

Influence of focal mechanism on peak accelerations of strong motions of the Whittier Narrows, California earthquake and an aftershock

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Abstract

Focal mechanisms affect the pattern of the peak accelerations of the October 1, 1987 Whittier Narrows earthquake and its October 4 aftershock. The peak accelerations observed on 21 Strong Motion Instrumentation Program and 22 United States Geological Survey accelerograms correlates well with the ratio of shear wave amplitude computed from the thrust mechanism of the mainshock and the strike-slip mechanism of the aftershock. This correlation means that seismic energy is radiated from the fault with close to the standard double-couple radiation pattern at the frequencies 3 to 6 Hz corresponding to the peak accelerations.

Introduction

The double-couple nature of earthquakes is well-known, as is the resulting pattern of radiated seismic waves (see Sykes, 1967, and Stauder, 1968, for example). The body of literature documenting the effect of radiation pattern on seismic waves with periods of 1 to 500 seconds is large. For the periods that typically control peak accelerations of strong motions, 0.1 to 1.0 seconds, however, such radiation patterns have not been observed. Liu and Helmberger (1985, figure 14) find that the radiation of an aftershock of the 1979 Imperial Valley earthquake shows a double-couple pattern at a frequency of 1 Hz but not at 2 Hz. These shorter periods, which are of most interest to earthquake engineers, might fail to show a clear radiation pattern for several reasons. Sufficient scattering in the crust, which would affect the short-period energy more than the long-period energy because it has traveled more wavelengths between the earthquake and the seismometers, would tend to blur the radiation pattern into a more uniform distribution. The fault plane itself might not be equally smooth on all scales, and so perhaps short-period seismic radiation is more complex than a double couple. The data in this paper show, however, that at frequencies of 3 to 6 Hz, the radiation pattern is observable. This result supports the conclusion that these two earthquakes have radiation patterns at high frequencies that are similar to the patterns at longer-periods and scattering does not significantly diminish the radiation pattern of the earthquake source.

The dataset of peak accelerations

The M_L 5.9 Whittier Narrows earthquake occurred on October 1, 1987. The hypocenter was located at 14.6 km depth, and the mechanism is a gently dipping thrust (Hauksson and Jones, 1989). Numerous aftershocks filled the volume from 8 to 17 km depth extending about 4 km in all directions

horizontally. Bent and Helmberger (1989) analyze the teleseismic body waves and propose a double source; their second source is 11 km deep and 5 times larger than the first with a slightly different mechanism. It is important to consider the location and mechanism of the largest patch of moment release to understand the peak accelerations. The double source they propose is best studied with teleseismic body-waves since the strong ground motions are more complicated by the Los Angeles basin near-surface structure. I use the depth and mechanism of their second and largest source to represent the mainshock in this paper. The M_L 5.3 aftershock that occurred on October 4, 1987 was located 2 km northwest of the mainshock at a depth of 13.3 km, with a strike-slip mechanism on a vertical plane (Hauksson and Jones, 1989).

Shakal et al. (1987) collected the data from 22 strong-motion stations that recorded both the mainshock and the aftershock. Etheredge and Porcella (1987, 1988) published records from an additional 30 stations that recorded both events. The locations of these 52 stations are shown in Figure 1. The University of Southern California also retrieved data for these two earthquakes from about 80 strong motion stations; however, these data are not yet available. Soon, digitized mainshock records from the USC network will be available, but the aftershock records are not available in unprocessed form nor is there a schedule for digitizing them. The USC data would fill a large gap in our coverage to the east of the hypocenters, so the conclusions of this paper can be tested against the USC data when it is processed and released. From the USC data, Trifunac (1988) has noted that the pattern of peak amplitudes of the mainshock differs from the pattern for the aftershock, and hypothesizes that this difference is due to the radiation pattern.

The peak horizontal accelerations for both the mainshock and the October 4 aftershock for each station are given in table 1 of Vidale (1989). The peak is estimated by computing the square root of the sum of the squares of the peaks from the published copies of the film records for the two horizontal components. This measure differs from Campbell (1981), who used the mean of the two horizontal components, and Joyner and Boore (1981), who used the larger of the two. The differences between these measures do not affect the conclusions of this paper. A more accurate measure of the peak accelerations would require digitized records, and is not yet possible since no aftershock records have yet been digitized. These stations are a mixture of free-field, basement, and ground floor installations. Although basement records have been reported to show smaller peak accelerations than free-field records (Campbell, 1981), the difference is small and will not affect the conclusions of this paper, which are drawn only from the ratios of the two events, not the absolute levels.

