Examination of a passive seismic dataset using beam steering

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ABSTRACT

A passive seismic dataset is searched using beam steering, in much the same way that a seismological network uses beam steering to detect events. A coarse sampling of incident energy as a function of time, velocity, and direction of incidence is performed. If significant energy is found in a particular beam, a finer study is done to further define the direction and velocity of the incident energy. For two anomalously strong measurements, I show the uncorrected and beam steered data, and discuss what the results tell us about the energy present in the data.

INTRODUCTION

I have recently acquired data from a passive seismic experiment. A conventional reflection survey was being conducted using a two-dimensional receiver array. At the end of one day's shooting, I was able to record approximately an hour's worth of passive data. Since the geophones were already in place, this entailed only a small amount of extra effort beyond that of the conventional survey. In this paper, I present the data, and show how beam steering can be used to give us some knowledge of the origins of the energy that is recorded.

The receiver geometry consisted of three parallel lines of receivers, spaced approximately one-half mile apart. Each line contained 341 geophone groups, with a spacing of 55 feet between the centers of adjacent groups. A two-dimensional array is probably a necessity in this work to be able to cancel horizontally-traveling energy. This array does not offer much noise cancellation ability in the crossline direction because of the coarse sampling, but it may be sufficient. The data were recorded in sign-bit form (one bit of amplitude information per geophone per sample) in 32 second records with a sampling interval of four milliseconds. I have 120 of these records, or a total of an hour and four minutes of data. At 1600 bytes per inch, this required six 2400 foot magnetic tapes.

A portion of one record is shown in Figure 1. Note that there is a significant amount of coherent energy present in the record, but the random noise level is extremely large compared to a conventional seismic reflection survey. We would like to be able to detect the coherent energy in the presence of noise, and know where it is coming from. Beam steering is a simple tool that allows us to use the power of stacking to analyze the incoming energy as a function of time, direction of incidence, and velocity.

