Chapter 1

A drill-bit source experiment

Several authors have used the drill bit as a seismic source. In one type of study (?), an accelerometer is placed on the drill string, giving an estimate of the signature of the drill bit source. Crosscorrelating this estimate with the data recorded by one or more geophones enhances drill-bit energy in the recorded traces and gives results whose quality is comparable to VSP data.

A second study (?) located the drill-bit signal using an eight channel array, with no accelerometer on the drill string, for the purpose of guiding the drill bit during drilling.

In a third study, Kostov (?) obtained an estimate of the drill-bit source signature from 2-D seismic data. A 1-D array containing up to 90 geophones was used, and the drill-bit signal was separated from other noise sources by virtue of its spatial coherency. While Kostov was able to detect direct arrivals from the drill bit, the strongest noise sources seen were surface sources located off the line, which could not be suppressed with the 1-D array. These noise sources complicated processing considerably.

A 2-D array with a large number of channels, such as that used in the passive seismic experiment of the previous chapters, offers improved ability to determine the arrival direction of incident energy and to suppress unwanted noise sources. In November 1990, I used a 240 channel 2-D array to record data during the drilling of a well in a producing oilfield in Wyoming. A diagram of the array is shown in Figure 1.1. The 240 channels were selected from a larger array of 480 channels that was previously used to study ambient noise in the same oilfield (?). The array consisted of 11 lines of geophones, with an average inline spacing of 100 feet and an average crossline spacing of 150 feet. On one line in the middle of the array a smaller spacing of 50 feet was used.

Data were recorded over a period of three days, during which the drill bit covered a range of depths from approximately 800 to 1400 feet. Operational constraints limited us to this fairly narrow range. A total of 64 records, each 99 seconds long and with a sampling interval of two milliseconds, were taken during that time. During most of

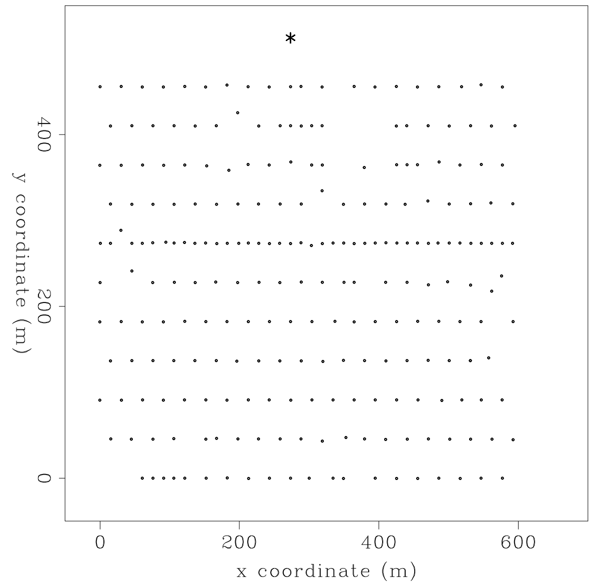

Figure 1.1: 240 channel array used for drill-bit study. Dots are geophone locations, asterisk at top is location of drilling rig. Geophones were cemented in place at a depth of 30 feet. drillbit-drillmap [NR]

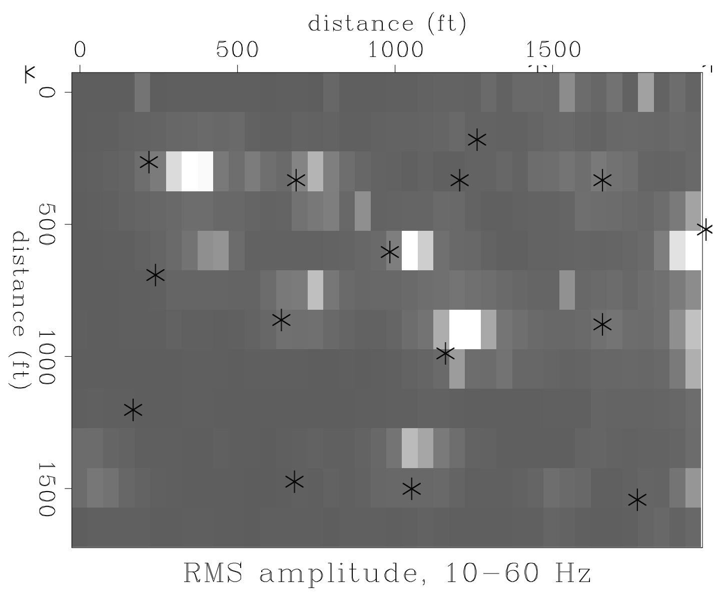

Figure 1.2: RMS amplitude for a portion of one data record as a function of receiver location. Asterisks mark the locations of pumps, a number of which were active during this record. drillbit-rms [NR]

the recording time, many strong surface noise sources were active, including drilling-related equipment and 10 to 12 producing pumps located throughout the array. We were fortunate to have been able to turn off these pumps at one point during the recording. Eight records were taken during this quiet period. As will be seen later in the paper, first results from this quiet period are much superior to the results obtained from other records.

