Chapter 6

Vertical Seismic Profiles

In this chapter the so-called Vertical Seismic Profile (VSP) is discussed: the seismic sensors are in the borehole while the seismic source is still at the surface. First, different types of VSP's are discussed. Next, it is explained how to obtain a reflectivity profile from raw VSP data. The result serves as a calibration for the surface seismic image: in VSP's we know both depth and time, so the velocity is much better known than from surface seismic.

6.1 Linking surface seismic to the borehole: Calibrating reflections at depth

In this chapter we will look at so-called Vertical Seismic Profiles. What is a Vertical Seismic Profile (VSP) ? It is a measurement where the seismic source is still at the surface but the receivers are lowered down into a borehole. The main advantage for such a type of measurement is that we know at which depth the receiver is, while from surface seismic we have to infer it from the time and the seismic velocity (which is inaccurate). Because in case of a VSP we know the depth of the receiver, we can obtain a more accurate profile of the velocity as a function of depth than from surface seismic.

In this chapter, we will first describe the geometry of different kind of VSP's, and what we can obtain from them. We will illustrate these different VSP's via some simple models. Then, we will look at a basic processing sequence to obtain a seismic trace from one simple (zero-offset) VSP that is similar to a trace from surface seismic.

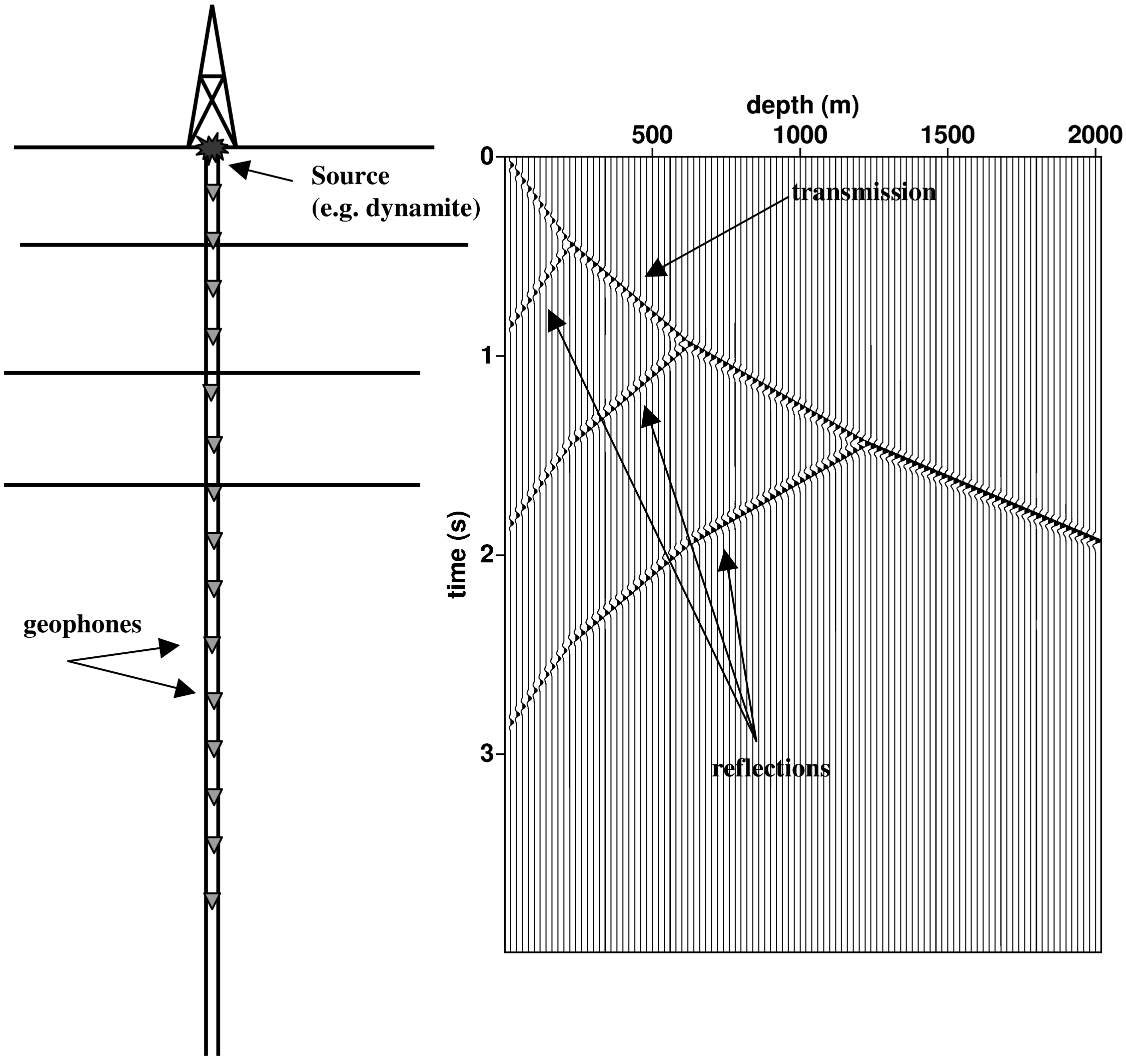

Figure 6.1: Zero-offset Vertical Seismic Profile; zero-offset means no horizontal distance between source position and the well.

6.2 Different types of Vertical Seismic Profiles (VSP's)

Figure 6.1 shows a configuration for a zero-offset VSP; here zero-offset means that the source is situated right on top of the borehole, i.e. no offset exists between the horizontal position of the borehole and the source. In the same figure, a linear event emerging from time $t = 0$ can be observed in the obtained recordings at depth, which can, of course, be interpreted as a direct wave from the surface to the receiver. Note that the horizontal axis is now *depth*, since we put the recordings of the receivers at different depths next to each other. Also note that below the first layer, i.e. , the receiver recordings taken inside the second layer, the slope becomes different; this is due to the different velocity