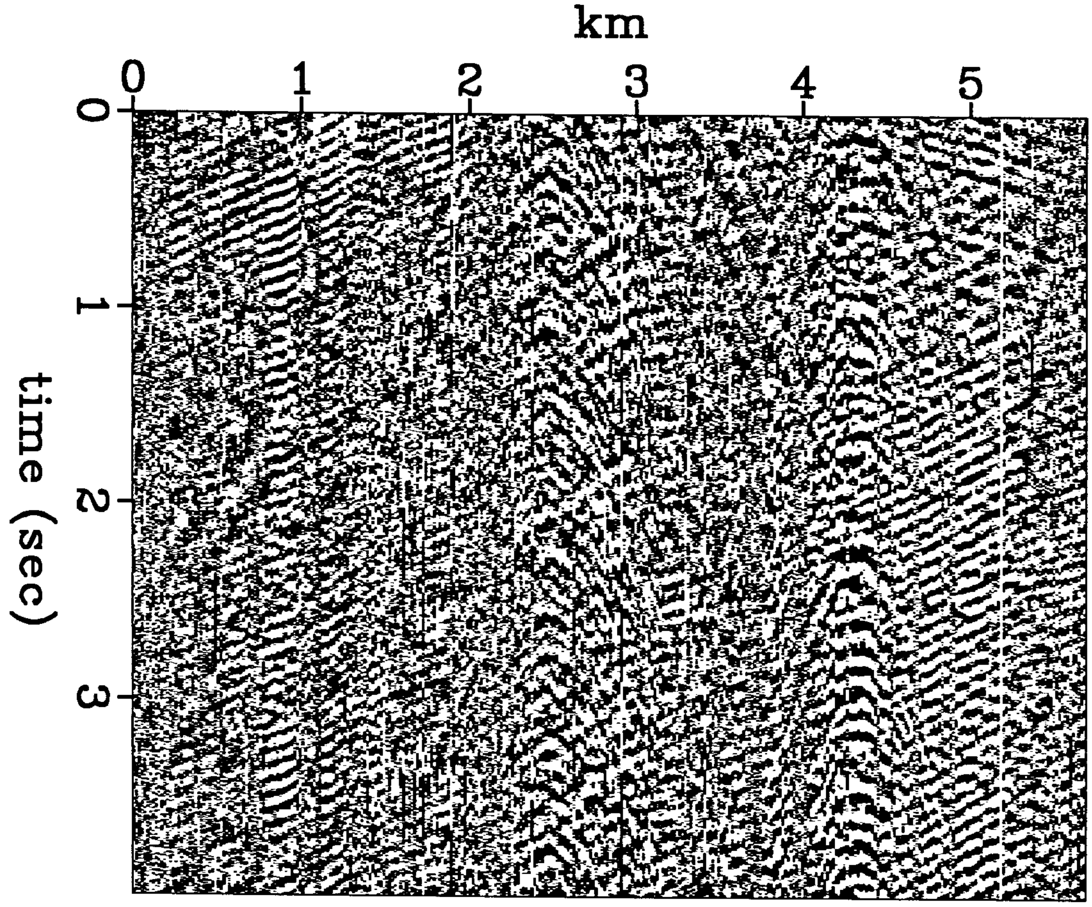


FIG. 1. A portion of a record from a passive seismic survey.

Beam steering for event detection

The problem of detecting coherent events and determining their direction of arrival is similar to the detection problem faced by a seismic network looking for distant earthquakes or nuclear blasts. Bungum, Husebye, and Ringdal (1971) discussed how beam steering was used to perform real-time event detection for the NORSAR large-aperture seismic array. The NORSAR array contained 132 short-period seismometers organized into 22 subarrays. To keep the volume of recorded data manageable, a real-time event detection system using beam steering decided when a significant event had occurred, triggering the permanent retention of all seismometer output, which could then be processed off-line. To cover all possible directions and velocities of incident energy, the system formed up to 600 beams in real time. Some beams were narrowly directed toward well-known areas of seismic interest. Others were used to provide a general surveillance of regions not covered by the narrower beams.

Borrowing this approach, I will first do a coarse scan of the time, direction, and velocity spaces. From these results, some areas with anomalously large incident energies will be selected for closer study. If necessary, I will do a finer beam steering study to define further the direction and velocity of the incident energy. By studying the data before and after beam steering, I will attempt to draw some conclusions about what coherent energy is present in the data.

Beam steering procedure

Aki and Richards (1980) show that the arrival time of a plane wave moving with apparent surface velocity c and arriving from a direction specified by an azimuthal angle ϕ at the i–th station of a seismic array is given by:

$$t_i = t_0 + \frac{\cos\phi}{c}(x_i - x_0) + \frac{\sin\phi}{c}(y_i - y_0) + \tau_i$$

where (x_i, y_i) are the coordinates of the receiver, t_0 is the arrival time of the wave at a reference point (x_0, y_0), and τ_i is the station residual. Thus to form a beam in a particular direction with a given velocity, we apply the time shifts prescribed by this equation, and stack the traces together. Also it is helpful to sum the resulting stack over short time windows, to reduce the effect that random noise has on the beams.

Note that the formula does not depend on the dip angle of the arriving wavefront. This is due to the ambiguity between velocity and dip angle for a two-dimensional array. A given apparent surface velocity could be due any of a number of combinations of dip angle and medium velocity.

