Chapter 1

Introduction

In September of 1988, the Stanford Exploration Project (SEP) conducted a passive seismic experiment. In a remote area of the Stanford campus, 4056 geophones were set out in a two-dimensional array. Ambient seismic energy was recorded over an eighteen hour period.

Several factors motivated us to perform such an experiment. First, the problem of observing and characterizing ambient seismic noise is an interesting one, particularly in a seismically active area such as this, where the San Andreas fault is only a few kilometers away. A two-dimensional receiver array allows us to determine the arrival direction of incident waves. A large number of channels offers the possibility to detect events weaker than those seen by isolated recorders.

Second, we hypothesized that whatever energy is present in the earth, we might be able to image structures in the near surface by observing how ambient energy interacts with these structures. Ambient energy could scatter or reflect off structures in the near surface, and we might be able to detect this by observing the pattern of arrival times across the array for various incident events. Work has been done along these lines by a group of Russian authors (?), (?), using ambient seismic energy as well as aftershocks of large earthquakes. They report imaging large-scale scatterers deep in the crust. Hedlin et al (?) use an analogous approach to image secondary sources in the coda of teleseismic events.

A third motivator was our hypothesis that the crosscorrelation of two passive traces should resemble what we might record from a shot at one location and a receiver at the other. Or that the autocorrelation of recorded traces would reveal the impedance structure of subsurface layering. Examples of work along these lines include studies by Scherbaum (?) and Tsutsui (?).

The final motivator was the availability of the right equipment. In 1988, Stanford received from Amoco the generous gift of approximately 200 seismic group recorders (SGR's) and associated hardware. SGR's are portable units that record on magnetic tape the amplitudes of ground motion for a single seismic channel. This equipment has made it possible in recent years for Stanford to conduct groundbreaking experiments in crustal and earthquake seismology. But its first use at Stanford was in our passive seismic experiment. The arrival of this equipment gave us the opportunity to experiment with some of our ideas on passive seismology.

Interest in recording ambient seismic energy in the reflection seismic community has usually been aimed at understanding noise contamination problems, though there have been occasional references to imaging with passive seismic energy, such as the work done by Baskir and Weller (?).

1.1 Experiment design

Some overriding logistical constraints guided the design of the experiment. We had roughly 200 seismic group recorders or SGRs. Each SGR records one channel of data on its own cassette tape. A controller sends timing signals to all the SGRs via radio to synchronize recording. We could sum together the outputs of 12, 24, or 36 geophones to produce the signal recorded at an SGR. These numbers arose because there are twelve geophones per string in our equipment (with 50 feet of cable between geophones) and we could have up to three strings per SGR before the combined resistance of the cables became too large.

A second logistical constraint was our survey area. We chose to conduct this experiment on Stanford land, rather than looking for sites elsewhere, to minimize the work needed to set up the array. The most appropriate site on Stanford property was a field roughly 500 by 500 meters. We filled this area with a 2-D grid of geophones space every 25 feet in each direction. Groups of 24 geophones were combined to form a group, as shown in Figure 1.2, giving 169 recorded channels in a 13 by 13 grid. The geophone spacing of 25 feet tells us that surface waves traveling at or near air velocity, which may not be unexpected in dry soil such as at this site, will be unaliased up to a frequency of 18 Hz. The 13 by 13 grid of geophone groups is shown in Figure 1.3. With this design, the group centers are 125 feet apart.

Approximately 200 man-hours were required to survey and lay out the array. We enlisted the full manpower of SEP, about 15 people, to do this in one weekend.

1.2 Quarry blasts

While most of our recording was done during the night to minimize interference from cultural noise sources, we also recorded some daytime records. The U.S. Geological Survey had planned to set off several blasts in a quarry in Cupertino, CA (about 15 km away) for a research project of their own, and they kindly scheduled the blasts so that we could try to record them with our array. The location of the quarry is shown in Figure 1.1.

There were three blasts, a large "quarry blast", with 1500 pounds of explosives in many different shot holes (this blast is used by the quarry to dislodge rock) and two smaller single charges of 300 and 100 pounds that were set off for experimental

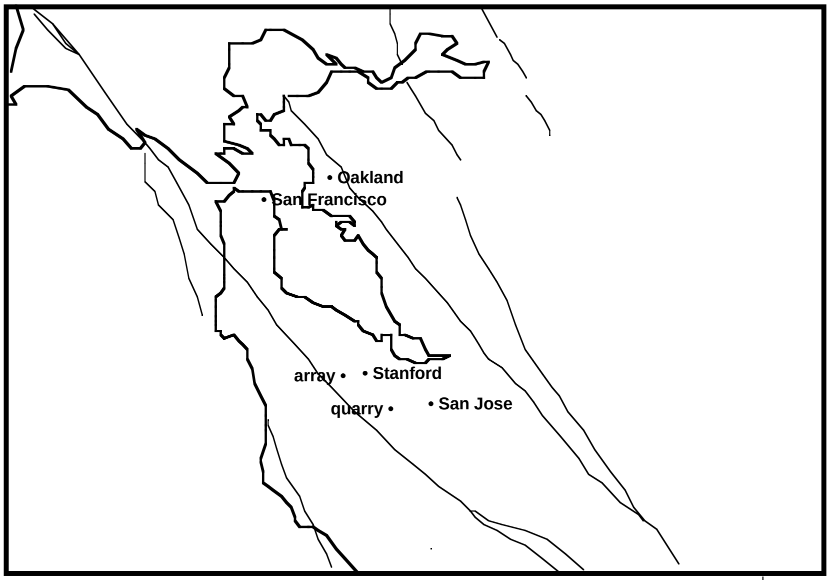

Figure 1.1: Map of San Francisco Bay Area, showing location of experiment. intro-map [NR]

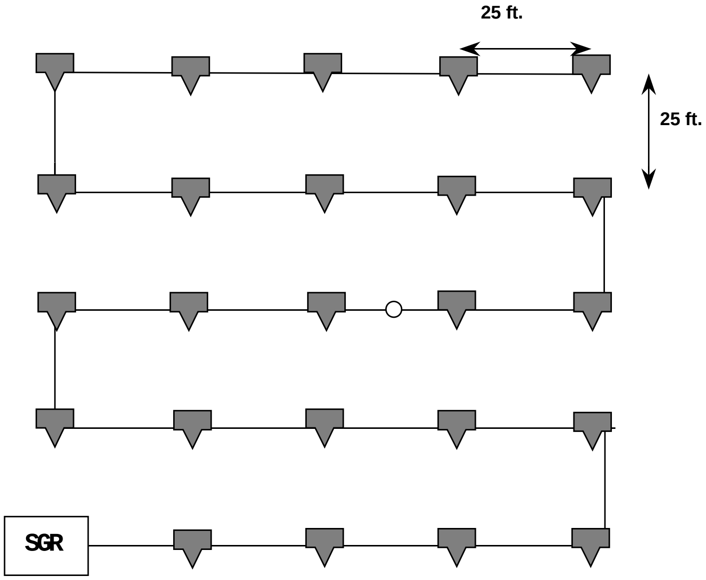

Figure 1.2: 24 element square array proposed for the experiment. intro-group [NR]

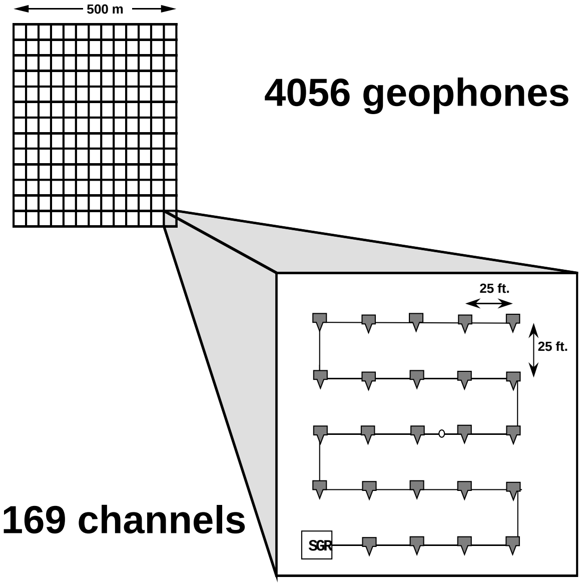

Figure 1.3: Overview of array. The array contains 169 groups, with 24 geophones per group, for a total of 4056 geophones. intro-array [NR]

purposes. USGS seismometers in the vicinity of our array clearly see the quarry blast (indeed, the quarry blast is visible for hundreds of kilometers) but not the smaller blasts.

