Chapter 1

Beam steering of passive seismic data

In this chapter, I present a technique that tries to improve upon the partial stacking results shown in the introduction, and give clearer pictures of where events present in the passive data are coming from. This technique is beam steering; semblance is computed as a function of plane wave arrival direction. The geometry of the problem is illustrated in Figure 1.1. Beam steering is applied here to the quarry blasts, and to the nighttime records where partial stacks showed evidence of near vertically incident events.

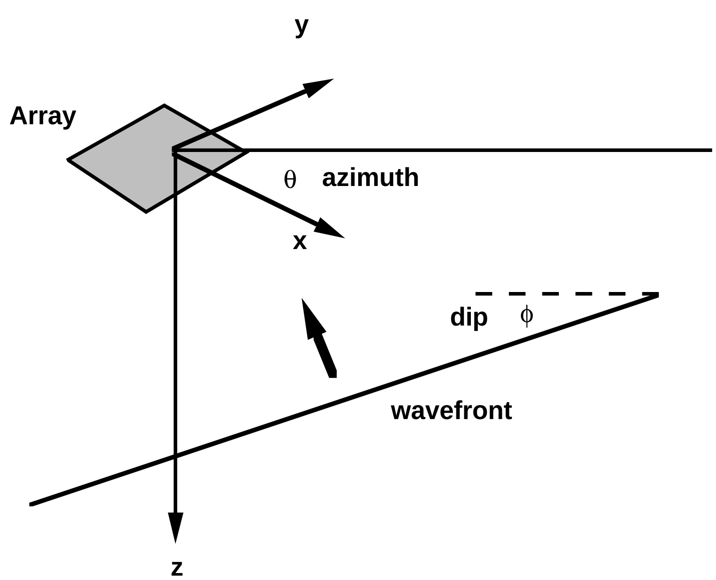

Figure 1.1: Beam steering parameters. Incident plane waves are characterized by azimuth angle and either the dip angle or apparent velocity. passive-beam [NR]

1.1 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.

1.2 Quarry blast recordings

Figure 1.2 shows portions of the seismograms recorded by one of our 169 groups for the three blast records. The quarry blast appears on the middle trace at 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.

We were lucky to record these blasts at all. Our recording equipment consisted of 169 seismic group recorders (SGRs), each recording data on its own cassette tape and powered by a battery. The rechargeable batteries have a lifetime of about a day of normal operation. They worked fine for our nighttime recording, but had to sit using power until the middle of the next day for the blast recordings, and battery failure began to take its toll. About half the SGRs were still working for the first blast at 11 AM, and only 38 of the 169 were still working for the third blast at 12 Noon.

While the blasts are not readily apparent on individual traces, beam steering has been a very useful tool for detecting and locating them. Figure 1.3 gives a schematic view of the disc-shaped beam steering plots which will be used frequently throughout this chapter. 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.

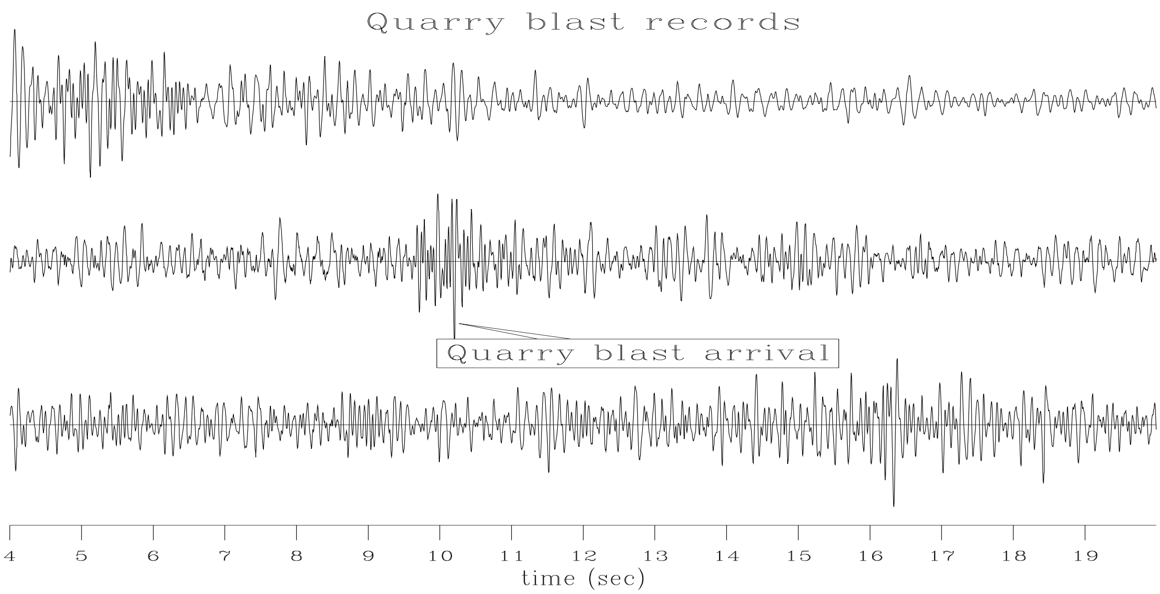

Figure 1.2: Traces from the same geophone group for three different recording periods, parts of the three daytime records where blasts were set off in a nearby quarry. The largest blast is the event on the middle trace arriving at around 10 seconds. The smaller blasts are not readily distinguishable on these single-trace displays. passive-traces [ER]

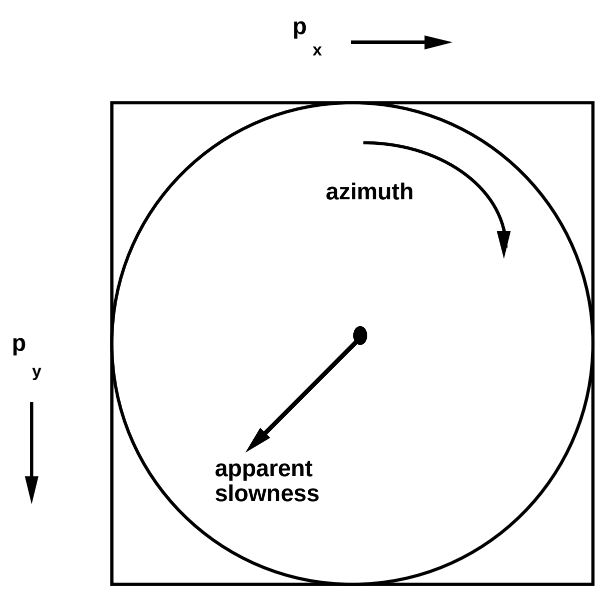

Figure 1.3: Beam steering parameters. Different azimuths are displayed around the circle, and different apparent velocities in the radial direction. A vertically incident event (infinite apparent velocity) would be plotted at the center. passive-beamexpl [NR]

Figure 1.4 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. I 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 1.4, 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.

