Chapter 4

Interpretation of raw seismic records

In this chapter some typical records as obtained on land and at sea are analysed. On land, typically, events such as direct waves, refracted/head waves, surface waves and reflections can directly be observed in records. From these events velocities and estimates of depths can be obtained. At sea, typically, events such as direct waves, refracted/head waves, reflections and multiple reflections can directly be observed in raw records. For both these cases on land an at sea, a first model for the subsurface is estimated (where the model is here seen as the first interpretation of the data). Using the Fourier transformation, a filtering example is shown with the aim to separate different events in these raw records.

4.1 Introduction

As said in the last chapter, the goal of exploration seismics is obtaining structural subsurface information from seismic data. In the last chapter we discussed the elements which do *NOT* say anything about the earth itself. *Seismic processing* concerns itself with removing or compensating for the effects of waves that propagate through the earth such that an *image* is obtained from the subsurface. In this chapter, we will concern ourselves with what is "signal" and what is "noise", with the interpretations of these two on seismic records as recorded in the field. Next we discuss the possibilities to separate "signal" and "noise" and the possibilities to remove the "noise".

4.2 Seismic processing and imaging

Wave propagation versus signal to noise ratio

In seismic processing we are going to manipulate our measured data, such that we obtain an accurate image of the subsurface. We can consider two ways of introducing seismic processing to a newcomer.

One is in terms of wave theory. We have to understand the physical processes that are involved all the way from the seismic source, through the subsurface, to the seismic recording instrument. We have to try to obtain only those features which are due to the structure of the subsurface and not related to other features. For instance, we want to know the source signal we put into the earth such that we can compensate for it from our data later: the structure of the subsurface does not depend on the source we use. In this way we can remove or suppress certain unwanted features in the image.

Another way of introducing seismic processing to a newcomer is more in terms of the image we obtain: signal-to-noise ratio and resolution. In order to see the image we need to have at least a moderate signal-to-noise ratio. We would like this ratio to be as large as possible by trying to suppress unwanted features in the final image. The other aspect of the final seismic image is the resolution: we would like the image to be as crisp as possible. As you may know, these two aspects cannot be seen separately. Usually, given a certain data set, an increase in signal-to-noise ratio decreases the resolution (as information is stacked together), and also an increase in resolution (by correctly incorporating wave theory) has normally the consequence that the signal-to-noise ratio gets worse. In seismic processing we would like to obtain the optimum between the two: a good, although not perfect, signal-to-noise ratio with a good resolution.

In these notes we take the view of trying to understand each process in the wave problem, and try to find ways to cope with them. In this way we hope at least to increase the signal-to-noise ratio, perhaps at some costs with respect to resolution. This is a very important characteristic of raw seismic data: it has a very poor signal-to-noise ratio, and it needs a lot of cleaning up before the image of the subsurface can be made visible. It is along this line that we will discuss seismic processing: trying to understand the physical processes. Sometimes, we will refer to the effect it can have on the total signal in terms of signal-to-noise ratio and resolution.

With seismic processing, we have many physical processes we have to take into account. Actually, there are too many and this means that we must make simplifying assumptions. First, we only look at reflected energy, not at critically refracted waves, direct body waves, surface waves, etc. Of course, these types of waves contain much information of the subsurface (e.g. the surface waves contain information of the upper layers) but these waves are treated as noise. Also critically refracted waves contain useful information about the subsurface. That information is indeed used indirectly in reflection seismics via determining static corrections, but in the seismic processing itself, this information is thrown away and thus treated as noise. Another important assumption in processing is that the earth is not elastic, but acoustic. In conventional processing, we mostly look at P-wave arrivals, and neglect any mode-conversion to S-waves, and even if we consider S-waves, we do not include any conversions to P-waves. Some elastic-wave processing is done in research environments, but are still very rarely used in production. Money is better spent on 3-D "P-wave" seismics, rather than on 2-D "elastic" seismics; 3-D seismics with three-component sources and receivers are still prohibitively expensive in seismic data acquisition.

