The ambient seismic field in three dimensions

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ABSTRACT

We conducted a passive seismic experiment, deploying a two-dimensional array containing over 4000 geophones, in an attempt to see what such a dense array could tell us about the ambient seismic noise field and the subsurface beneath the array. Beam steering analyzed the incident plane wavefield as a function of arrival direction. It revealed interesting, near vertically incident events that were consistent in arrival direction throughout the recording period. Some possible explanations for these events, such as electronic interference or nearby cultural noise sources, can be ruled out. The angle of incidence constrains the source of these events to two regions — a small zone beneath the array, and a much larger and more distant zone roughly a thousand kilometers away. Further field work would be able to determine which is the correct explanation.

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

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of arrival times across the array for various incident events. Work has been done along these lines by a group of Russian authors (Nikolaev and Troitskiy, 1987), using ambient seismic energy as well as aftershocks of large earthquakes. They report imaging large-scale scatterers deep in the crust.

The final motivator was the availability of the right equipment. In 1988, Stanford received a gift of approximately 200 portable seismic group recorders (SGR's) and associated hardware from Amoco.

EXPERIMENT DESIGN

Some overriding logistical constraints guided the design of the experiment. We had roughly 200 seismic group recorders, so we were limited to that number of recorded channels. For each channel, we could deploy a geophone group of 12, 24, or 36 geophones.

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 uniformly with a 2-D grid of geophones spaced every 25 feet in each direction. Groups of 24 geophones were combined to form a group, as shown in Figure 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 (expected in the dry soil such at this site) will be unaliased up to a frequency of 18 Hz.

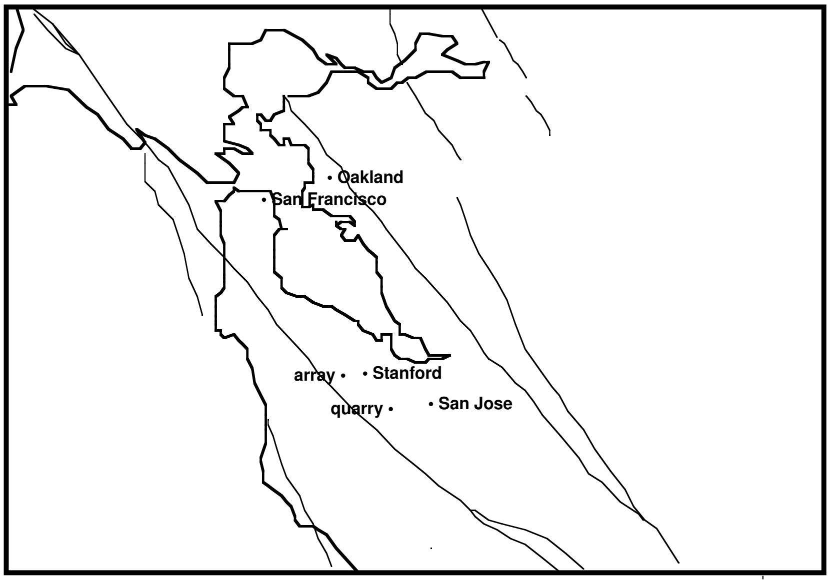

Figure 1: Map of San Francisco Bay Area, showing location of experiment. (map) [NR]

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.

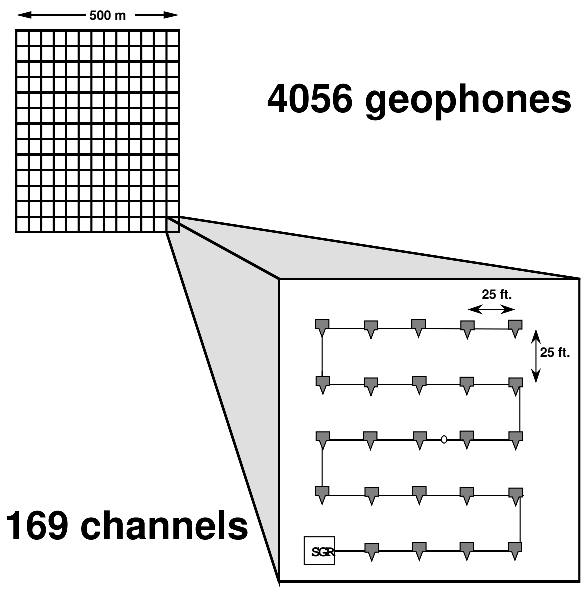

Figure 2: Overview of array. The array contains 169 groups, with 24 geophones per group, for a total of 4056 geophones. (array) [NR]

OMNIPRESENT EARTHQUAKES

The rest of this paper will describe in detail the principal result of this experiment, the discovery of frequent, low-amplitude near-vertically incident events during quiet nighttime recording conditions. There are two possible sources of these events, which are illustrated in Figure 3. One is directly beneath the array, in the upper 15 km or so of the crust where earthquakes occur. This is the cone-shaped region in Figure 3. The orientation of the cone is indicative of the observed arrival direction of the incident waves. The size of the cone is due to the fact that our resolution in apparent velocity space was somewhat limited. The lateral extent of this cone is illustrated in Figure 4.

The second possibility is that this energy is from a more distant source, and that the energy has followed a raypath similar to that shown in Figure 3, travelling down to some depth, then turning toward the surface. A large distance is required to explain the very steep angle of incidence.

PARTIAL STACKING

Figures 5 and 6 show the data for parts of two of the 32 second records. Figure 5 is for a record taken during the night. Figure 6 is 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.

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 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 aziumth

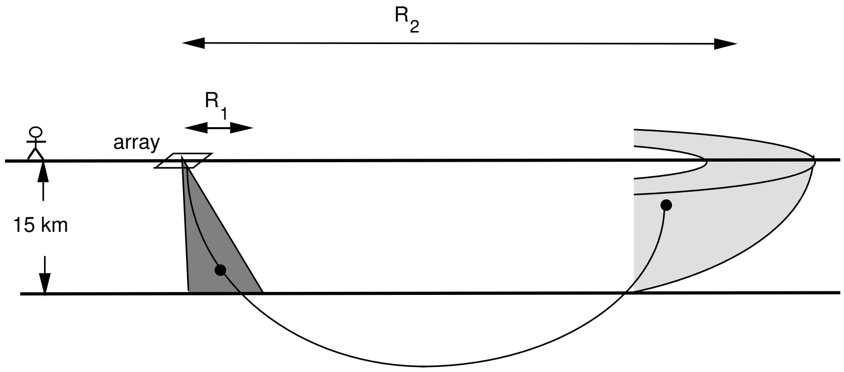

Figure 3: Illustration of possible sources of near-vertical events seen in passive data. Events could originate in a relatively narrow zone beneath the array, or from a larger, more distant zone. ellipses [NR]