In this paper, I begin the study of the data by searching for sources of energy in 3-D. I construct a cube of possible source locations and then, given an estimate of the velocity model, stack the data (or compute semblance) along the moveout trajectory corresponding to each source location. To begin, I use a constant velocity. When applied to data from the "quiet" period where pumps located within the array were turned off, this technique reveals what appear to be direct arrivals from the drill bit. Two different records from that time period give a consistent picture. In contrast, data from outside the quiet period present a noisy background against which it is not possible, at least with this simple method, to detect the drill bit signal.

While stacking with a constant velocity appears to do a good job, it would be useful to obtain velocity information directly from the data, rather than arriving at a good stacking velocity by trial and error. A velocity analysis can be performed at the drill rig location; I scan for hyperbolic events whose tops lie beneath the surface location of the drill rig. The parameters are stacking velocity and the depth of the source. This analysis also reveals the drill bit signal, when applied to data from the quiet recording period, and concludes that the constant velocity value that seemed to position the drill bit energy well in 3-D was in fact a good choice.

Finally, having found via constant velocity stacks what I believe to be energy from the drill bit, I stack the data along the correct moveout trajectory to come up with an estimate of the drill bit source signature, analogous to the source signal estimate obtained by Rector et al. from an accelerometer placed on the drill string. Crosscorrelation of the data with this estimate enhances drill bit energy, preserves the moveout present in the data, and compresses the continuous-time drill-bit signal to a narrow window centered around the zero lag of crosscorrelation.

1.1 Locating sources in 3-D

To search for sources (such as the drill bit) in 3-D, I first construct a cube of possible source locations. Then, given an estimate of the velocity structure, I compute the moveout trajectory for energy arriving at the array from each possible source. I compute semblance over this moveout trajectory and examine the resulting 3-D semblance cube.

Figure 1.3 shows constant-depth slices from such a cube, taken at the known depth of the drill bit. A constant velocity of 10000 ft/sec has been used to compute moveout trajectories. The four frames correspond to four different data records; the two top records are from the "quiet" period where pumps within the array were turned off. In the case of the bottom two records the pumps were operating. The asterisk denotes the surface position of the drilling rig. When the pumps are turned off, the largest semblance values (shown in white) occur at the drill bit location. These semblance values are likely due to direct arrivals from the drill bit.

Figures 1.4 and 1.5 show constant y-coordinate and constant x-coordinate slices through the same cube, for the same four data records. The agreement with the drill bit location in all three dimensions strengthens the claim that these large semblance values are due to direct arrivals from the drill bit. The resolution in space is not very good because only frequencies up to 40 Hertz have been used. Higher frequencies degrade the pictures – probably not because the drill bit signal does not contain higher frequencies but rather because the moveout of the signal departs from a constant-velocity hyperbola, and the higher frequencies are more sensitive to mis-stacking.

1.2 Velocity analysis

Rather than selecting a good stacking velocity by trial and error, it would be better to perform a velocity analysis. Velocity analysis proceeds much like the search for sources in 3-D, except now we scan over velocity in addition to scanning over the three spatial dimensions and over time.

The result of velocity analysis is a five-dimensional data volume. This means that the technique is expensive. As an example, using 20 points in x and y, a single depth, 30 velocities, and records containing 4000 time samples and 240 input channels requires roughly 80 minutes of cpu on a Convex C-1. More importantly, the five-dimensional volume means that the result will be difficult to display and interpret. We can easily remove one dimension from the result by performing semblance computations over a single window whose length is that of the entire trace. For sources that should be operating continuously over time, this is a sensible thing to do.

To further simplify interpretation of the results, we can hold one or more parameters fixed while the others are varied. This approach is taken in the following section. I hold x and y fixed to the known location of the drill bit (and other sources) and compute semblance as a function of stacking velocity and source depth.

1.2.1 Velocity analysis at fixed surface positions

We know not only the drill-bit location, but also the locations of other sources. Sixteen pumps (some not operating during this experiment, others operating intermittently) and one steam injection well are also located within the bounds of the array. We can simplify velocity analysis by limiting ourselves to hyperbolic trajectories whose tops are below these points.

In this section, I perform velocity analyses at the surface locations of the drill rig, the steam injection well, and three pumps. This is done for two different data records