As said previously, the conventional way of processing is to obtain an image of the primary P-wave reflectivity, so the image could be called the ”primary P-wave reflectivity image”. All other arrivals/signals are treated as noise. As the name ”primary P-wave reflectivity” suggests, multiples are treated as noise (as opposed to ”primaries”); S-wave are treated as noise (as opposed to P-waves); refractions are treated as noise (as opposed to reflectivity). Therefore, we can define the signal-to-noise ratio as:

$$\frac{S}{N} = \frac{\text{Signal}}{\text{Noise}} = \frac{\text{Primary P-wave Reflection Energy}}{\text{All but Primary P-wave Reflection Energy}} \tag{4.1}$$

It can be seen now that processing of seismic data is to cancel out and/or remove all the energy which is not primary P-wave reflectivity energy, and ”map” the reflectivity in depth from the time-recordings made at the surface. In terms of total impulse response of the earth $G(x, y, t)$, we want to obtain that part of the impulse response of the earth which is due to primary P-wave reflections:

$$G(x, y, t) \overset{\text{Processing}}{\rightarrow} G_{\text{primary,P-wave,reflectivity}}(x, y, z) \tag{4.2}$$

In this chapter, we will look at the interpretation of raw seismic data as recorded in the field, but then mainly to see which ”event” is interpreted as what, and therefore can be categorized as being ”signal” (desired) or ”noise” (undesired).

4.3 Interpretation of some field seismic records

Land record

Let us consider first a record, which has been recorded on land. In Figure 4.1 a field recording is shown. The first event we are considering, is the ”first arrival”. It shows itself by giving a pulse after a quiet period. This arrival is interpreted as a *refraction* which we already discussed in a previous chapter. The velocity with which it propagates along the surface is: 2400 meters in 500 ms = 4800 m/s. This is a relatively high velocity so is probably some very hard rock. Below the record in figure 4.1, a simple model is shown that explains this first arrival; the synthetic record belonging to this model, is given on the top right of the figure.

The next events we consider are the strong events which crosses 2400 meter at some 1.3 seconds. This event is interpreted as ground-roll or surface waves (they propagate along the surface). Calculating the velocity, we come to 1850 m/s. Again, the simple model below the record explains this ground roll; the synthetic record on the top right of the figure also shows this arrival.