1.3 Data overview

In Figure 1.4, amplitude spectra (computed by averaging over all the recorded traces) are shown for each of the 48 data records. In general daytime records (records 42 and above) are noisier, as expected. Isolated nighttime records have strong noise levels, probably due to vehicles passing on the nearby freeway. In Figure 1.5, the spectra are normalized so that each has the same RMS level. From this it can be seen that certain low frequencies are consistently present during the nighttime records. These may be due to site amplification of incident waves. The strong energy above 20Hz on record 46 is due to the largest of the three quarry blasts.

Figures 1.6 through 1.9 show the data for two of the 32 second records. Figures 1.6 and 1.7 are for a record taken during the night. Figures 1.8 and 1.9 are for a record taken during the day, timed to record a blast set off by the U.S. Geological Survey in a quarry approximately 15 km from the array.

1.4 Partial stacking

Stacking is a simple and effective method to enhance the useful signal and eliminate noise. In a conventional reflection experiment we use data redundancy to enhance

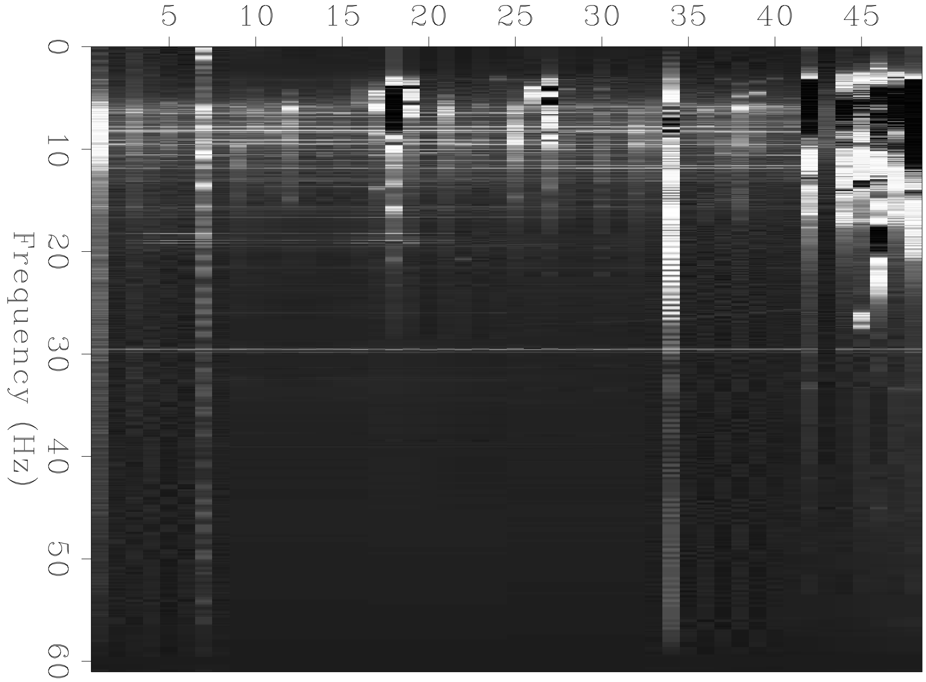

Figure 1.4: Amplitude spectra for the 48 records taken during the survey. intro-spec [ER]

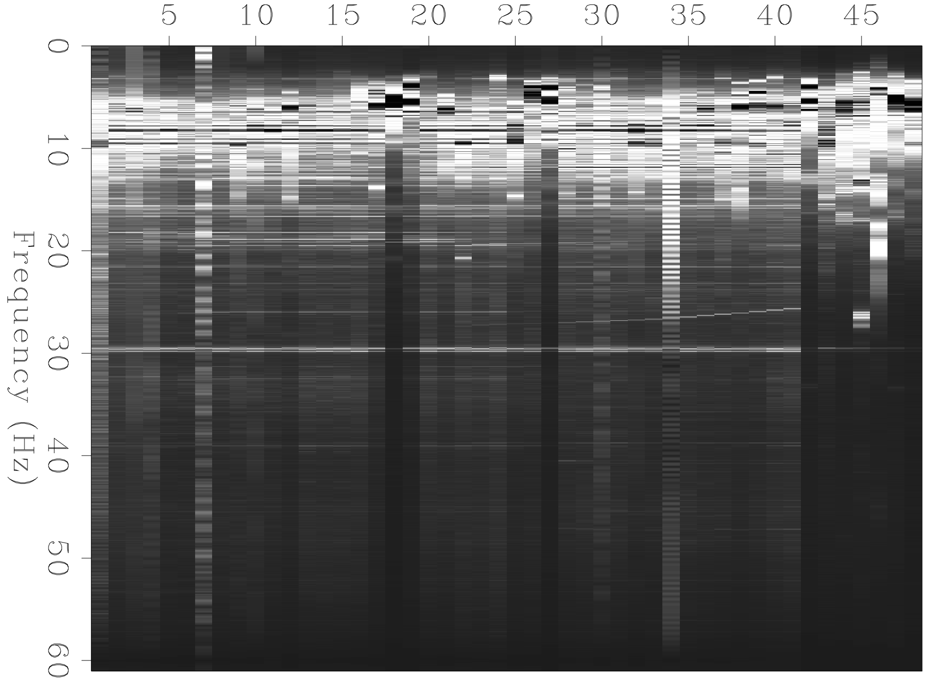

Figure 1.5: Amplitude spectra after normalization. intro-specnorm [ER]