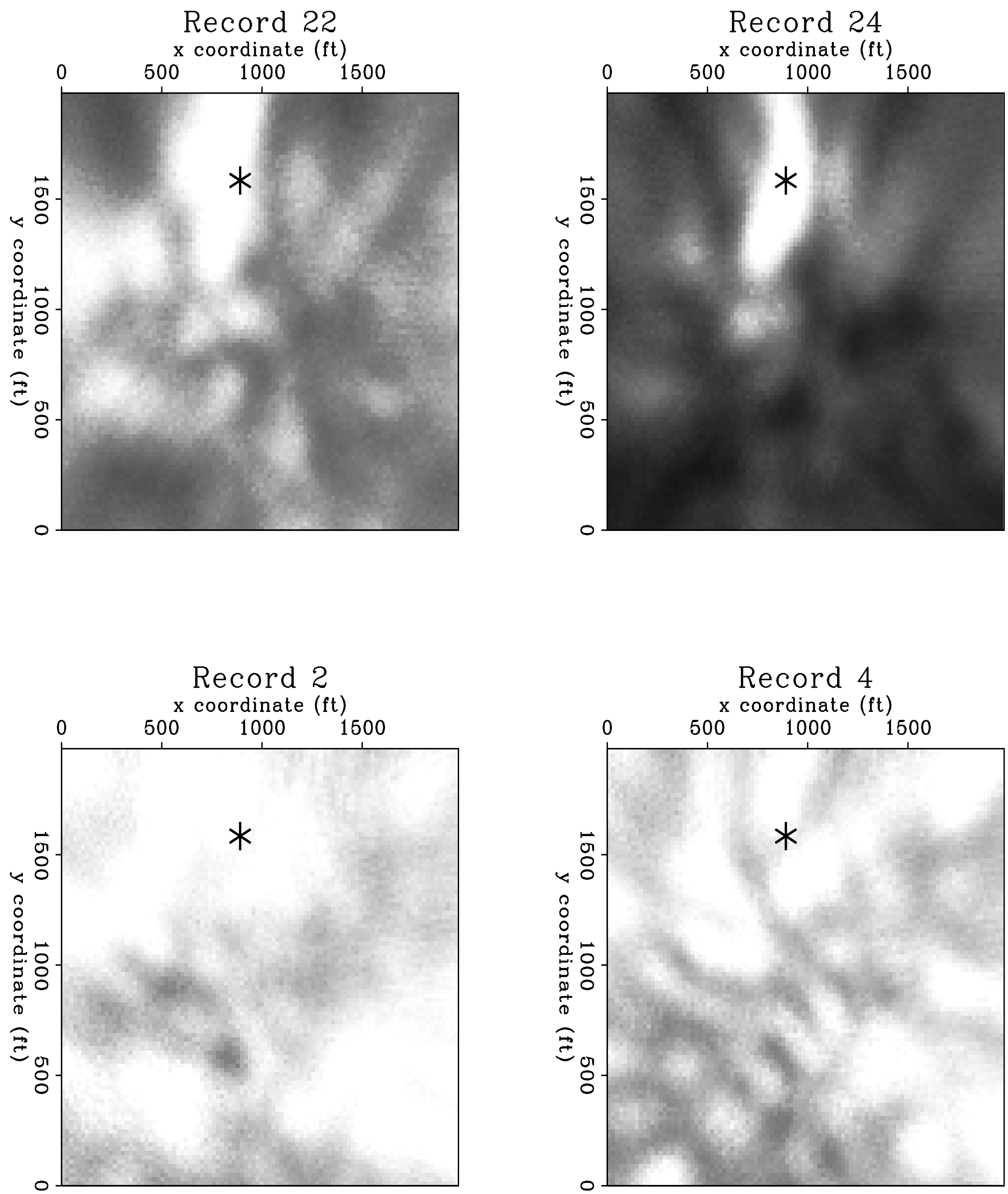

Figure 1.3: Stacking semblance as a function of x and y coordinates at the drill-bit depth for four different data records. The largest semblance values are shaded in white. For the top two records, taken while pumps within the array were turned off, the largest semblance values are at the drill bit location, suggesting that we are able to see direct arrivals from the drill bit. For the bottom two records, where the pumps were operating, the results are much poorer. Note that the top and bottom plots are scaled differently for comparison; the largest semblances in the top plots are nearly three times those on the bottom. drillbit-plotxy [CR]