The peak accelerations from the mainshock and the aftershock are plotted in Figures 2 and 3. The waveforms are all displayed in Etheredge and Porcella (1987, 1988) and Shakal et al. (1987). Large changes in peak amplitude occur over short distances. Such changes are not likely to result from radiation pattern, which varies smoothly over the focal sphere, but instead may be the variations in near-receiver focusing, reverberations, and receiver shear impedance that has been amply documented (see Vidale and Helmberger, 1988, for example). These near-receiver effects should be minimized by the use of ratios.

Since the mainshock and the aftershock have different focal mechanisms and occur in nearly the same place, as seen in Figure 1, the near-receiver effects

may be mostly canceled by considering only the ratio between the peak accelerations of the two events. The cancellation will not be perfect because the polarization of the seismic waves incident on each station differs between the two events, and the site response can depend on polarization. Cancellation of station effects by taking the ratio of a pair of events has been a standard tool in studying teleseismic body-waves and long-period surface waves.

Figure 4 shows the ratio of peak accelerations from the mainshock to those of the aftershock. Most of the horizontal peak accelerations have a peak frequency in the range 3 to 6 Hz, estimated visually. The ratio averages 2, so the mainshock produced about twice the peak acceleration in the 3 to 6 Hz range as the aftershock, although from standard M_L -moment relations (see Chavez and Priestly, 1985, for example), the mainshock produced 4 to 8 times more moment release than the aftershock.

Not all stations allow the recovery of a reliable estimate for the ratio of the mainshock peak acceleration to that of the aftershock in a consistent frequency range. Stations 141, 262, 289, 436, 634, 969, 5239, 5030, and 5031 are omitted from Figures 4, 6, and 7. Stations 141, 436, 634, and 5239 are dominated by motions whose frequencies are less than 3 Hz for the mainshock, but not the aftershock. Apparently, the mainshock produced much more than twice the 1 to 3 Hz energy of the aftershock. Only stations with similar frequency content for both events will be included in subsequent analysis. Bandpass filtering would allow the use of these records, but fewer than a quarter of the records we use have been digitized. Stations 262, 5030, and 5031 are too weak (less than 0.02 g) to reliably measure the peak acceleration for the aftershock. Station 289 is located on the crest of a dam and shows a strong linear polarization in the same direction for both events, suggesting strong polarization-dependent receiver effects. All the stations were judged with uniform criterion for frequency content and sufficient strength. Station 289 was rejected after its disagreement with the predictions from radiation pattern were noted, but its site on the crest of a dam should have excluded it from consideration at the outset, and no other stations in such questionable locations are included. The reason for omitting Station 969 will be given below.

The peak amplitude ratios shown in Figure 4 vary much more smoothly than the peak amplitudes shown in Figures 2 and 3. Amplitude ratios less than 1.6 cluster in two pockets located just north and west-southwest of the epicentral region. The ratios above 2.0 cluster in three areas to the west-northwest, south, and southeast of the epicentral region. The smoothness of the variations suggest that most of the near-receiver structure has been canceled out.

In a whole space, the radiation pattern of S waves, rather than the weaker P-waves, determines the strength of body waves as a function of direction from the source. The magnitude of the total S wave vector is computed by taking the square root of the sum of the squares of the SH and SV magnitudes, see Aki and Richards (1980), for example. The total S wave pattern has six nodal points evenly spaced around the focal sphere, and four lobes evenly spaced on the great circle that passes through the pressure and tension axes. Figures 5a and 5b show the total S-wave radiation pattern for the mainshock and aftershock focal mechanisms, respectively. The nodal points lie in different places on the focal sphere for the two mechanisms. Figure 5c shows the ratio of the two patterns, which may be considered as a prediction of the ratio of the S-

wave amplitudes of the mainshock to those of the aftershock.