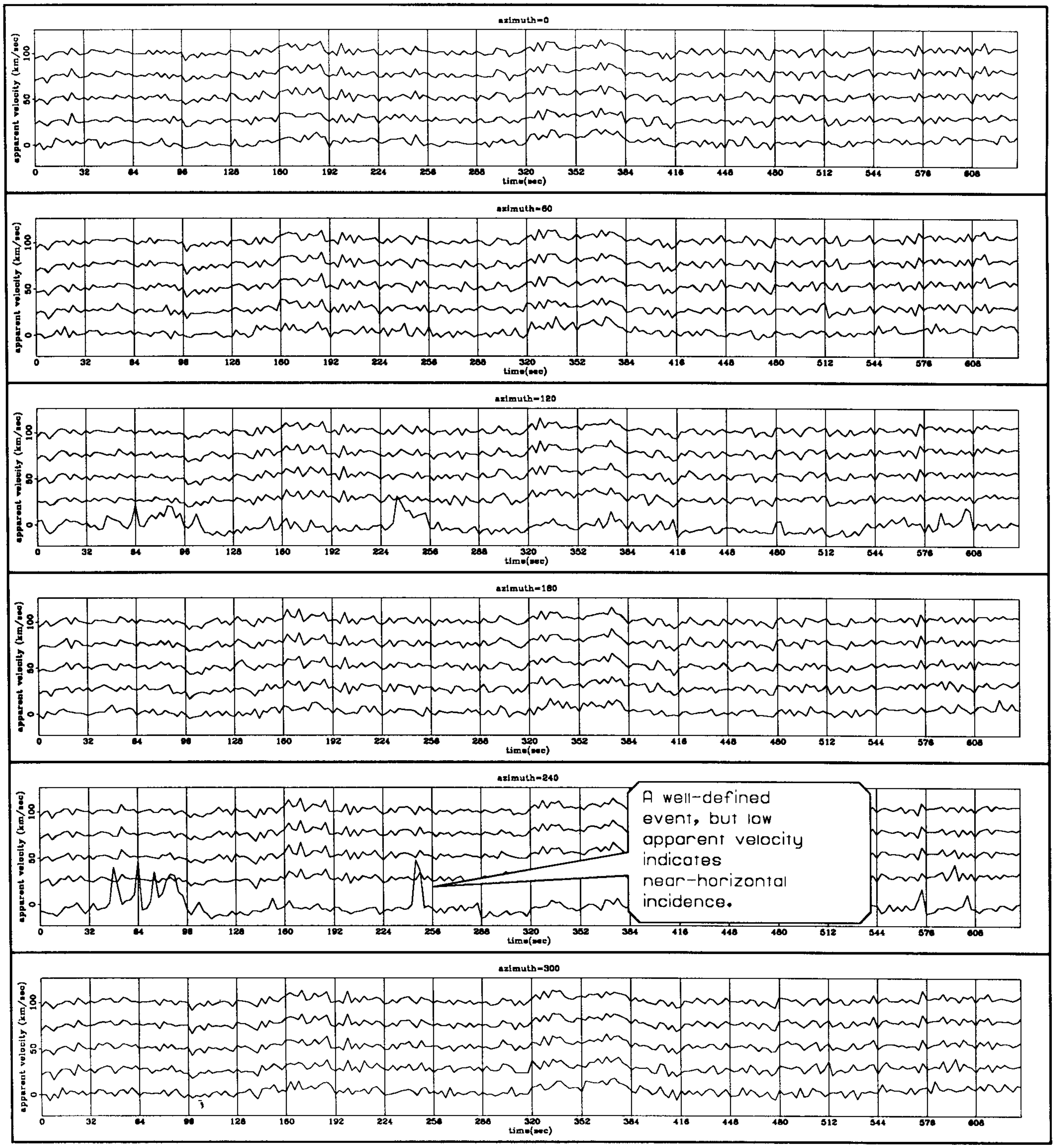
RESULTS

Searching for horizontally incident energy

To perform the coarse scan of the passive seismic dataset, I read each of the 120 thirty-two second records from tape. I divided each record into ten time windows, and then formed for each window 30 beams covering six different azimuths and five different apparent surface velocities. The azimuths are the two inline directions, and the four directions sixty degrees away from inline. I avoided steering in the crossline direction because of its coarse sampling. The apparent surface velocities range from 1000 meters/second up to 100 km/sec, an apparent velocity which is approaching the point at which no shifts at all are applied, and beam steering is reduced to simple horizontal stacking. I chose these velocities thinking that for a near surface velocity on the order of 2000 meters/second, this range allows us to cover the entire range of possible apparent surface velocities resulting from waves traveling with different azimuths and dip angles, all the way from vertically incident energy to energy that is traveling horizontally. A beam is simply a stack along a trajectory that is a function of the azimuth and apparent surface velocity. We then compute the power in the beam and sum over short windows.