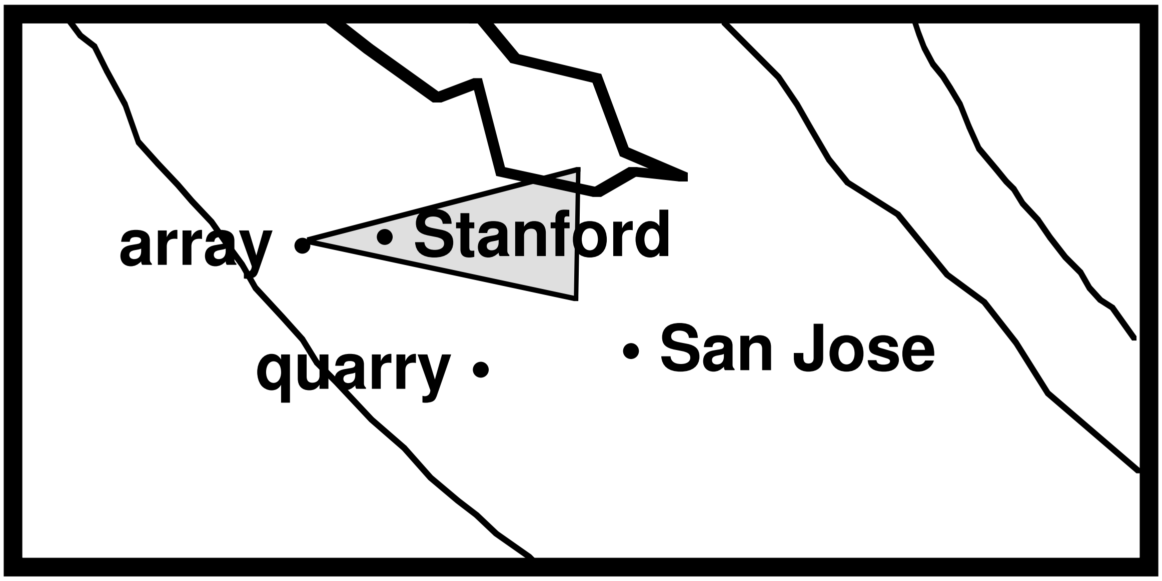

Figure 4: Close-up of map of survey area showing approximate boundaries of the near-field zone of possible source locations that could have generated the events seen in the data. mapzoom [NR]

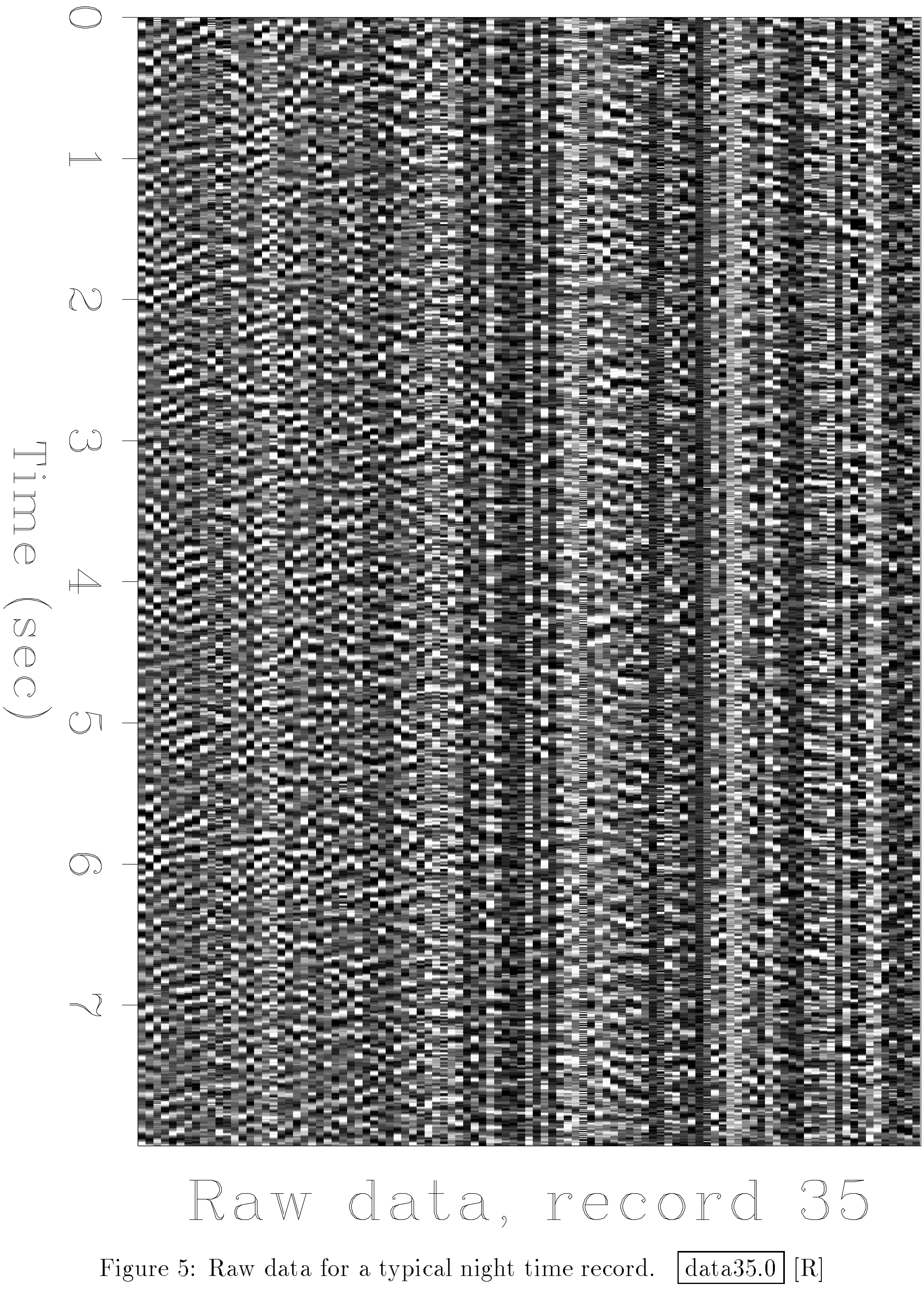

Figure 5: Raw data for a typical night time record. data35.0 [R]