inside the second layer. It can be seen from this direct arrival that we can use the slope of the event to determine the seismic velocity, either being the average velocity from the surface to the receiver, or the local seismic velocity between to consecutive receiver-positions. When we take the average velocity, we cannot directly use it for the surface- seismic since in surface seismic we used a root-mean-square velocity. It is important to realize this difference; of course, one can convert one into the other.

In the model of figure 6.1, a reflector is also present. In the recordings, this is the other linear event that has opposite slope than that of the direct arrival. Some points can be made here. First, note that the time is *increasing* with decreasing depth; this is clear since the wave is a reflection so is propagating *upwards*. Next, notice that that the event "stops" at the direct arrival; this is clear when it is considered that the reflected arrival can of course not be observed *below* the reflector, and that is where the receiver recording is taken. This crossing of the direct and reflected arrival can be used to determine the depth of the reflector itself. Finally, notice that the slope of the reflected arrival is the same as the one from the direct arrival, the same, only of opposite sign; this may be clear since the wave is travelling upward the same path as the direct wave travelling downward.

In the next section we shall discuss how to deal with such a zero-offset VSP from a processing point of view; first some other types of VSP's are discussed. In Figure 6.2 the configuration of a so-called offset-VSP is given; next to it recordings are modelled. The difference with the zero-offset VSP is that the source is now not right above the borehole but is displaced in the horizontal direction, i.e., has some offset; hence the name offset-VSP. In practice, this is always the case because it is quite awkward to put the source (e.g., dynamite or seismic vibrator) right on top of the casing. Usually, the offset is not too large compared to the depths of the receivers. In that case, the direct arrival shows some hyperbolicity in the shallow recordings. When the offset becomes relatively large compared to the depth of recording, one should be careful with interpreting the first arrival as the direct arrival: it could well be a refracted arrival from a deeper faster layer, comparable to a refraction in surface seismic.

