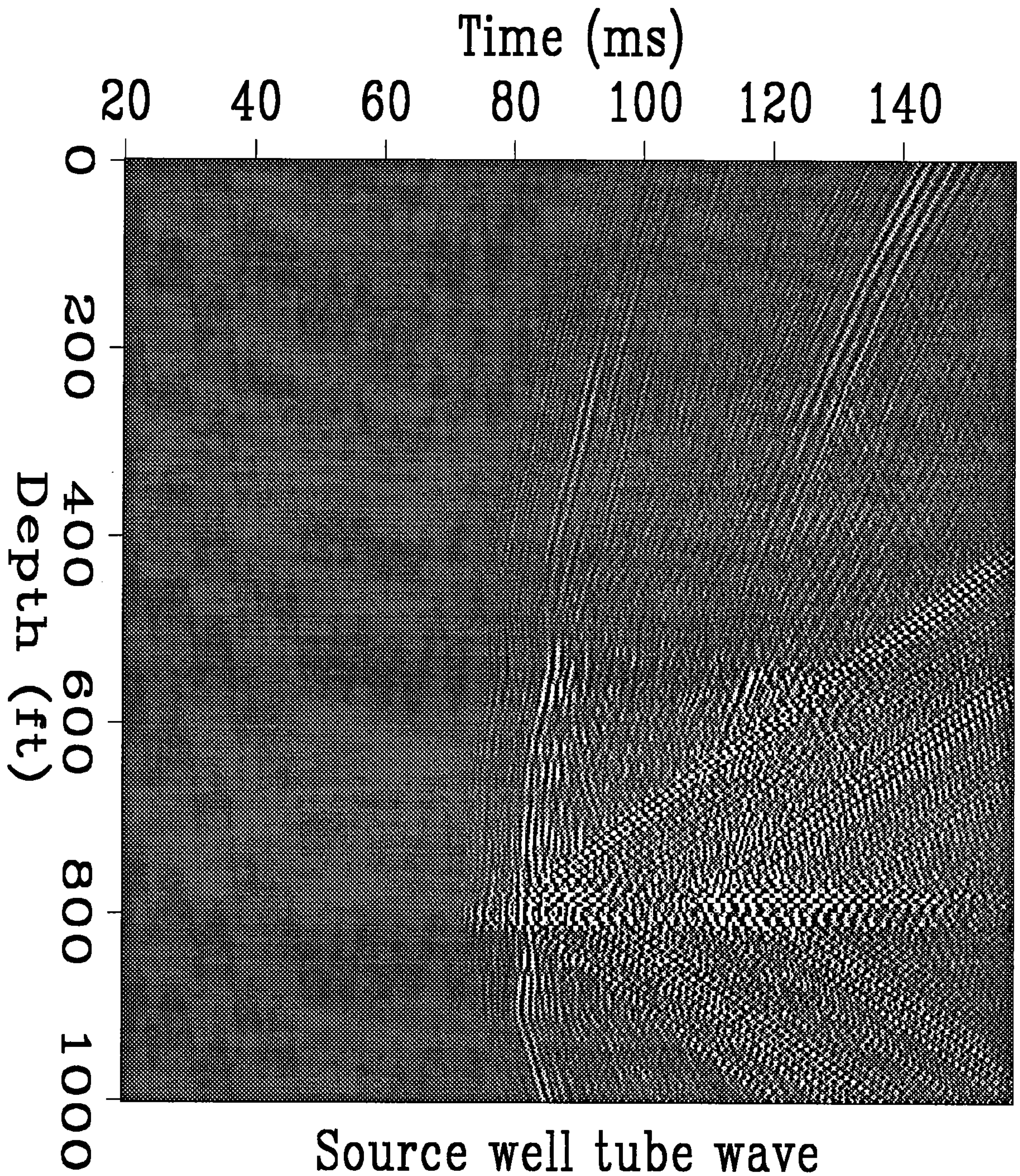

Figure 7 Estimated source well tube wave on the CSG data of Figure 5.