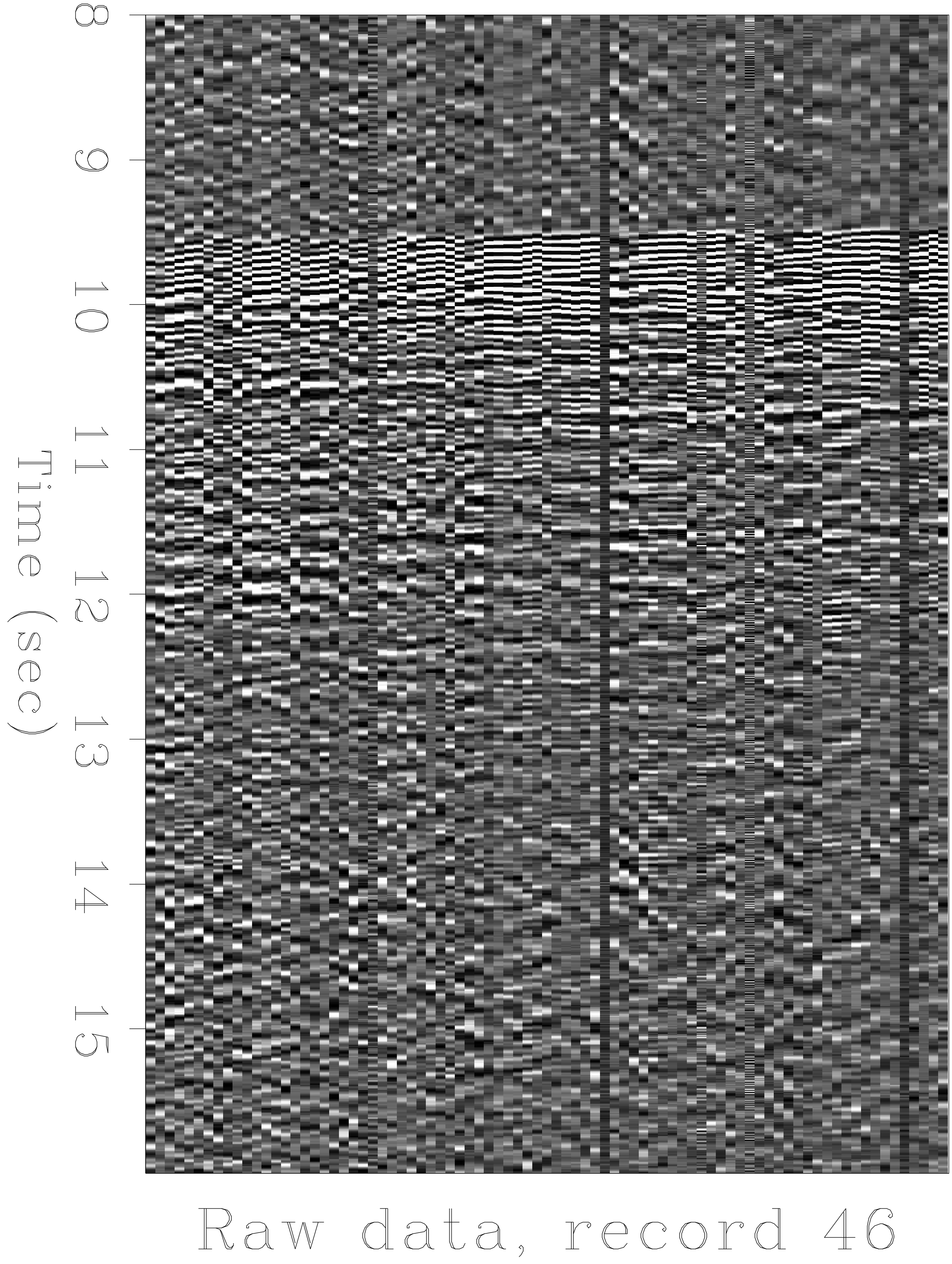

Figure 6: Raw data for a daytime record containing a quarry blast. data46.8 [R]

direction. In these examples we choose the inline and crossline directions as well as the two diagonal directions shown in Figure 7.

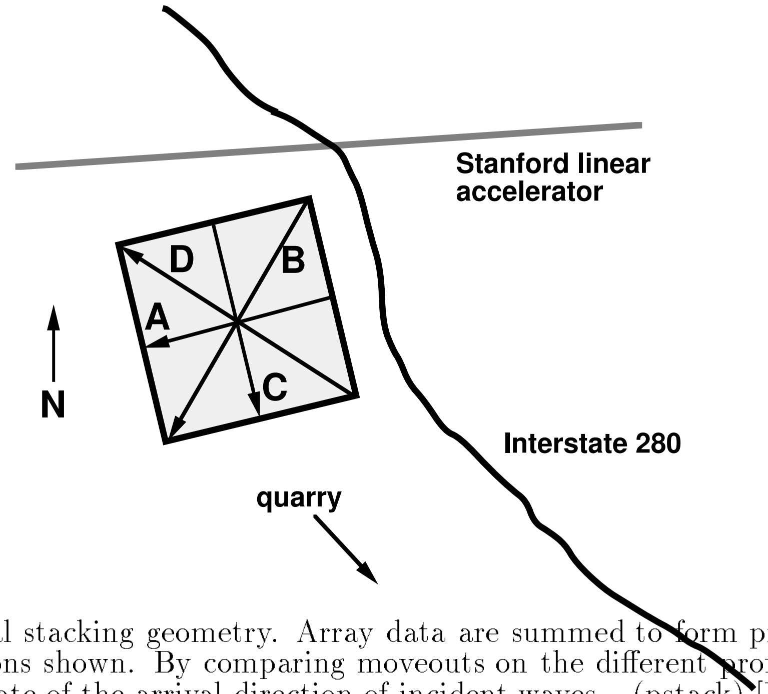

Figure 7: Partial stacking geometry. Array data are summed to form profiles along the four directions shown. By comparing moveouts on the different profiles, we can get a first estimate of the arrival direction of incident waves. (pstack) [NR]

Partial stacks for the two raw data records shown are above are displayed in Figures 8 and 9. Interestingly, the stack reveals events (for example, at around 2.3 seconds in Figure 8) 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 7. 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.

BEAM STEERING

Beam steering can give us more detailed information about the arrival direction of incident plane waves. Semblance is computed as a function of plane wave arrival direction. Figure 10 gives a schematic view of the disc-shaped beam steering plots which will be used frequently throughout this section. Stacking semblance is displayed as function of arrival direction (azimuth) and apparent slowness in polar coordinates. An apparent slowness of zero, corresponding to vertically incident events, is plotted at the center. The highest slowness value, at the edge, corresponds on these plots to an apparent velocity of 2 km/sec. These plots could also be described in terms of ray parameters p_x and p_y as shown in the figure, illustrating the equivalence of beam steering and slant stacking.

Figure 11 shows portions of the seismograms recorded by one of our 169 groups for the three quarry blast records. The quarry blast appears on the middle trace at