Figure 6 projects the predicted ratio on the surface of the earth. A small correction to the pattern seen in Figure 5c is required since the two events occurred in slightly different locations. Thus the rays to nearby receivers depart from the focal sphere at different take-off angles and azimuths. This projection requires the assumption of a source depth and a velocity structure to convert take-off angle into epicentral distance. A smooth, laterally-invariant basin shear-wave velocity structure is assumed. It is similar to the basin structure given in Vidale and Helmberger (1988). The range that corresponds to each take-off angle is determined with the travel time scheme of Vidale (1988). An 11 km depth has been assumed for both sources, following Bent and Helmberger's (1989) 11 km depth estimate for the dominant source in the M_L mainshock and in the absence of any centroid depth estimate for the M_L 5.3 event, for which the aftershocks ranged in depth from 10 to 14 km (Hauksson and Jones, 1989). I do not doubt the deeper epicentral depths, but the 11 km depth I used probably corresponds to the peak moment release and the source of the peak accelerations. The change in pattern resulting from placing the sources at 14 km depth in accord with their hypocentral locations is discussed below.

Comparison between Figure 4 and Figure 6 shows that the predicted and observed patterns are very similar. The high and low ratio lobes that appear are all predicted, and all predicted lobes appear, if there are stations located to sample them. The stations nearest the epicenter show a systematic overestimation in the predicted shear wave ratios compared with the observations. Adjusting the locations and the mechanisms of the earthquakes would probably improve the fit. However, I think the results are more unbiased when the initial model is used than if additional free parameters corresponding to variations in mechanisms and locations are introduced after inspecting the misfit. The assumptions of point sources and one-dimensional velocity structure are likely to be the largest sources of errors. If both sources are placed at 14 rather than 11 km depth, the areas of high and low relative amplitude predicted from the mechanism move farther from the source. Station 969 is not included in Figure 4. The mechanism coefficient for the aftershock is 0.03 and that for the mainshock is 0.25, giving a predicted ratio of 8.3, far to the right of the rest of the points in Figure 4. The model predicts that the peak for the mainshock would be one fourth of that at a lobe, and the peak for the aftershock would be one thirtieth of that at a lobe. The observed ratio of 2.2 indicates that, as one might expect, the node for the aftershock is not clean enough to drop the amplitude to only 0.03 of maximum value, therefore this ratio is considered unstable.

Figure 7 compares the observed and predicted ratios directly. Despite considerable scatter, a correlation of 0.63 exists between the observed ratio and the ratio of peak accelerations predicted by the focal mechanisms.

Discussion

The influence of focal mechanism on the observed peak acceleration is demonstrated in Figure 7. The ratios of the observed peak accelerations correlate well with the ratios predicted by the focal mechanisms. The scatter seen in Figure 7 may be due to numerous causes. The polarization of the shear waves incident on a station will differ between the two events, and to the extent that the

receiver amplification and path effects are functions of polarization, the observations will differ from the predictions. The source locations are assumed to be known, to be small, and to be at the same depth, but the mainshock and aftershock are not point sources compared to the shear wavelength at 3 to 6 Hz, directivity has been shown to affect accelerations (Boatwright and Boore, 1982), and the depth of the source of the peak accelerations is not precisely known. Scatter also arises from variation in the dominant frequency of the peak acceleration. Since the source spectra of the mainshock and the aftershock probably differ, the variation in frequency will cause deviations from the predicted pattern. Above, I discarded the 4 worst cases where the mainshock peak accelerations have frequencies markedly lower than the aftershock peak accelerations, but such frequency differences probably remain to some extent.

If the peak acceleration is modulated by the focal mechanism, i.e. nodes show very small accelerations, the points in Figure 7 should cluster about a straight line through the origin like line A. If the pattern from the focal mechanism were completely obscured, the points would cluster about the horizontal line B. Line A fits much better than line B. The tendency is that at locations where a node in the radiation pattern is expected, the observed peak acceleration is less and conversely, in a lobe, the peak acceleration is higher.

Line C, with a non-zero intercept but nearly constant slope where the predictions range from 0.5 to 1.5, is the shape of curve I would expect to observe. The non-zero intercept would reflect that some energy is observed where shear wave nodes are predicted, either from scattering of body waves by the geological structures over a solid angle wide enough to partially fill in the nodes or surface waves or P waves may fill in where S body waves are weak. Small-scale variation in the orientation of the fault plane or slip direction would also tend to obscure the nodes. The data do not require a significantly non-zero intercept.