So far, we kept the source at a fixed position, but it is of course possible to let the source change position and keep the receiver position(s) fixed. This is called a walk-away VSP, and is shown in Figure 6.3. In this figure, the same model of the subsurface as above is shown, and recordings are modelled next to it. What can be seen is that the direct arrival becomes hyperbolic as the reflections. These recordings are pretty similar to surface-seismic recordings. Because of its similarity, similar processing steps as in surface-seismic can be taken (although with some adaptation) such as CMP-processing, NMO, stacking, etc. This is how such a VSP if often used: it links reflections from the VSP directly to the reflections in the surface seismic. Often, the resulting seismic section from the walk-away VSP can be "spliced" into the surface-seismic section.

We have now briefly discussed some typical set-ups, but still more are possible. First to mention is that we can go around the borehole with the source positions. In that way

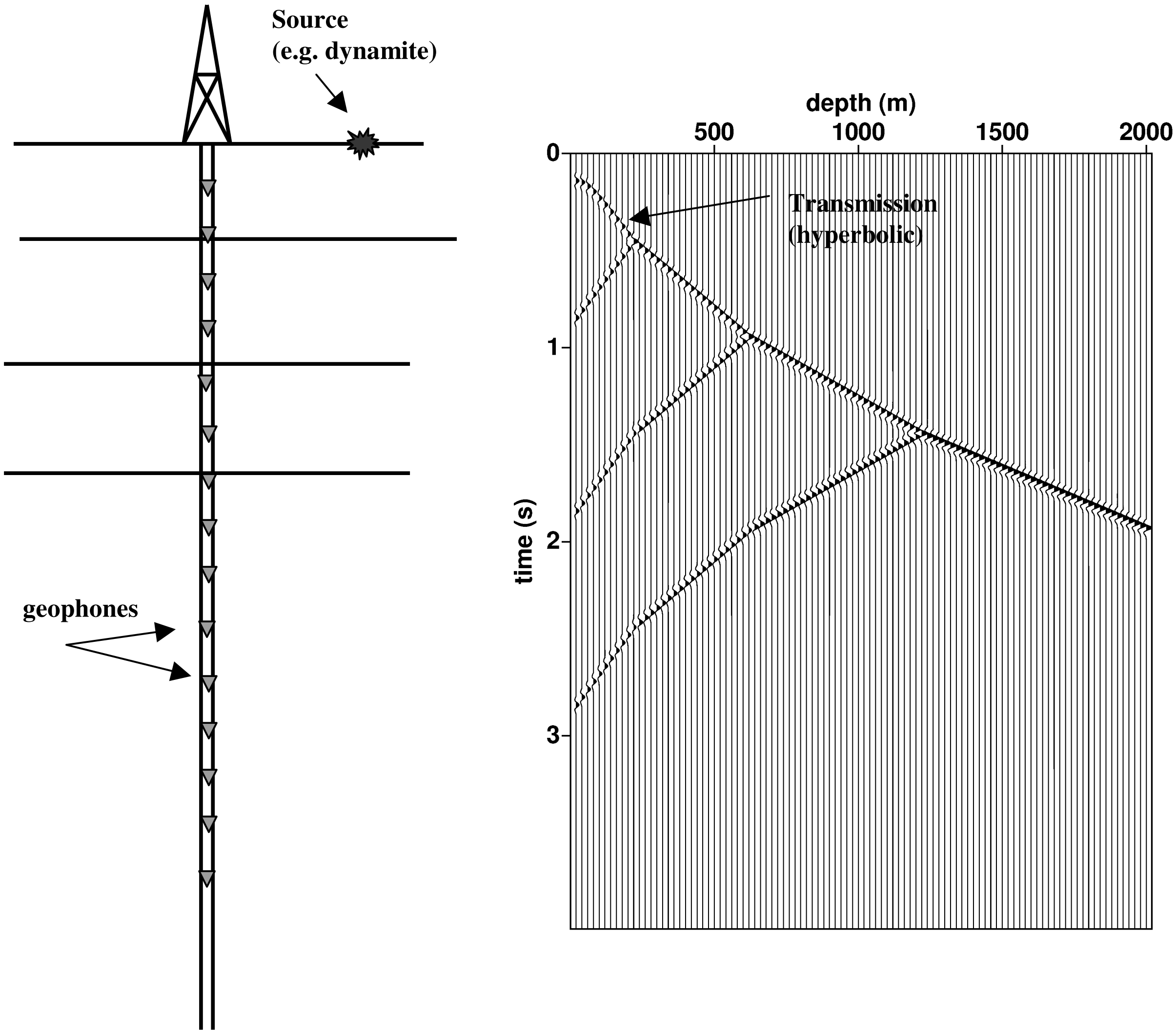

Figure 6.2: Offset Vertical Seismic Profile; offset means a fixed horizontal distance between source position and the well.

