# Crosswell Seismic Imaging Using Reflections

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## ABSTRACT

The use of reflected as well as transmitted energy in crosswell imaging can provide broad coverage and high-resolution sections between the wells. This paper discusses the general processing flow for the analysis of direct and reflected arrivals. We develop two procedures for crosswell reflection analysis: VSP-type and CDP-type flows.

In the VSP-type procedure, upgoing and downgoing reflections in shot or receiver gathers can be separated and mapped as offset VSP's. These individual maps are then stacked into a final section. On the other hand, more complete shot and receiver coverage may justify the implementation of a CDP-type stacking procedure. This CDP-type procedure includes trace gathering around a common source-receiver mid-depth (CMD gather) as well as a vertical move-out correction (VMO) between the various CMD locations. The VMO velocity is determined by scanning across CMD gathers. The VMO-corrected traces are then sorted into their correct lateral bins and stacked. These novel, yet simple, processing concepts are effective with the crosswell geometry.

These procedures are applied to ultrasonic data acquired in a physical modeling facility. The physical model and survey geometry were designed to simulate a crosswell field survey of an enhanced oil recovery (EOR) monitoring experiment. We find that the CDP-type procedure produces a better image in the zone of interest than does the VSP-type flow. The CDP-type procedure used also requires less operator intervention.


## INTRODUCTION

Crosswell seismic surveying is a recent procedure which investigators have hoped will provide very high resolution images of the subsurface. The analysis of crosswell data naturally began with the high-amplitude, unambiguous direct arriving energy. Processing concepts borrowed from tomographic theory were applied to these direct-arrival traveltimes (e.g., Peterson et al., 1985; Stewart, 1988; Bregman et al., 1989a). The resultant velocity images or tomograms provided an exciting beginning to crosswell imaging. However, upon further analysis and critical assessment, it was often found that these images suffered from non-uniqueness, artefact contamination, inappropriate coverage, and insufficient resolution (Bregman et al., 1989b). This does not doom crosswell imaging, but understandably suggests that transmitted (direct) arrivals contain a limited amount of useful geophysical information. So, similar to surface seismic processing, we must go well beyond velocity analysis to produce a final section. A comparable evolution occurred in VSP analysis, which started as check shot surveying using direct arrivals for velocity information, then progressed to wavefield imaging using the full seismic trace (Stewart, 1984).

Because of the similarity of VSP and crosswell geometry (and wave types), some workers have tried to adapt VSP processing algorithms to exploit later arrivals in the crosswell traces (Baker and Harris, 1984; Iverson, 1988; Abdalla et al.,1990). This can work reasonably well but often requires a great deal of operator intervention and interpretation. While many VSP concepts are directly applicable to the crosswell geometry, we can also borrow from the wealth of proven methods used in CDP processing (Whiteley et al., 1990; Stewart et al., 1991). Simple but powerful concepts in surface seismic have included CDP gathering and stacking, and statistical velocity analysis via coherency. We find that very good crosswell images can be derived from processing procedures based on these concepts. These CDP-type algorithms can be applied more automatically and faster than conventional VSP-type methods.

In the crosswell geometry, different types of data gathers are appropriate for various kinds of information extraction. Source and receiver gathers are used for automatic velocity analysis and tomographic direct arrival imaging. There are two additional and straightforward types of gathers: the common interval (CI) and common mid-depth (CMD) gathers. In the CI gather, the difference between source and receiver depths is constant (see Figure 1). Therefore, in a constant velocity layer, direct arrivals will have equal traveltimes in the CI gather and the first breaks will align. CI gathers can be used to process the direct arrivals (both P and S). In the CMD gather, the sum of the depths is constant (Whiteley et al., 1990 called the CMD gather a yo-yo gather): Energy reflected from a layer will have the same traveltime for all traces. Thus reflections will be flat just by virtue of the gather in the constant velocity case. CMD gathers provide partial images of reflectors, and can be used as an intermediate step to enhance the reflected arrivals. They can also be a starting point for a mapping procedure. A convenient way to view the types of gathers and their fold is via a crosswell stacking chart (Figure 2). This chart is similar to the stacking chart used in surface seismic analysis. Arrows on the chart indicate which traces are grouped into a specific gather type.

We are interested in this paper in developing and evaluating processing flows based on VSP- and CDP-type processing. To have a complete and simple, yet somewhat realistic data set describing a known section, we have used a physical model. The model, ultrasonic survey, and data processing are described in the following sections.

## PHYSICAL MODELING

The physical modeling facility consists of a large water-filled tank, source and receiver ultrasonic transducers, support for the transducers, control electronics, and digital recording. This apparatus has been described in detail by (Cheadle et al., 1985) and is similar to that discussed by other authors (French, 1974; Lo et al., 1988). A schematic diagram of the modeling facility is shown in Figure 3.

The physical model used was built to simulate a crosswell enhanced oil recovery (EOR) experiment. The EOR model is made with three layers: PVC, plexiglas, and phenolic. All distances and times in the model and survey are scaled by a factor of 5000 to simulate the field case.The scaled model gives a well separation corresponding to 500 m. The two major interfaces are found at scaled depths of 785 m (PVC/plexiglas) and 2785 m (plexiglas/phenolic). An additional 50 m layer has been carved into the plexiglas and filled with plaster of Paris. The lower velocity and density of this fill are intended to simulate a $CO_2$-flood which extends half-way between the two wells. Because the modeling facility was designed to survey in the x-y plane, the model is lain on its side to simulate surveying in the x-z plane.

A schematic diagram of the physical model and survey geometry with a shot gather are shown in Figure 4. There were 72 shot positions and 146 receiver positions for each shot acquired in testing. In Figure 4, the source lies just below the low velocity zone. Both transmitted P and S waves are strong, while we observe that, in general, pure S reflections are stronger than pure P. The reflection events processed in this paper are pure S reflections.

## PROCESSING PROCEDURE

### VSP-like Flow

To begin the processing flow, we generally view the frequency content of interpreted signal and noise on the shot, receiver, or CI gathers. The traces may then be bandpass filtered. Their P and S direct arrival times are next picked. Interval velocities, used in the later imaging stages, can be computed at this point using a traveltime inversion technique (e.g. Bregman et al., 1989b; Abdalla et al., 1990). The direct arrivals are removed by first flattening them on their first break times and median filtering (Hardage, 1985; Stewart, 1985; Kommedal and Tjøstheim, 1989). The median-filtered traces are subtracted from the original traces to give the residual data as shown in Figures 5 and 6. Upgoing and downgoing waves are next separated from the residual traces by f-k filtering. Each separated gather is then mapped independently into true or complementary depths via a VSPCDP map (Dillon and Thomson, 1984). Maps of data from several shot depths are shown in Figure 7. The partial images (upgoing and downgoing) are then registered (manually or by crosscorrelation) and stacked to provide the final image (Figure 8). In this section, the top interface is reasonably well imaged. The "$CO_2$ flood" area is visible just above 2000 m but, we cannot resolve the top and the bottom of the anomaly. The bottom interface is represented by only a weak event on the section.