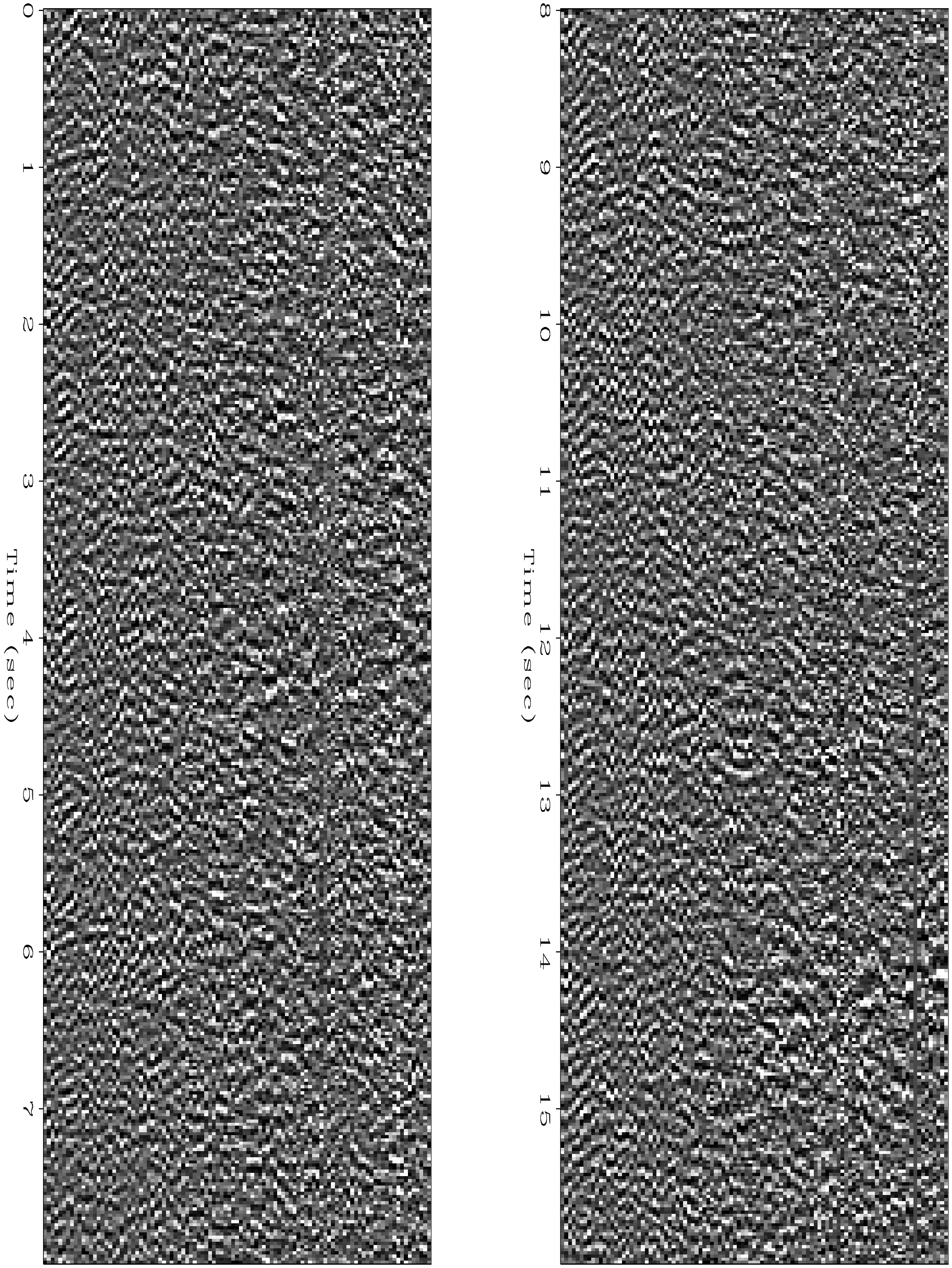

Figure 1.6: Raw data for a typical night time record. intro-datpl1.35 [ER]

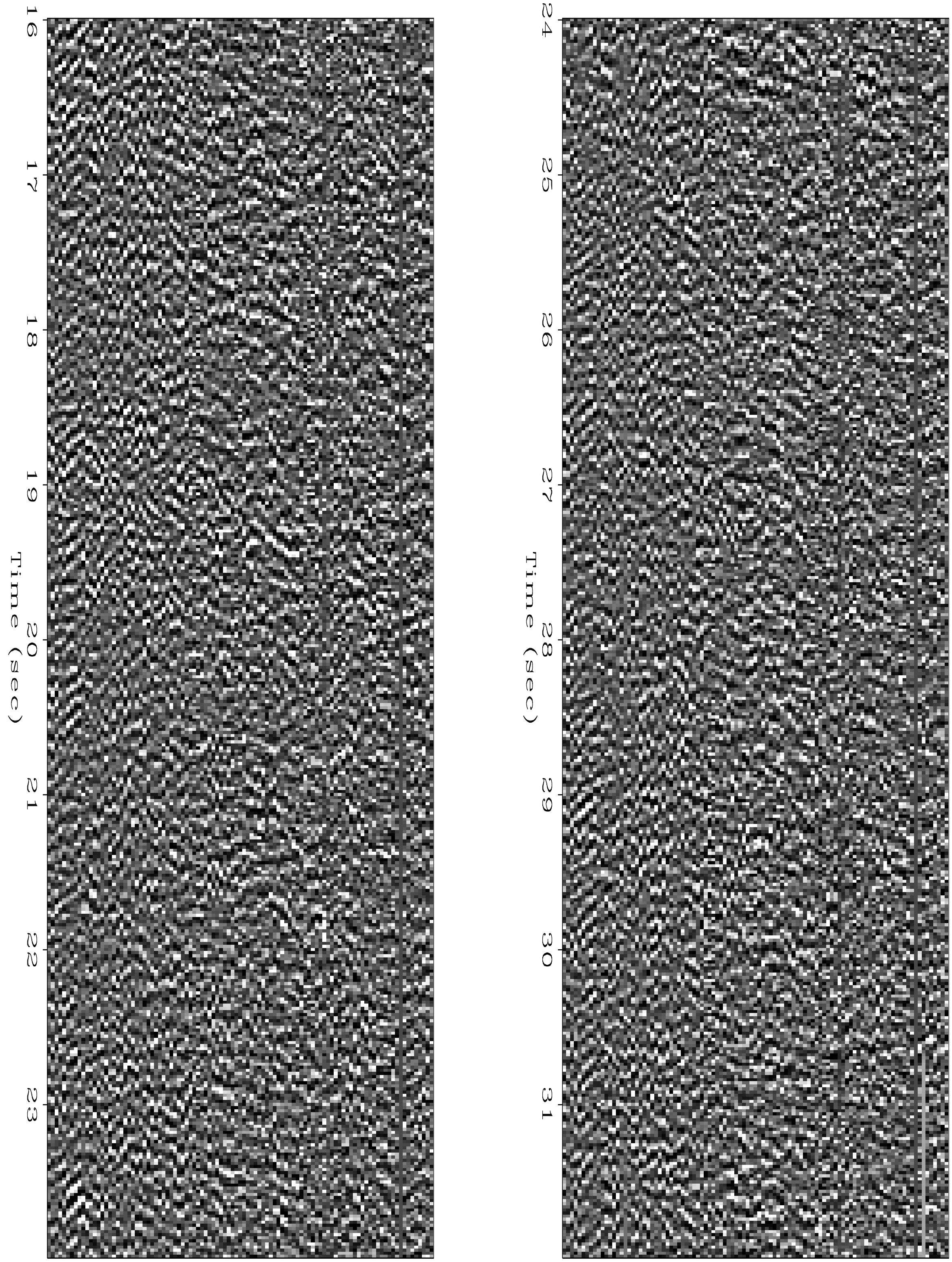

Figure 1.7: Continuation of Figure 1.6 intro-datpl2.35 [ER]

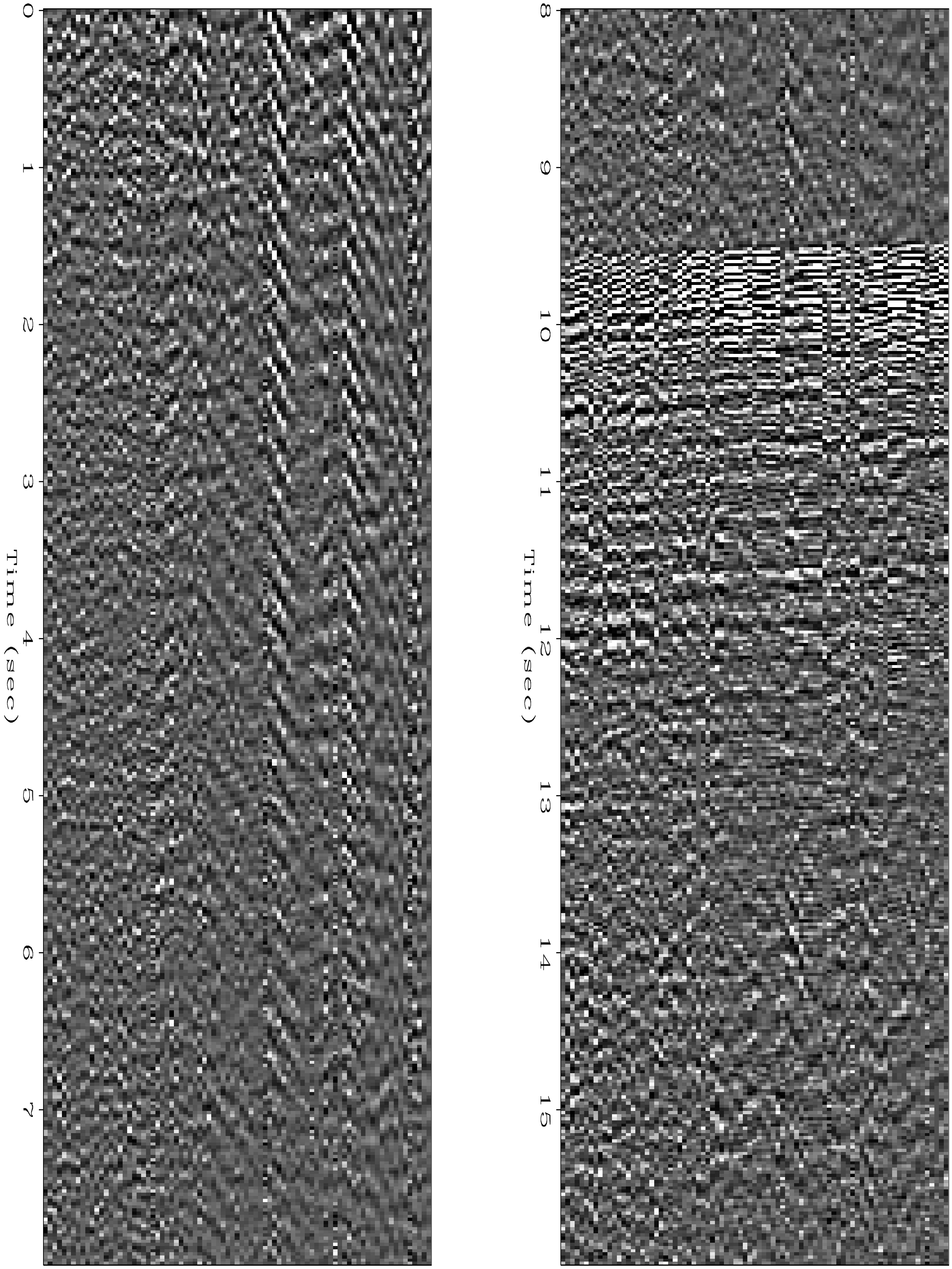

Figure 1.8: Raw data for a typical day time record. The largest quarry blast is visible, beginning at around 9.5 seconds. intro-datpl1.46 [ER]