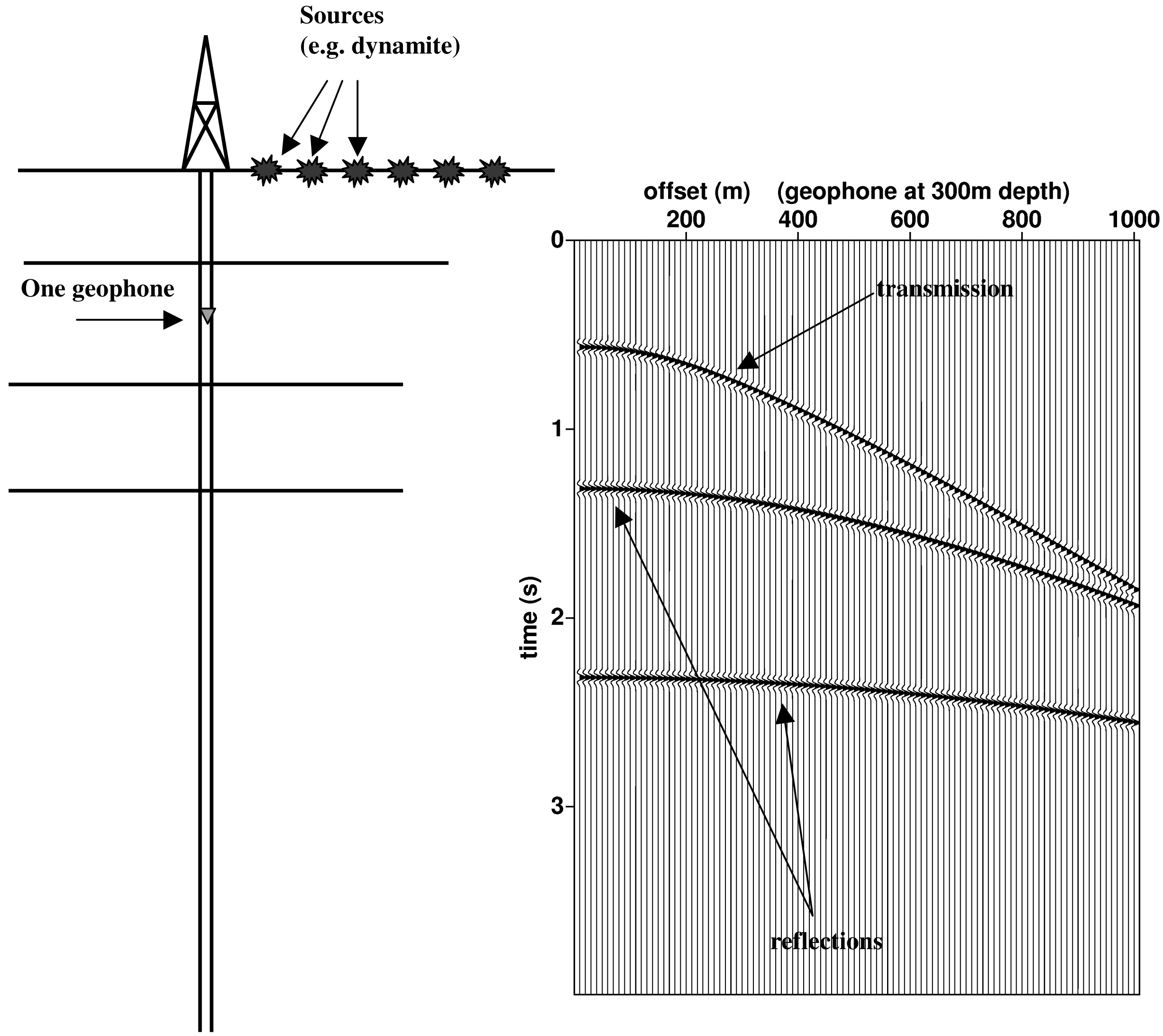

Figure 6.3: Walk-away Vertical Seismic Profile; walk-away means variable offset and fixed position (geophone) in the well.

we can obtain the velocities and reflectors near the borehole in an *azimuthal* sense; this can be very worthwhile when changes in velocity and/or reflectors are expected in different lateral directions. Next to mention as set-up is the most general one. One could do a full 3-D survey with a VSP: one could take the receiver depths as variable, the offset variable and the azimuth variable. Often, it is far too expensive to carry out such a survey, but in principle it is possible. From this set-up one can obtain a 3-D image of the whole area around the borehole.

6.3 Processing of a Zero-Offset VSP

In this section, we shall discuss how to deal with data that is obtained from a zero-offset VSP geometry. As discussed before, from this data two products are obtained:

- Velocity profile as a function of depth;
- Seismic trace, comparable to a surface-seismic trace.

For the first product, the direct or transmitted wave is used, while for the second product the reflected waves are used. However, for the second product, intermediate results from the first one are used. Let us start with the recordings as already shown in figure 6.1. The first step in the processing of such data is to align the first arrival, i.e., shift the first arrival to time $t = 0$; this is shown in figure 6.4. When the arrival is perfectly aligned, we know what time shift was needed; together with the depth of the receiver, we can determine the velocity profile in the borehole. This is our first product, and is shown also in figure 6.4.

What we observe in the figure 6.4 is that the reflected event is now even less from aligned, and the different events are not separated, the transmitted arrival is not separated from the reflected arrivals. To that end, the first arrival can be windowed out (the samples around $t = 0$ are set at zero). This is a too simplistic approach since there may be more transmitted waves than the direct arrival. Therefore a trace is generated that is an average of the direct-arrival-aligned data, and this trace is subtracted from the whole data set. This is shown in Figure 6.4. Since the data that aligned is subtracted, the figure now only shows the reflected up-going events. When we now down-shift the data with *twice* the static shift that we applied to align the direct arrival, we see that the reflected events now line up (see Figure 6.4). The final step in the processing is that the data of figure 6.4 is stacked/summed. The result is that one trace, the second product that we aimed for.

The processing steps that are important steps but may not have been clear in the previous example, are the subtraction of the average of the direct-arrival-aligned data and the stack. The reason is that these processes are able to remove *multiple* reflections. To that end, we have modelled recordings in the same earth-model as before but now with multiples in the first layer. In Figure 6.5 the intermediate results of the processing steps are given to show that the multiple reflections have been suppressed. The main differrence in the processing is the stacking. Now the summing (stacking) is done over a corridor,