### CDP-type Flow

The first step in CDP-type processing is, once again, to remove the direct arrivals. Next, we sort the data into CMD gathers. This largely flattens pure-mode events (P and S) in the gather. In Figure 9 we can see a flattened downgoing reflection (at just greater than 1 second) coming from a depth of 785 m. To prepare the various CMD gathers for stacking, we need to remove the variation in vertical traveltimes between the common mid-depths. We call this VMO (vertical move-out) removal. Using the geometry of Figure 10, we can derive the straight-ray traveltime t from a source at depth s, reflecting at z, to receiver at depth r:

$$t = \frac{2(z-m)}{v}\left[1 + \frac{x^2}{4(z-m)^2}\right]^{\frac{1}{2}}, \tag{1}$$

where m = (s+r)/2, x is the distance between wells, and v is the velocity.
So, if the distance from the CMD depth to z is large, then to first-order, the VMO of time with respect to CMD-reflector distance is linear. Upgoing and downgoing reflections have positive and negative (respectively) slopes across CMD gathers. Thus, we can search for a linear coherence (velocity analysis scan) across the CMD gathers to find the VMO stacking velocity (shown schematically in Figure 11). Once we have found the VMO stacking velocity we can remove time variations among CMD gathers. As Figures 12a and 12b indicate, VMO is an effective technique for aligning and separating upgoing and downgoing wavefields. In this case, the same linear VMO function has been applied with positive and negative sign to the 0 to 625 m CMD gather range. The upgoing reflections come from the PVC/plexiglas interface, whereas the downgoing reflections are from the surface.

After removing VMO, we next need to process the traces across all CMD gathers so that their reflection points are located in the correct lateral positions. In order to place the traces at their correct lateral position, we find the offset Δx from the midpoint x/2 as a function of source depth s, receiver depth r, and reflector depth z. Referring to Figure 10, it is straightforward to show, in a constant velocity medium, that for pure P and S events

$$\Delta x = \frac{x(r-s)}{4(z-m)} \quad . \tag{2}$$

Clearly as z changes so does Δx (for example, as z becomes large, the reflection point approaches the midpoint). So to be exact, we would need to use a procedure like the VSPCDP map or pre-stack migration to place the trace amplitudes in their appropriate lateral positions: The trace maps cross bins or offset location boundaries. However, as discussed previously, mapping procedures are time consuming and have their attendant problems.

In the CDP-type flow, we do not map traces but order them in their approximately correct lateral positions. This ordering position is determined by selecting a target depth some distance away from the CMD range. Given this target depth, the whole trace is put at the position determined by (2). Thus, the lateral position of the trace is correct for the target depth, but approximate elsewhere. The traces from the CMD gathers are now ordered according to reflection point offset in a supergather (Figure 13). Residual statics and coherency filtering can be applied in this supergather. Adjacent traces in the supergather are stacked into an appropriate bin width - in this case, 10m. The bin width can be chosen according to desired fold or trace spacing. This produces the final reflection image (Figure 14). In this image, we can see complete and continuous events for all of the interfaces. Comparing the section in Figure 14 to that of Figure 8, we see that the CDP-type flow has produced a better image of the $CO_2$ zone. In fact, we appear to be able to see the top and bottom of the anomaly. Furthermore, the two other interfaces are more complete and resolved in the CDP-type image.

## CONCLUSIONS

Using reflections in the crosswell survey can provide complete and accurate sections. We have outlined two general processing strategies to create these sections: VSP- and CDP- type procedures.

As practised here, VSP-type processing requires more work and manual intervention, but it is presently more flexible because it can deal with low-fold data and irregularities in the acquisition geometry. The CDP-type flow introduced in this study rests on simple assumptions but is fairly automatic. Results from our ultrasonic test model indicate that the CDP-type image provides a better picture of the target zone than does the VSP-type section.

## ACKNOWLEDGEMENTS

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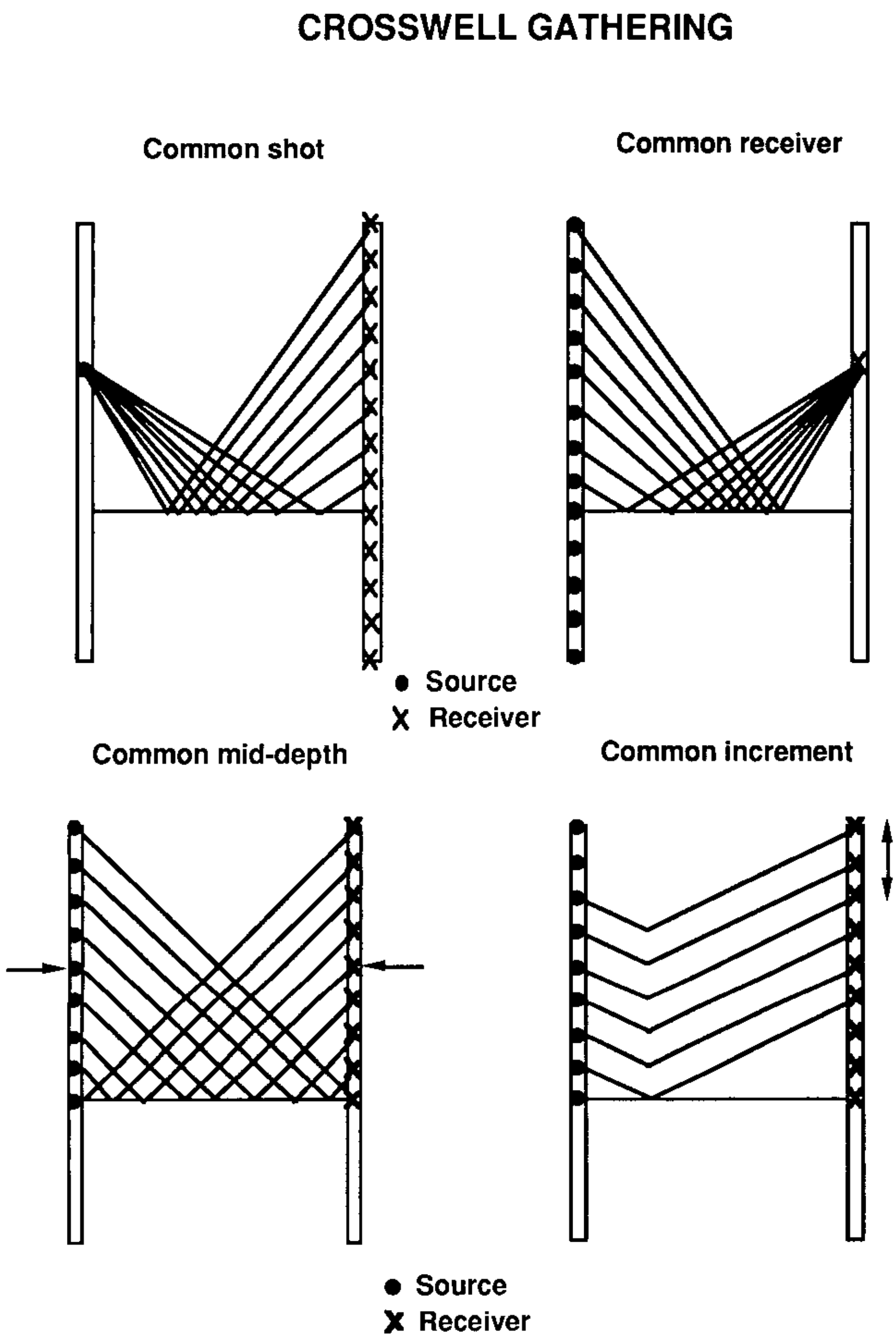


Figure 1. Four types of data gathering in the crosswell geometry.