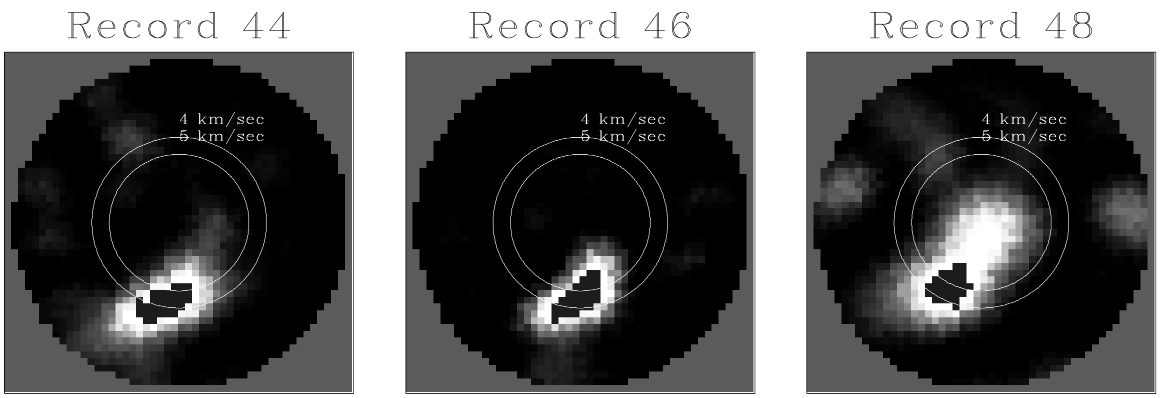

Figure 1.4: Beam steering result for 100 msec windows centered on the first arrival of energy from three blasts in a quarry 15 km distant from the array. Refer to figure 1.3 for an explanation of the individual plots, and compare to the map in Chapter 1 to relate these directions to the survey geometry. All three blasts arrive in the same direction with apparent velocities around 4-5 km/sec. passive-blasts [ER]

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 shown earlier. 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 then rerouted by 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 1.5 though 1.7 shows many 100 msec frames from the large quarry blast following the first arrival shown in Figure 1.4. 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 1.6 and 1.7 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. The frame at time 14.1 seconds has a fairly high semblance value right at the center, indicating vertical incidence. This is possibly a reflection off the moho.

1.3 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.

Figures 1.8 through 1.11 show the result of beam steering the 48 different records in 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 illustrate why I think the events are not due to electrical interference, I 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 1.12 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.

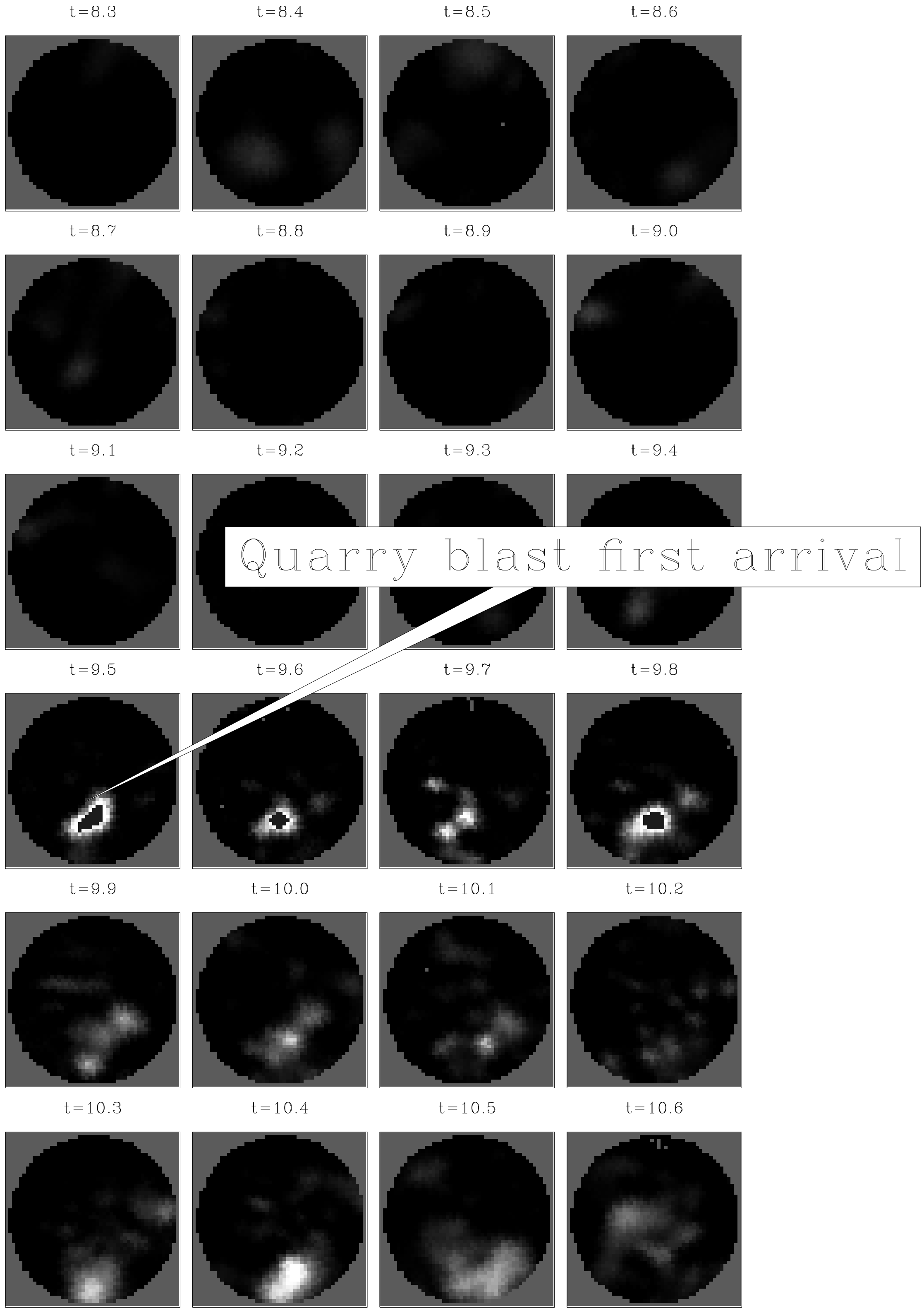

Figure 1.5: Frames showing the result of beam steering for 100 msec windows following the first arrival shown in the middle frame of Figure 1.4. This is the largest of the three quarry blasts. The energy in these frames is much stronger than that in the rest of the 32 second record, so all this energy must be due to the quarry blast, suggesting multiple travel paths or scattering. passive-beamwin46.1 [ER]