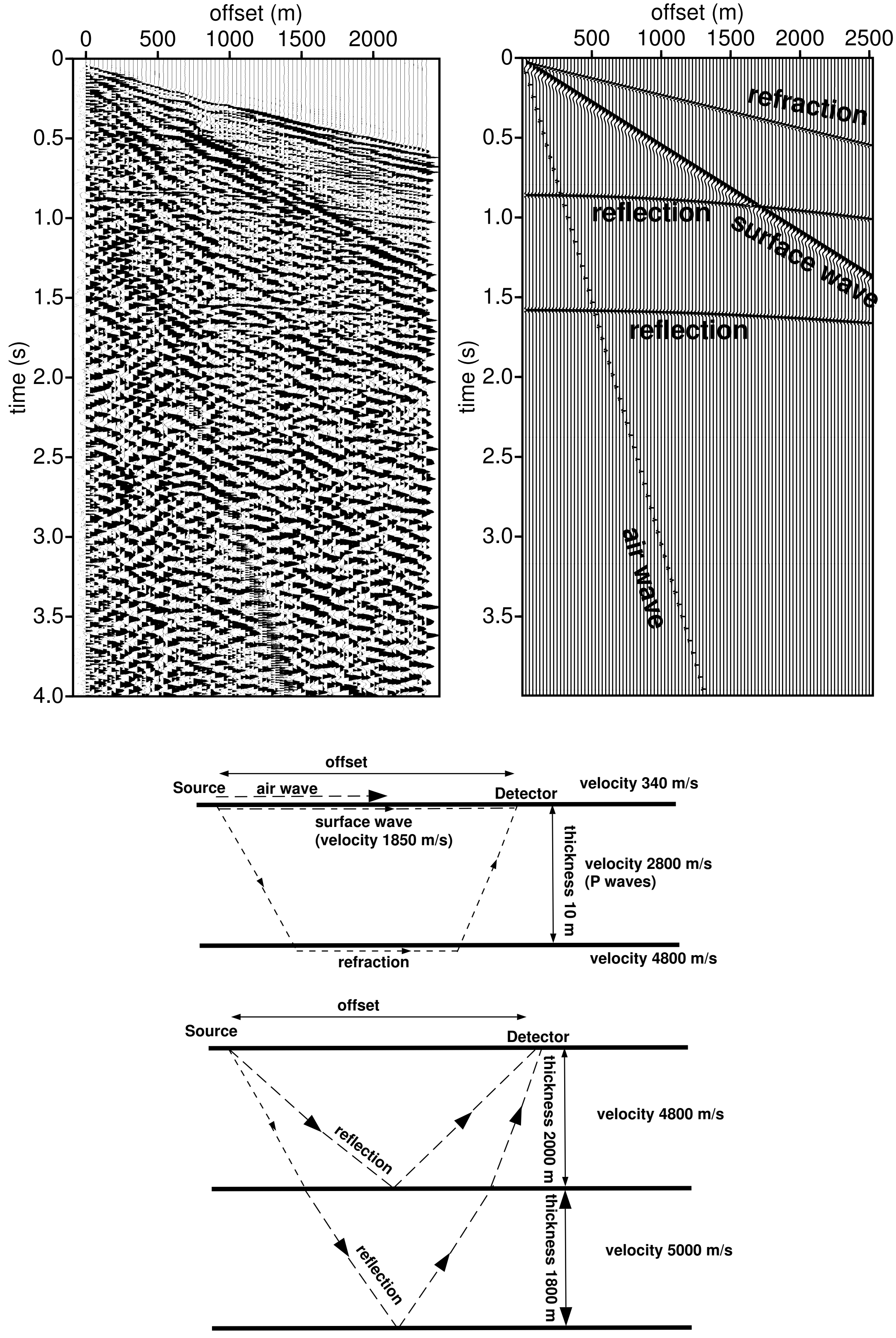

Figure 4.1: Field seismic shot record from land survey (top left), its synthetic seismogram (top right) using model of near surface (middle) and model at larger depths (bottom).

Also in this field record, a "high-frequency" event can be observed which goes through the 4-seconds mark at about 1300 meters distance. Calculating the velocity from this, we come to some 325 m/s. It may be clear that this is a wave that goes through the air. This event is also synthesized in the top right figure, using the model as given below it.

Last, but not least, are "high-frequency" events which are slightly curved, e.g. the ones at 0.9 and 1.6 seconds. These events are interpreted as reflections from layer boundaries in the deep subsurface. Those are usually the events we are interested in, when we want to obtain an image of the subsurface. Using a simple model as given at the bottom of the figure (which explains the deeper part of the earth), the synthetic record for these events is also shown in the top right of the figure.

In the above, we have interpreted four types of events, which can be captured in one combined model and are shown in one combined synthetic seismogram. These synthetics explain the most important events in the raw seismic record. Still, when looking at the resulting synthetic seismogram, we see that we are very over-simplifying the situation since the synthetic and field record are only resembling in the arrival times of the most important events. When looking at the general characteristics, they are very different indeed.

The field record we discussed so far, was recorded on some hard rocks where the velocities are relatively high. However, when shooting data on land with some loose top soil, the characteristics are much different. In Figure 4.2, a field record of such a situation is given. Again, we can determine the main events in this record. Let us first consider the "first arrival", i.e. the arrival that is coming in first after a quiet period. As usual, this is interpreted as a refraction as shown in the figure below the record. The velocity can be determined: we come to some 1600 m/s. This velocity is very near the velocity of water, so this refraction may be due to the water table. In the right figure, the synthetic shows this arrival.

The next event is the most prominent one, namely the event which goes through the 1-second mark at some 180m, so its velocity is around 180 m/s. This arrival is interpreted as "ground-roll"/surface waves, which travel along the surface. The model which explains this arrival, is given again below the record, and its synthetic shown on the top right.

The most important events for this record, are the "high-frequency" events which are the sightly curved arrivals, which can all be interpreted as reflections from deep layers. The number of reflections are too many; only a few are synthesized in the record on the top right, using the model as given at the bottom of the figure.

Again, when comparing the synthetic to the field seismogram, it is obvious that we have very over-simplified the earth; the positive side is that we have probably been able to understand most of the events in the field record.