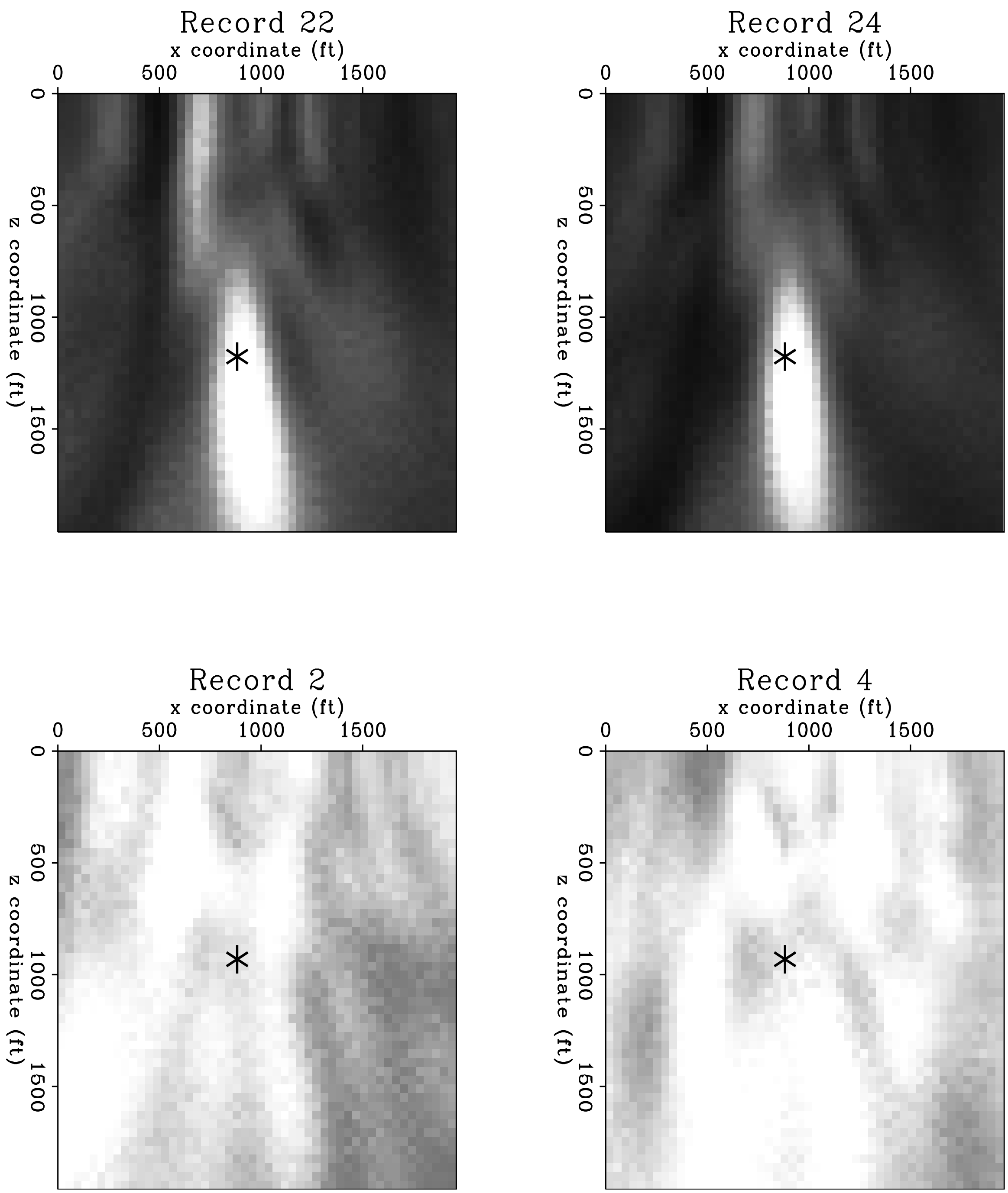

Figure 1.4: Stacking semblance as a function of x and z coordinates for a plane passing through the drill bit location. The asterisk denotes the location of the drill bit; note the change in depth between the top and bottom pictures. The largest semblance values, shaded in white, coincide with the drill bit location for the two records from the recording period where pumps within the array were turned off. drillbit-plotxz [CR]