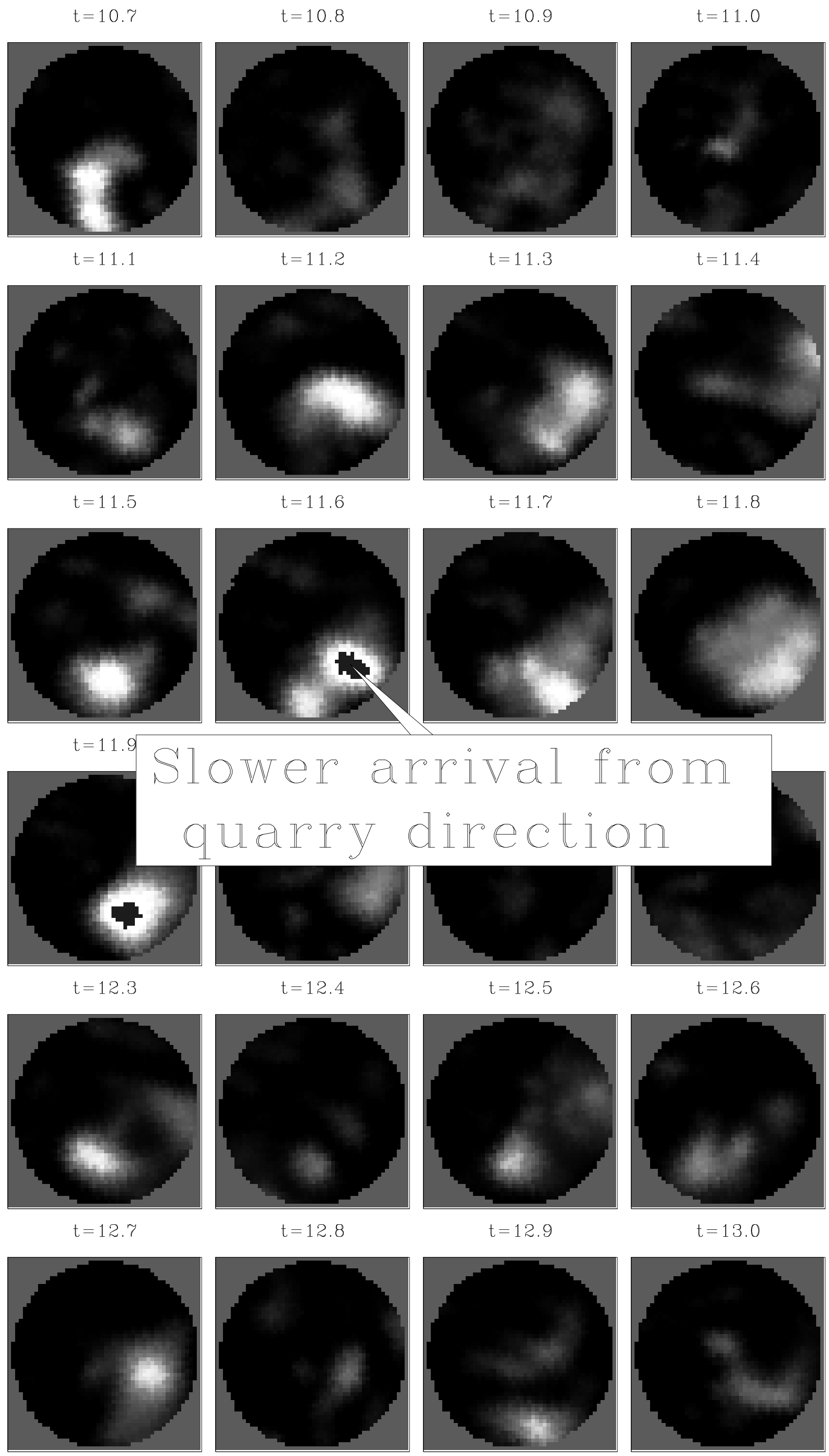

Figure 1.6: The continuation of Figure 1.5. passive-beamwin46.2 [ER]

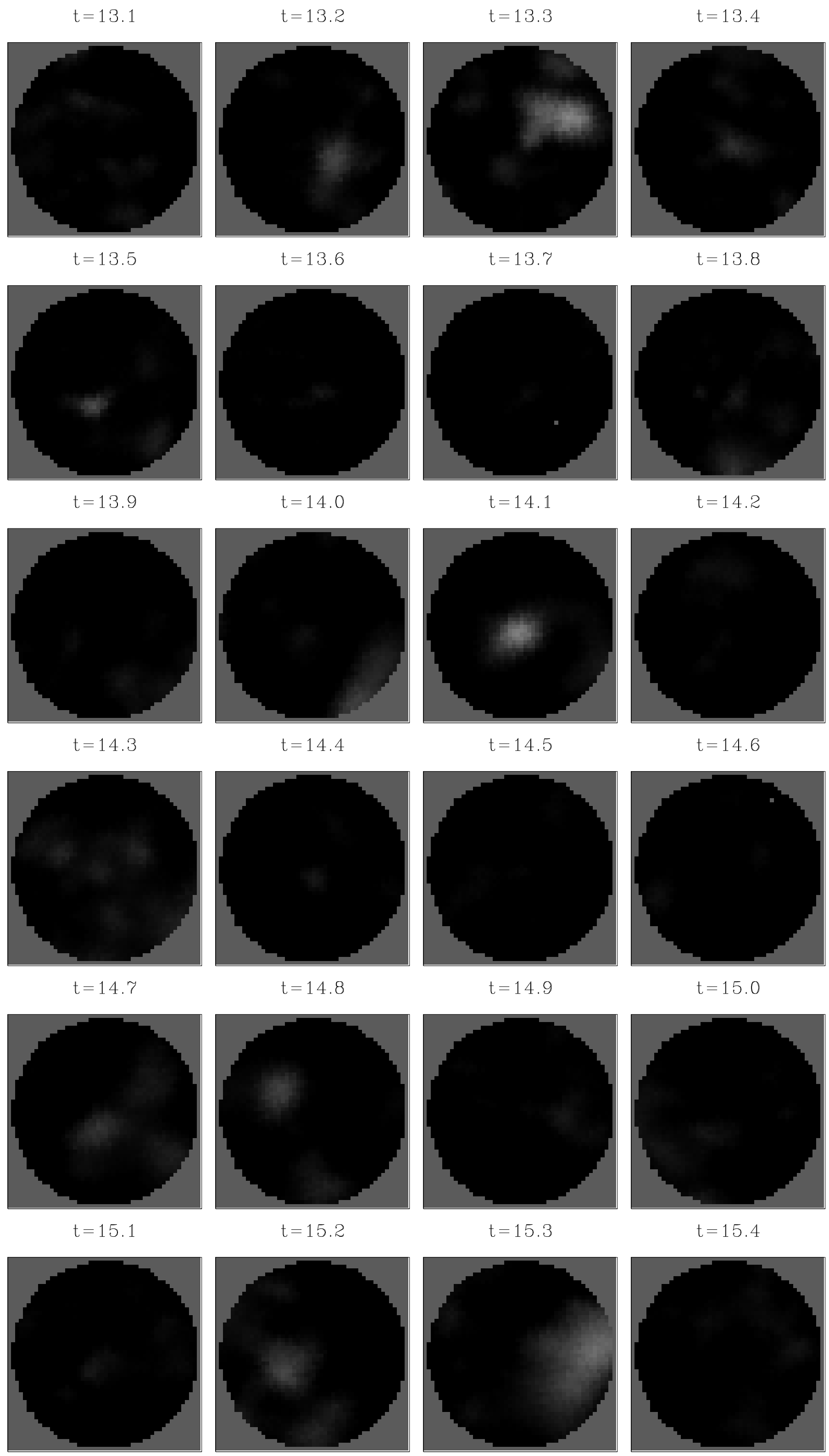

Figure 1.7: The continuation of Figure 1.6. passive-beamwin46.3 [ER]

