Measurement of Earthquake Ground Shaking at Characteristic sites in Christchurch

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Contents

Summary

The relative ground response due to microearthquakes has been examined at six sites in Christchurch. The five recording sites in central Christchurch all experienced considerably greater shaking than a rock site in the Cashmere Hills. This result is in general agreement with recent modelling studies that predicted greater shaking in central Christchurch. The greatest shaking was recorded at Christchurch Womens Hospital, where the response spectra was 10-20 times the value of the rock site spectra in the period range 0.3 to 0.6 sec. A site at Latimer Square produced ratios of 4 to 10 times the rock site at short periods while three other sites showed 2-4 times the shaking of the rock site.

The sites were chosen to sample the range of soil types and depths in the central city. A total of 12 earthquakes were used in the study. The earthquakes ranged in magnitude from 3.0 to 5.7 and occurred between 25 and 700 km from the centre of the seismograph array. The results are presented as velocity seismograms at each site and as averaged ratios of Fourier and response spectra of the seismograms compared with the site on bedrock.

There is a wide scatter about the mean for all sites. Ratios for individual earthquakes can range from 0.5 to 1.5 times the mean ratio. Thus relative amplifications can vary significantly for different earthquakes.

Results from other studies suggest that the frequency of amplified shaking often remains the same for large damaging earthquakes. The amount of amplification for large ground motions is dependent on the properties of the underlying geologic materials. Some soft soil sites will experience less amplification during large motions, however greater damage is still expected at the soft soil sites relative to the firm sites for earthquakes occurring outside of Christchurch.

1. Introduction

The importance of localised variations in earthquake ground motions has become widely recognised in the past few years, particularly after the amplifications seen in Mexico city in 1985 and San Francisco in 1989. Ideally one would measure strong ground motion directly at a variety of sites to determine the relative levels of shaking, but sufficiently large events are too infrequent to provide enough information. Alternatively, in regions similar to New Zealand where damaging earthquakes are expected, but infrequent, the ground response due to microearthquakes has been successfully used to identify areas which subsequently experienced damaging shaking in a large earthquake (Borcherdt, 1991).

Christchurch has experienced damaging earthquakes in the past and thus damage in future earthquakes can be expected. The city is underlain by a thick sequence of silt, sand, and gravel that is likely to amplify incoming seismic waves and localised variations in the shallow subsurface layers are likely to cause localised variations in shaking.

This report describes a pilot ground motion study in Christchurch whose purpose was to measure ground response at sites where the response has been predicted by Soils and Foundations, Ltd (Elder *et al.*, 1991). They compiled a comprehensive model of the soil profile beneath Christchurch and modelled the ground motion on a 500 m grid across the city. Comparisons have also been made to two other modelling studies (Berril *et al.* 1993; Haines, 1993a,b).

In this survey, microearthquakes have been recorded simultaneously at six sites within the city to measure the relative levels of shaking throughout the region. The recorded ground motions were very much smaller than the motions which could cause damage in Christchurch, and thus these results are presented in terms of relative levels of shaking between sites. (For the absolute expected response at a rock site near Christchurch, see Elder *et al.* (1991)). The amplitude response of each site relative to a bedrock reference site is defined as the amplification and is presented as a function of frequency so that the effect of ground motion on different sized structures can be estimated.

2. Data Collection

Three-component digital seismographs were installed at 6 sites in Christchurch between September, 1992 and January, 1993. (Figure 1, Table 1). The 1 Hz natural period seismometers (Kinemetrics L4-3D) were operated with portable seismographs recording at a sampling rate of 100 Hz (see Gledhill *et al.* (1991) for a description of the EARSS seismograph). The central city seismographs were sited in the basement or ground floors of public buildings of 4 stories or less.