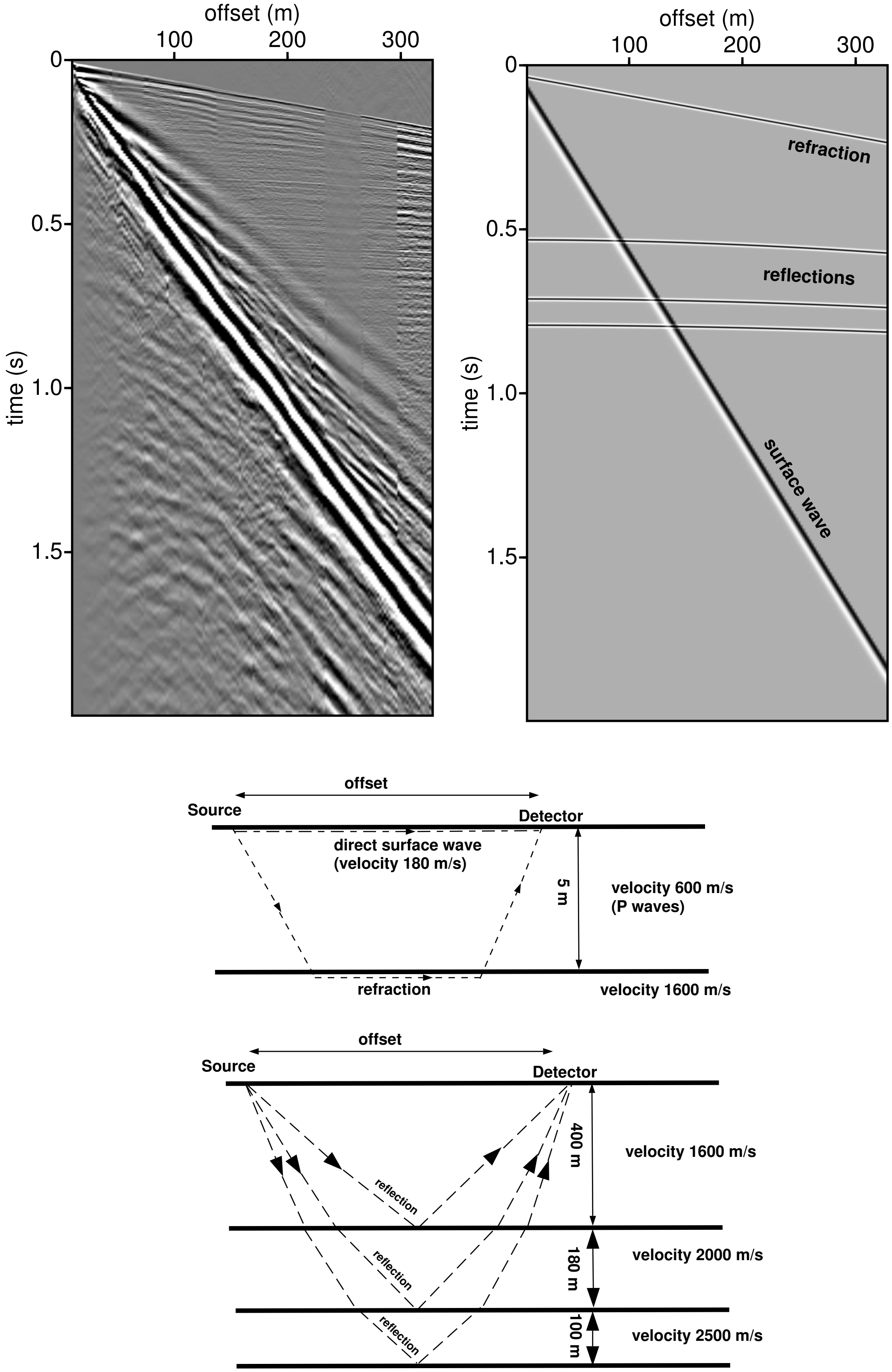

Figure 4.2: Field seismic shot record from land survey with loose top soil (top left), its synthetic seismogram (top right) using model of near surface (middle) and model at larger depths (bottom).

Marine record

Figure 4.3 shows a raw seismic recordings, made at sea. This record is much "cleaner" than the land record, as we measure in a water layer, which is a good conductor for sound.