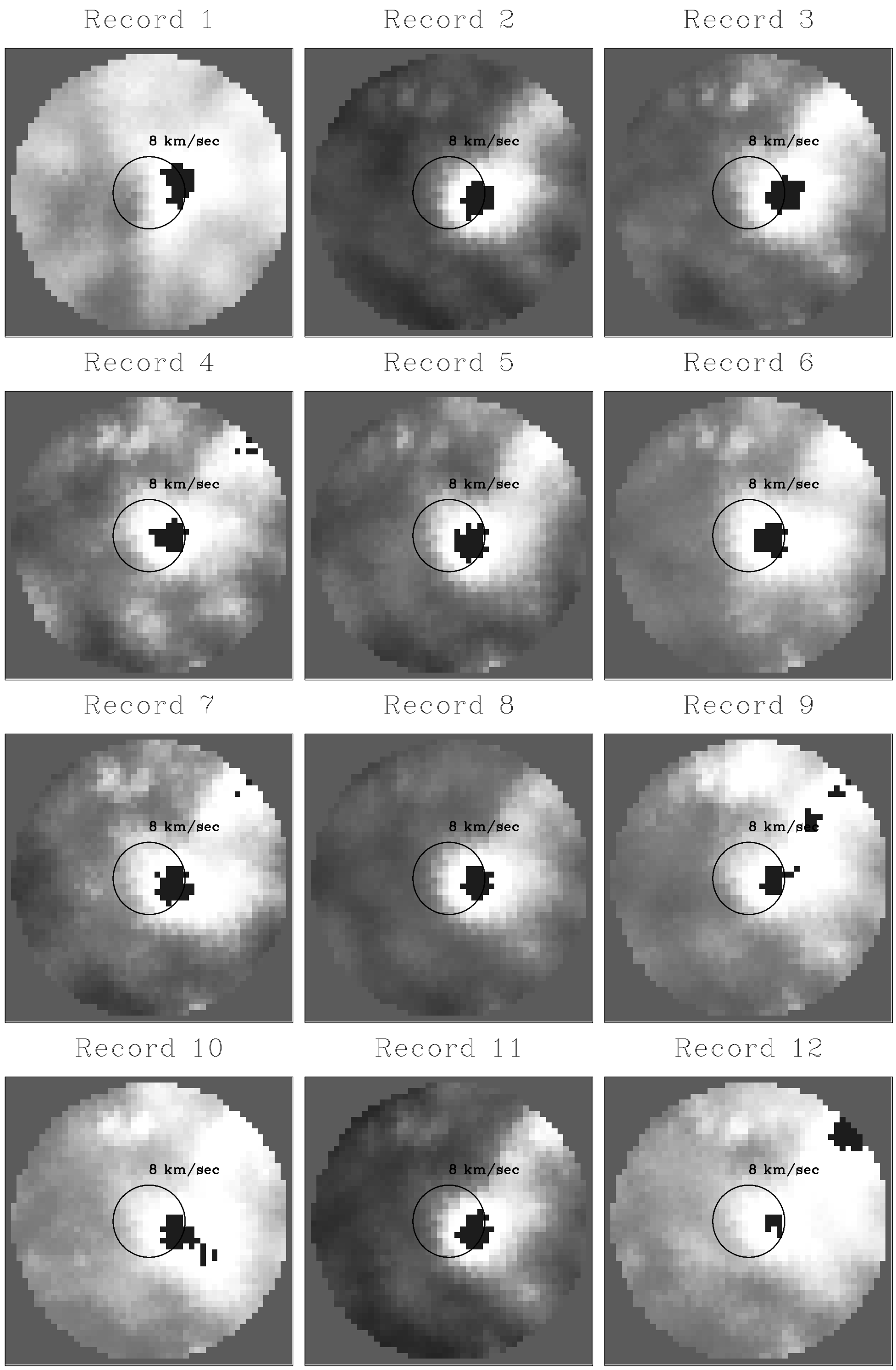

Figure 1.8: Result of beam steering for 12 different nighttime records (records 1-12). The feature consistent from plot to plot represents near-vertically incident events, arriving from the east with an apparent velocity of around 12 km/sec. passive-vertbeam1 [ER]

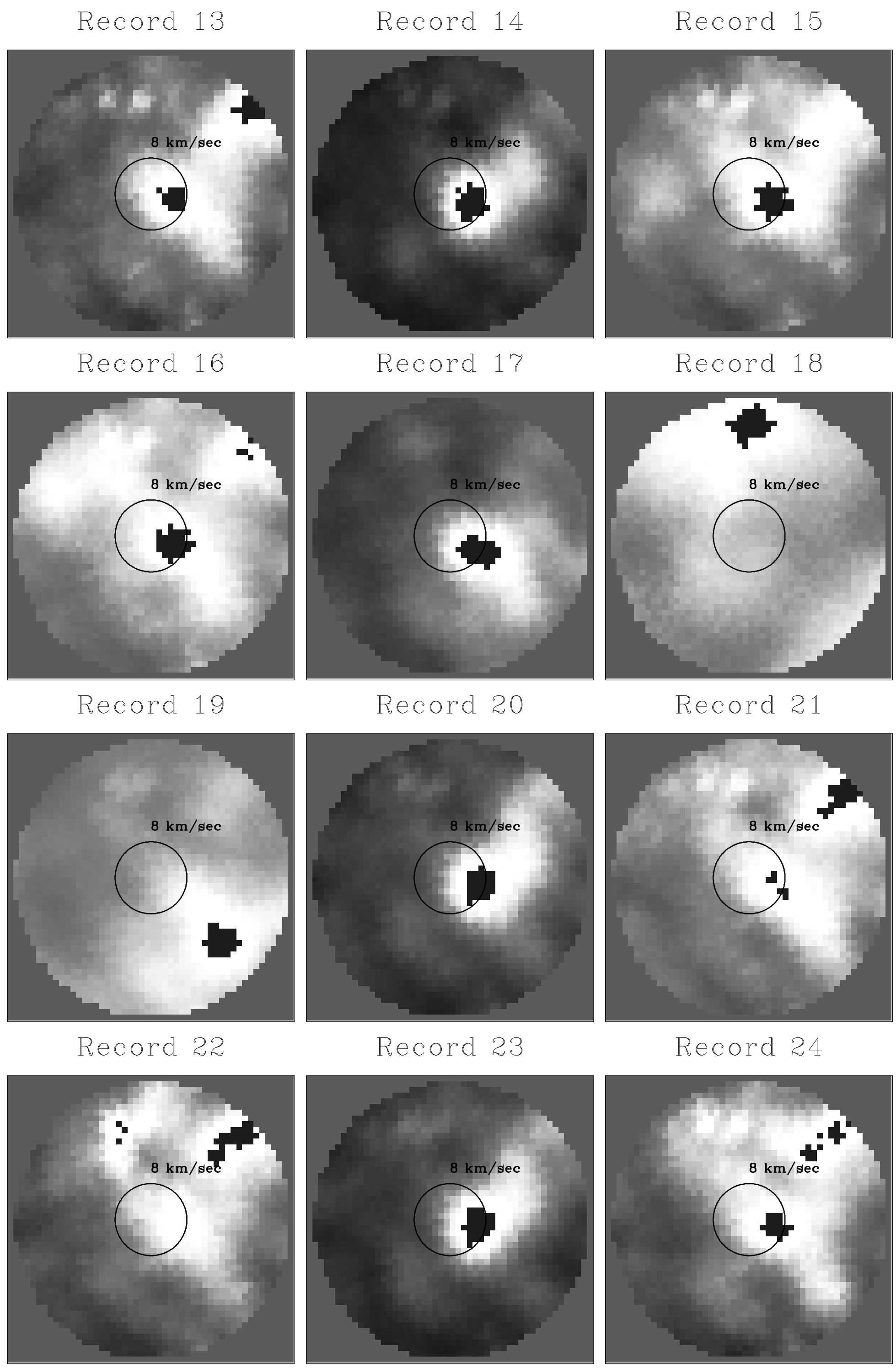

Figure 1.9: Result of beam steering for records 13-24. passive-vertbeam2 [ER]