The strength of the correlation means that these node-filling mechanisms are weak. The correlation between S wave strength and peak accelerations means that surface waves are either generated near the receiver or do not influence peak accelerations. In the longer-period range 1 to 10 sec, Vidale and Helmberger (1988) show that each basin generates new surface waves, so conversion of shear body waves to surface waves is probably common.

The S body waves are not scattered enough to obscure the nodes. Previous studies have not had the advantage of two events with different focal mechanisms in the same place, consequently have failed to resolve the radiation pattern at the frequencies of the peak accelerations where receiver effects are also strong. Boatwright and Boore (1982) compare two events with a similar focal mechanism, which minimizes differences in motions due to distinct mechanisms, leaving differences that they attributed to directivity. Liu and Helmberger (1985) looked for the 4-lobed SH radiation pattern from an impulsive strike-slip event on the transverse component. They fail to see the pattern at the 4 to 6 Hz frequency characteristic of the peak accelerations, but they see the pattern emerge when the records are low-passed at 1 Hz. My observations here may disagree with those of Liu and Helmberger (1985) for several reasons. Two events with different mechanisms are compared here, while Liu and Helmberger (1985) attempted to see the radiation pattern from a single event. The observation of Liu and Helmberger (1985) is from the Imperial Valley, which shows

extended coda duration, implying that the basin sediments produce more scattering and surface wave generation than most areas. Finally, total S strength is used here, allowing SH and SV mixing, whereas Liu and Helmberger (1985) assume no contamination of the transverse component by SV energy.

Since the radiation pattern has a measurable effect on the peak accelerations in this case, I address briefly the question of generic patterns that arise from strike-slip and thrust mechanisms. Joyner and Boore (1981) and Campbell (1981) empirically determined the attenuation of peak acceleration with distance, such empirical formulae could be improved by incorporating focal mechanisms. Campbell (1981) examined peak accelerations statistically and notes that reverse faults generate 28 per cent stronger peak accelerations than strike-slip events. A possible explanation of this is obtained by considering that the total shear wave radiation pattern has 6 nodal points that are located at the pressure, tension, and the neutral axes of the focal sphere. There are also 4 lobes that are placed along the great circle connecting the pressure and tension axes, each placed midway between a pressure and a tension axis. By considering the S-wave radiation patterns in Figures 5a and 5b, for sources placed at 10 km depth in a basin structure, the thrust case is seen to have 4 nodes for rays that leave the source horizontally, which surface at a distance of 15 km. The two lobes in the lower hemisphere contain rays that surface hundreds of km from the source, outside the regions of strong motions. The two lobes in the upper hemisphere send rays that appear within 10 km of the epicenter.

The strike-slip event also has 4 nodes for rays that leave the source almost horizontally. The lobes, however, are located such that they concentrate strong motions in the distance range 10 to 40 km. Depending on the range over which that strong motions are recorded, the thrust pattern could appear to be two patches of very strong shaking surrounded by an area of lesser shaking. The strike-slip case would show a more even distribution of strong and weak shaking. Within 10 km, the thrust event would produce stronger shaking. In the range 10 to 40 km, the strike-slip event would produce stronger shaking. A similar conclusion may be drawn from the average body-wave radiation coefficients listed in table 5 of Boore and Boatwright (1984).

Conclusions

The focal mechanism modulates the level of peak accelerations in the 1987 Whittier Narrows earthquake and its October 4, 1987 aftershock. This observation precludes great variations in mechanism in the 3 to 6 Hz range, which corresponds to a 300 to 1000 m scale length on the fault plane. This also suggests that the energy contributing to the peaks in acceleration left the source region as direct S body waves. Scattering does not obscure the influence of earthquake focal mechanism at 3 to 6 Hz.

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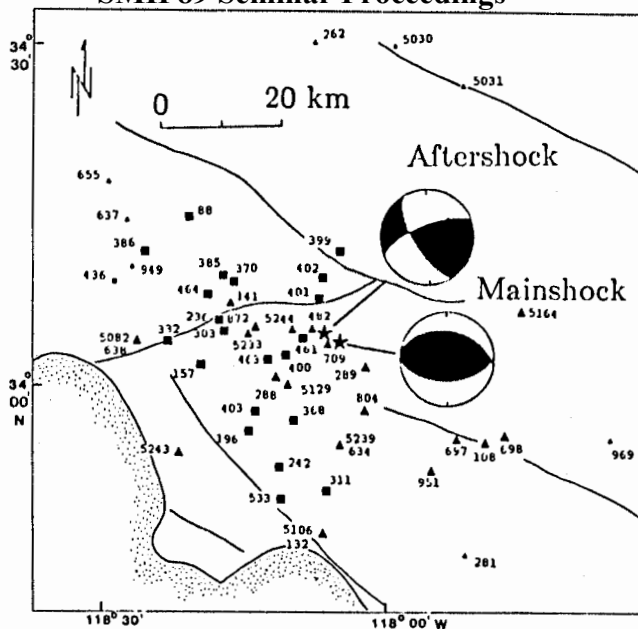