Figure 2 shows the result of the coarse scan of the first twenty records discussed above. The different frames correspond to the six different azimuth directions. Within each, the five traces represent different apparent surface velocities, with the lowest apparent velocity on the bottom and the highest (corresponding to near-vertical incidence) on the top. Each trace has one sample for each time window over which beams are averaged. The time on the axis corresponds to the time at the center of the window. The time windows used were 4 seconds long. The quantity displayed is the sum over the window of the power in the given beam.

There are several features to note in the coarse scan. Generally speaking, the low velocity beams have the most energy, implying that most of the energy incident on the array is coming in from the side, rather than from below. Such energy is most likely due to cultural noise. I've used a balloon to highlight a particularly strong, sharply-defined event on one of the low velocity traces. Since it is so well defined, I decided to take a look at the data that went into forming this beam, to see what it could tell us. Figure 3 shows the data from one of the three lines during that time interval. The data as recorded is on the top, and on the bottom is the data after beam steering, using the parameters (azimuth of 240 degrees, apparent surface velocity of 1000 meters/second) that gave rise to the large-amplitude beam. Steeply-dipping coherent energy (especially easy to see on the right side of the top figure) has been flattened by the beam steering correction. I've stacked the two data sets, and the stack power is more than doubled after beam steering, due to the improved alignment of the coherent energy.



A well-defined event, but low apparent velocity indicates near-horizontal incidence.

FIG. 2. Beam power as a function of time for a ten minute recording interval. Each frame is a different azimuth direction, and within each frame the traces correspond to different apparent surface velocities. Note that low velocities dominate, indicating energy incident from the side of the array.