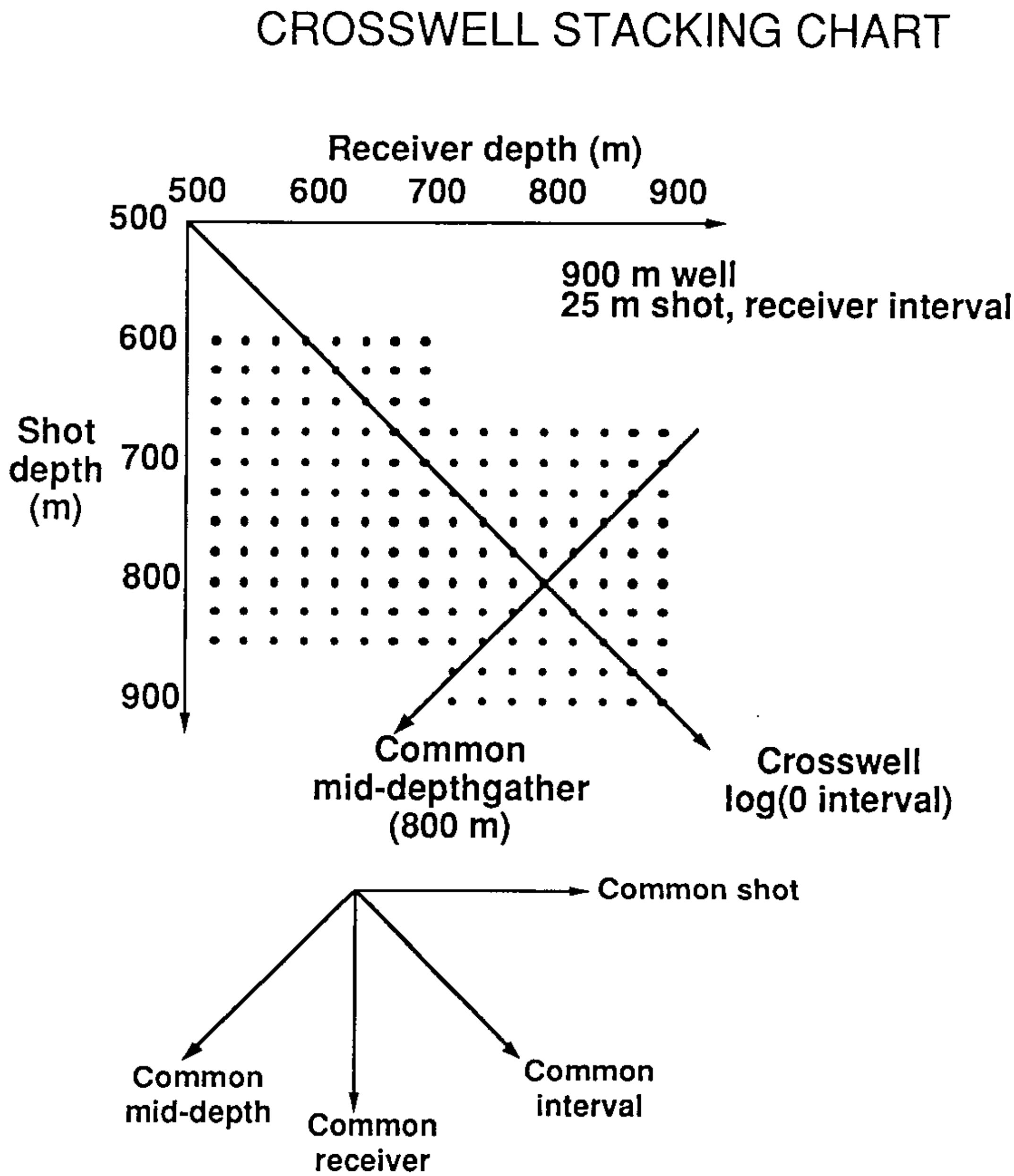


Figure 2. Crosswell stacking chart with arrows indicating several types of gathers.

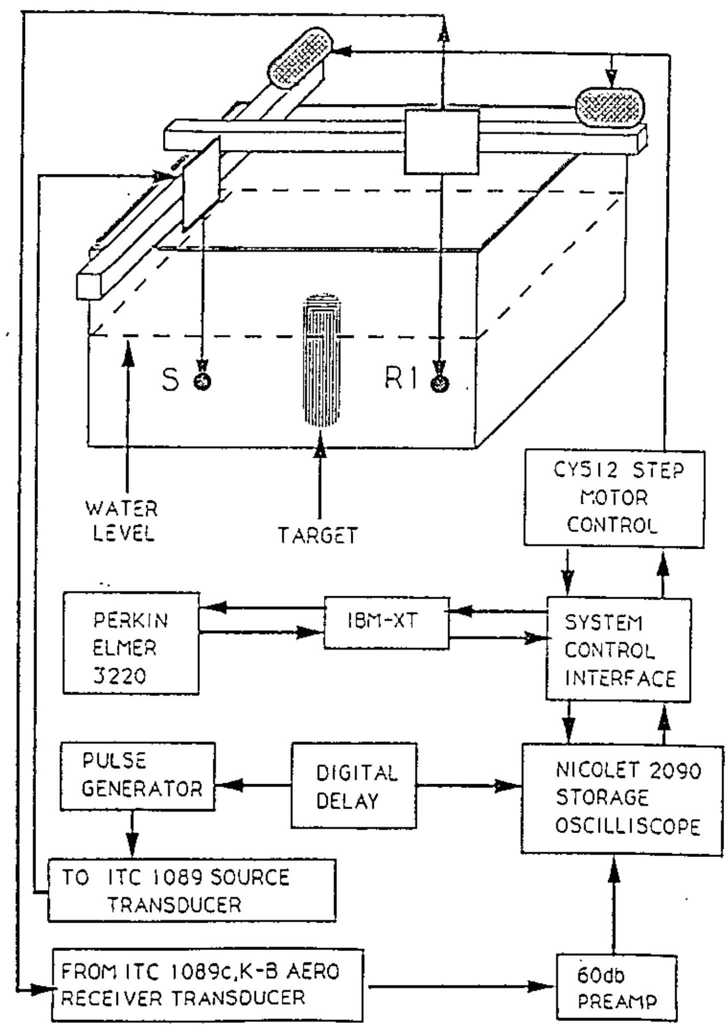


Figure 3. Schematic diagram of the physical modeling facility.