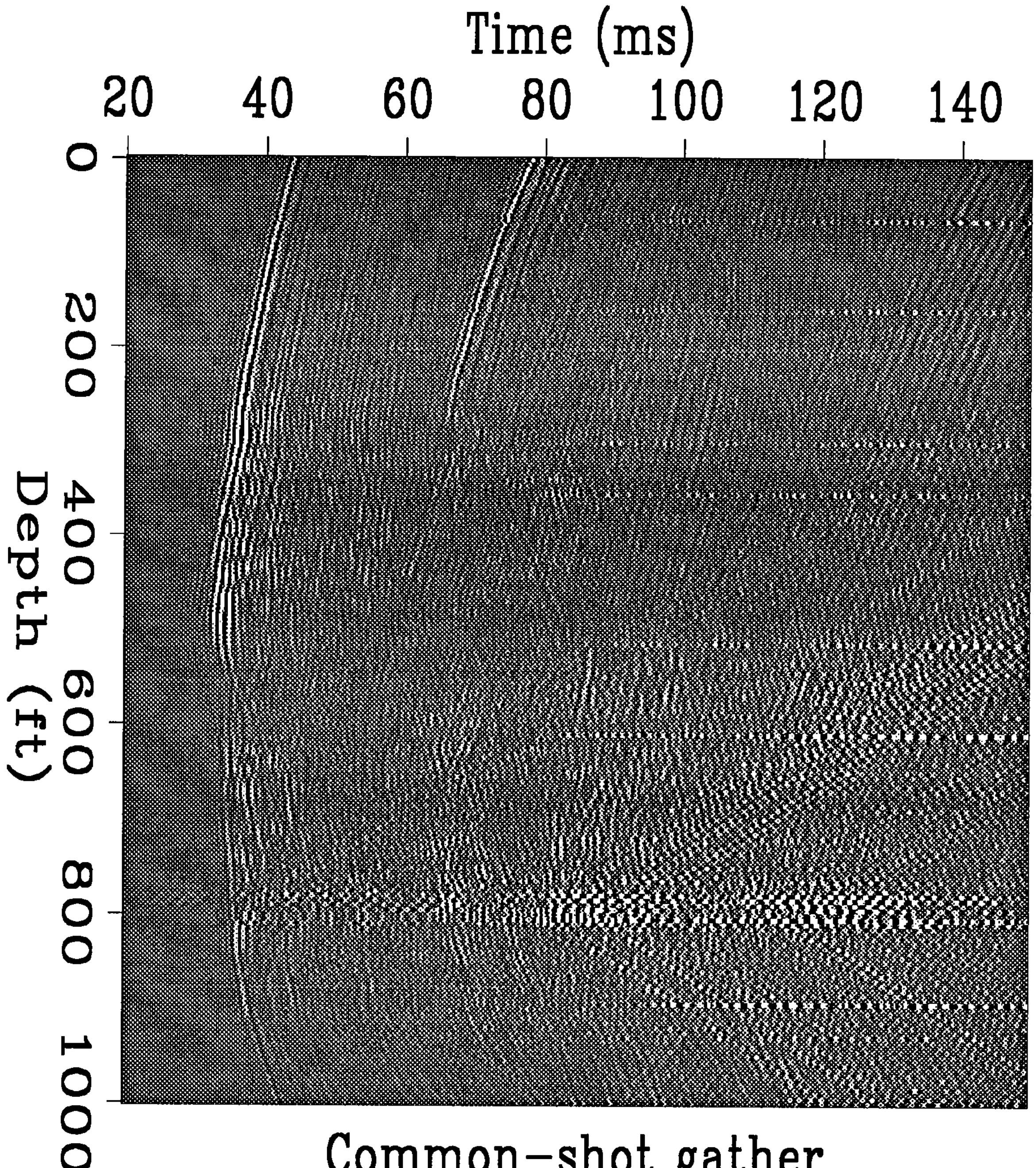

Figure 8 Common-shot gather of Figure 5. Source well tube waves have been attenuated.