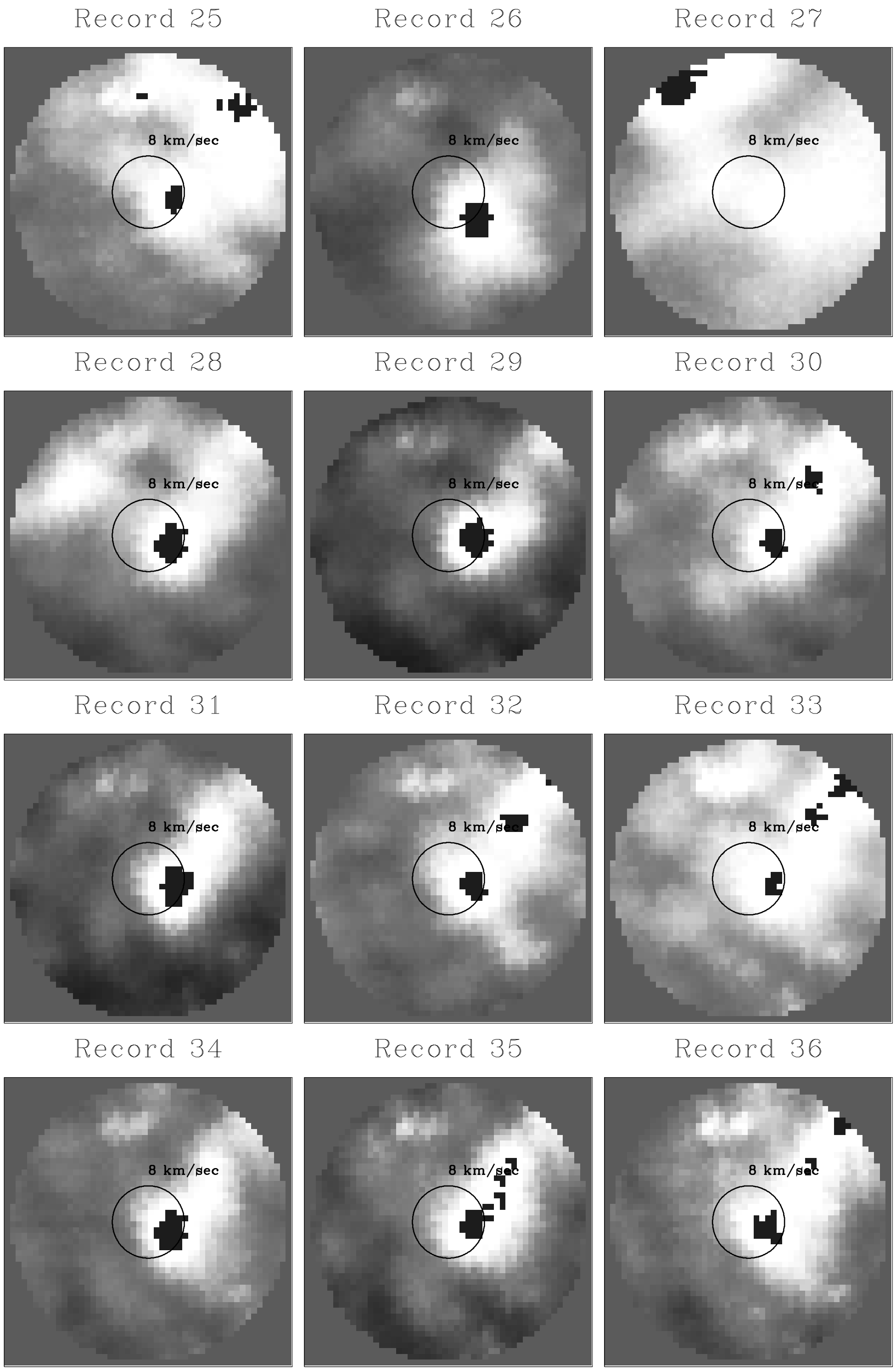

Figure 1.10: Result of beam steering for records 25-36. passive-vertbeam3 [ER]