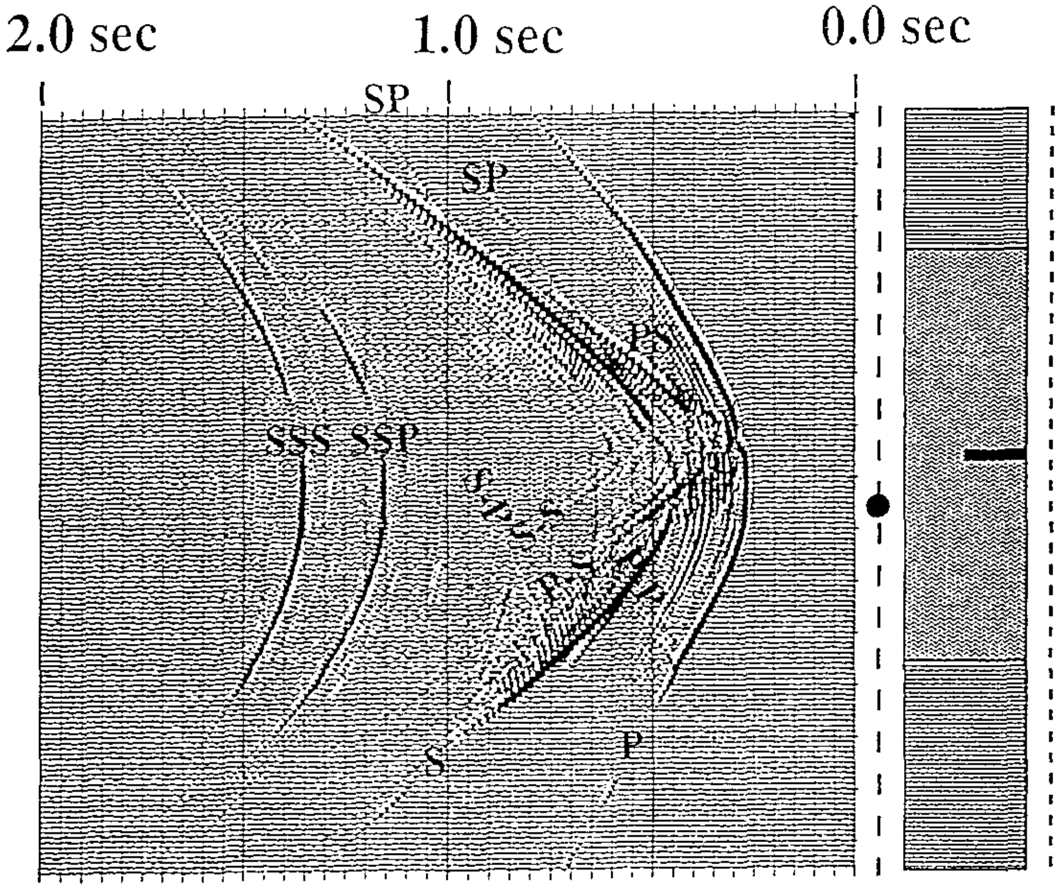


Figure 4. Schematic diagram of the EOR model and a shot gather.

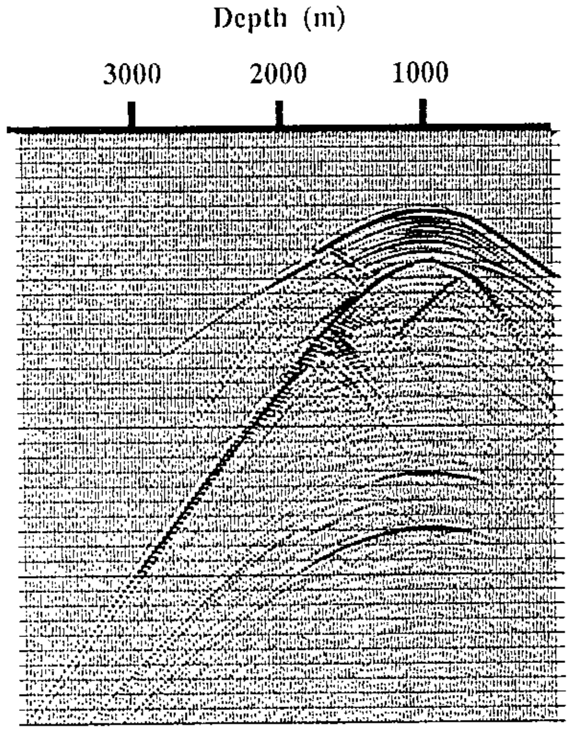


Figure 5. A shot gather with the shot at a depth of 975 m. Receiver depths are annotated.

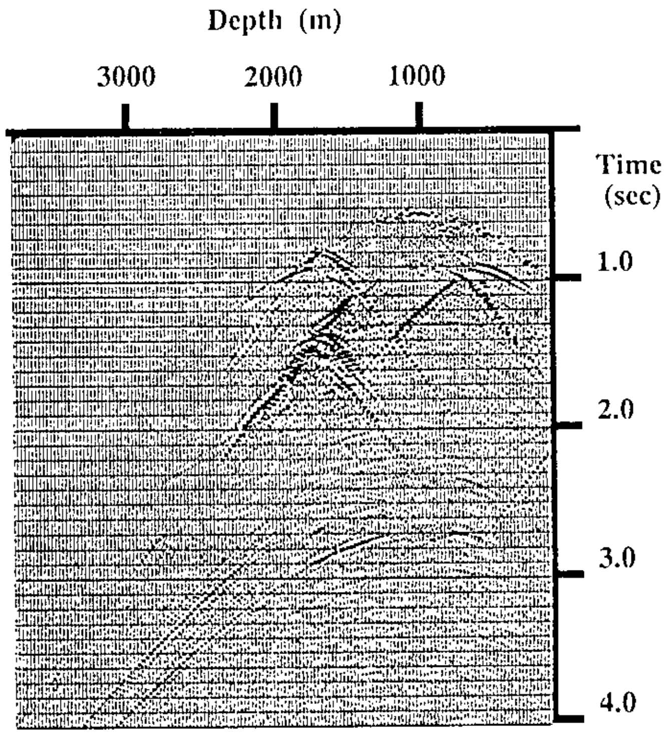


Figure 6. The residual wavefield of the gather shown in Figure 5 after removing the direct arrrivals. Receiver depths are annotated with the shot at 975 m.