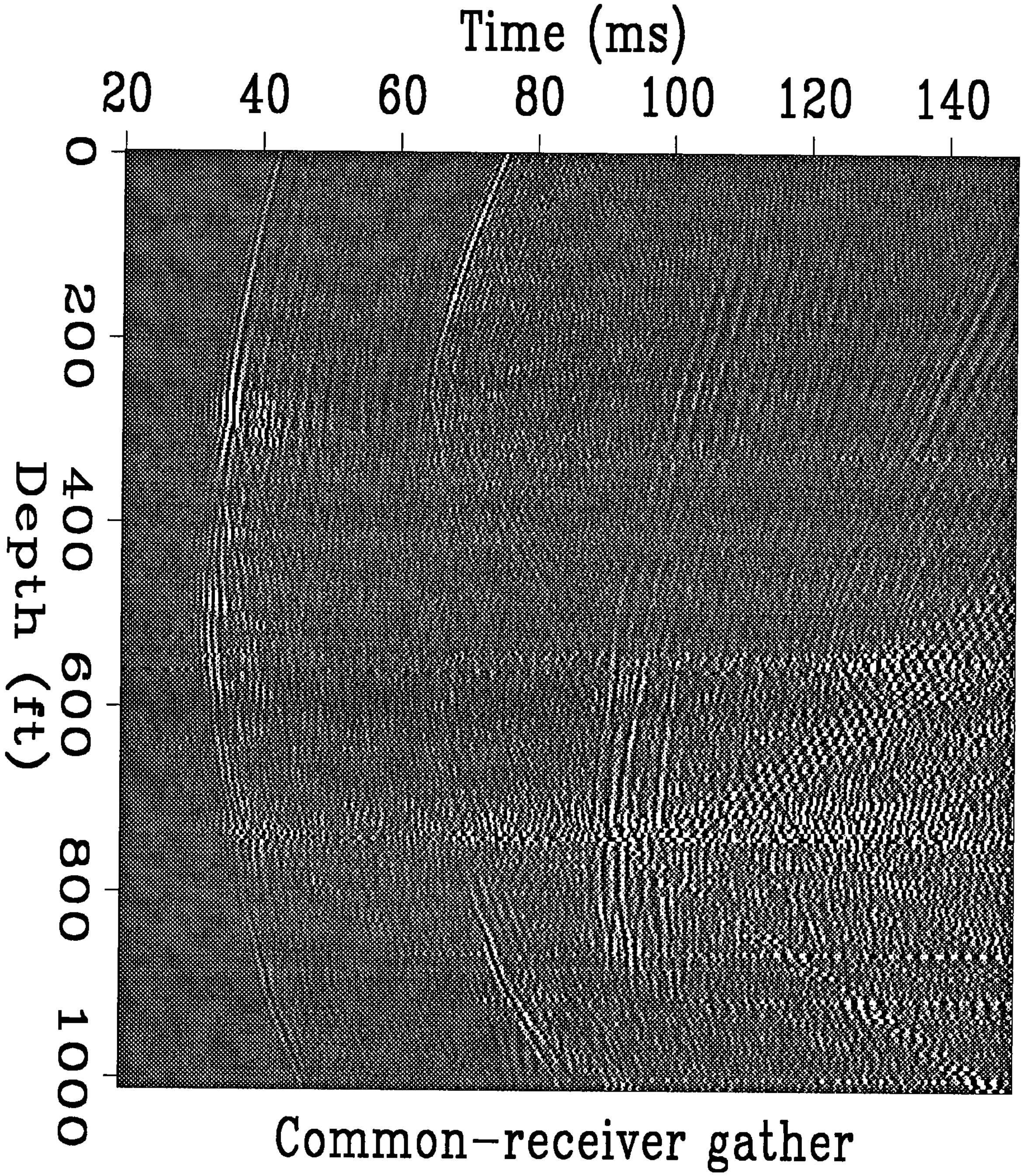

Figure 9 Common-receiver gather of Figure 6. Source well tube waves have been attenuated.