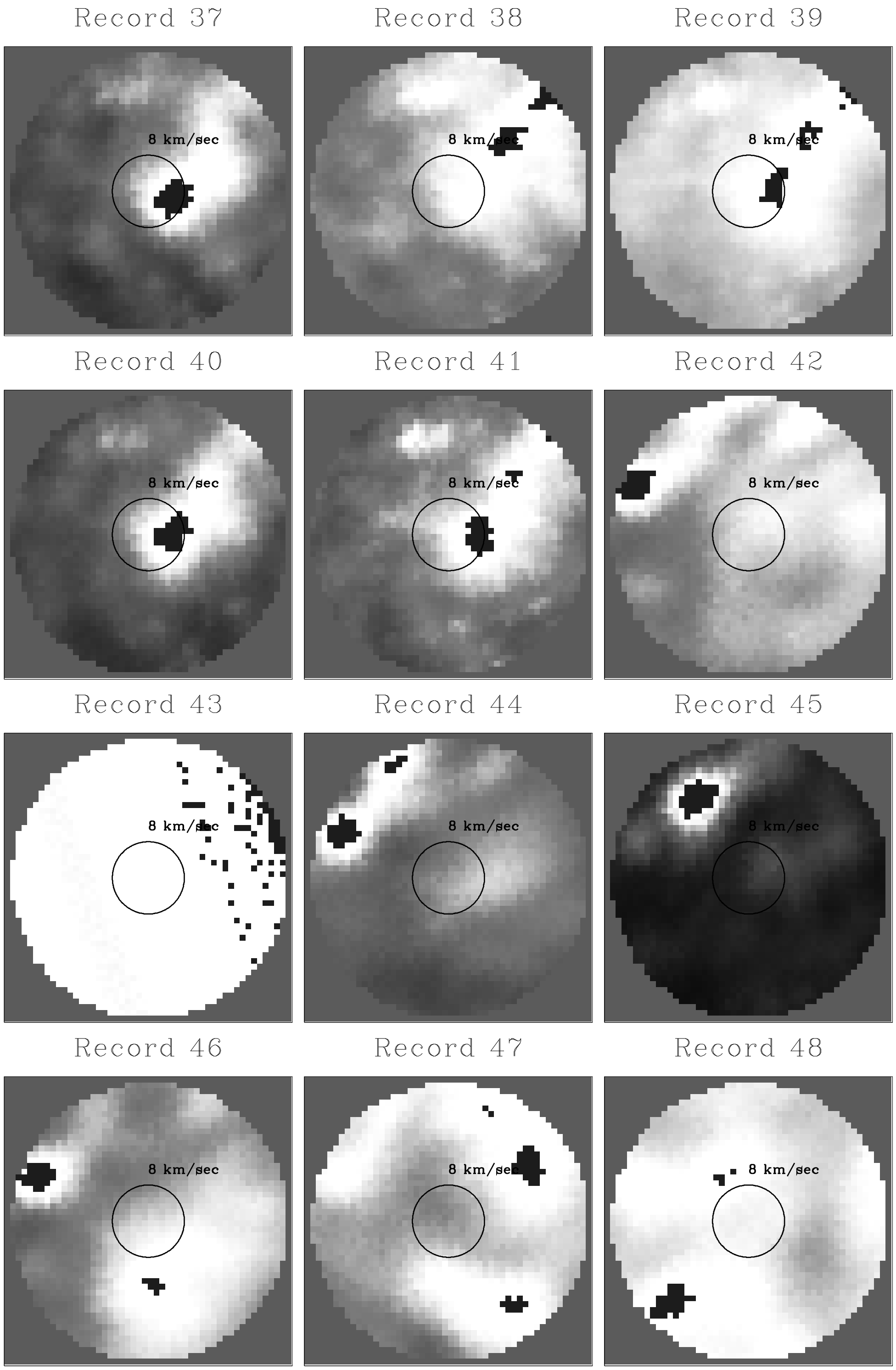

Figure 1.11: Result of beam steering for records 37-48. Records 42 and above were recorded during the day. passive-vertbeam4 [ER]

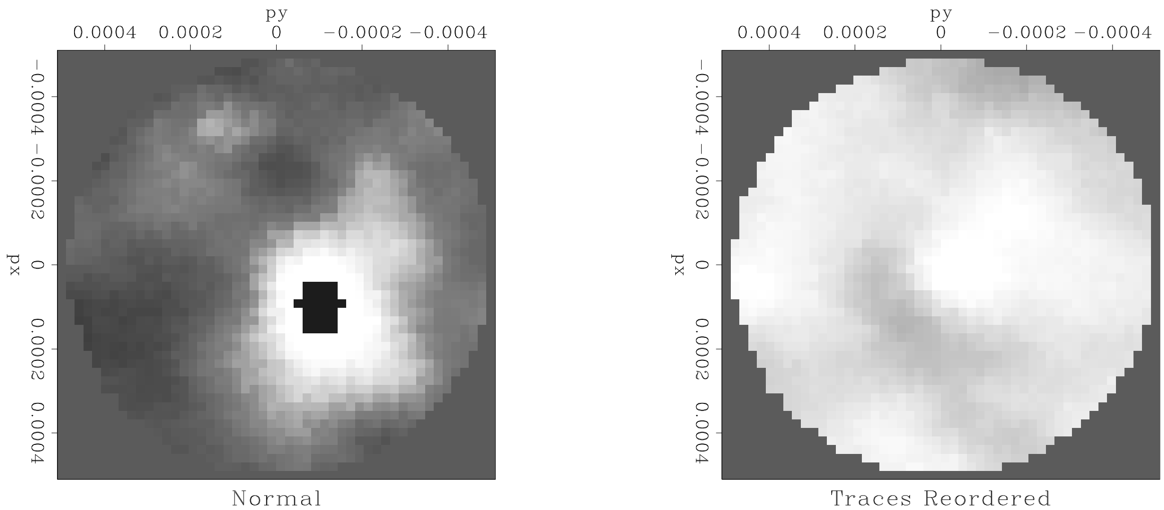

Figure 1.12: One of the records from Figure 1.8 (left) and the result of applying the same processing to data where the trace positions have been randomly re-ordered (right). The re-ordering has removed the high-semblance values seen on the left, verifying that the high semblance values near the center of the left plot were due to actual events and not some sort of interference. passive-bcomp.26 [ER]

1.4 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:

$$\arcsin \frac{0.3km/sec}{10km/sec} = 1.7^\circ \tag{1.1}$$

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 1.13. 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 1.13. 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 1.13, 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 strong $v(x, z)$ velocity gradient could mean this energy came from somewhere other than the two regions shown in Figure 1.13. 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.

1.5 Decimation tests

Given that the 169 channel, 4056 geophone array is able to analyze the arrival direction of incident waves, an important question is, how much of this array was required in order to do this work? Can the same results be obtained with half as many geophones and channels, or even fewer?

To answer this question, I performed a series of tests where I decimated the data records, keeping one out of every 2,4,8, or 16 channels. Figures **??** through **??** show the beam steering results for a set of 12 records (the same records shown in Figure 1.8) at these various decimation levels.

The results do not seem to be severely affected when only half the available channels are used, but further decimation has an adverse effect. Using only every four channels, the near-vertically incident feature is not present on a large number of channels. From this result, we can conclude that for an array of this spatial extent, the minimum number of channels needed is on the order of half the number we deployed, which would be 85 channels compared to 169 in our array. Below that number, a significant decline in directional resolving power occurs.