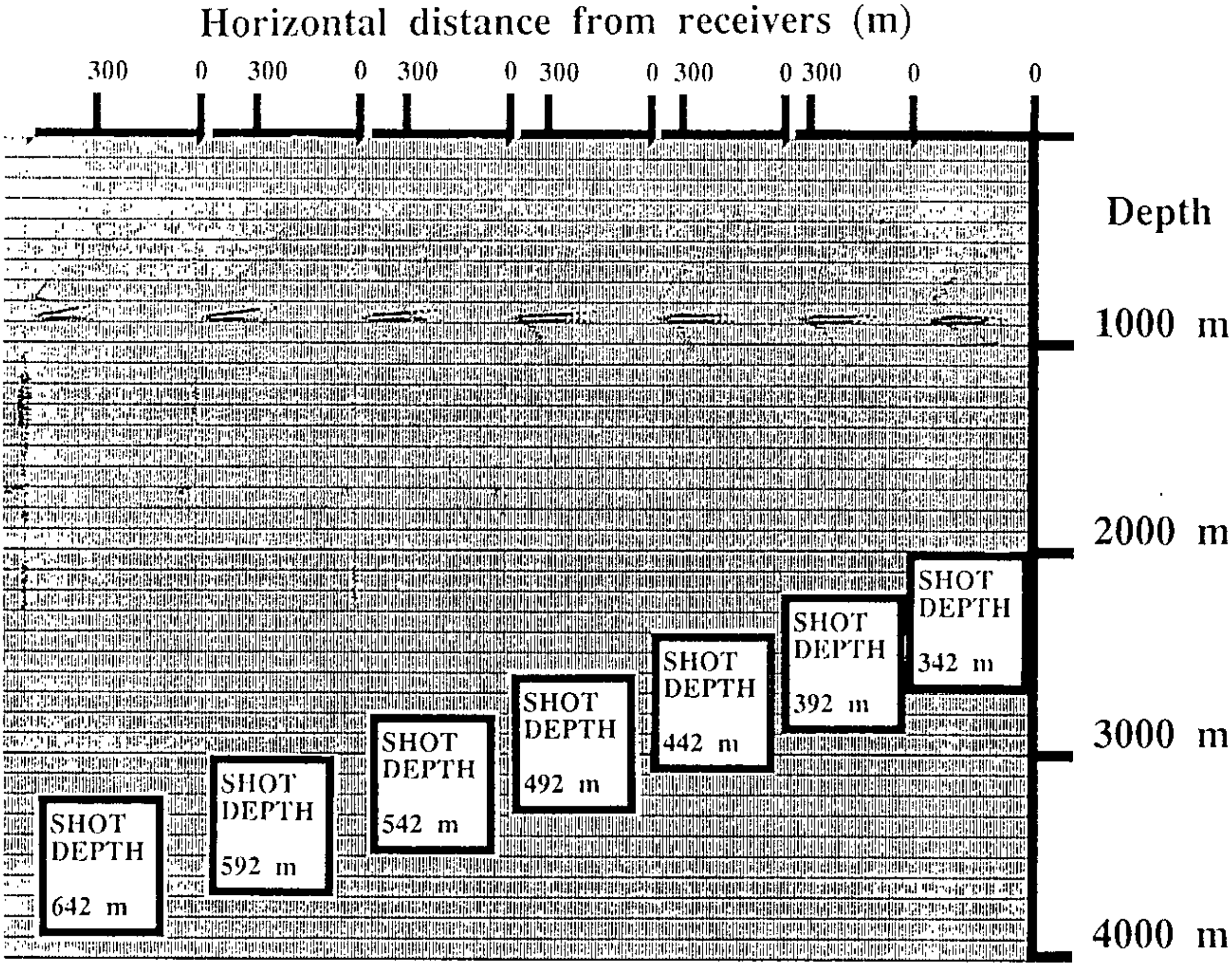


Figure 7. The VSPCDP maps of a several shot gathers.

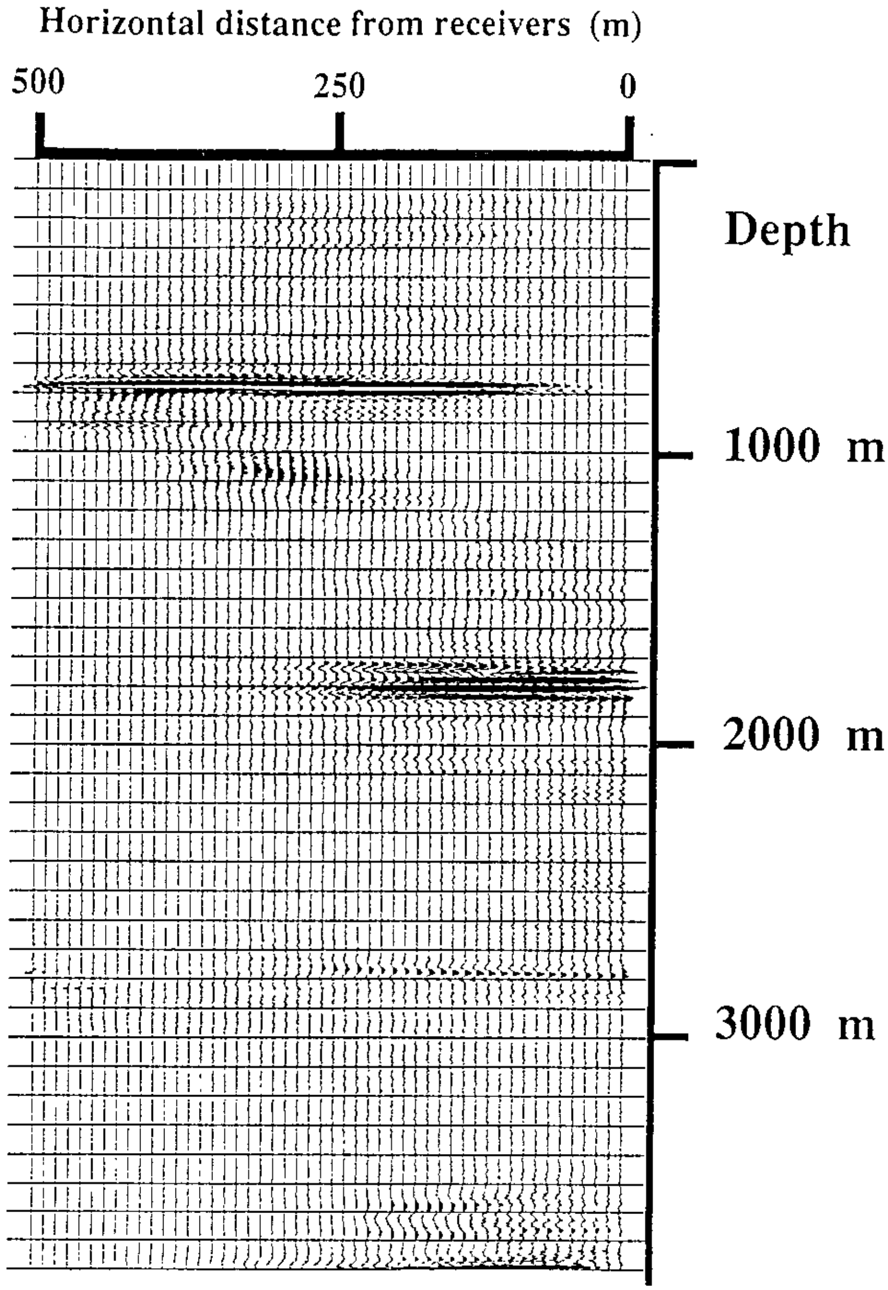


Figure 8. The final stack of 72 shot gather VSPCDP maps.