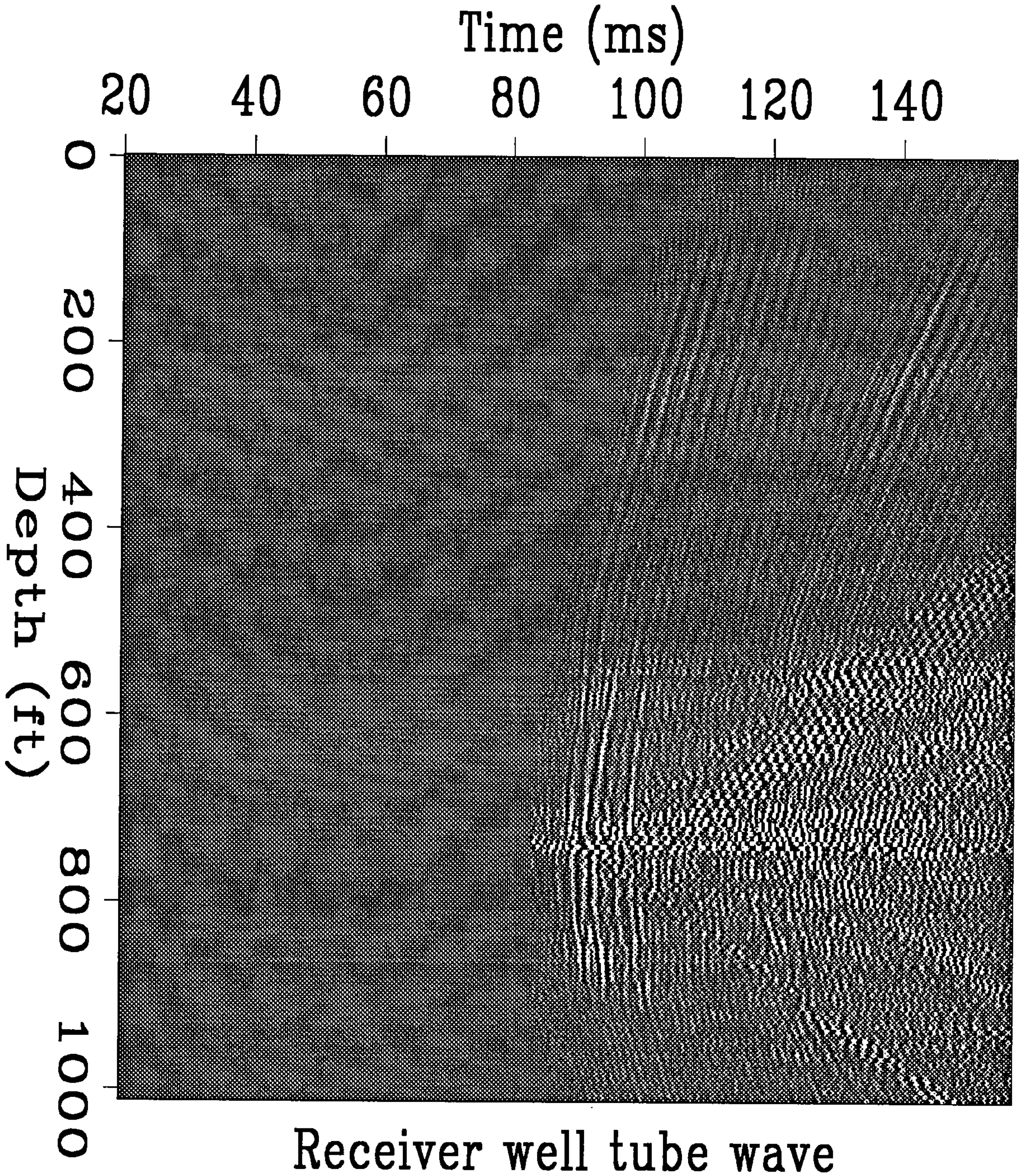

Figure 10 Estimated receiver well tube wave on the CRG data of Figure 9.