Figure 1. Map showing the locations of the 52 stations listed in Table 1, which recorded both the Oct. 1 mainshock and the Oct. 4 aftershock. Triangles indicate stations described by Shakal et al. (1987) and squares indicate stations described by Etheredge and Porcella (1987, 1988). Smaller symbols indicate stations that are disregarded in this analysis for reasons explained in the text. The epicenters given by the USGS for the mainshock and aftershock are shown as stars. The mechanism for the mainshock is taken from Bent and Helmberger (1989) and the mechanism for the aftershock is taken from Hauksson and Jones (1989). The light lines show faults and the coastline; see Hauksson and Jones (1989) for a discussion of the regional tectonics.

Mainshock Peak Accelerations

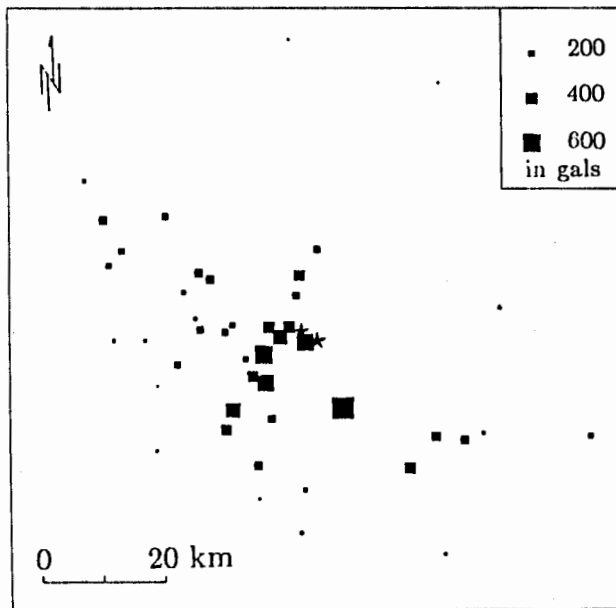


Figure 2. Map showing the peak horizontal accelerations from the Whittier Narrows mainshock for 47 of the stations listed in Table 1. The size of each symbol is proportional to the peak acceleration, which ranges from 50 to 770 gals.

Aftershock Peak Accelerations

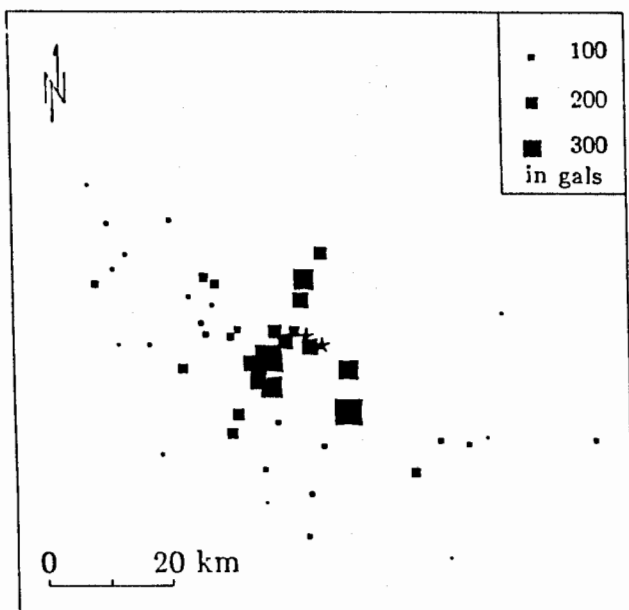


Figure 3. Map showing the peak horizontal accelerations from the Oct. 4 aftershock for 43 of the stations whose aftershock peak accelerations are listed in Table 1. The size of each symbol is proportional to the peak acceleration, which ranges from 30 to 480 gals.