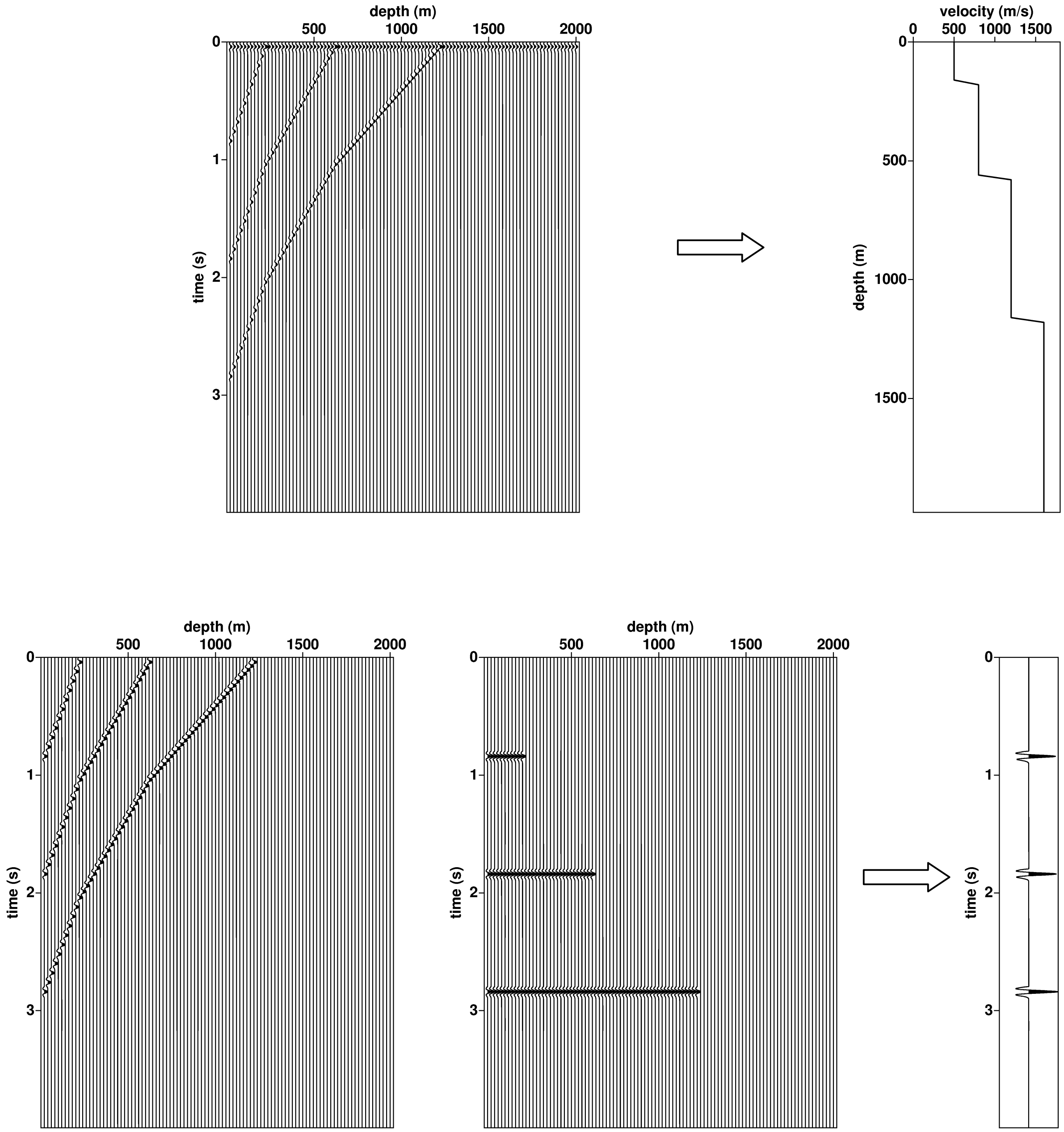

Figure 6.4: Processing VSP-data: aligning first arrival (upper left), resulting into velocity model (upper right); substracting first arrival (lower left); aligning reflections at two-way traveltime (lower middle) and stacking the reflection-aligned data (lower right).