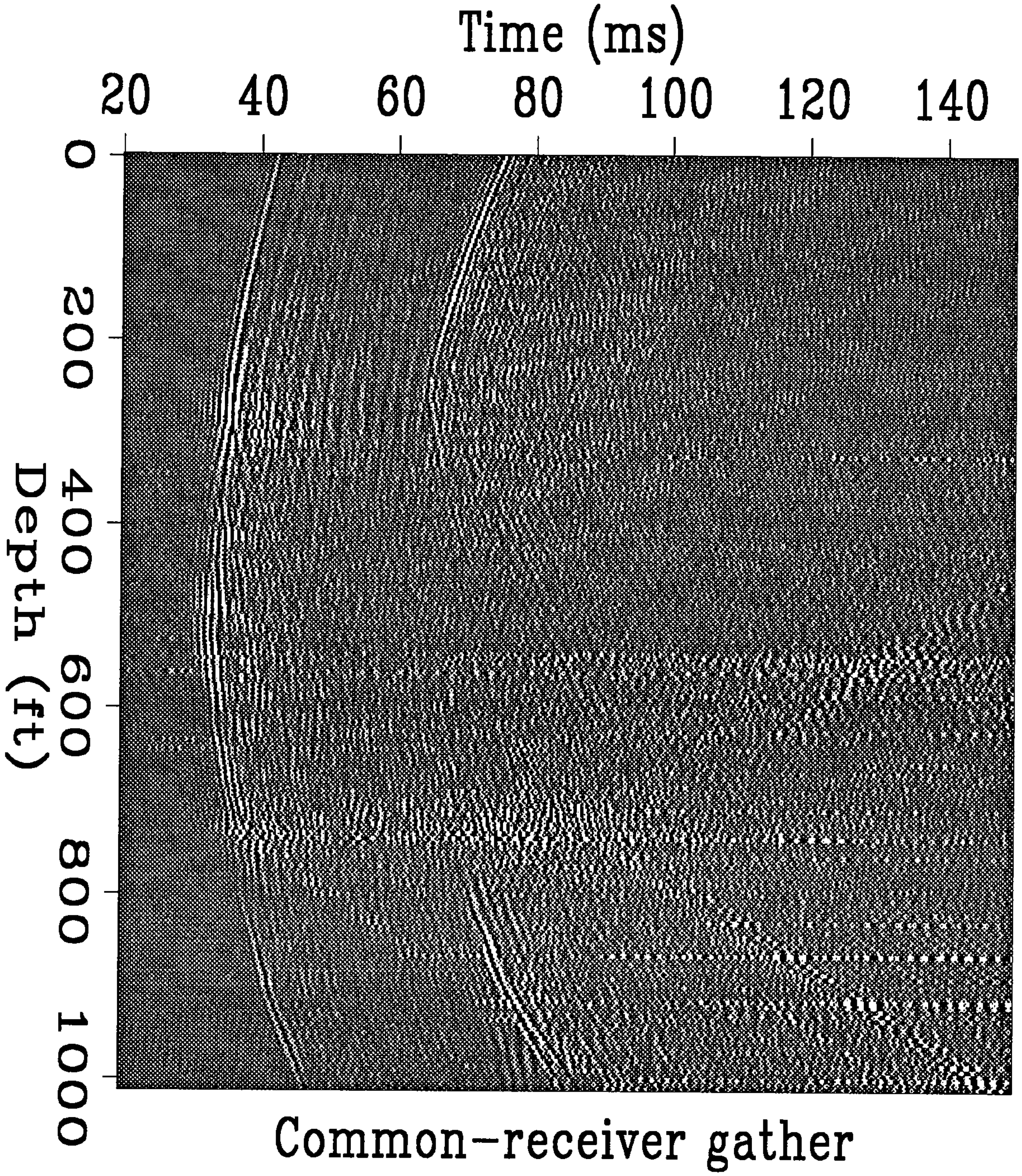

Figure 11 Common-receiver gather of Figure 9. Receiver well tube waves have been attenuated.