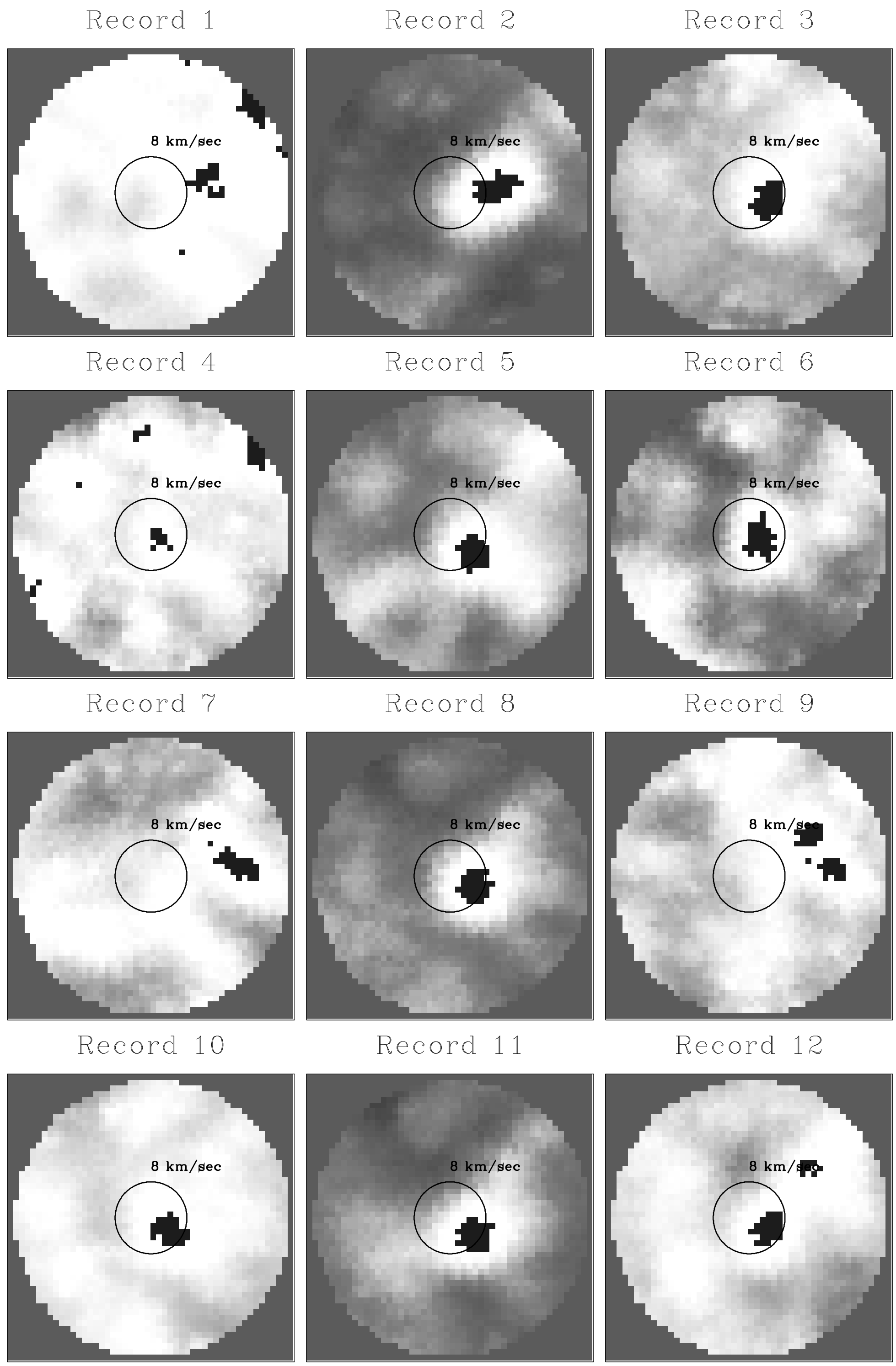

Figure 1.15: Beam steering results for records 1-12, with only half of the channels used. passive-decim.2.1 [ER]

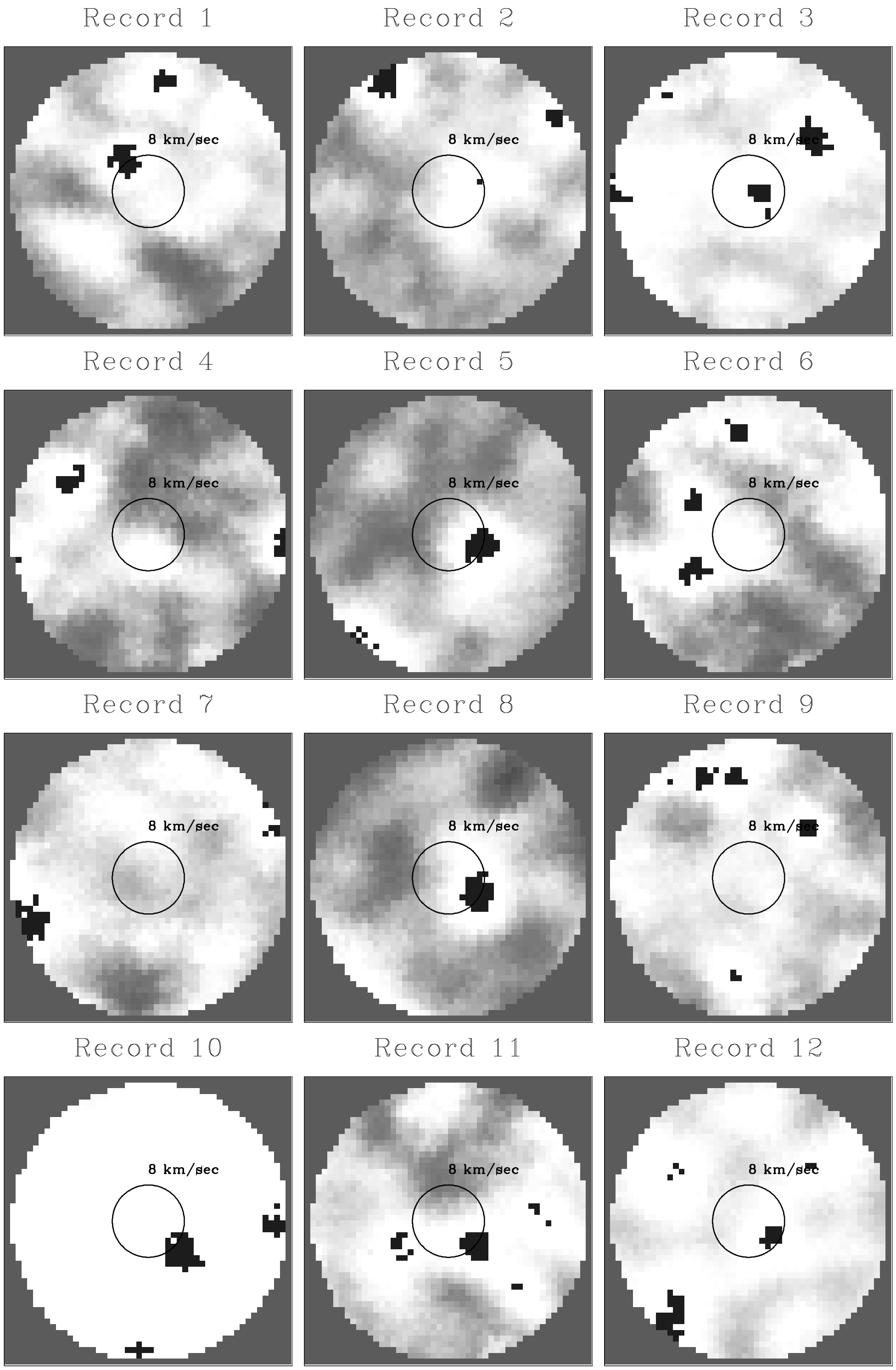

Figure 1.16: Beam steering results for records 1-12, with only one out of every four channels used. passive-decim.4.1 [ER]