The sites were chosen in order to sample the range of soil types (near surface geologic materials) in the city, as determined from the borehole compilation of Elder *et al.* (1991). A rock reference site was chosen in the Cashmere hills in an artificial cavern that was excavated during World War II. The simplified soil profiles for the top 30 m of the other five sites are shown in Figure 2. The profiles were simplified from Berril *et al.* (1993), borehole data compiled by Soils and Foundations Ltd., and a subsurface model by Haines (personal communication). Beneath the top 30 m is a sequence of sand and gravel layers 675 m thick, underlain by 300 m of weathered volcanics overlying greywacke basement (Berril *et al.*, 1993). The site conditions range from C02 (Christchurch Womens Hospital), which is underlain by over 20 m of fine grained silt and peat with layers of sand, to C05 (Arts Centre) which is underlain primarily by gravel. No shear wave velocity measurements have been made at the sites but estimates of the velocity of the peat and silt layers range from 100 to

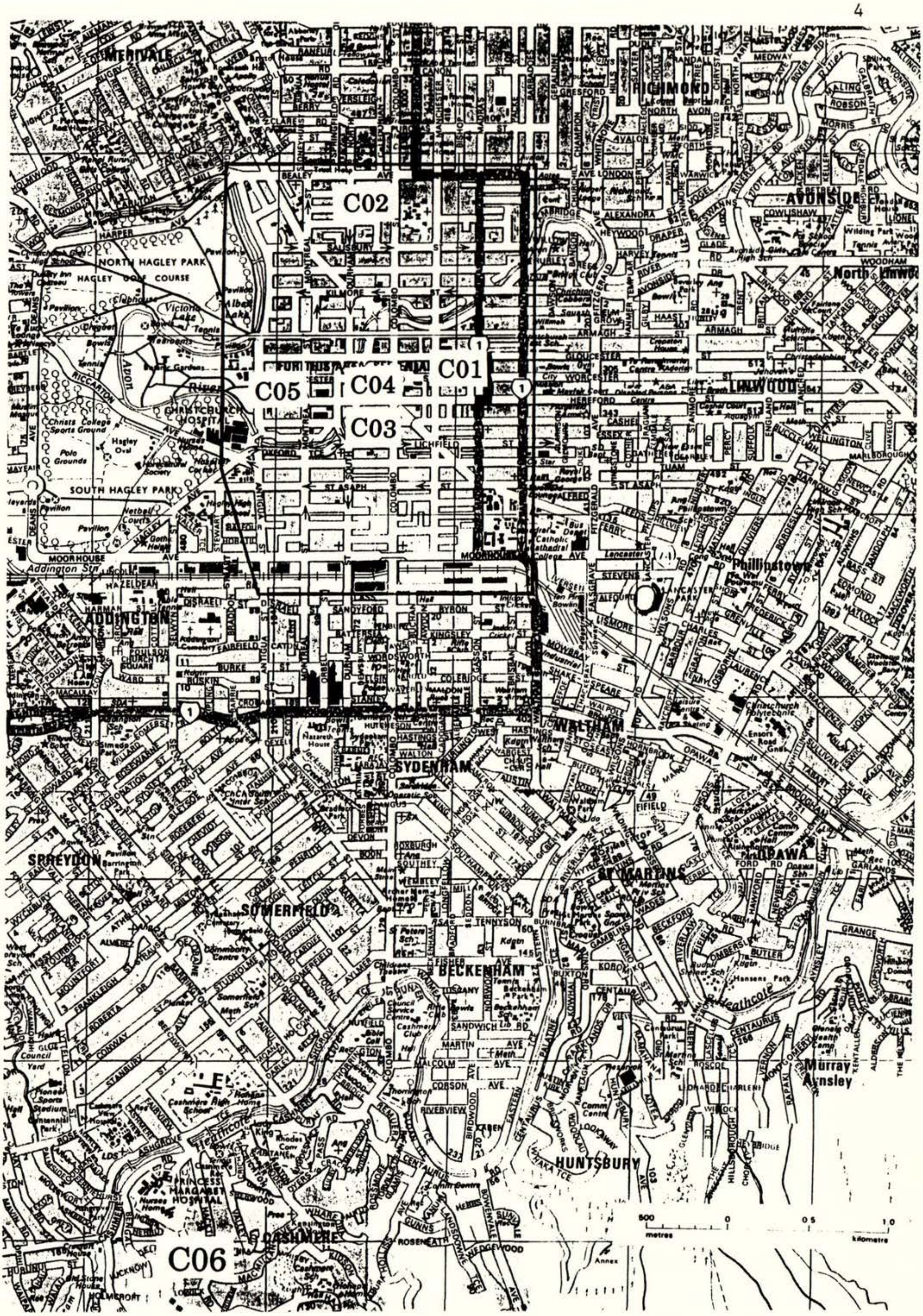

Figure 1a. Location map of the six sites used in the survey. C06 is the rock reference site.