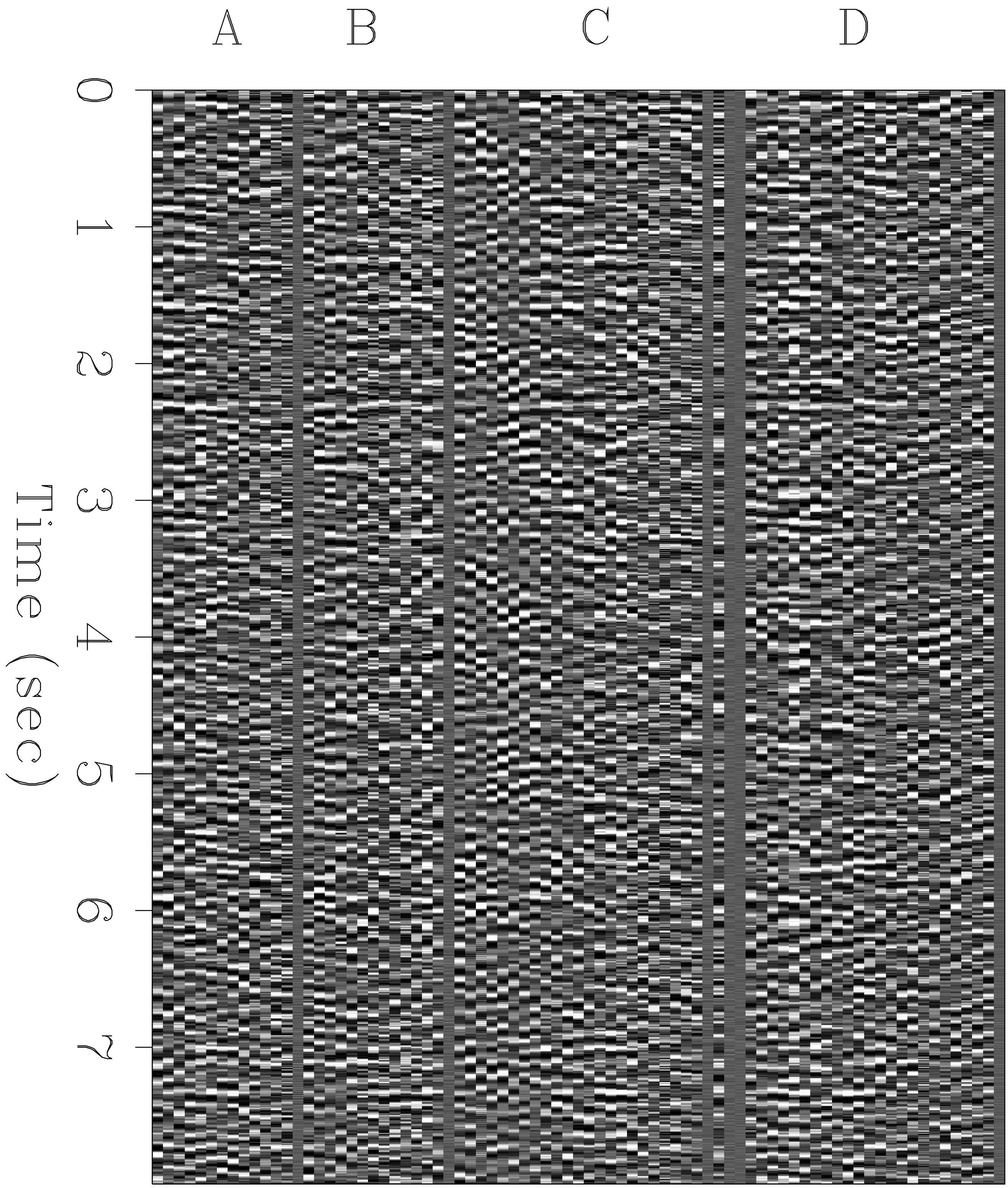

Figure 8: Partial stack of data in Figure 5. Note the nearly flat event at around 2.3 seconds that is not visible in the raw data of Figure 5. pstack35.0 [R]

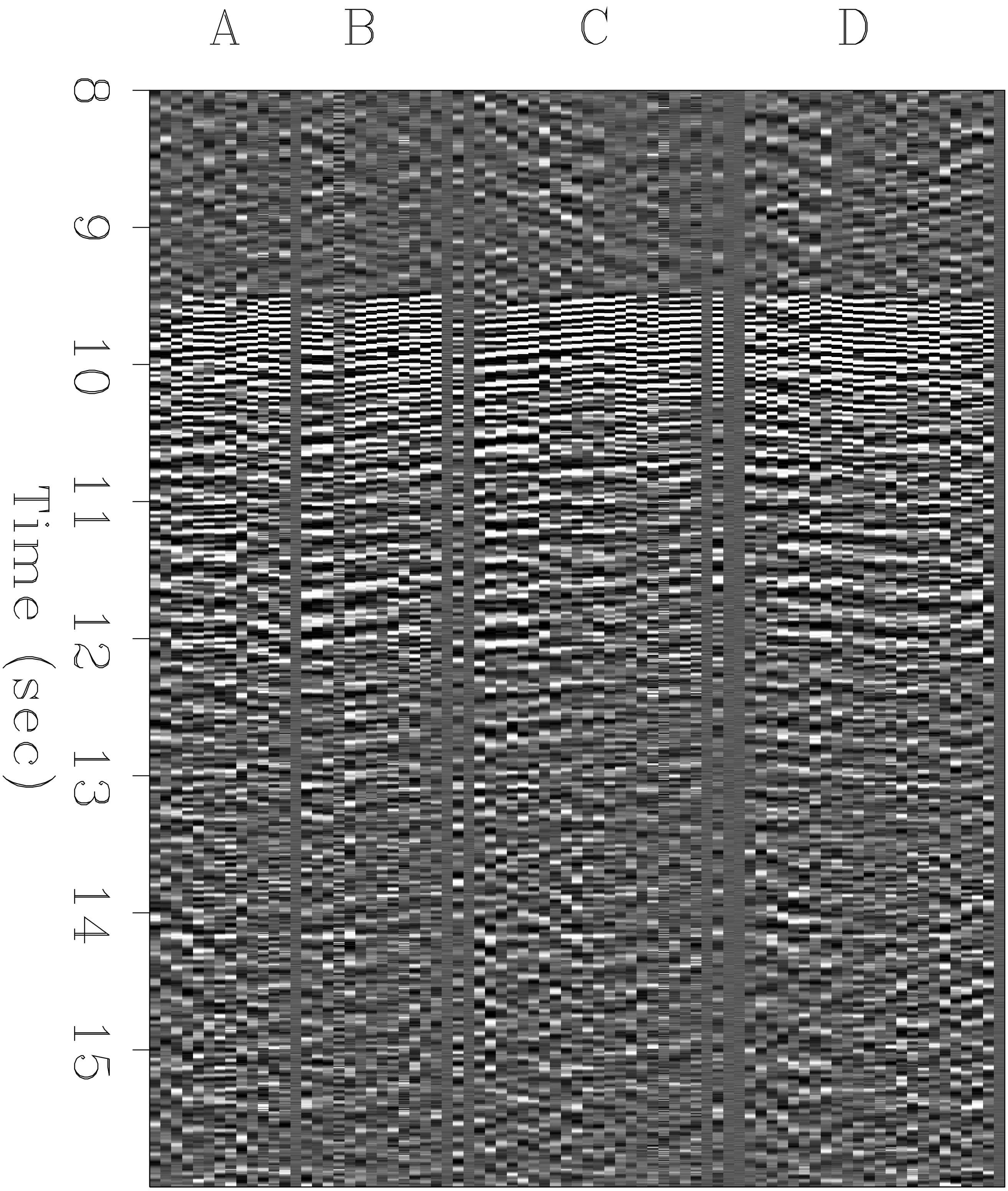

Figure 9: Partial stack of the data in Figure 6. Note the various blast arrivals. pstack46.8 [R]