Peak Acceleration Ratios

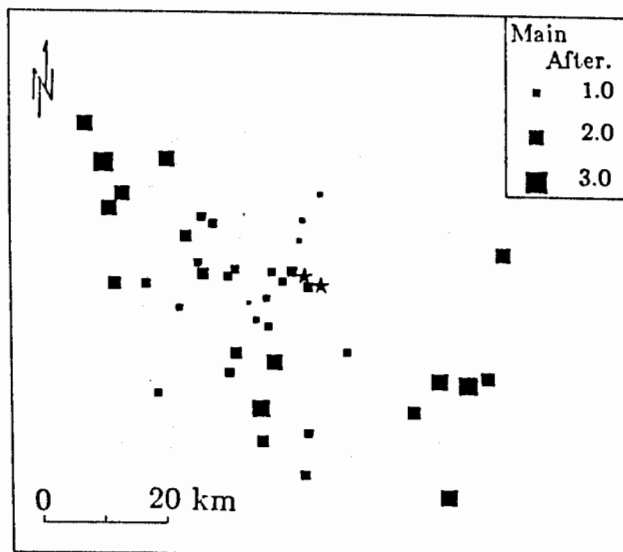


Figure 4. Map showing peak acceleration from the mainshock divided by the peak acceleration from the aftershock for the 43 stations for which a predicted ratio is given in Table 1. The size of each symbol is proportional to the ratio, and the ratios range from 0.7 to 4.0.

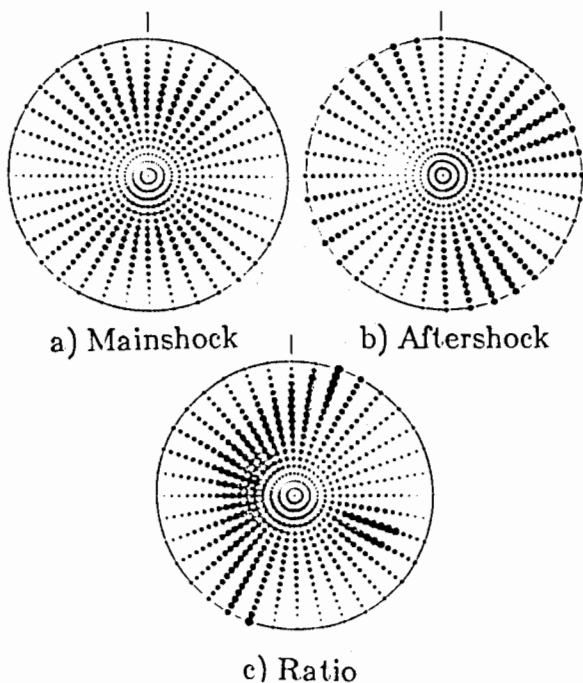


Figure 5 (a). Lower hemisphere projection of the total shear wave radiation pattern for the Whittier Narrows mainshock. The symbols are plotted every 10° in azimuth and every 5° in take-off angle. The size of the symbols is proportional to the strength of the shear waves radiated at that take-off angle and azimuth. The mainshock mechanism has $\phi = 280$, $\delta = 40$, and $\lambda = 98$. (b). The shear wave radiation pattern for the Whittier Narrows aftershock. The aftershock mechanism has $\phi = 250$, $\delta = 70$, and $\lambda = 25$. (c). The shear wave pattern from the mainshock divided by the shear wave pattern of the aftershock. This plot is not corrected for the difference in epicentral location of the two events. The plotting is clipped at a maximum ratio of two.