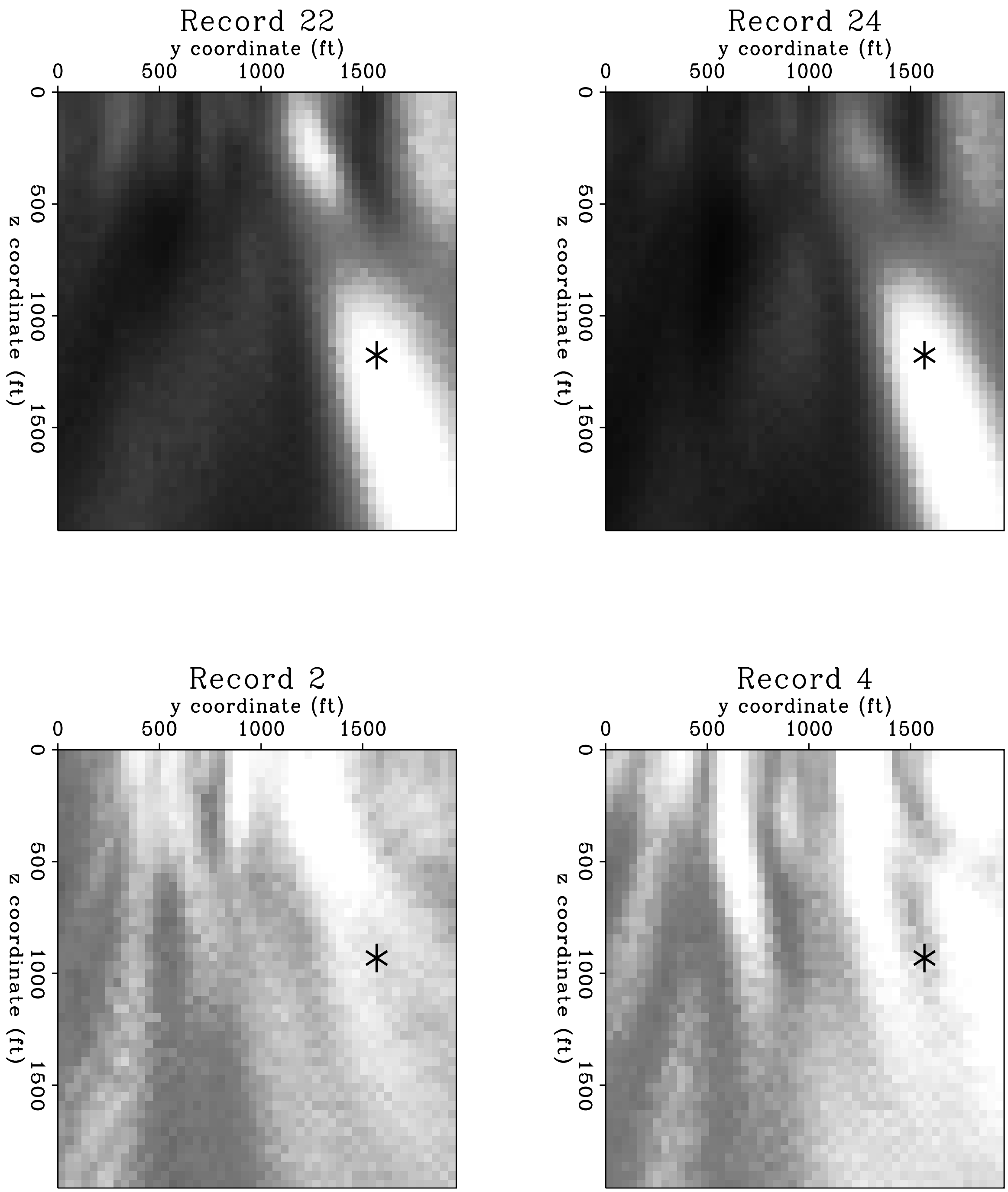

Figure 1.5: Stacking semblance as a function of y and z coordinates for a plane passing through the drill bit location. The asterisk denotes the location of the drill bit. As in the previous two plots, the largest semblance values correspond to the drill bit location, further suggesting that the semblance values are due to direct arrivals from the drill bit. drillbit-plotyz [CR]

– one where the pumps were operating, and one where they have been temporarily turned off.

Figure 1.6 shows the result of velocity analysis at the drill rig location. Again the largest semblance values are shown in white. The top 1% of semblance values are clipped by the plot program and shown in black. As in the case where a constant velocity was used to compute semblance in 3-D, here we get a clear picture of what I believe to be direct arrivals from the drill bit. The horizontal line on the plots indicate the depth of the drill bit. This line intersects the main feature of the plots (for the records from the "quiet period") near the constant velocity of 10000 feet/second that we found in the previous section to do a good job of stacking. As in the previous section, when the pumps are operating there is no good evidence of drill bit signal.

The dominant features in most plots dip toward lower velocities at greater depths. This feature can easily be explained. Energy from a source at great depth will exhibit very little moveout across the array. The same moveout can be expected from shallower sources only if the medium velocity is correspondingly higher. There is a tradeoff between depth and stacking velocity, and this tradeoff explains the dipping features. This tradeoff is a necessary consequence of the fact that our source is operating continuously over time rather than being impulsive.

1.3 Source signal estimation and crosscorrelation

Once we have found the position of the drill bit and the velocity that best stacks its energy, we can stack the data along the appropriate moveout trajectory to obtain an estimate of the drill bit source signal. This is analogous to the signal from the accelerometer placed on the drill string by Rector et al. Crosscorrelating the data with this source signal estimate enhances drill bit energy in the data.

A plot of data after such a crosscorrelation is shown in Figure **??**. Here the traces have been sorted by their offset from the well. There is an event at zero lag on the near offsets that can be tracked across nearly all offsets. It is important to note that crosscorrelation preserves the moveout of the drill bit signal. We would just need to back out the moveout correction applied to align drillbit energy, then we could perform the same search for sources described above after crosscorrelation.

In correlating the stacked trace against a given input trace, that trace is omitted from the stack, to avoid the obviously large correlation that would result. To show that this correlation is not an artifact of the processing, consider Figure **??**, where the same analysis was performed, but an incorrect moveout correction was used. With the wrong moveout applied, the drillbit energy does not stack properly and the correlation reveals nothing.

Figure **??** shows the result of summing after correlating the eight records taken while the pumps within the array boundaries were turned off. This summation improves the picture of the direct arrivals somewhat, but unfortunately it does not bring out any reverberations of drillbit energy as we might have hoped. Probably we