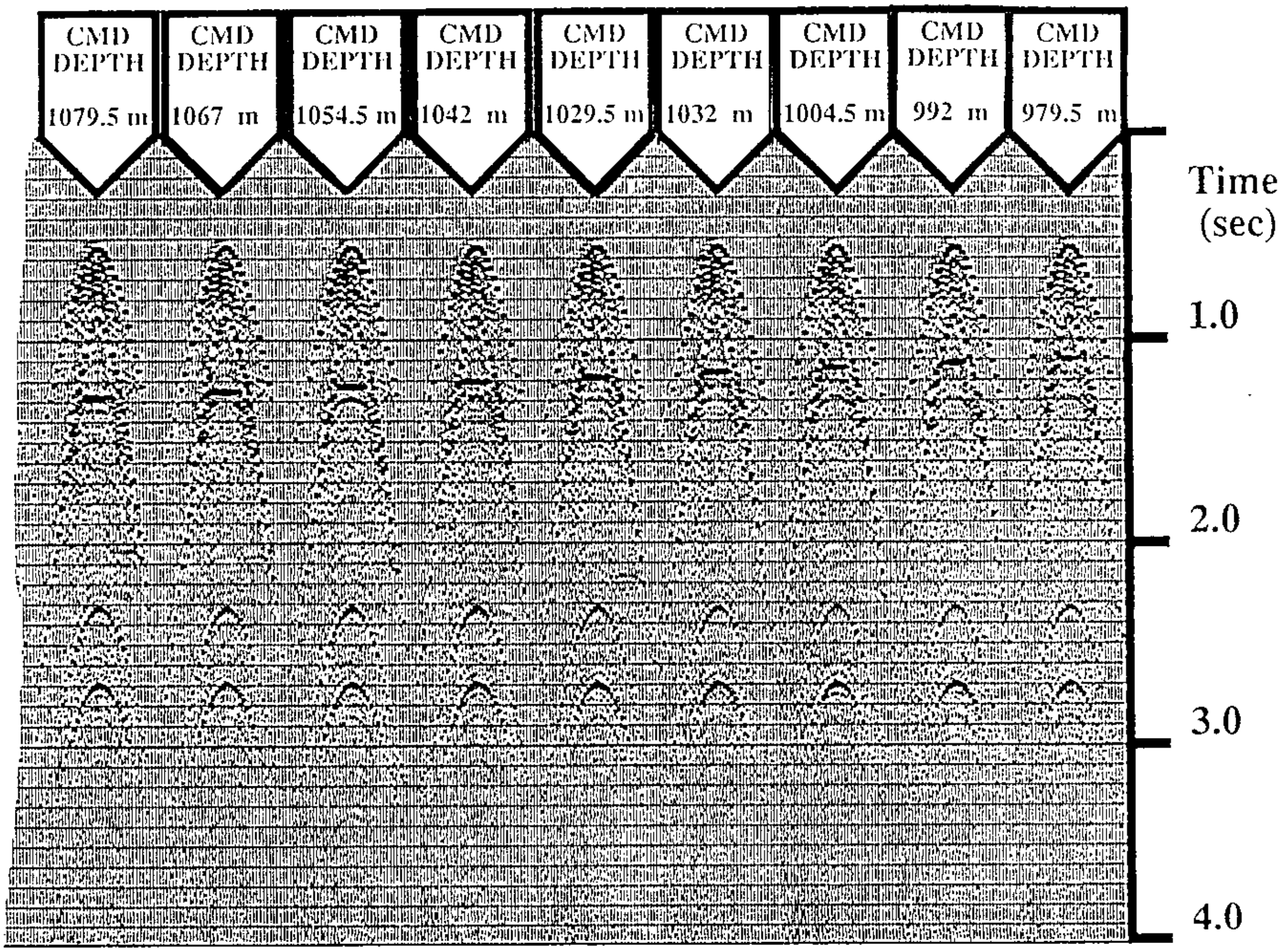


Figure 9. Common mid-depth (CMD) gathers for a range of depths.

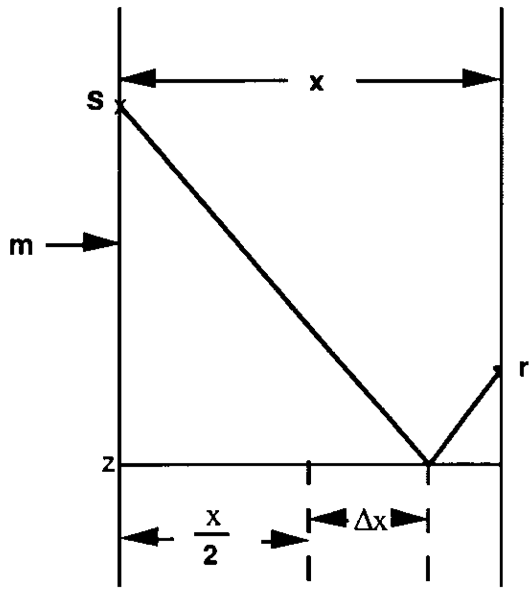


Figure 10. Schematic diagram illustrating the geometry used to correct reflection times between CMD gathers and to position laterally the traces in various gathers.