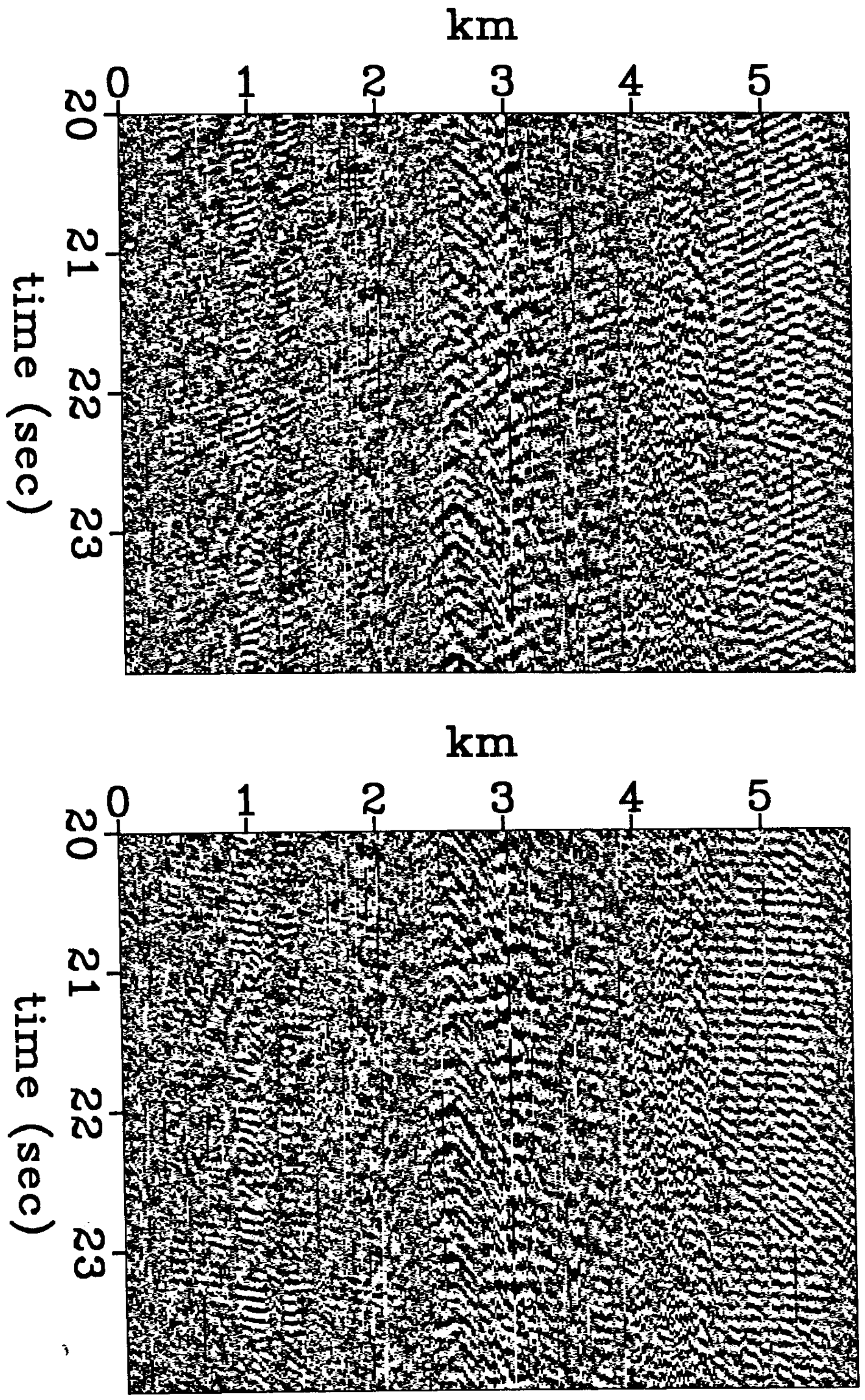


FIG. 3. Data before (top) and after (bottom) beam steering that gave rise to the strong amplitude beam noted in Figure 2. The coherent energy visible on the right side of the top section has been flattened by beam steering, indicating that it was responsible for the anomalous measurement. The apparent velocity of this event is quite slow, implying that it is likely to be cultural noise incident on the array nearly horizontally.

Searching for vertically incident energy

We have used beam steering to detect and identify some of the coherent energy incident on the array. It is clear that there is plenty of coherent energy incident on the array from the side, and that this method is capable of detecting it and locating its arrival direction. Such energy is most likely due to cultural noise. It would be more interesting if we could identify some energy in the data that is more nearly vertically incident. Such energy would more likely correspond to arrivals from distant sources or reflections off layers within the earth.

A quick look at the beams in Figure 2 shows that vertically incident energy is certainly not as plentiful as horizontally incident energy. Vertically incident energy will have a high apparent surface velocity. But there are no cases in Figure 2 where, for a given azimuth, the high-velocity beams are significantly stronger than the lower-velocity beams. A beam steering scan of another twenty records using the same parameters is shown in Figure 4. The most noticeable feature of Figure 4 is the strange behavior at around 240 seconds. This is due to a bad record in the passive data. There were several bad geophones that overwhelm the rest when stacked. More interesting to note is the region of the 120 degree azimuth panel indicated by the balloon. Here is an example where the high-velocity beams are strong compared to the lower-velocity beams for the same azimuth. While this anomaly is not as strong as the low-velocity anomaly we examined earlier, it appears to be significant enough that we should look closer to see if there is some vertically incident energy here.

As a first step, I took the data in the vicinity of the anomalous measurement and did a more detailed beam steering analysis. There was little beyond what can be seen in Figure 4 to be learned from it, except that the strength of the beam was not due to any one event. When I divided the same data into many windows, beam steering showed several smaller anomalies, which because of the windowing just happened to sum to produce the large reading seen in Figure 4. This is a disappointing result; a single strong event would have been much easier to see in the data than several weak ones. With very weak events, it is difficult to tell if these are truly near vertical-incidence events, or just chance alignments of random noise and coherent but not vertically incident energy.