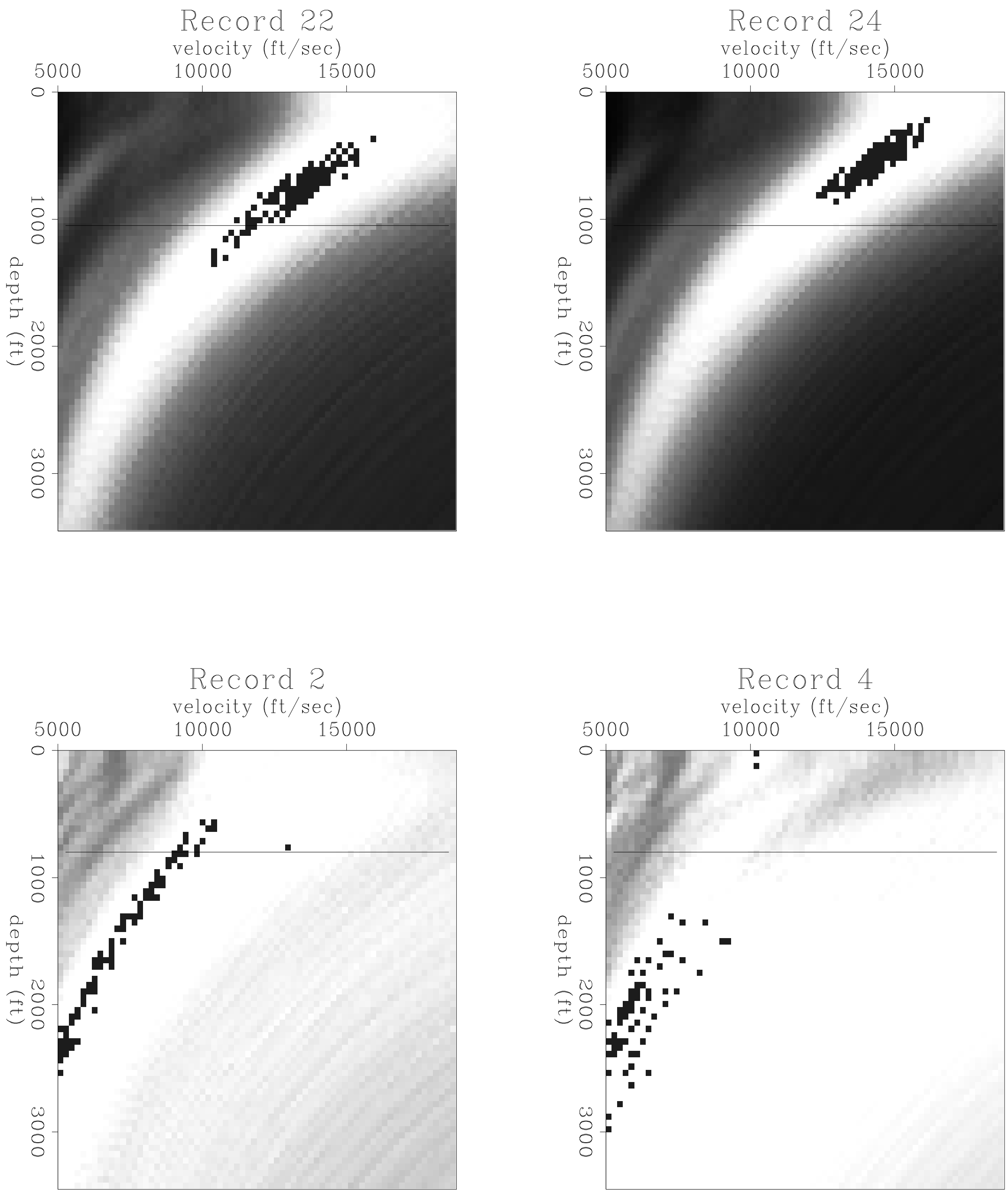

Figure 1.6: Semblance as a function of velocity and depth for a fixed surface location, the point above the drill bit. The depth of the drill bit is shown on each plot by the horizontal line. Larger semblance values are shaded white, with the largest 1% clipped and shown in black. The top plots are for records where pumps within the array have been turned off. In this case the direct arrivals from the drill bit are easily seen. Pumps were still operating during the recording of the two records shown at bottom. The result is that there is no clear drill-bit signal. drillbit-vzd [CR]

need longer correlation times that are available with conventional reflection seismic recording hardware.