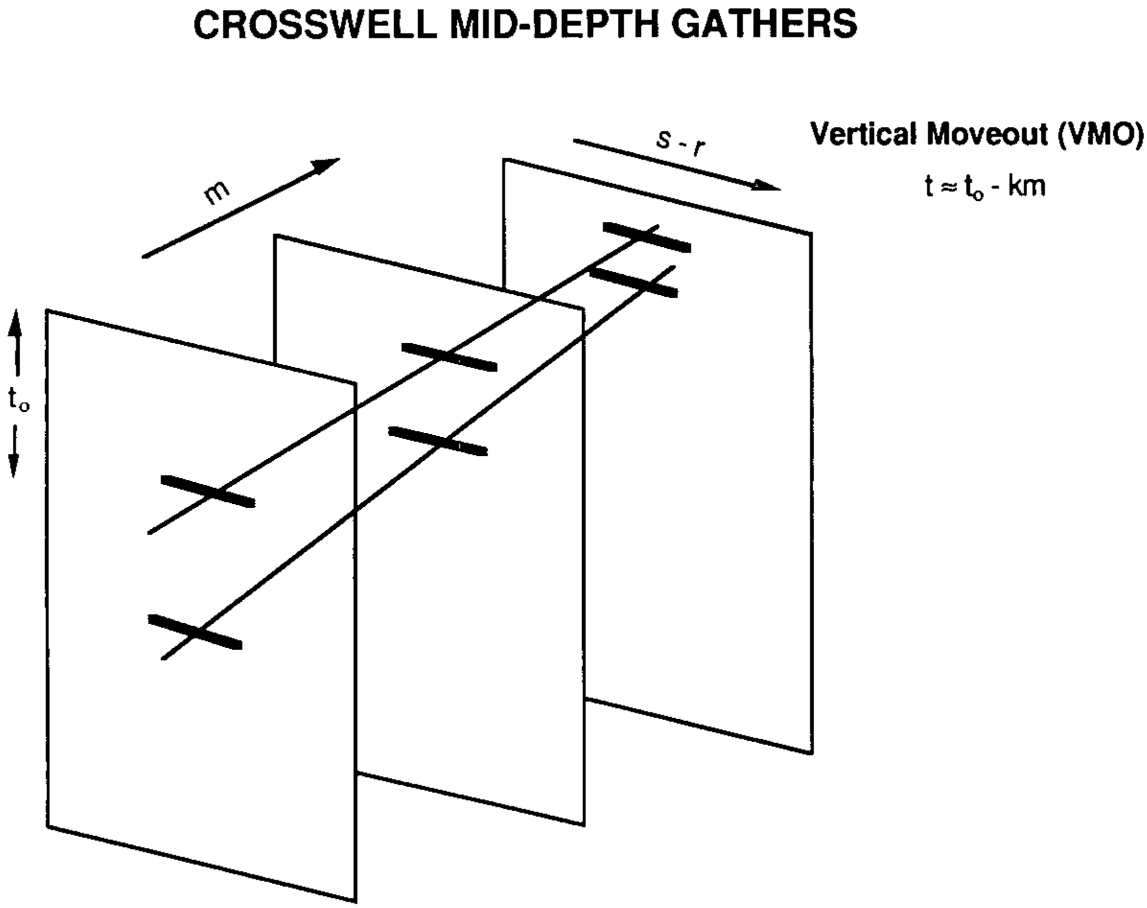


Figure 11. Schematic diagram of reflection time across CMD gathers.

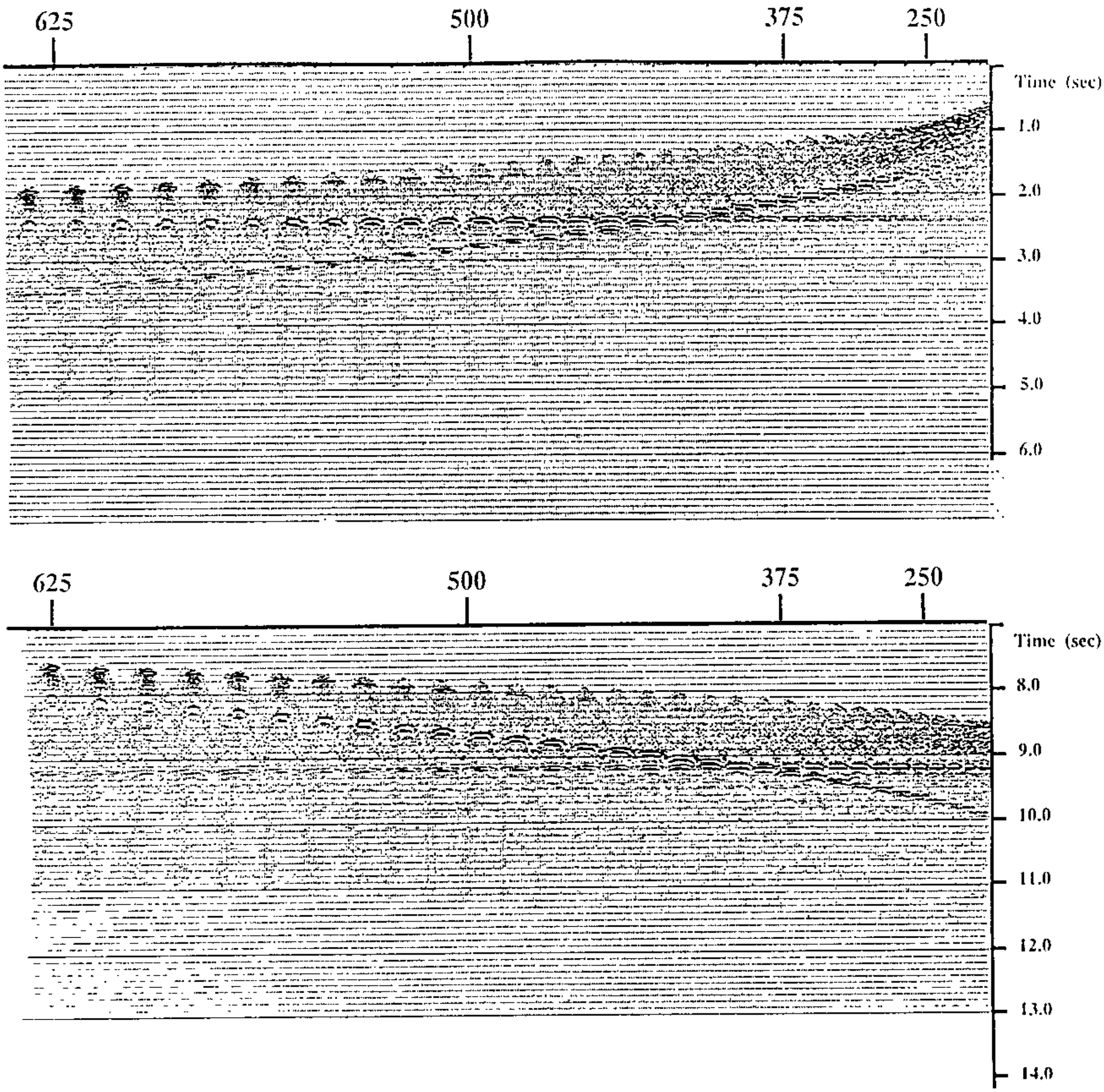


Figure 12. a) Vertical moveout (VMO) removal across CMD gathers for upgoing events
b) VMO removed for downgoing events. CMD depths are annotated.