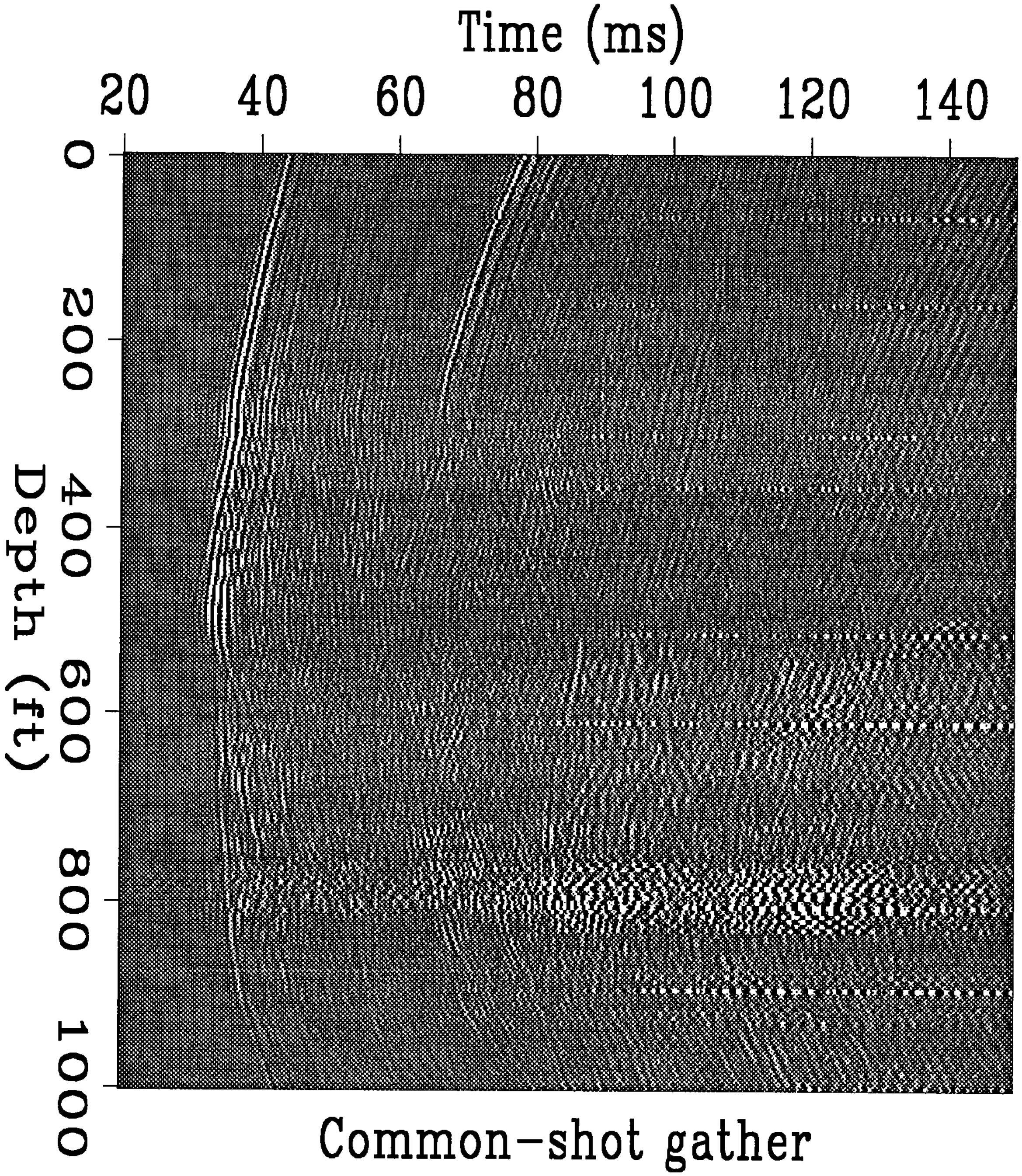

Figure 12 Common-shot gather of Figure 8. Receiver well tube waves have been attenuated.