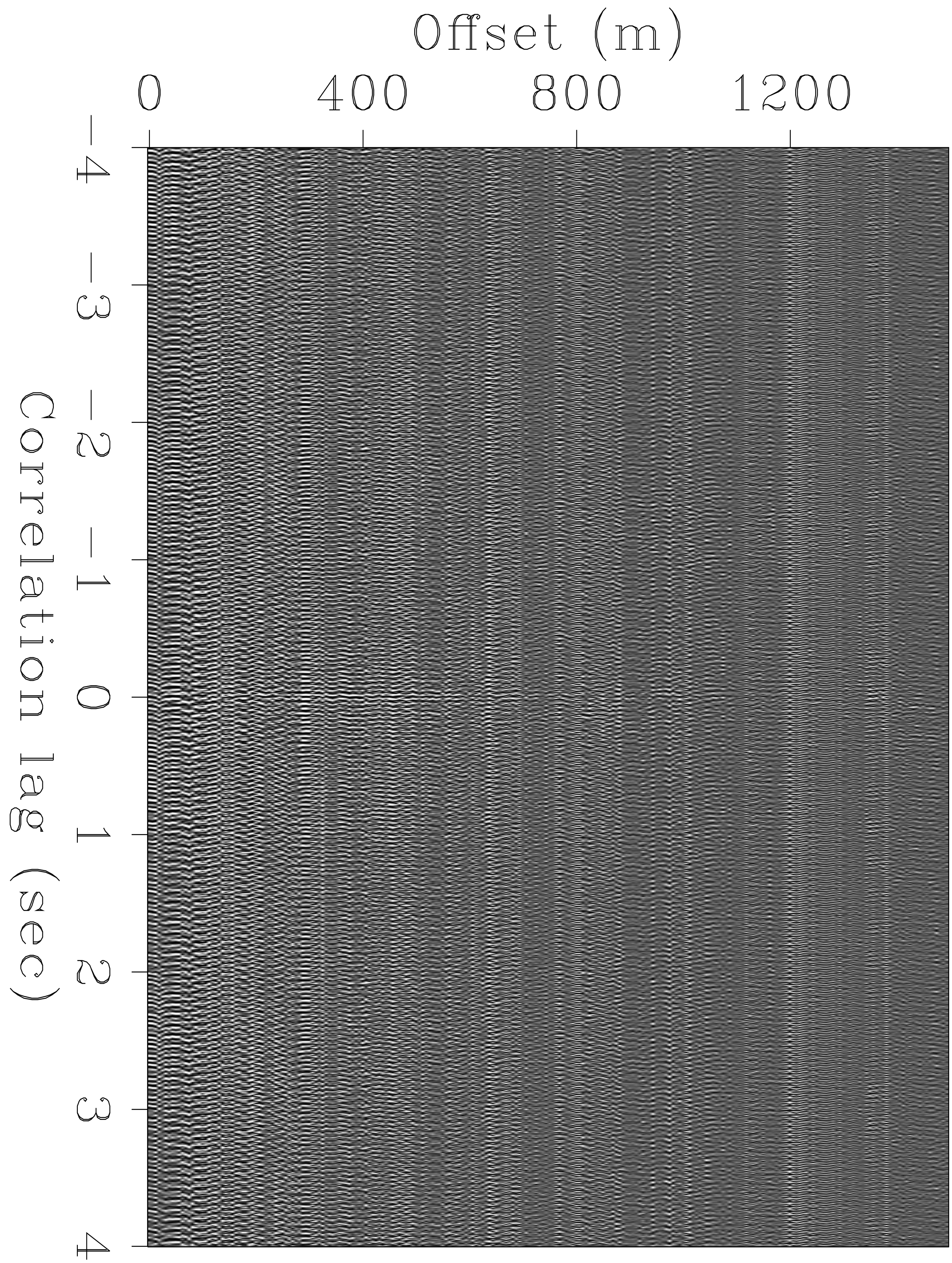

Figure 1.7: Data after crosscorrelation with an estimate of the drill bit source signal. The event at zero lag is the direct arrival from the drill bit. drillbit-xcor.21 [ER]