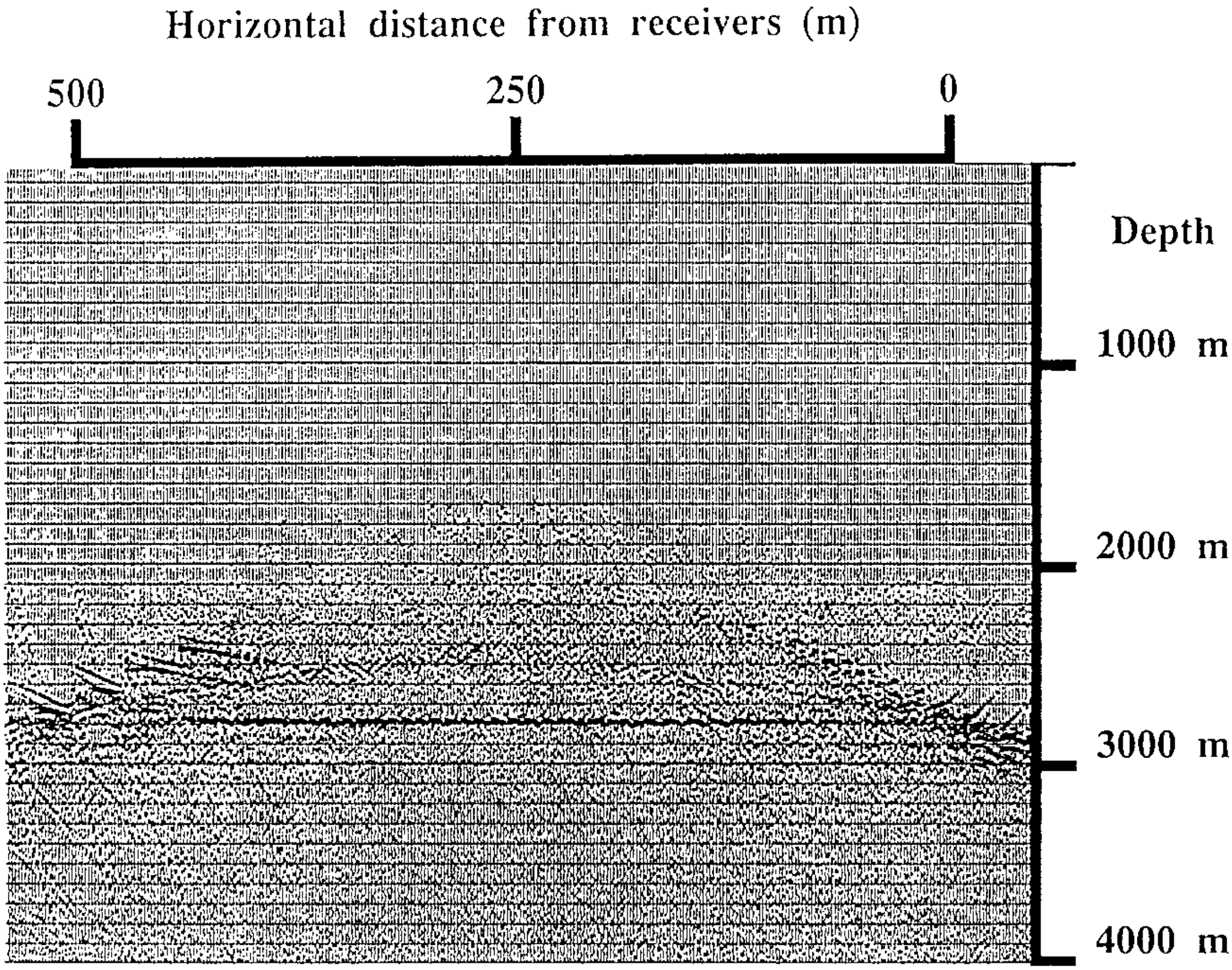


Figure 13. Traces ordered in their correct lateral position from a number of CMD gathers This new assemblage is called a supergather.

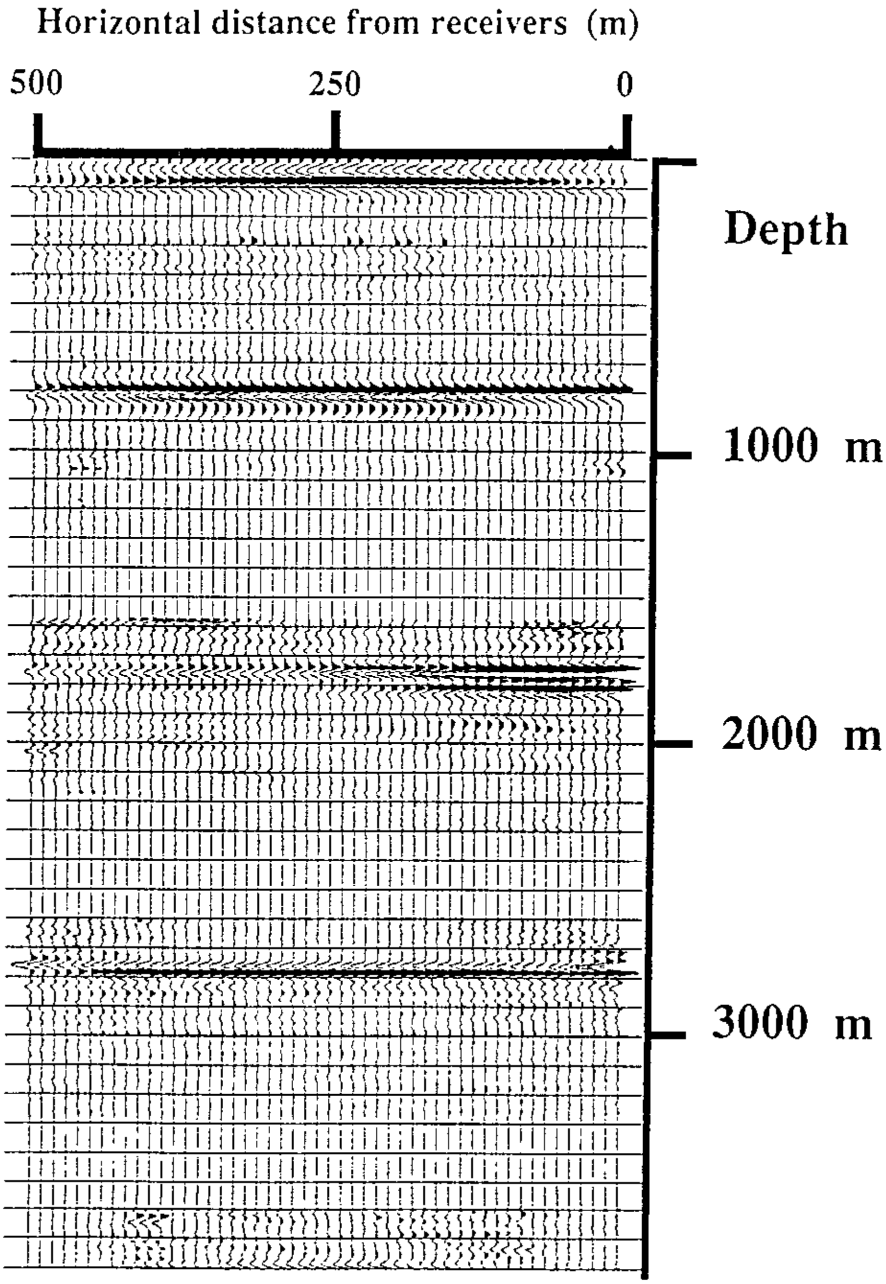


Figure 14. The supergather traces are stacked in appropriate bins to create the final section.