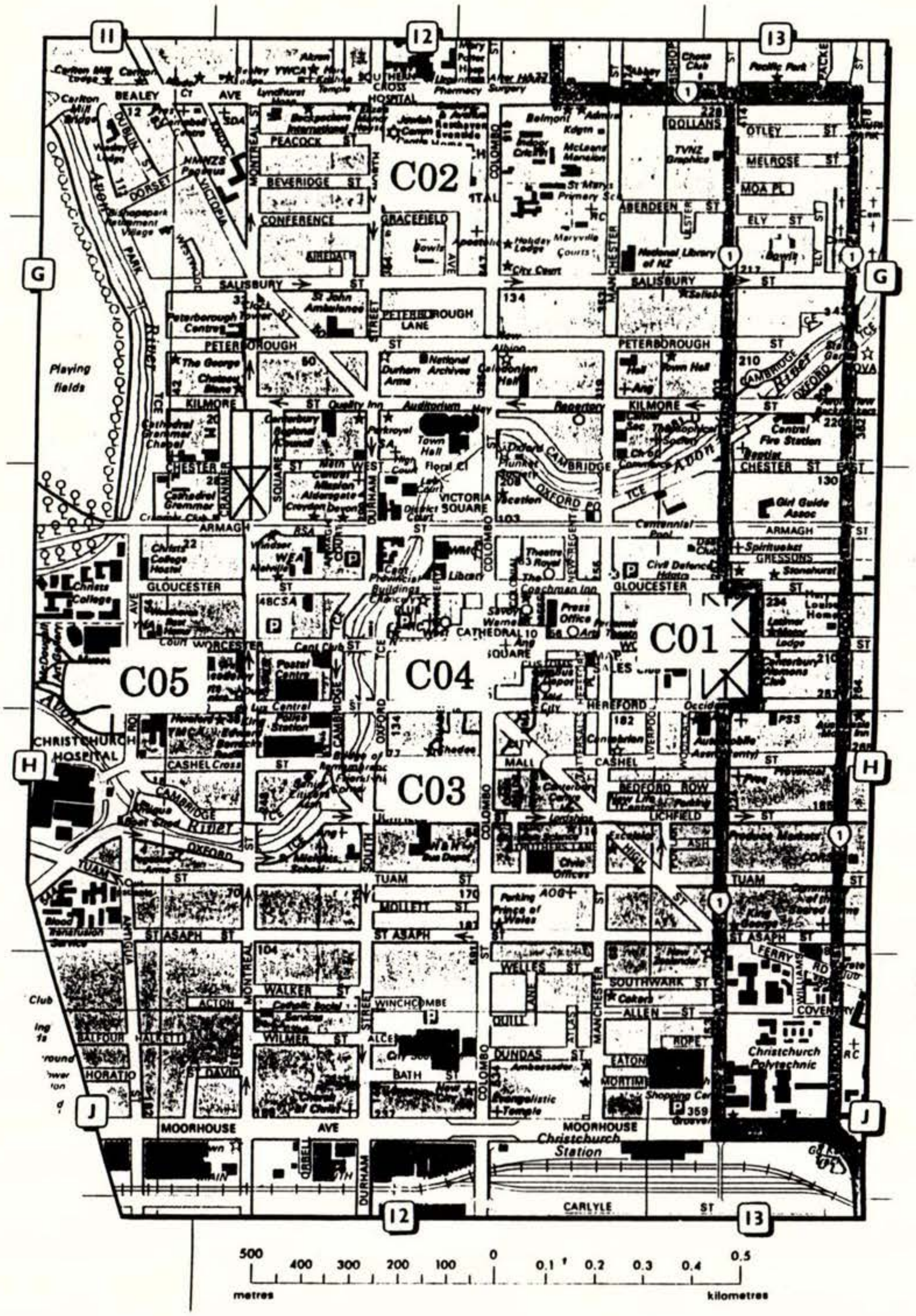

Figure 1b: Detail showing the location of the five sites in central Christchurch.

Table 1. Station Locations

Station	Location	Latitude	Longitude	NZMG(EN)	
C01	Council carpark, Latimer Square	-43.5325	172.6417	2481060	5741780
C02	Christchurch Womens Hospital	-43.5242	172.6347	2480490	5742700
C03	Guthrie Centre	-43.5352	172.6354	2480550	5741480
C04	Regent Centre	-43.5333	172.6355	2480560	5741690
C05	Arts Centre	-43.5334	172.6283	2479980	5741680
C06	Cashmere tunnel	-43.5777	172.6221	2479500	5736750

Table 2. Earthquake locations (from IGNS Seismological Observatory)

Year	Mon	Day	Hrmn	Sec	Lat	Lon	Depth	Mag
1992	SEP	26	1319	44.33	43.35S	172.44E	21.6	3.0
1992	SEP	27	242	4.95	42.72S	171.82E	5.0	4.0
1992	OCT	20	1306	50.28	39.39S	174.50E	189.9	5.0
1992	NOV	1	1158	40.60	43.21S	172.15E	14.4	3.6
1992	NOV	27	1559	12.53	43.17S	170.71E	5.6	4.7
1992	NOV	30	1459	30.55	41.35S	173.13E	90.1	4.2
1992	DEC	3	1846	25.16	43.24S	172.14E	5.5	3.2
1992	DEC	4	1301	31.75	42.02S	171.82E	5.0	3.9
1992	DEC	4	2145	47.82	41.95S	171.77E	13.3	4.4
1992	DEC	5	2318	51.37	41.97S	171.78E	12.0	4.3
1992	DEC	15	817	12.53	42.78S	171.99E	5.0	3.6
1993	JAN	2	1232	30.14	37.77S	176.47E	205.0	5.7