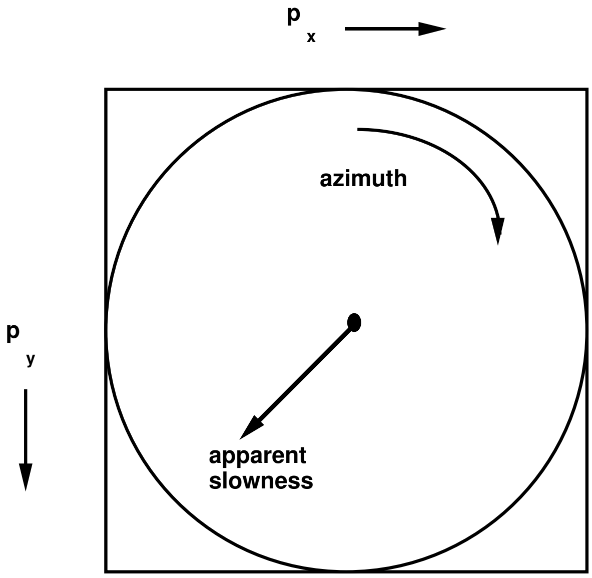

Figure 10: Beam steering parameters. Different azimuths are displayed around the circle, and different apparent velocities in the radial direction. A vertically incident event (infinite apparent velocity) would be plotted at the center. (beamexpl) [NR]

around 10 seconds, but is not very obvious on a single-trace display. The smaller blasts arrive around 10.5 seconds on the other two traces, and are not at all apparent. The signal-to-noise ratio in our data, at least for daytime recording, is obviously quite small. Figure 12 shows the result of beam steering the data from the three blasts and summing over 100 msec windows centered around the first arrivals from the blasts. It can be seen that the three blasts arrive from the same direction, all with an apparent velocity of around 4-5 km/sec. We gained the three panels independently so that the three blasts would have the same relative strength. In fact the blast from the middle panel, the quarry blast, gives a much higher semblance value than the other two. If we were to perform the same summation over time as shown in Figure 12, but using the entire 32 second records instead of a small window, the quarry blast would still dominate the middle plot, while the two smaller blasts would no longer stand out. Restricting the summation to a small window located at the right time has enabled us to see all three blasts.

While the blasts arrive in a consistent direction, that direction surprisingly differs considerably from the direction of the quarry, as can be seen by comparing these plots and the quarry direction indicated on the map in Figure 1. The difference is on the order of 45 degrees. One possibility is that these first arrivals have traveled along a path that does not follow a straight line from the quarry to the array. The local geology gives some support for this theory. A direct path from the quarry to our survey would pass through large amounts of sandstone and conglomerate, while a path that initially turned further to the west and then came back to our array would remain for the most part in a faster, more well-consolidated basalt formation that parallels the San Andreas fault, which passes about 5 km to the southwest of our survey area. Another possibility is that the energy follows a more direct path and is

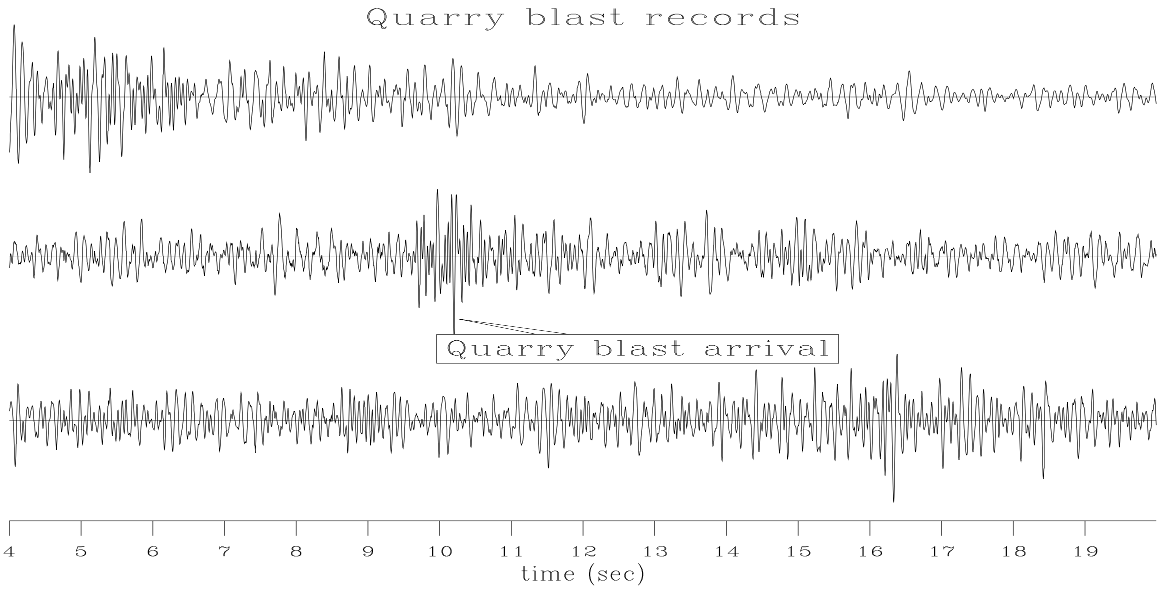

Figure 11: Traces from the same geophone group for three different recording periods, parts of the three daytime records where blasts were set off in a nearby quarry. The largest blast is the event on the middle trace arriving at around 10 seconds. The smaller blasts are not readily distinguishable on these single-trace displays. $\boxed{\text{traces}}$ [R]

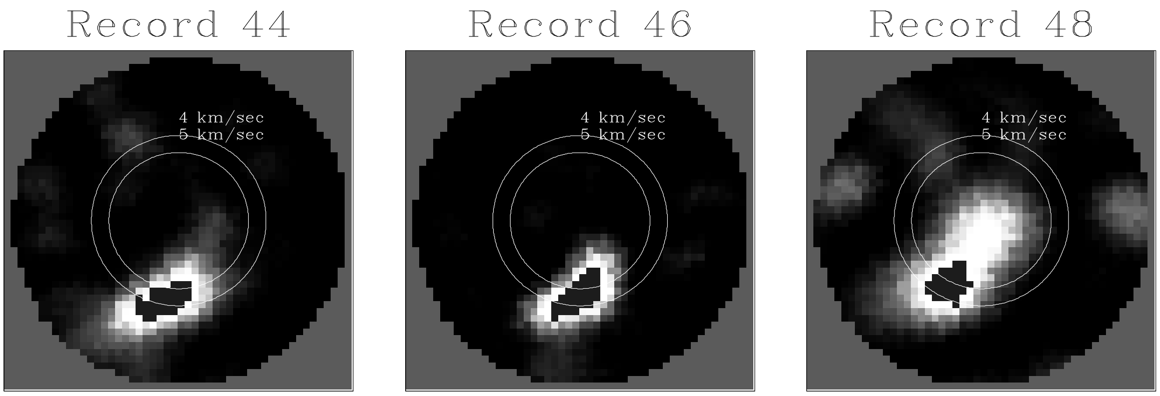

Figure 12: Beam steering result for 100 msec windows centered on the first arrival of energy from three blasts in a quarry 15 km distant from the array. Refer to figure 10 for an explanation of the individual plots, and compare to figure 1 to relate these directions to the survey geometry. All three blasts arrive in the same direction with apparent velocities around 4 km/sec. $\boxed{\text{blasts}}$ [R]

then rerouted by lateral velocity gradients in the near surface, for instance by a tilted weathered layer beneath the survey.