Let us analyze some separate events again. The first event in the marine record is the faint one, going nearly through the origin. It crosses the 500 meter at some 340 ms; this means a velocity of some 1470 m/s. It may be clear that this is the direct arrival from the source to the receivers through the water, as explained in the model below the record. This direct arrival is thus a body wave, since it travels with the velocity of water.

The next event is the first arrival at farther offsets; this arrival is interpreted as a refractive event. When analyzing the distance travelled over time, i.e. the apparent velocity, a velocity of roughly 2000 m/s is obtained. Using the results for a refraction in the first chapter, a depth of 300 meter is obtained. This is quantified in the model below the figure, and its associated synthetic seismogram in the figure on the top right.

The third event we analyze is the first strong event that looks hyperbolic: starting at some 0.4 seconds and bending down to some 2.2 seconds at 3200 m offset. Clearly, because of its hyperbolic behaviour, it is interpreted as a reflection. When looking at later times, we some more strong hyperbolic events, such as at 0.8 seconds (bending downward toward some 2.3 seconds), and at 1.2 seconds (bending downwards toward 2.4 seconds), and even more. These events are interpreted as so-called multiply reflected waves, i.e., waves that bounce up and down in the water layer. In fact almost all events we see below 0.8 seconds are due to multiply reflected waves, or short-hand: multiples. The times at which the multiply reflected waves arrive, seem to be periodic; this is indeed the case. A simple model explaining these events, is shown in the figure below the record, with a water layer of 300 meter. The resulting synthetic seismogram is shown on the top right of the figure. It may be clear that the multiply reflected waves come from the same reflective boundary in the subsurface, namely the sea bottom (and the sea surface, of course), and are therefore superfluous. They are considered as noise, the only one being "signal" is the one at around 0.4 seconds.