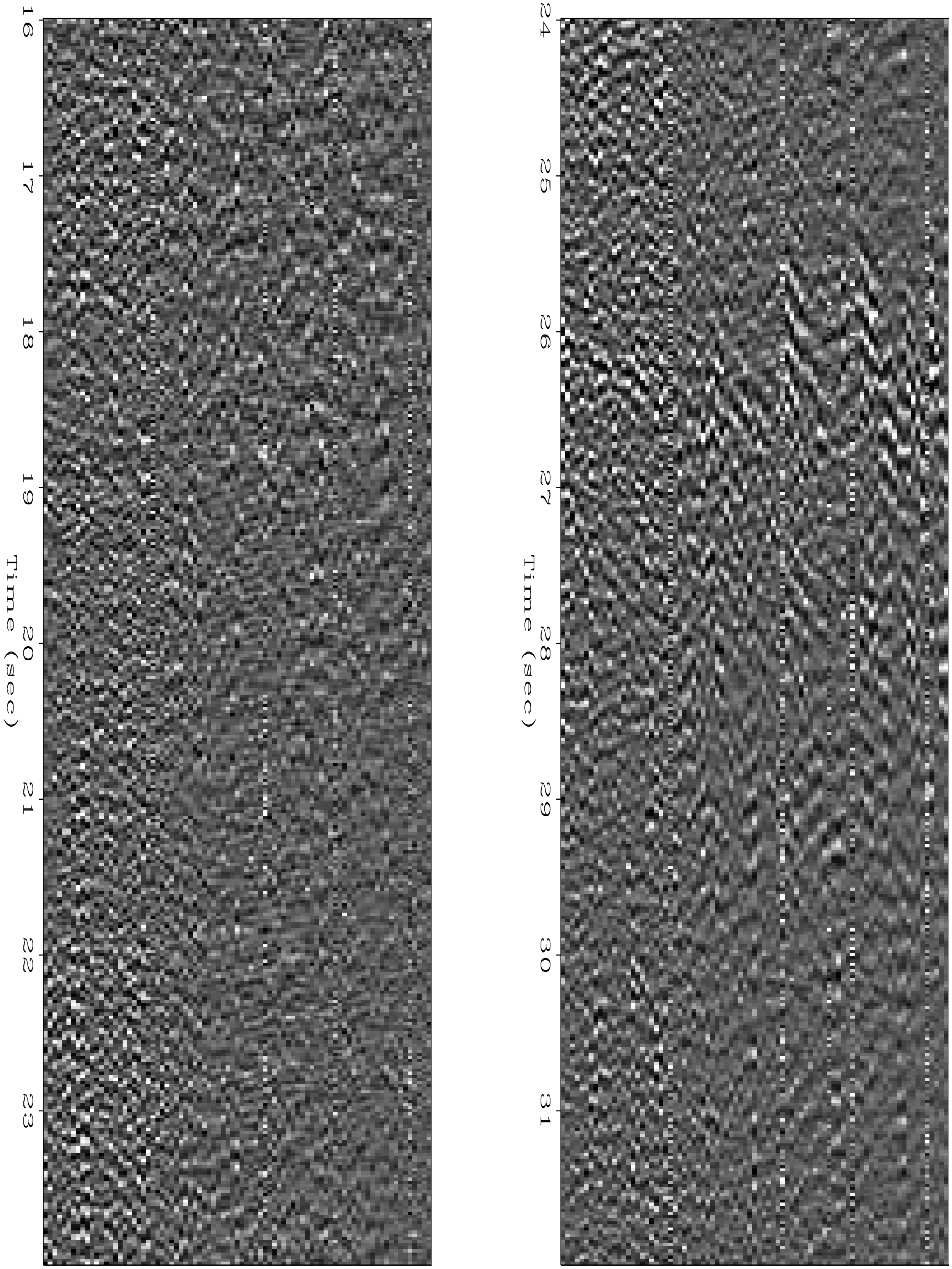

Figure 1.9: Continuation of Figure 1.8 intro-datpl2.46 [ER]

the reliability of the data. For our passive data we can point the array in a particular azimuth direction by stacking the data along the lines perpendicular to that azimuth direction. In these examples we choose the inline and crossline directions as well as the two diagonal directions as shown in Figure 1.10. Stacking along this set of profiles was suggested by my colleague Lin Zhang.

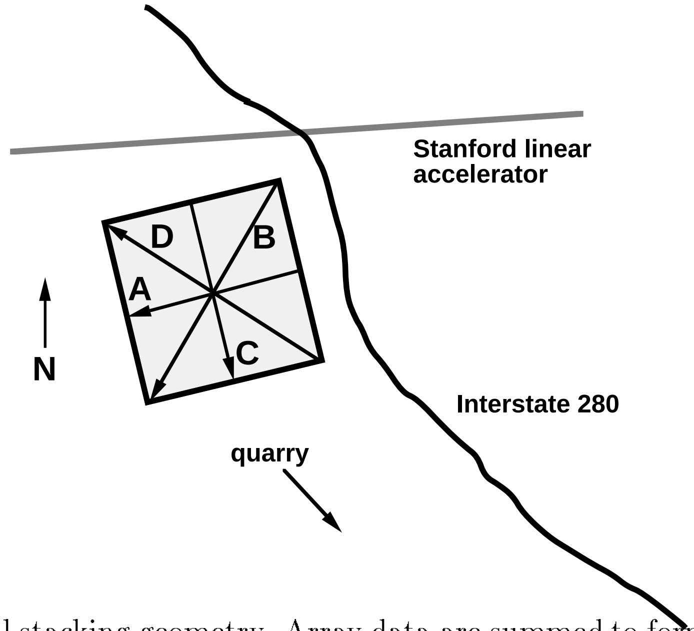

Figure 1.10: Partial stacking geometry. Array data are summed to form profiles along the four directions shown. By comparing moveouts on the different profiles, we can get a first estimate of the arrival direction of incident waves. intro-pstack [NR]

Let $P(it, ix, iy)$ be the recorded 3-D data. The equations for stacking are

$$P_1(it, ih) = \sum_{ix} P(it, ix, ih + ix)$$

$$P_2(it, ih) = \sum_{ix} P(it, ix, ih - ix + nx)$$

This operation has the following advantages and disadvantages:

- Advantages
  1. Reduce the effects of dead traces.
  2. Along the diagonals, create a profile longer than either the inline or crossline profiles.
  3. Partially cancel white noise.
  4. Partially eliminate surface waves.
  5. Reduce the work required in subsequent processing.
- Disadvantages

1. Two dimensional models can not fully represent 3-D wave propagation.
2. Resolution in the azimuth direction is low.
3. When stacking along the diagonals the stack fold is not uniform.

Partial stacks for the two raw data records shown are above are displayed in Figures **??** through **??**. Interestingly, the stack events (for example, at around 2.3 seconds in Figure **??**) that were not apparent in the raw data. The labels A, B, C, and D on the plot refer to the profile directions shown in Figure 1.10. These four profiles are synthesized by partially stacking the data onto these four lines. By comparing the apparent dips of events on the four profiles, one can get a rough idea of where a particular event is coming from. A more precise tool for analyzing arrival directions will be developed in Chapter 2.