Pattern of Shear Wave Amplitude Ratios

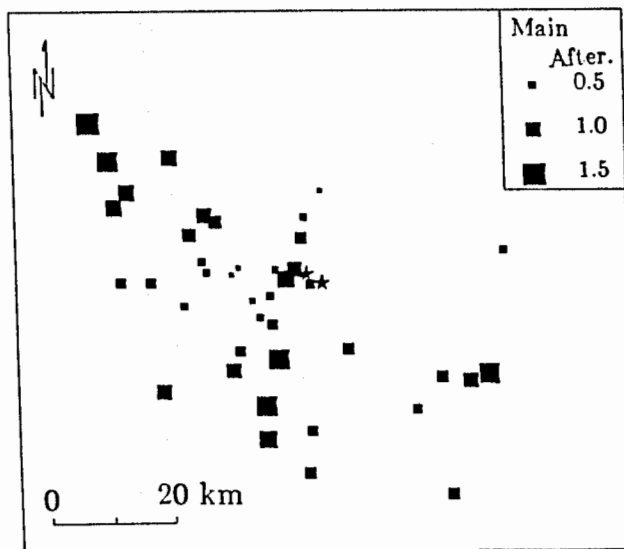


Figure 6. The ratio of motions from the mainshock to motions from the aftershock expected from the S-wave mechanism mapped to the Earth's surface. The difference in source location between the mainshock and aftershock is taken into account. The size of each symbol is proportional to the ratio, and the ratios range from 0.3 to 1.5.

Predicted vs. Observed Peak Acc. Ratios

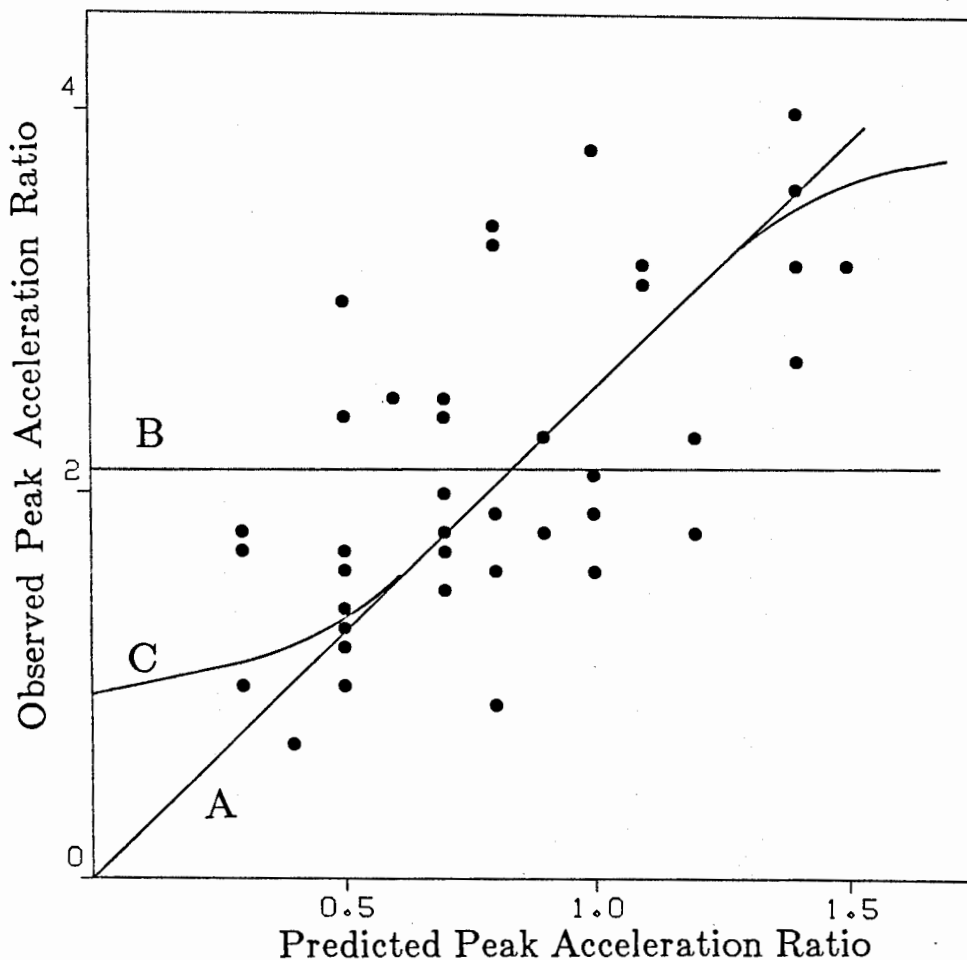


Figure 7. Predicted ratios of peak accelerations from the mainshock and aftershock compared to observed ratios for the first 43 stations listed in Table 1. If the amplitude is proportional to the radiation pattern, the points should scatter around a line that passes through the origin, such as line A. The slope need not be one since the two earthquakes were of different size. If the amplitudes did not depend on focal mechanism, the points would scatter about a horizontal line, such as line B. There is a suggestion that the nodes are not as devoid of seismic energy as predicted, since line C fits marginally better than lines A or B.