Another interesting fact to note about the blasts is that there is strong evidence of energy from the blast following different paths to reach our array. Figures 13 and 14 shows many 100 msec frames from the large quarry blast following the first arrival shown in Figure 12. All these frames have been gained identically, so the later arrivals do give semblance values that are quite high. Before the blast arrives, semblances are all much smaller. Thus we can assume that all the strong events shown in Figures 14 are due to the blast. Note that this late-arriving energy comes in a variety of directions, some of it arriving in a direction much closer to the direction of the quarry. One possibility is that the earliest arrivals traveled through the faster basalts to the west, and then later energy traveling in the straight-line direction arrived.

NEAR-VERTICAL EVENTS

One of the most interesting features of the dataset, discovered earlier by partial stacking, was the presence of near-vertically incident events in the nighttime records. These events are weak and not noticeable on individual seismograms. But partial stacking displayed them quite clearly.

Our first thought was that since the events are almost vertically incident, they must be due to some electrical interference. More careful beam steering now suggests that this is not so; these events seem to have a consistent direction of propagation that is close to vertical but not quite vertical. If that is so, they cannot be due to electrical noise.

Figure 15 shows the result of beam steering 12 different records from our survey. The entire 32 second records were used to produce each of these plots. The dominant feature of most of them, near the center, is the near-vertically incident events. While these events are close to the center, they are consistently just off-center. Their azimuth and apparent slowness indicate a fairly consistent arrival direction, from the east, with an apparent velocity of around 12 km/sec.

To show why the events are not due to electrical interference, we took one data record and randomly re-ordered the positions of the 169 traces in our array. If the events are real, and not perfectly flat, then re-ordering the traces in this way should effectively eliminate them. Figure 16 shows the result of beam steering the re-ordered traces, along with the original beam steering result for that record. There are some strong semblance values near the center, but they are not as strong as the values in the original beam steering result. More importantly, they are no longer in the same place, but are mostly clustered around the center. This is precisely what we would expect to happen; the semblances are not going to drop to zero because there was strong, near-vertically incident energy present. After re-ordering it will still stack in to some extent. But the directional consistency should be, and is, lost. Thus it is clear that these events are not due to electrical interference.

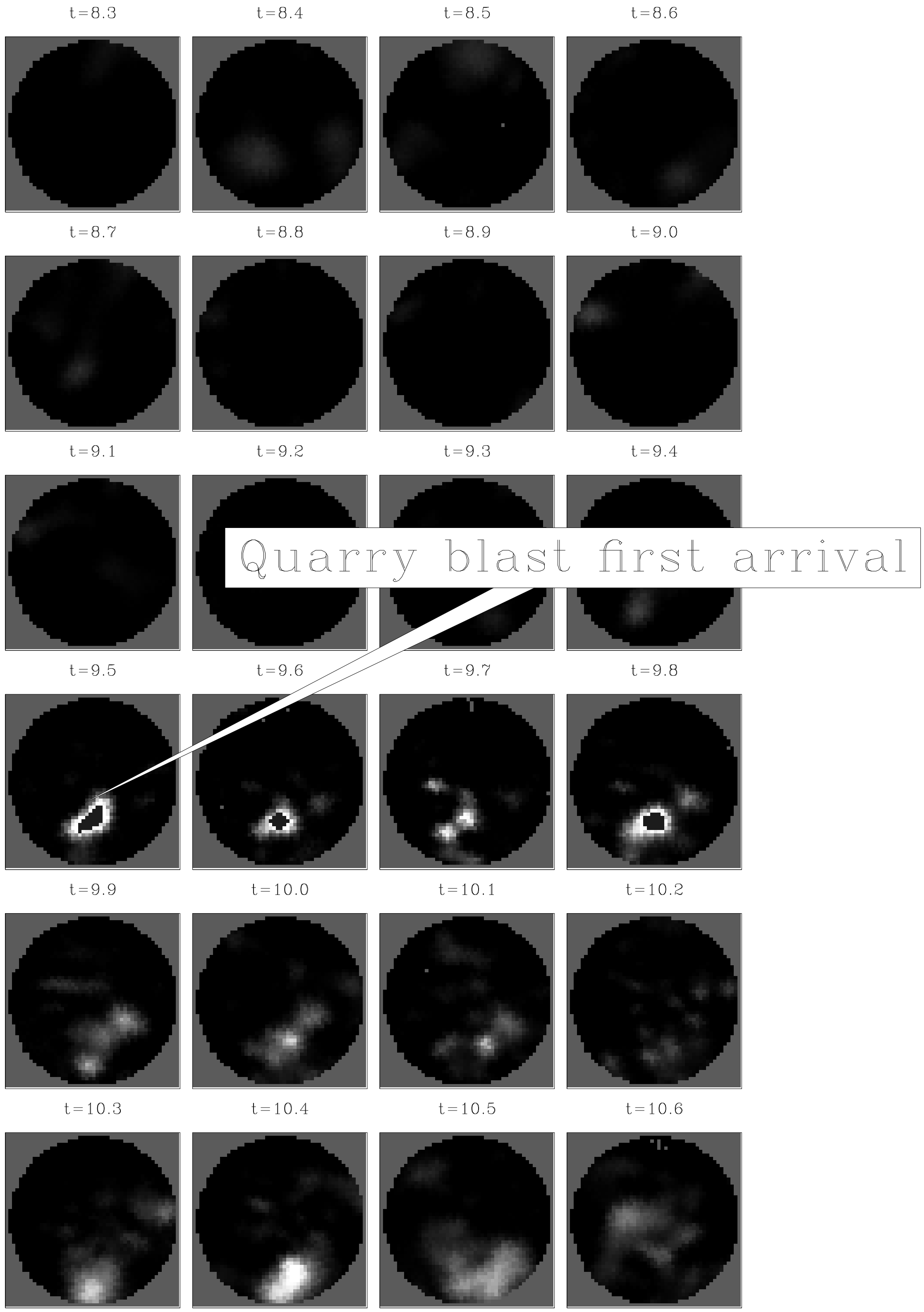

Figure 13: Frames showing the result of beam steering for 100 msec windows following the first arrival shown in the middle frame of Figure 12. This is the largest of the three quarry blasts. The energy in these frames is much stronger than that in the rest of the 32 second record, so all this energy must be due to the quarry blast, suggesting multiple travel paths or scattering. beamwin46.1 [R]