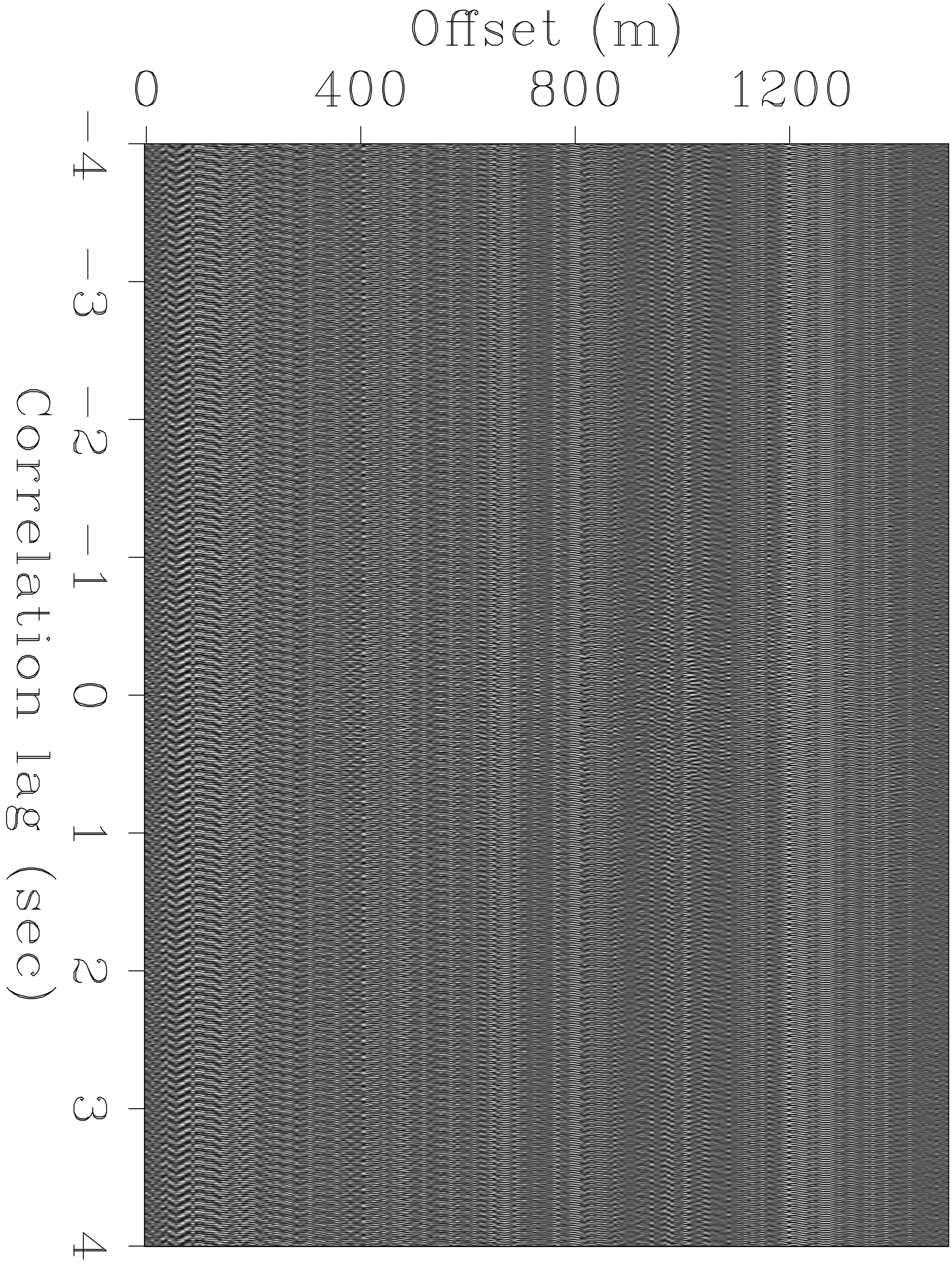

Figure 1.8: An incorrect moveout correction has been made prior to stacking and crosscorrelation, verifying that the energy seen at zero lag in the other crosscorrelations is not an artifact of the processing sequence, and is therefore most likely direct arrival drill bit energy. drillbit-xcorb.21 [ER]

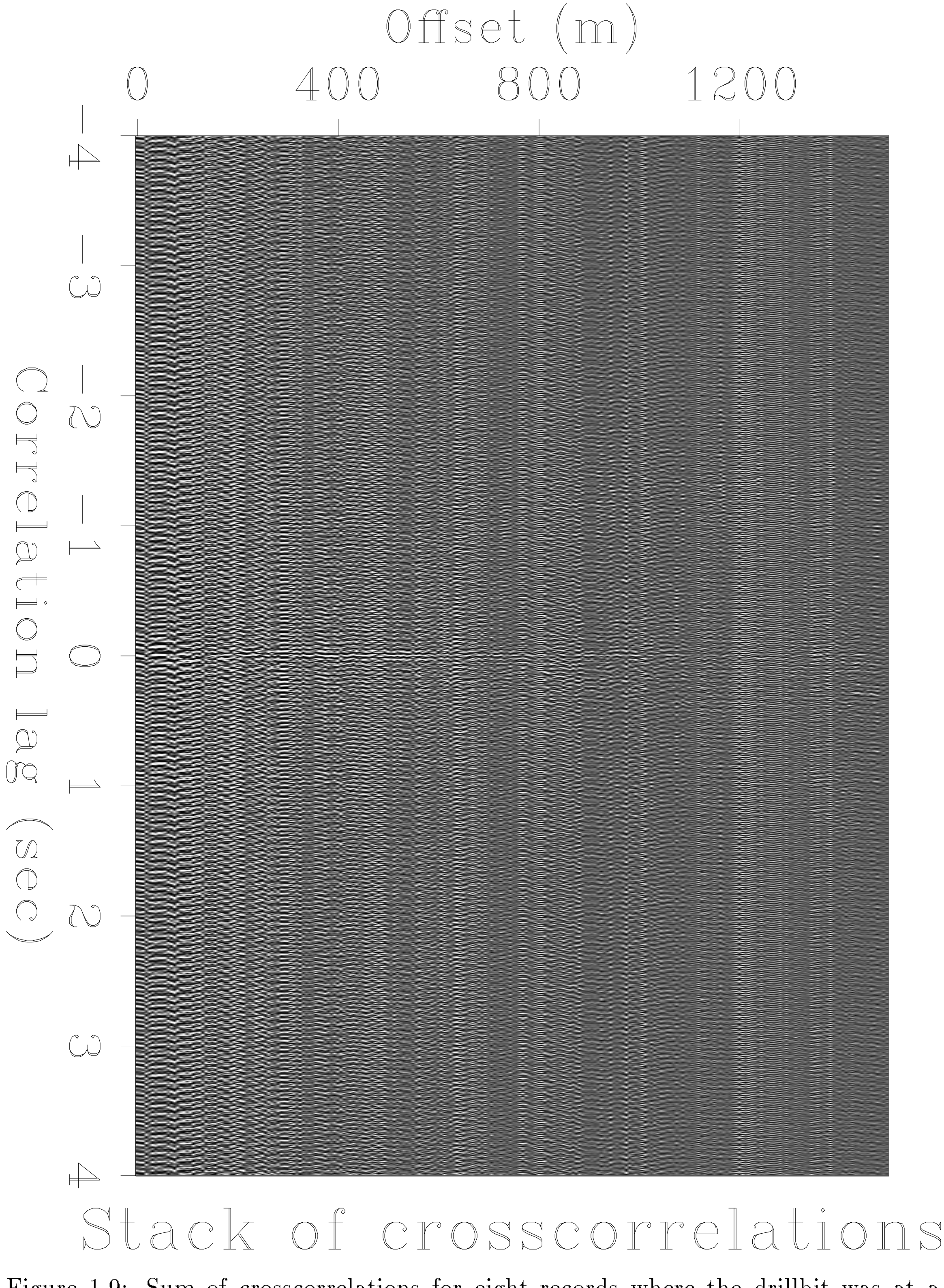

Figure 1.9: Sum of crosscorrelations for eight records where the drillbit was at a constant depth and all pumps within the survey area were turned off. Stacking records in this way gives a longer effective crosscorrelation length, but still no arrivals are visible other than the direct arrival. drillbit-xcor.sum [CR]