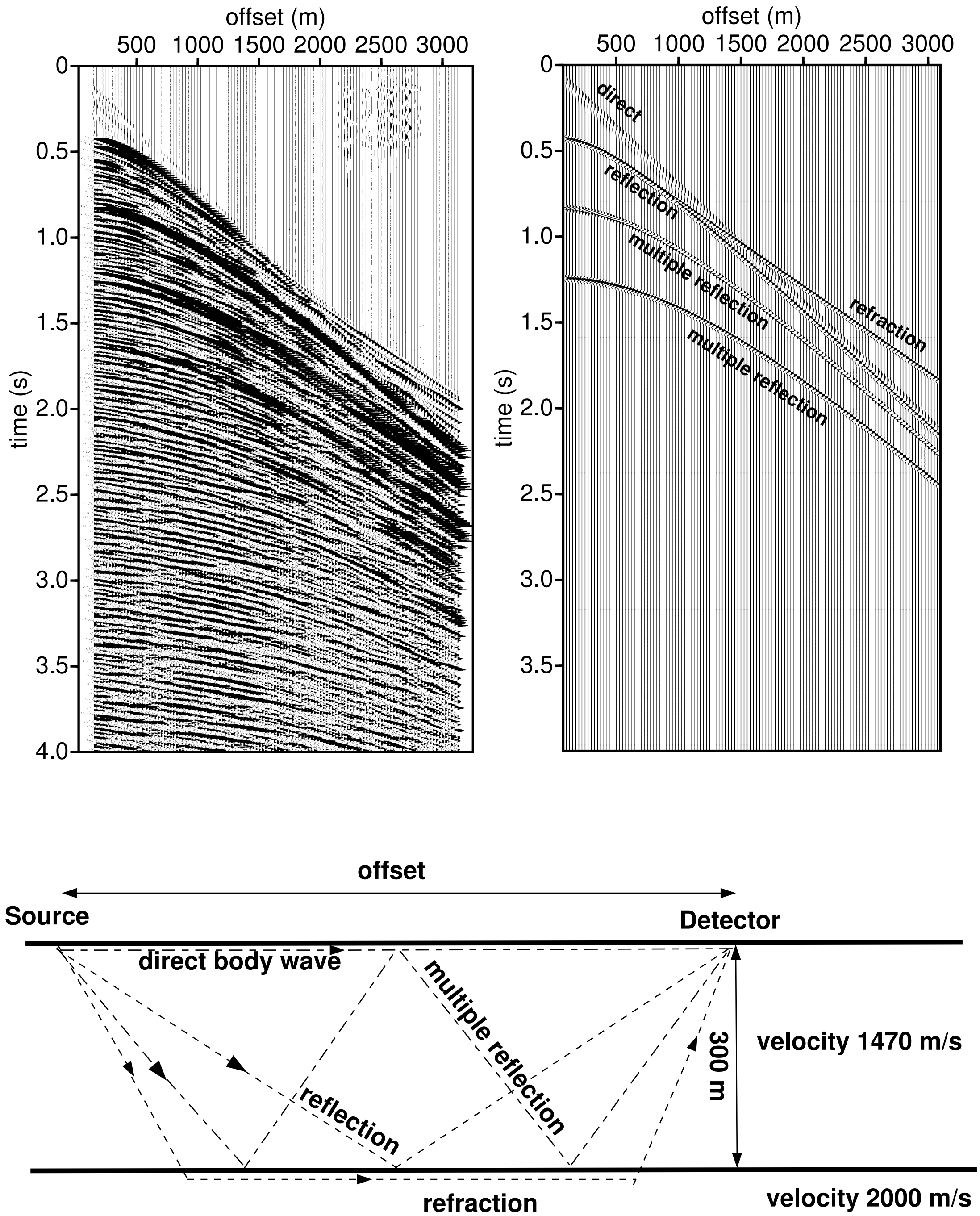

Figure 4.3: Seismic shot record from marine survey (top left), its synthetic seismogram (top right) using model of water layer and sea-water bottom, where only the path of one multiple reflection is drawn (bottom).

4.4 Spectral analysis and filtering of field seismic records

In the previous section, we analyzed the data as they are recorded in the field. However, we only looked at the data as a function of *time*, not of frequency. When we look at the data of the previous section in more detail, we see that the events have a wavelength which differs for the type of event. In particular, let us consider the data from figure 4.2. The surface wave has a longer waveshape (lower-frequency) than the reflections and refractions; in the modelling we already took account of this, as can be seen in the synthetic seismogram on the top right of the figure. Also in the other land record, figure 4.1, a difference in length of waveshape can be observed. The surface wave has also here a longer waveshape than the reflections. The event with even another length of waveshape is the air wave. It has a very "high-frequency" shape.

It may now be clear that when we make *spectra* of these data, i.e., transform the time-axis to a frequency axis using the Fourier transformation, that different arrivals will give different peaks in the Fourier spectra. What we achieve is that we can analyze and interpret different frequencies in terms of different events. Moreover, we can start thinking about using the Fourier-transformed data for filtering purposes, i.e., removing certain frequency bands with the aim to remove undesired signal, like, e.g. the surface wave. Let us look at some spectra.

In figure 4.4, we have selected only 3 traces to illustrate our points. On the left of the figure, we plotted the 3 traces as a function of time; we can still observe the first arrival and the surface wave, which is characterized by its long waveshape. In the plot next to it, we have plotted the amplitude spectra of these 3 traces. First of all, notice that we obtain frequencies up to 500 Hz, which is the Nyquist frequency $f_N = 1/(2\Delta t)$, associated with the sampling interval: $\Delta t = 1$ ms. Next, it is evident that the largest amplitudes occur at the low frequencies, i.e., around 10 to 15 Hz. It may be clear that these frequencies are associated with the surface wave. Finally, it is not clear from the amplitude spectra where the reflection information is; when we look at the whole record we would expect it to be at higher frequencies.

Let us now *filter* the data, i.e., make the amplitudes zero at certain frequencies. Since we are *not* interested in the surface waves, we can make the amplitudes zero at the low frequencies. This is done in the next plot; notice that the plot is scaled to the maximum of the spectrum, so now other amplitudes become visible. When we transform this data back to the time domain, we obtain the rightmost plot. We see that we have effectively removed the surface wave.

From this plot, we cannot see whether we have changed the character of the whole record. To that end, all the traces of the original field record have been filtered with the same filter as we did for the 3 traces, and the result before and after filtering is shown in figure 4.5. What we can now see is that the surface wave is indeed pretty well removed, although not completely, and that the reflection are hardly affected. We can now even see the reflections that were masked by the surface wave before we did any filtering.