In Chapter 2, I use more sophisticated techniques to determine the arrival direction of incident waves such as the one revealed in Figure **??** by partial stacking.

In Chapter 3, two techniques, a scattering method and a correlation based approach, will be used to attempt to image the subsurface using passive data.

In Chapter 4, the techniques developed for passive data work will be applied to another novel seismic source, the drillbit. Passive seismic work and drillbit studies are united by the common feature that in these case, unlike conventional controlled source seismology, there is no time zero at which a source is set off. Thus the processing techniques developed for passive work will also be applicable to the drillbit case. One advantage in the drillbit case is that the source is at a known position.

In Appendix A, I develop tools for interpolation of 3-D data that have been useful in dealing with these datasets. In Appendix B, I describe `xtpanel`, a tool for for building interactive X Window system interfaces that I developed along with Dave Nichols. It is used frequently at SEP for adding interactivity to the CD-ROM version of documents such as this thesis. Thesis figures have a button in the caption when viewed on the computer. Clicking on this button brings up an interactive panel where the user can adjust parameters and reproduce the figure.

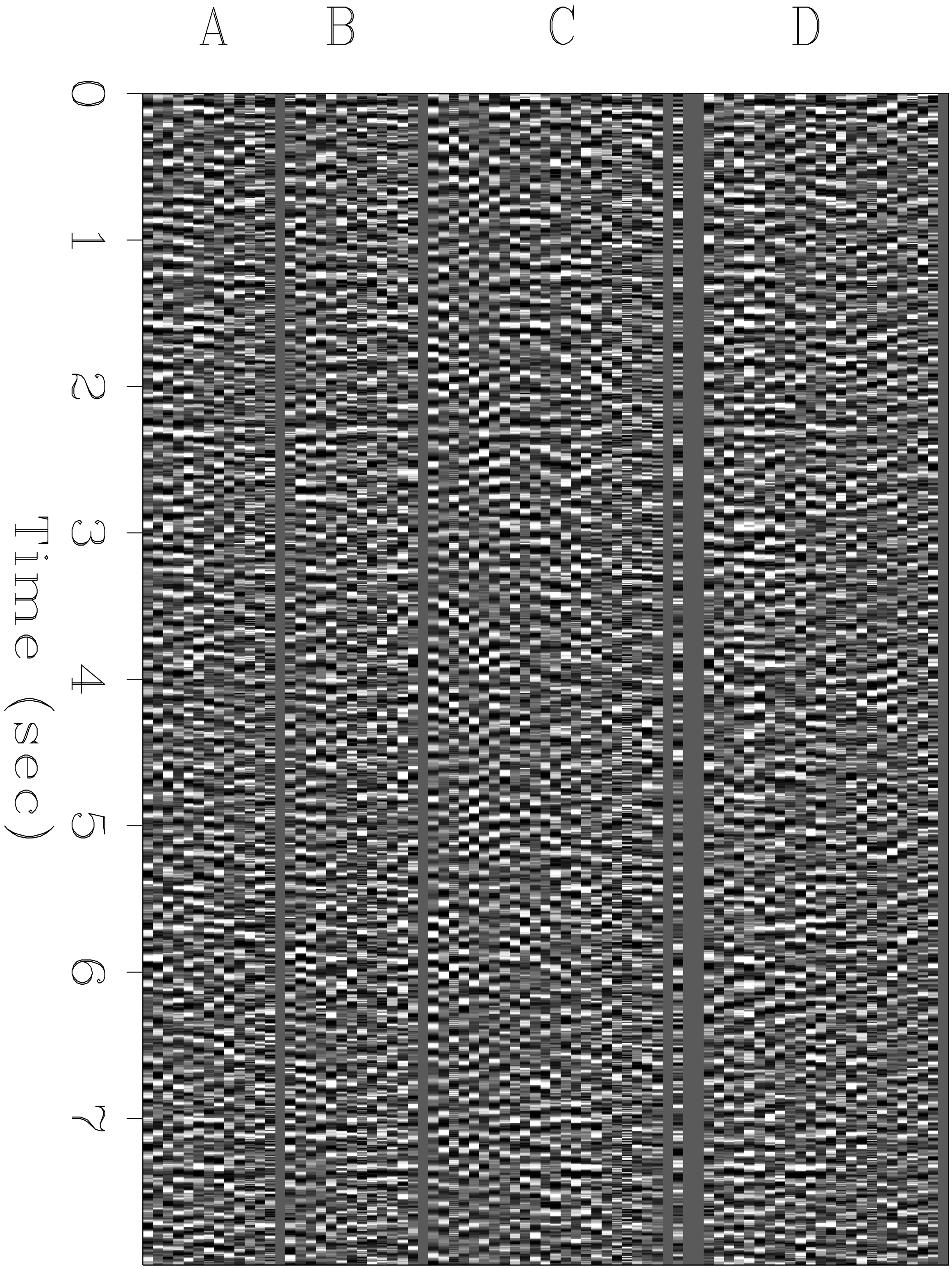

Figure 1.11: Partial stack of data from the left side of Figure 1.6. Note the nearly flat event at around 2.3 seconds that is not visible in the raw data of Figure 1.6. intro-pstack35.0 [ER]

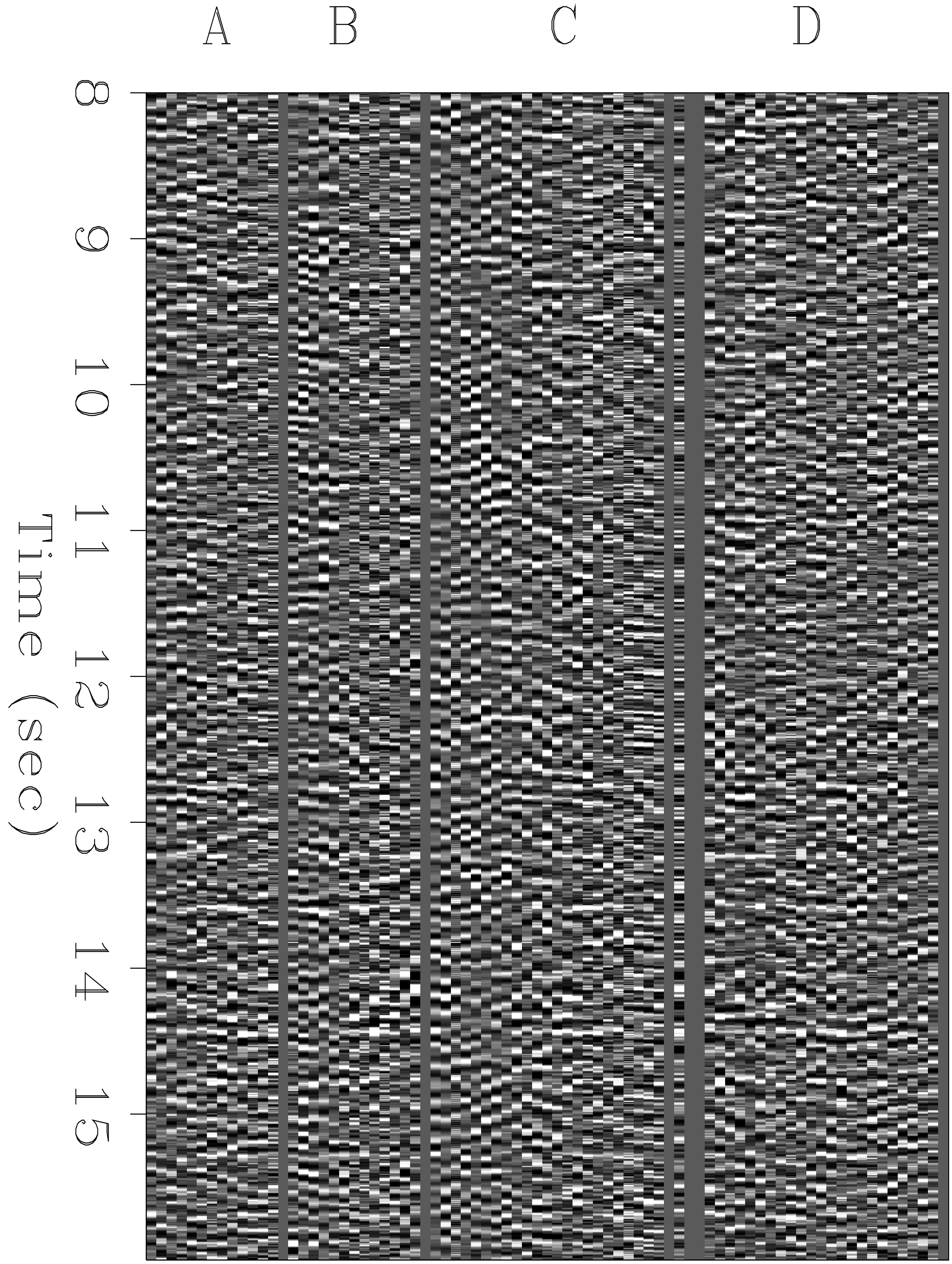

Figure 1.12: Partial stack of the data from the right side of Figure 1.6. intro-pstack35.8 [ER]