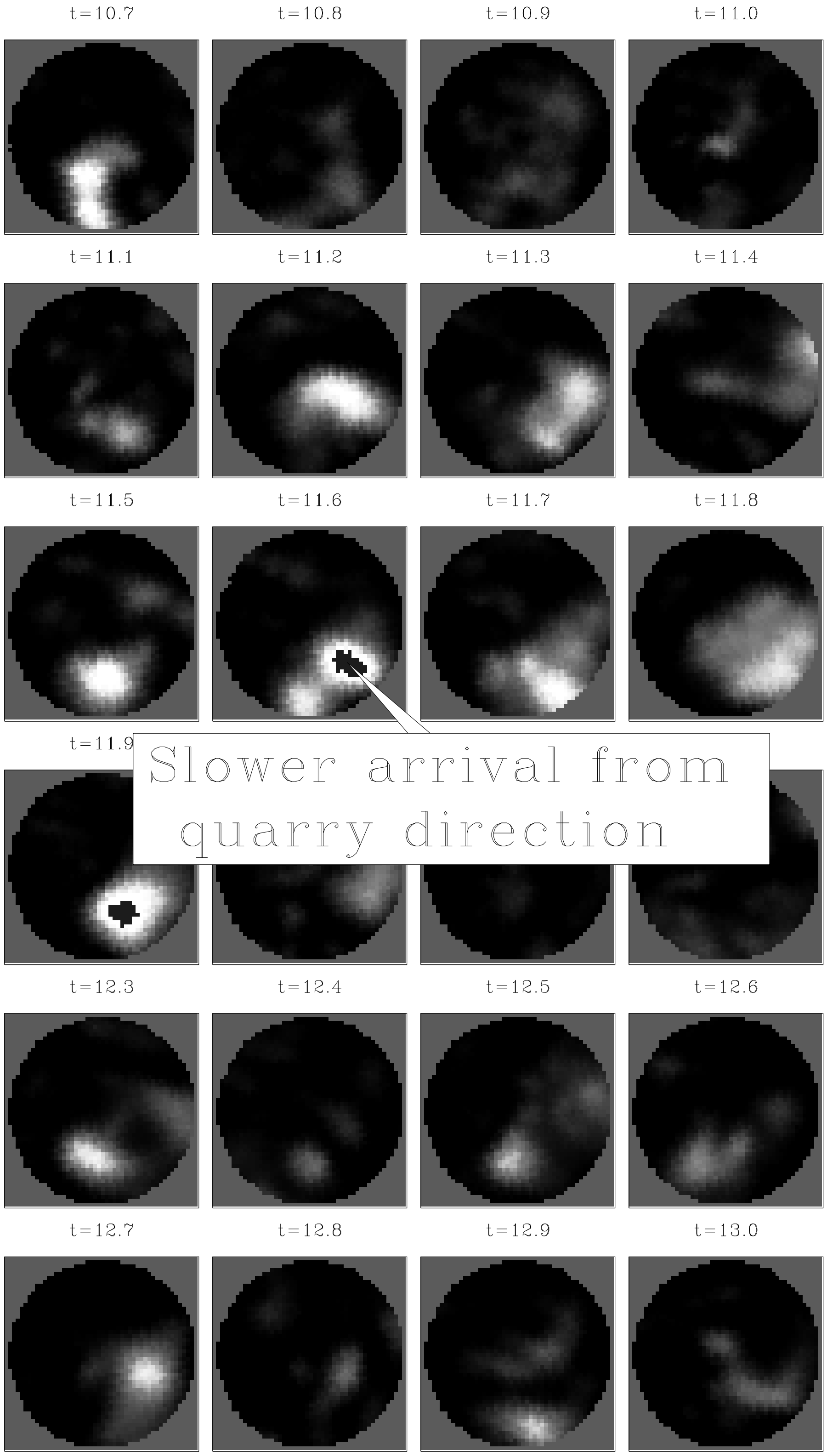

Figure 14: The continuation of Figure 13. beamwin46.2 [R]

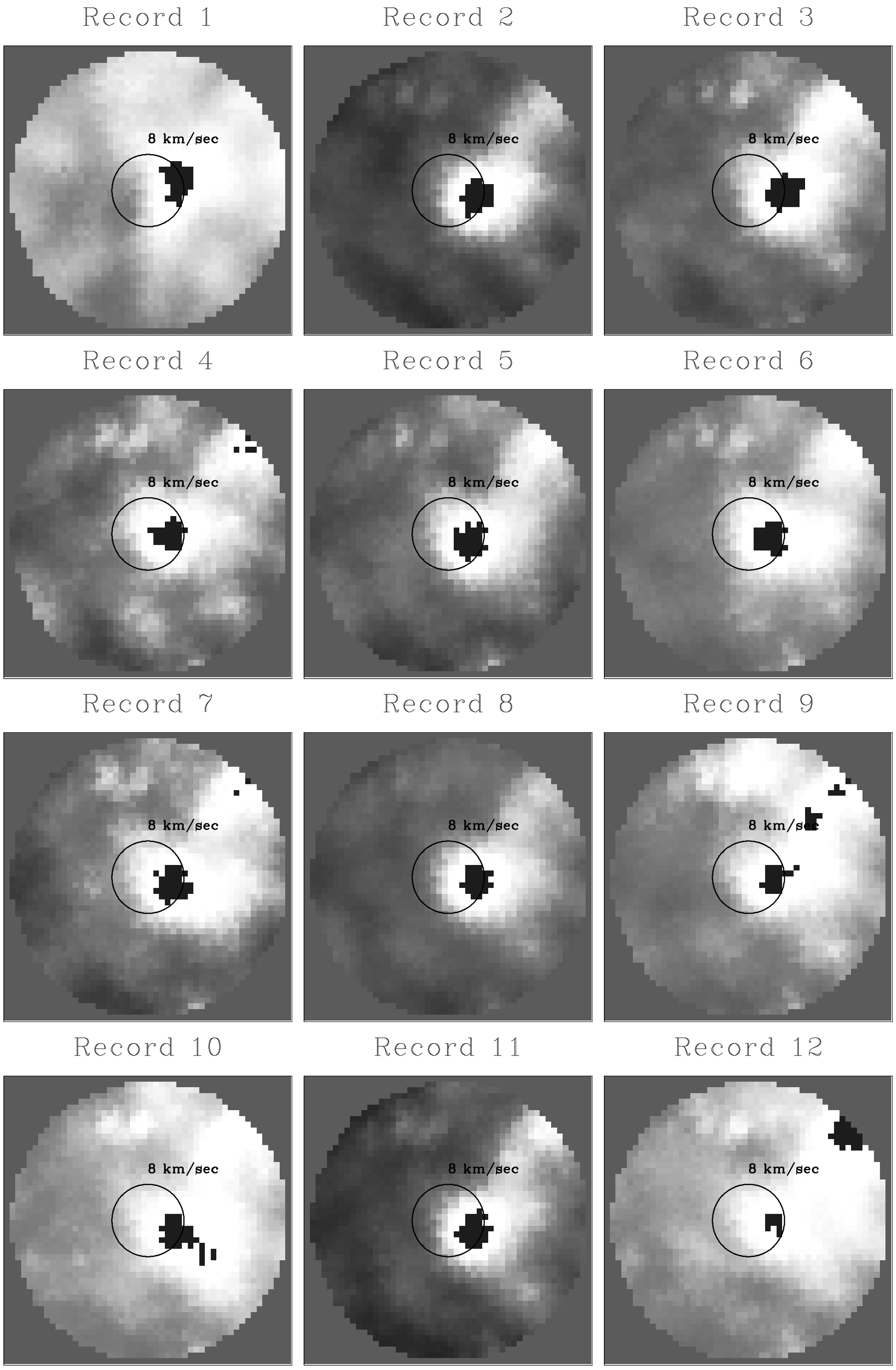

Figure 15: Result of beam steering for 12 different nighttime records (records 1-12). The feature consistent from plot to plot represents near-vertically incident events, arriving from the east with an apparent velocity of around 12 km/sec. vertbeam1 [R]