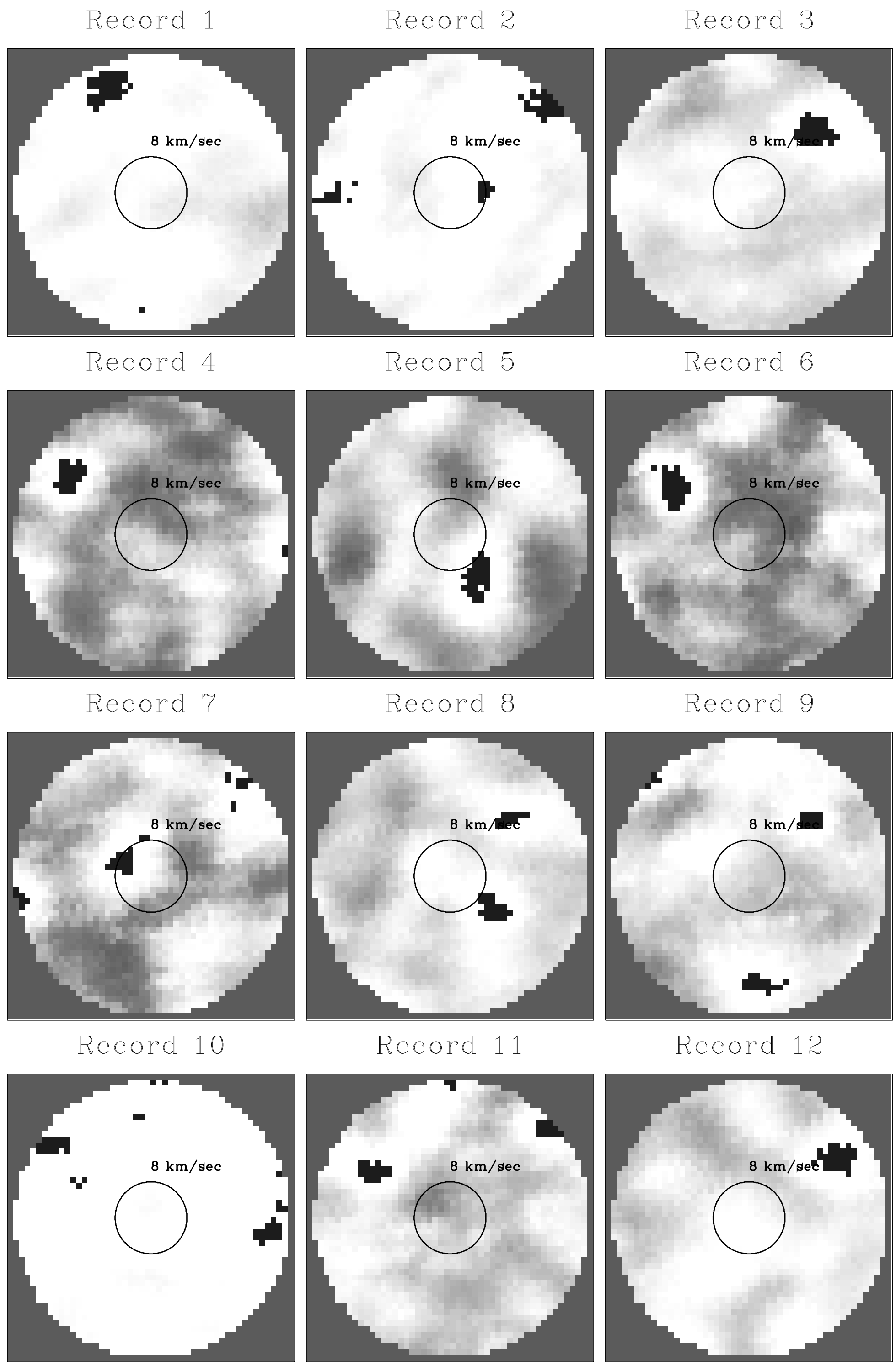

Figure 1.17: Beam steering results for records 1-12, with only one out of every eight channels used. passive-decim.8.1 [ER]

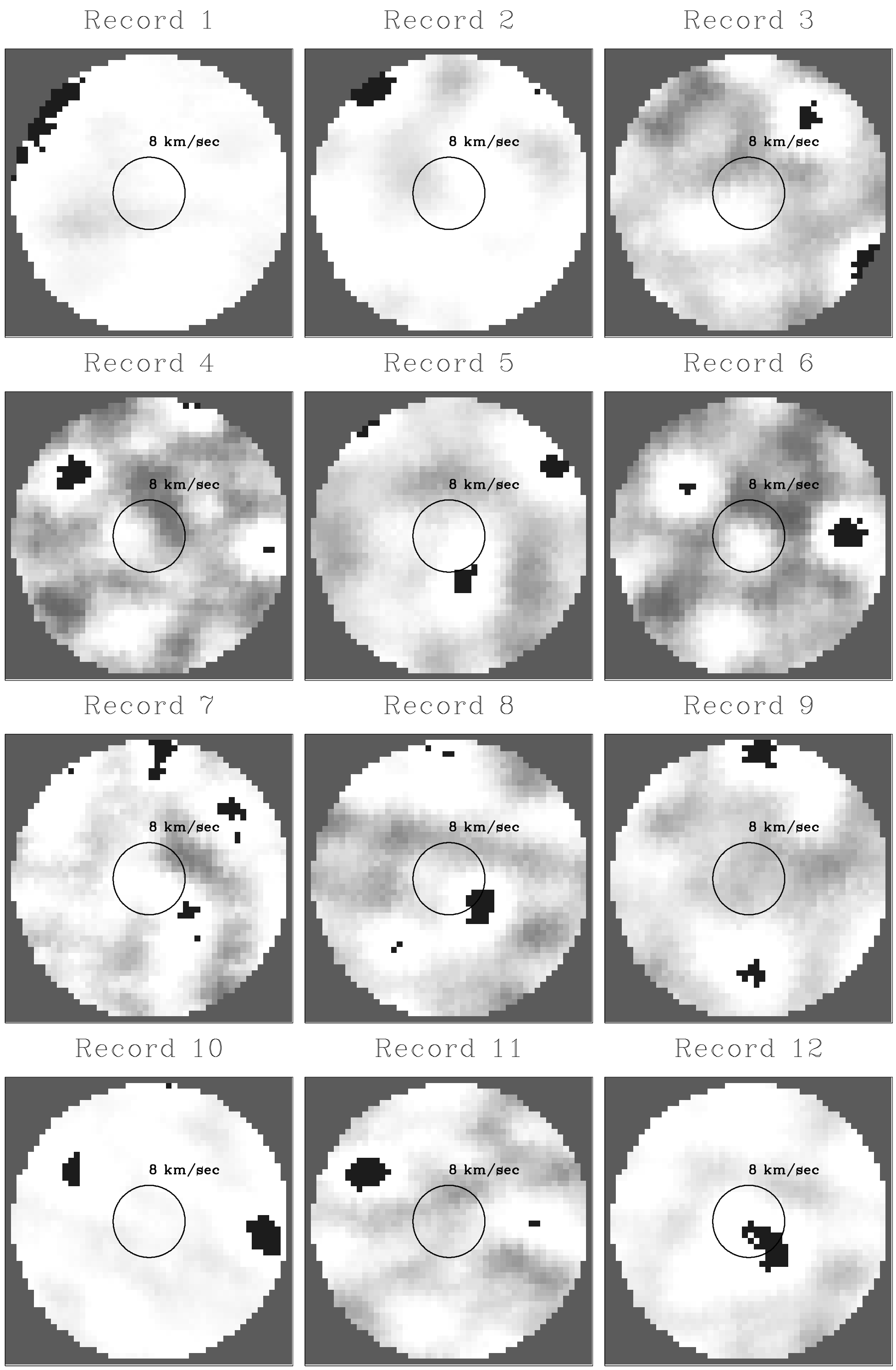

Figure 1.18: Beam steering results for records 1-12, with only one out of every sixteen channels used. passive-decim.16.1 [ER]