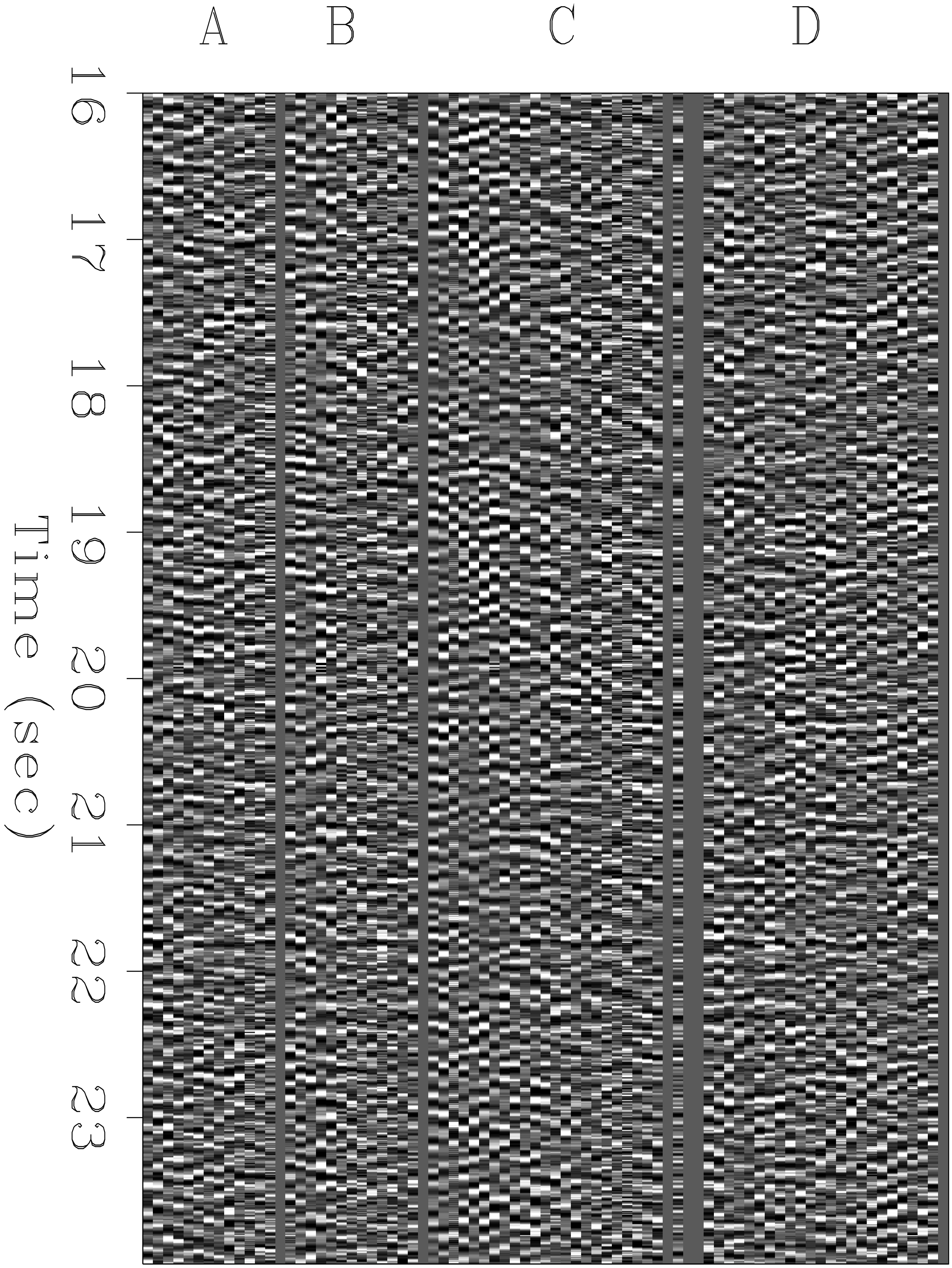

Figure 1.13: Partial stack of the data from the left side of Figure 1.7. intro-pstack35.16 [ER]

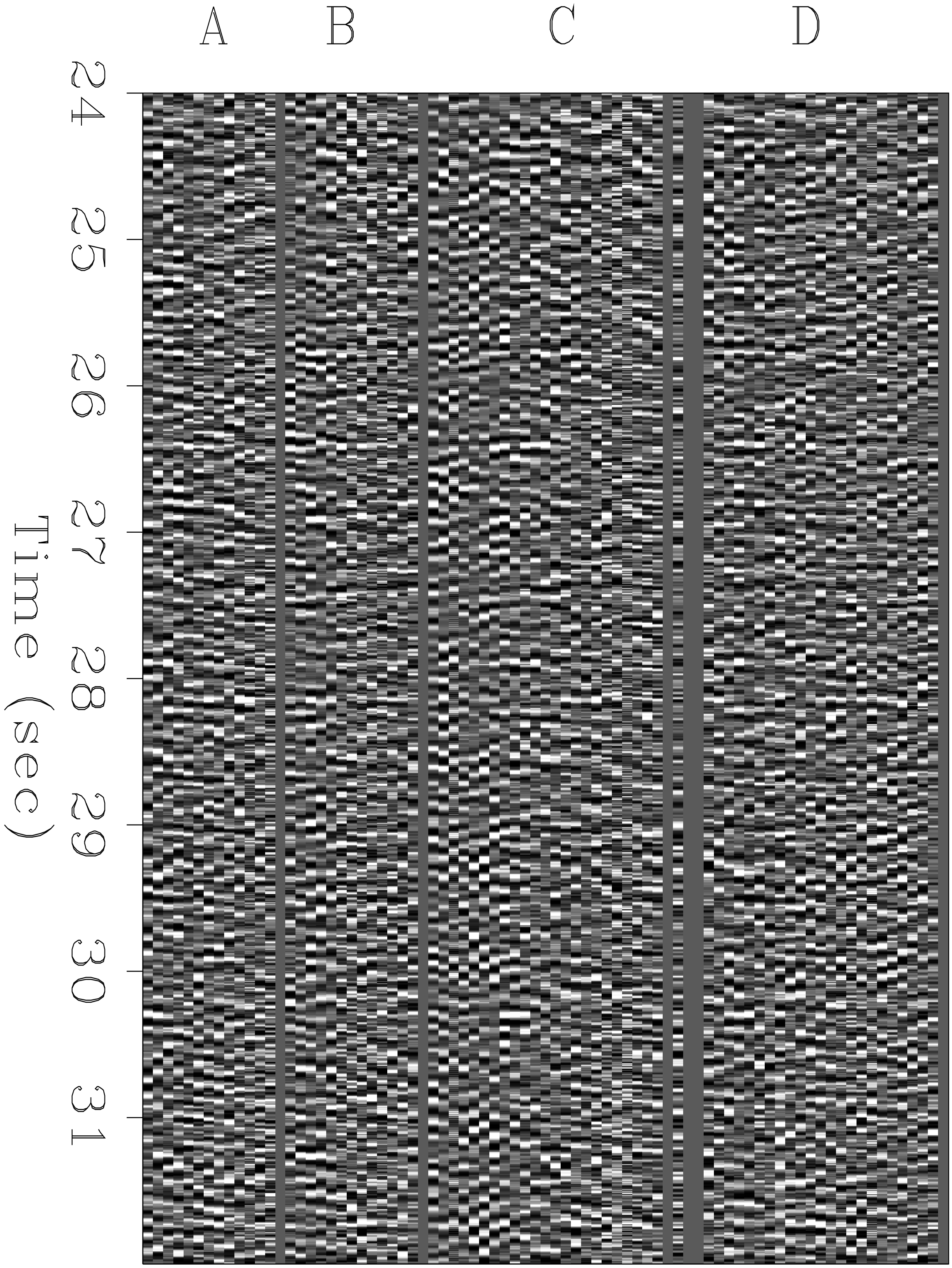

Figure 1.14: Partial stack of the data from the right side of Figure 1.7. intro-pstack35.24 [ER]