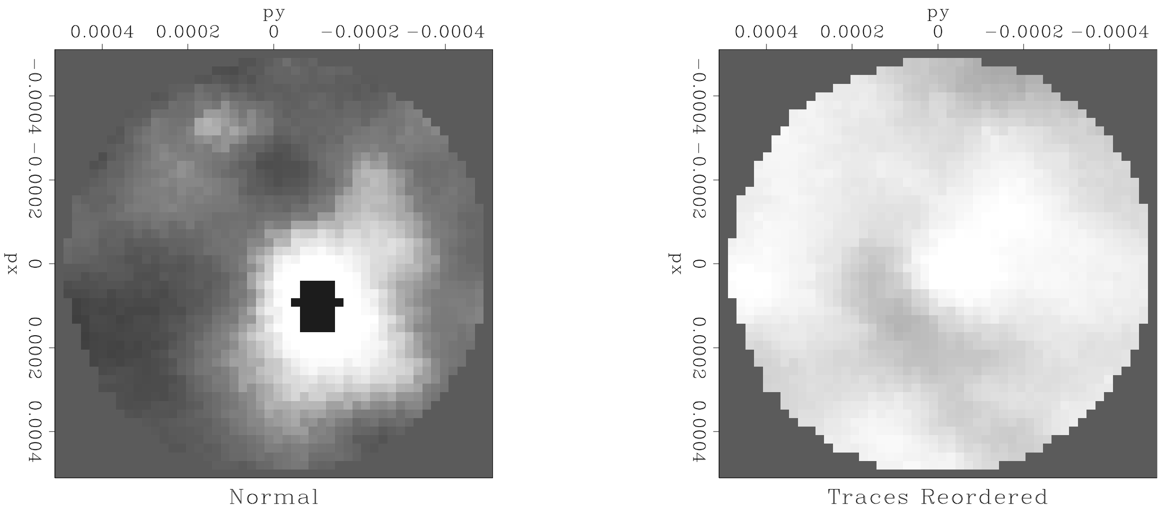

Figure 16: One of the records from Figure 15 (left) and the result of applying the same processing to data where the trace positions have been randomly re-ordered (right). The re-ordering has removed the high-semblance values seen on the left, verifying that the high semblance values near the center of the left plot were due to actual events and not some sort of interference. bcomp.26 [R]

POSSIBLE SOURCES OF NEAR-VERTICAL EVENTS

Given that we have ruled out electrical interference, what could be the cause of such events? One possibility is that these are not seismic waves travelling in the Earth but sound waves travelling in the atmosphere, incident on the array from above. Two factors suggest that this is unlikely. First, the steep angle of incidence implies that such a source would be located within 2 degrees of the zenith, almost directly overhead:

$$\arcsin \frac{0.3km/sec}{10km/sec} = 1.7^\circ \tag{1}$$

Second, the source would have to be stationary throughout the experiment, which spanned an 18 hour period, in order to mimic this seismic response.

Having ruled out electrical interference and atmospheric disturbances leads us to conclude that these events are seismic in origin. We would like to know where the source of these events is located. There are two possibilities, which were illustrated in Figure 3. One is directly beneath the array, in the upper 15 km or so of the crust where earthquakes occur. This is the cone-shaped region in Figure 3. The orientation of the cone is indicative of the observed arrival direction of the incident waves. The size of the cone is due to the fact that our resolution in apparent velocity space was somewhat limited; the near-vertical events arrived at between 8 and 12 kilometers per second.

A problem with the near source hypothesis is that the steep angle of incidence restricts the location of such sources to a relatively small zone located beneath the array. This would mean either that we were very lucky in choosing the site for our array, or that such small-scale seismic activity occurs in many places.

The second possibility is that this energy is from a more distant source, and that the energy has followed a raypath similar to that shown in Figure 3, travelling down to some depth, then turning toward the surface. A large distance is required to explain the very steep angle of incidence. While quarry blast energy from 15 kilometers away reached the array at an apparent velocity of 4-5 kilometers/second, energy arriving at the much steeper angle implied by 8-12 kilometers/second must have come from a much more distant source. An apparent velocity of 8 km/sec corresponds to a source at a distance of approximately 1000 kilometers for P waves. An apparent velocity of 12 km/sec corresponds to a distance of 3000 kilometers.

A problem with the distant source hypothesis is that a source hundreds of kilometers away would have to be quite strong, or a distributed source that encompasses a wide area, to be detected at this distance.

Lateral velocity variation can invalidate almost any seismological analysis including those above. A $v(x, z)$ velocity gradient could mean this energy came from somewhere other than the two regions shown in Figure 3. The quarry blasts did reveal evidence of lateral velocity gradients. These gradients affected the azimuth angle of the incident waves, changing some by as much as 45 degrees, but had little effect on their apparent velocities. Following the same logic, the near-vertical events could have been precursors to the October 1989 Loma Prieta earthquake, whose epicenter was approximately 60 kilometers to the southeast of this array, whose arrival direction has been changed by strong lateral velocity gradients near the array. In addition to changing the azimuth, however, the gradient would need to change the apparent velocity from 8 or more km/sec to near 6.5 km/sec, which is the apparent velocity for a P wave source at a distance of 100 kilometers. There is no evidence that velocity gradients at this site are that strong.

Having two or more of these arrays separated by some distance would allow us to triangulate and reduce the uncertainty in determining where these events are coming from.

CONCLUSIONS

We have used a dense receiver array containing thousands of geophones to characterize the ambient seismic wavefield. The large number of channels made it possible to pick out events that were not distinguishable on single-channel displays or using linear arrays. These events included distant quarry blasts, and the interesting near-vertically incident events that were seen throughout the experiment during quiet night time recording. Various non-seismic explanations for these events can be ruled out. The angle of incidence constrains the source of these events to two regions — a small zone beneath the array, and a much larger zone roughly a thousand kilometers away, though the potential for near-field lateral velocity gradients makes it impossible to sharply define the extent of either zone. A followup study would help to determine which is the correct explanation.

REFERENCES

Nikolaev, A.V., and Troitskiy, P.A., 1987, Lithospheric studies based on array analysis of P-coda and microseisms: Tectonophysics, **140**, 103-113.