Figure 5 shows some of the data that gave rise to the interesting measurement in Figure 4. The finely detailed beam steering suggested that correcting for an azimuth of 120 degrees and an apparent velocity of 100 kilometers/second would maximize the lateral continuity, so I have applied those shifts prior to displaying the data. Since 100 kilometers/second corresponds to near vertical incidence, the shifts are small – a maximum of 14 samples across the whole array. Yet those shifts increase the power of the resulting stack by 30 per cent. It is difficult to see much lateral continuity in Figure 5. Thus the seemingly promising result we got from beam steering is unfortunately not due to a single, strong, vertically incident event. We knew from the relatively weak amplitude of the near-vertical incidence beams

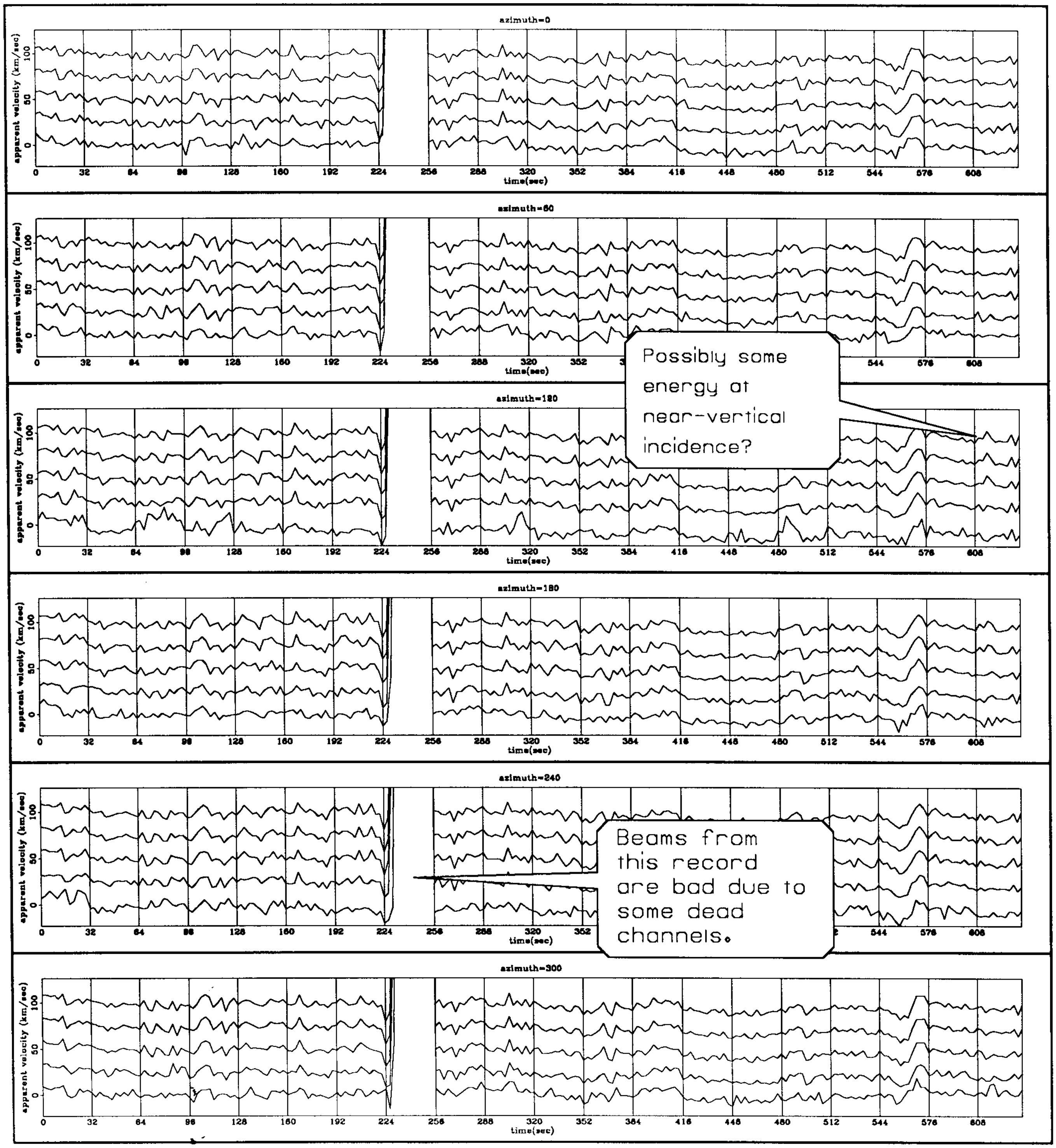


FIG. 4. Beam steering results for a second ten-minute recording interval. While energy with low apparent surface velocities still dominates, a case where there is more energy at high velocities, indicating near-vertical incidence, is noted for closer study.

in Figure 4 that we were not going to find the same strong events that we found for near-horizontal incidence earlier. But if those anomalously strong beams had been due to a single event, we might have had a chance to see it with beam steering.