It may now be clear that we have removed the most important ”noise” in the field record. Before we did the filtering, we had a signal-to-noise ration which was well below 1; after filtering the signal-to-noise ratio is larger than 1 since the highest amplitudes now seem to be the reflections themselves. What is important to realize is that, using the Fourier transformation, we have obtained a method to *separate* the surface waves from the reflections. In the time-domain, the surface waves crossed the reflections and therefore we could not make the ”time”-amplitudes of the surface wave zero: we would then also have removed part of the reflections.

In this example, we have shown the power of filtering via analysis of Fourier-transformed data. This has solved one problem, namely the one of surface waves. However, many cases exist where such a filtering is partly successfull, and other types of filters are necessary. In the case of multiple reflections, as seen in the marine record (figure 4.3), transforming the time axis to a frequency axis does not solve anything since the multiple reflections have the same frequency contents as the primary reflections: we cannot achieve a separation between ”signal” (primaries) and ”noise” (multiples), so filtering cannot help us here.

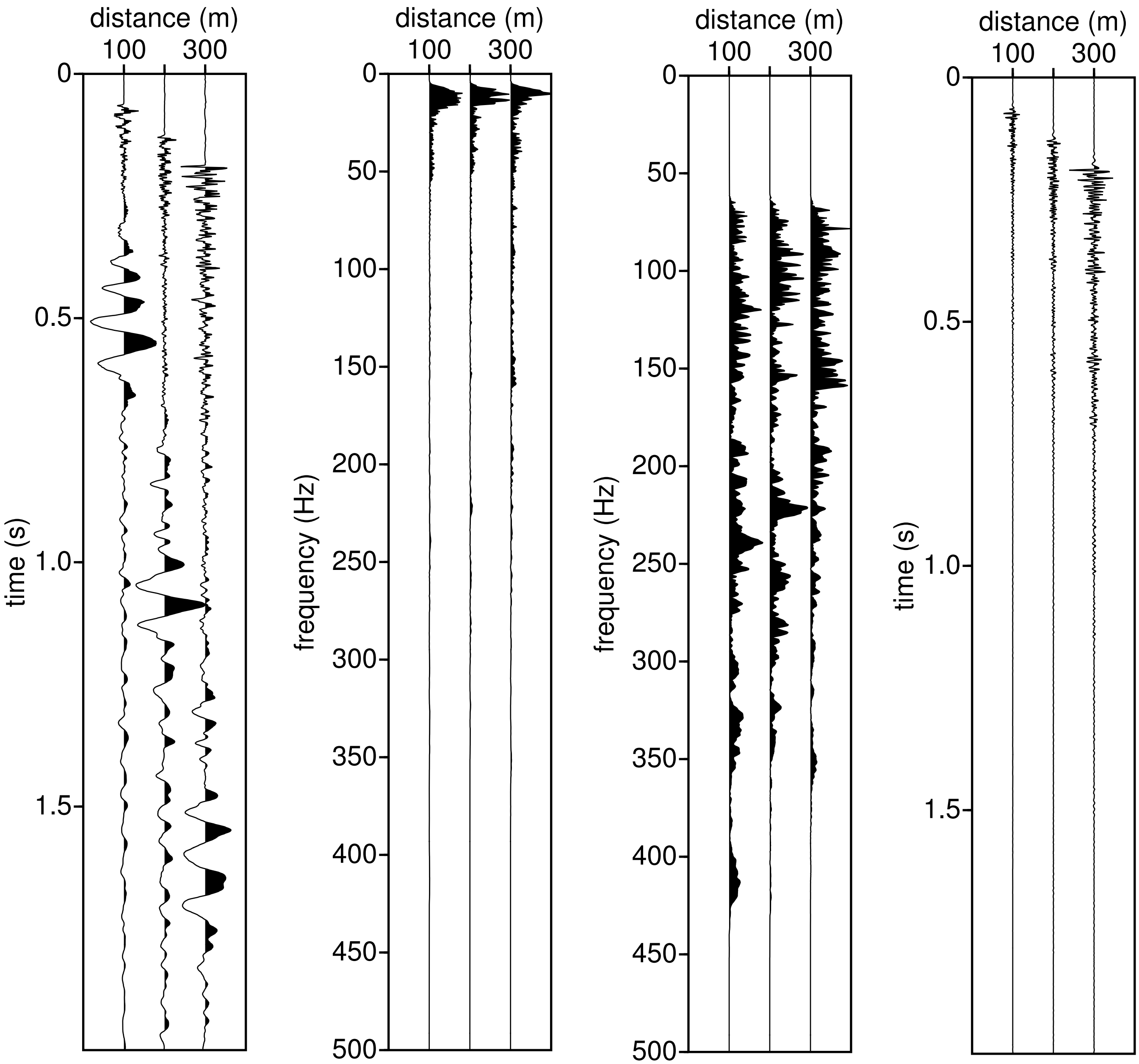

Figure 4.4: 3 seismic traces from raw seismic field record for analysis. From left to right: 3 original traces; amplitude spectra from Fourier-transformed traces; amplitude spectra from Fourier-transformed filtered traces; filtered traces.

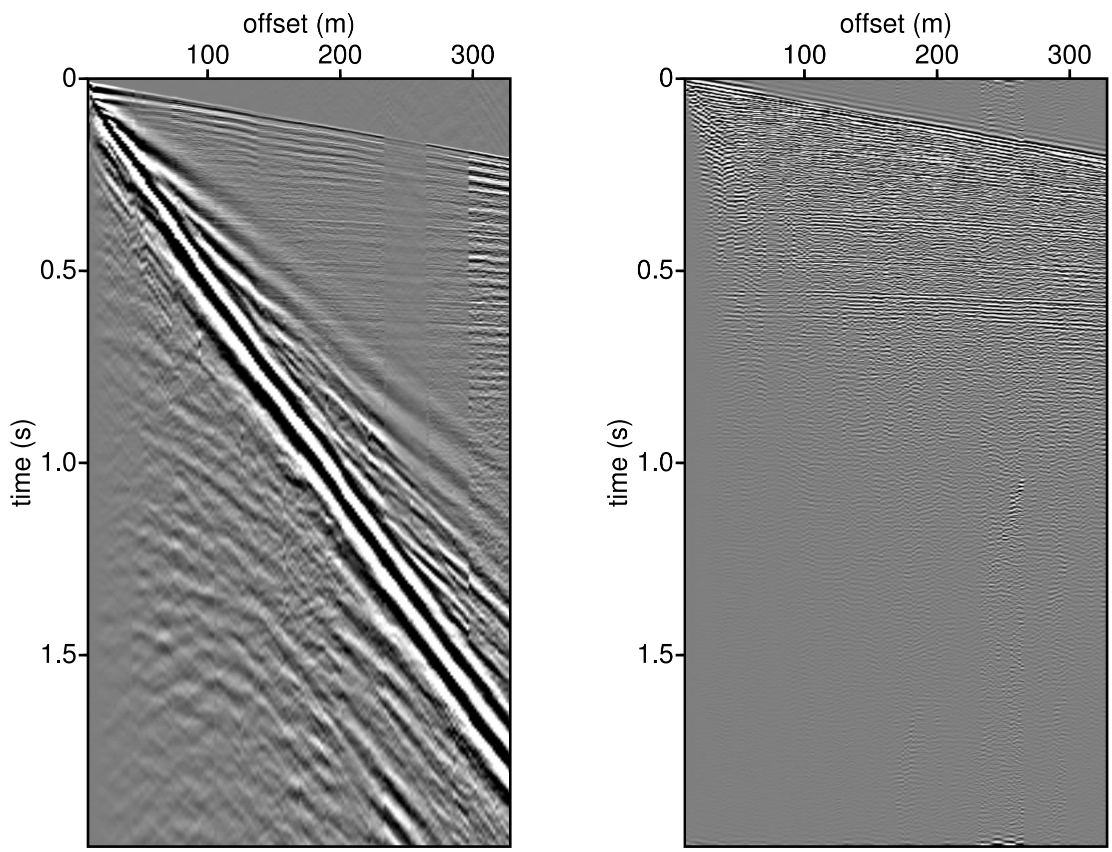

Figure 4.5: Seismic shot record from land survey with loose top soil. Original record (left) and record after removing low frequencies (right).