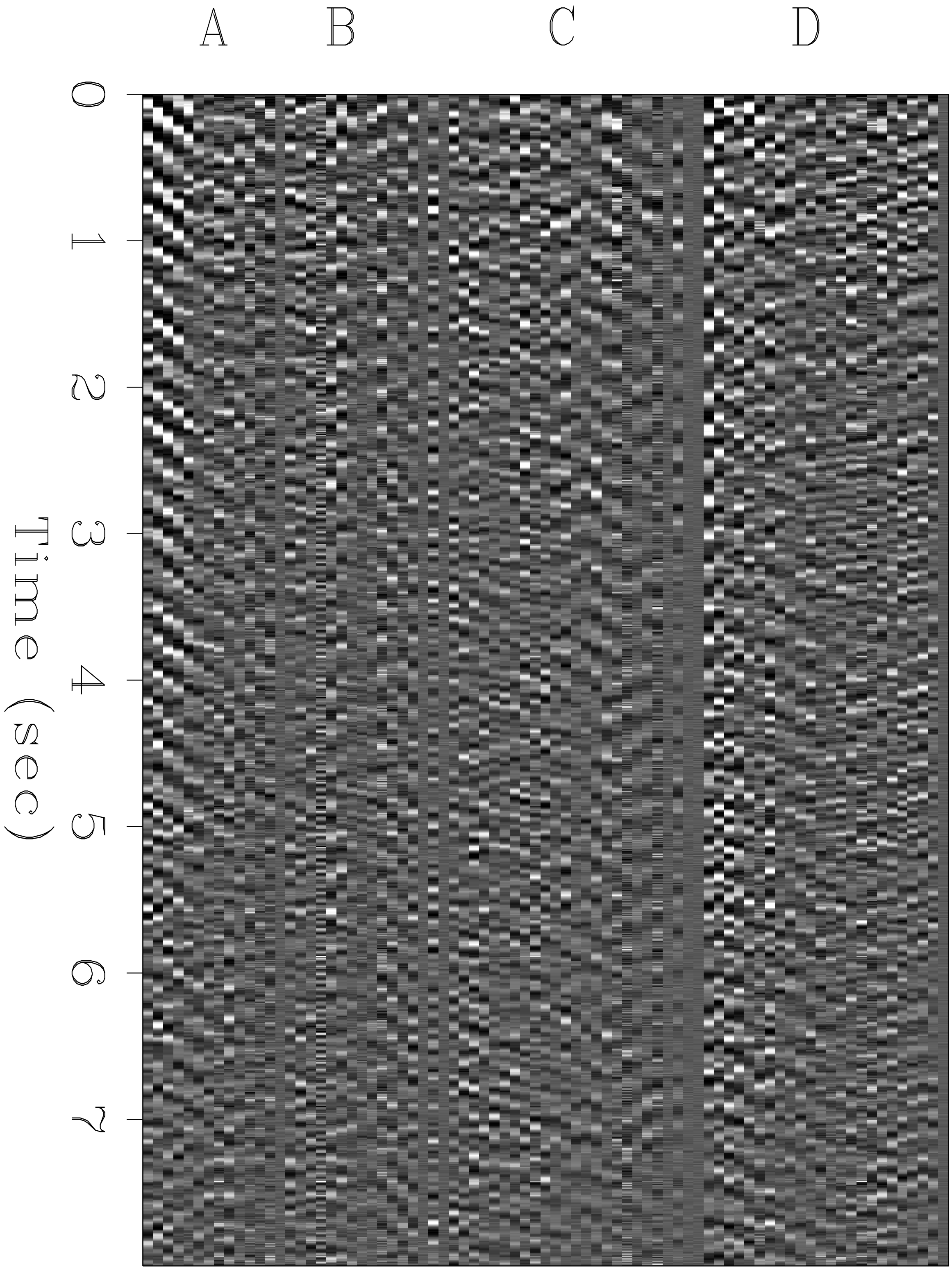

Figure 1.15: Partial stack of the quarry blast data from the left side of Figure 1.8. intro-pstack46.0 [ER]

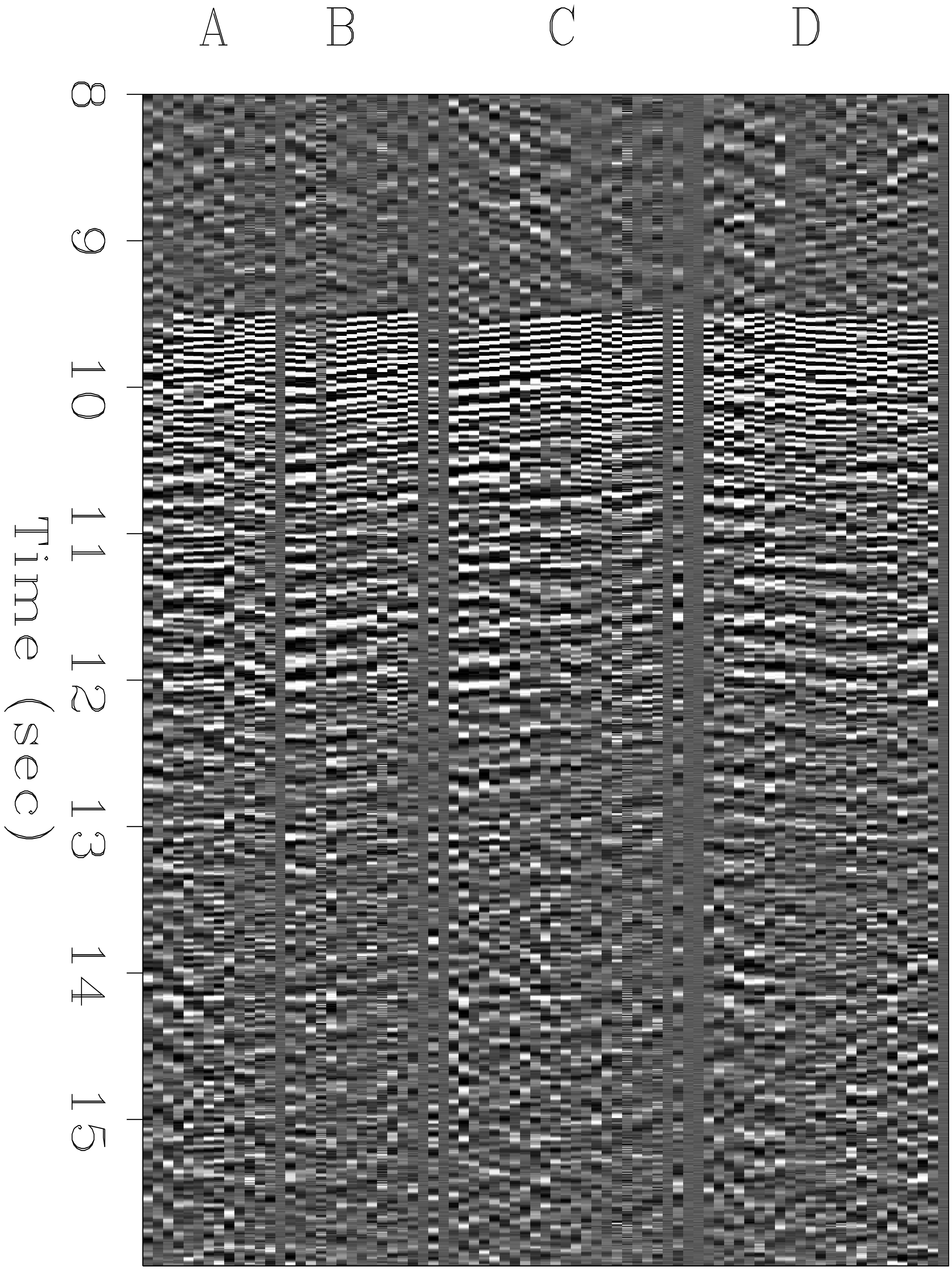

Figure 1.16: Partial stack of the data from the right side of Figure 1.8. Note the various blast arrivals. intro-pstack46.8 [ER]