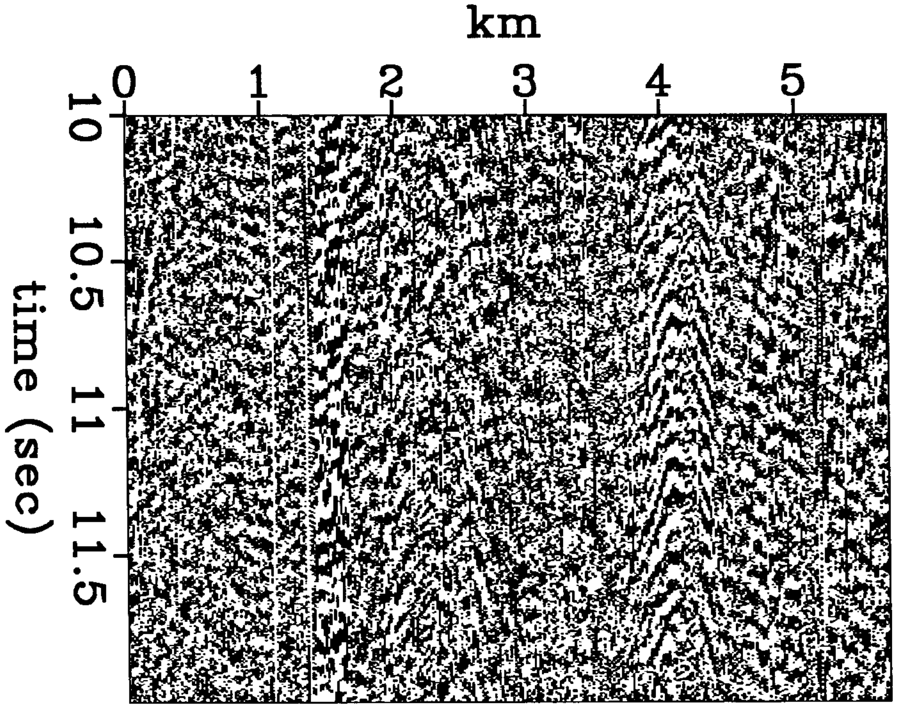


FIG. 5. Data that gave rise to the large beam amplitude for near vertical incidence indicated in Figure 4. Unlike the near-horizontal incidence case, here it is difficult to discern the events responsible for the beam steering result.

CONCLUSIONS

The passive seismic dataset has a large amount of coherent energy. Beam steering is able to identify near-horizontally incident energy, most likely due to cultural noise, which is relatively strong. Attempts at using beam steering to find weaker, more vertically incident energy, which one would attribute to more distant sources, or reflection off subsurface structures, haven't been successful. Possible conclusions are that such vertically incident energy is so weak that it is totally overwhelmed by other energy, or that stacking-based methods such as beam steering aren't powerful enough tools to see past the contaminating noise to the weak vertically incident events. A logical next step is to try using techniques that may be able to see past this noise, such as multichannel filtering.

REFERENCES

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