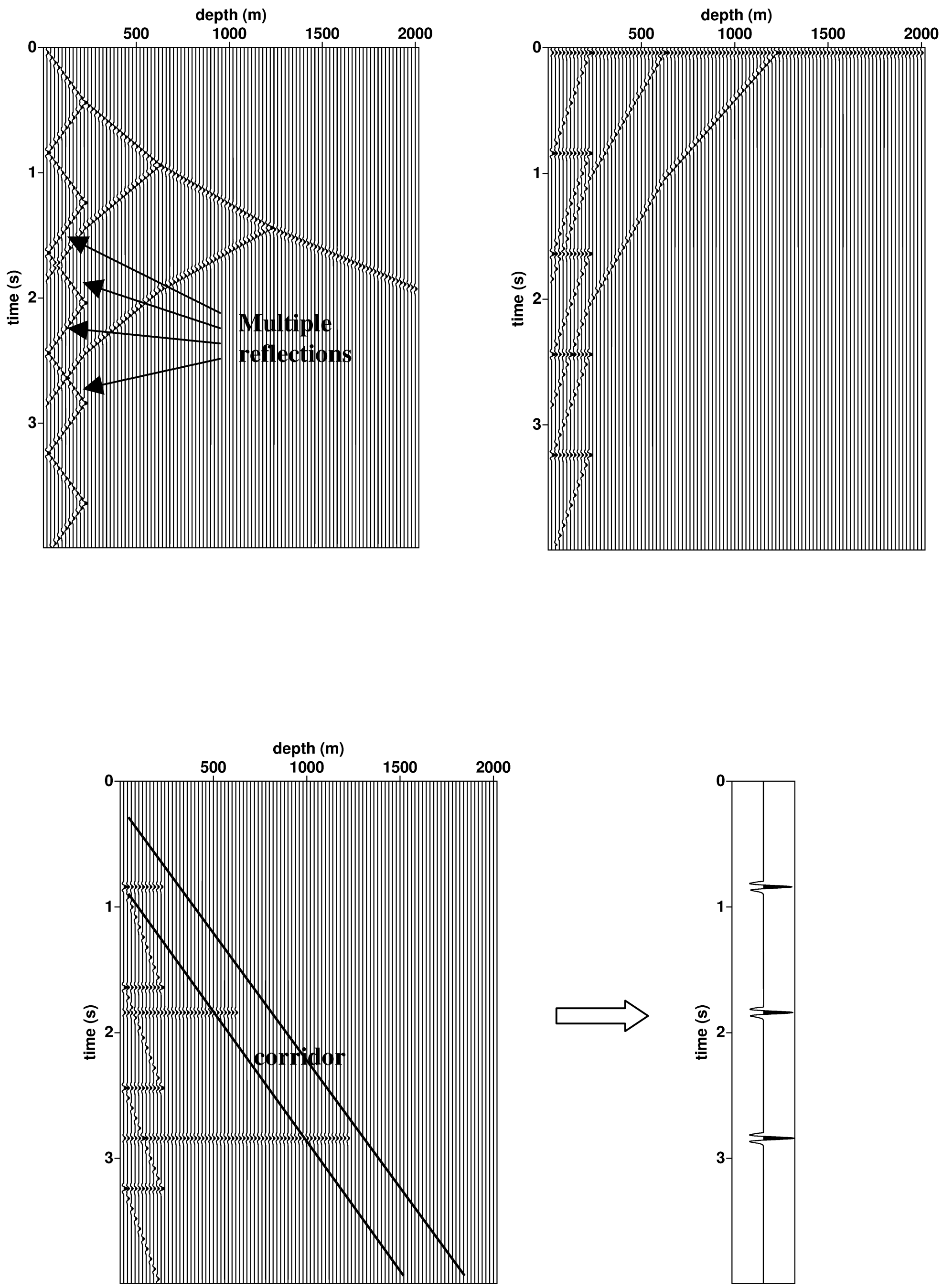

Figure 6.5: Zero-offset Vertical Seismic Profile with multiple reflections in first layer. Full recording (upper left), after aligning first arrival (upper right), after removal first arrival and aligning reflections (lower left) and after corridor stack (lower right).

since we do not want to have the multiples. Choosing this corridor judiciously prevents us from including the multiples in the stack. Again, the resulting trace, which can be compared with surface seismic but now *without* the multiples, is shown in that figure.

One last note with respect to VSP's in practice, which does not need showing via modelling, and that is the signal-to-noise ratio. In general, receivers at the surface pick up more noise (coherent and non-coherent noise) than receivers at depth. Therefore, VSP's have characteristically higher Signal-to-Noise ratio's than surface seismic.