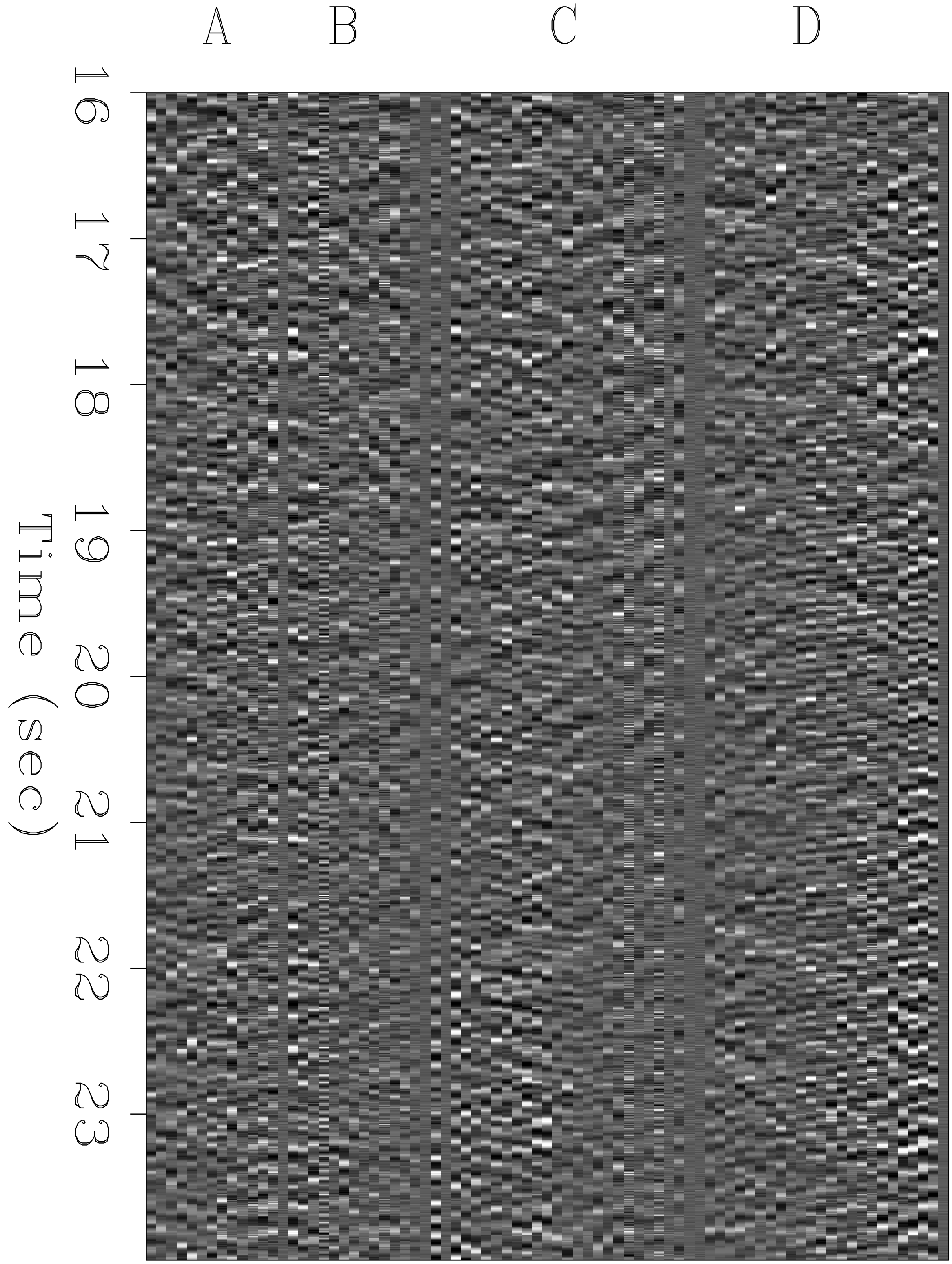

Figure 1.17: Partial stack of the data from the left side of Figure 1.9. intro-pstack46.16 [ER]

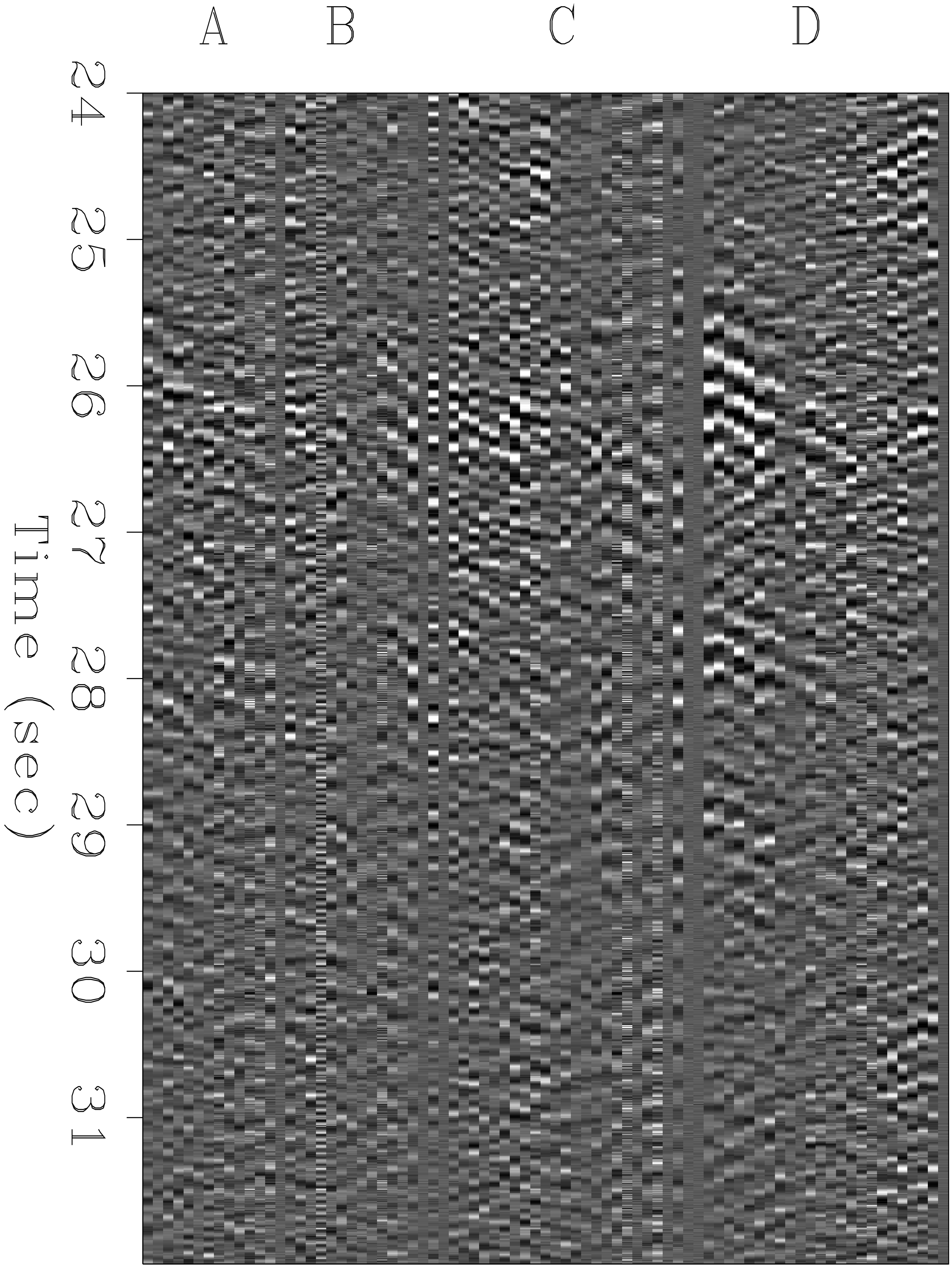

Figure 1.18: Partial stack of the data from the right side of Figure 1.9. intro-pstack46.24 [ER]