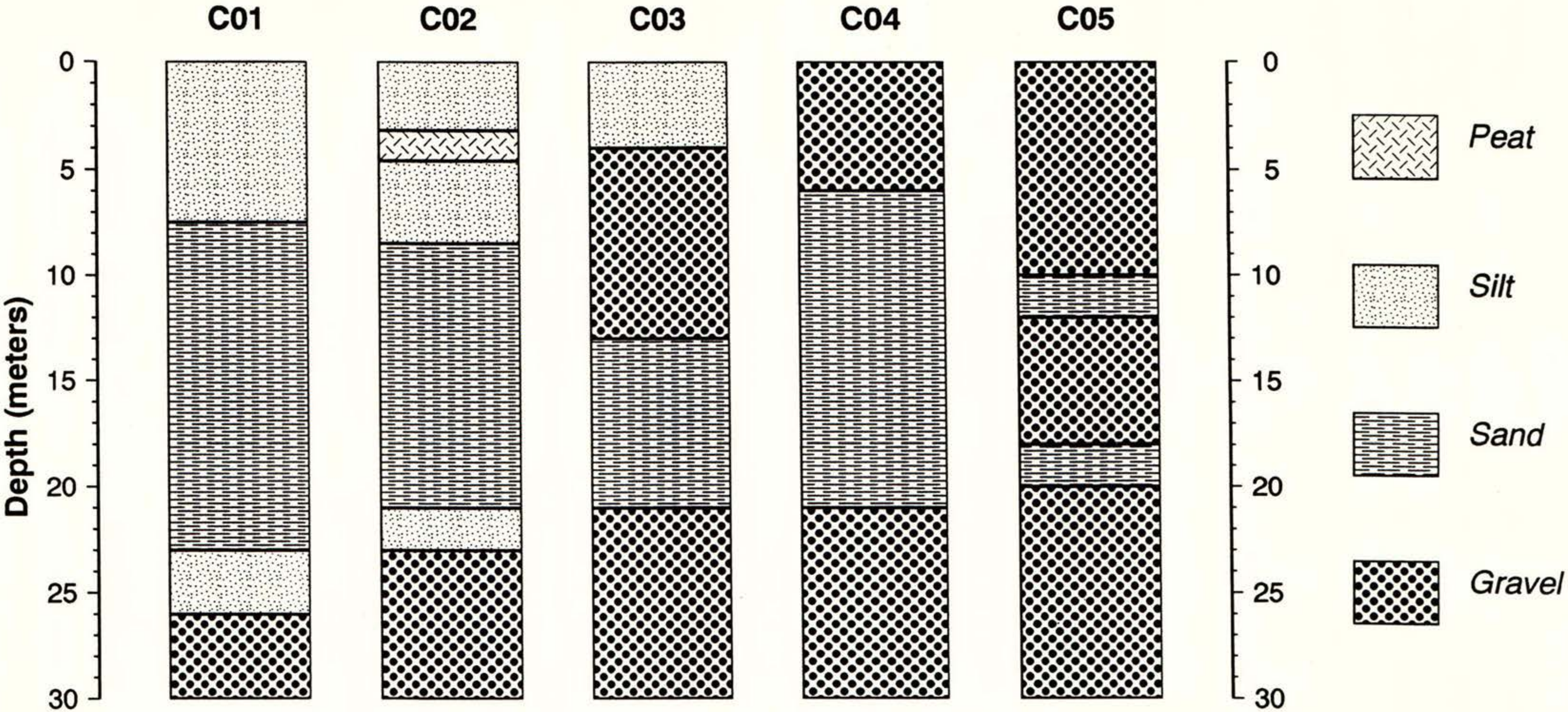

Figure 2. Approximate soil profiles of the top 30 m for the five central city sites (simplified from Elder *et al.* (1991), Berril *et al.* (1993) and Haines (pers. comm.). Beneath the top 30 m is a sequence of sand and gravel layers 675 m thick, underlain by 300 m of weathered volcanics overlying greywacke basement (Berril *et al.*, 1993).

250 km/sec. For the sand layers the estimates range from 200 to 350 km/sec, and for the gravel layers the range is 150 to 350 km/sec. For a detailed discussion of the geology of the Christchurch area, see Elder *et al.* (1991) and Brown and Weeber (1992).

Twelve earthquakes were used for the study (Figure 3 and Table 2). They ranged in magnitude from 3.0 to 5.7 and occurred between 25 and 700 km from the centre of the seismograph array. Nine of the earthquakes were in the depth range of 5-25 km, while the remaining three were deeper than 90 km. Fewer earthquakes were recorded during the survey than expected due to the unusually low rate of activity during the second half of 1992 (Smith, 1993). One earthquake was recorded at all six sites, while all 12 earthquakes were recorded at at least two sites. The largest event had a recorded acceleration of 0.1% g while the peak acceleration of the smallest event was only 0.002% g.

3. Data Analysis and Results

The ground velocity recorded by the seismographs allows a visual comparison of site response in terms of peak amplitude, approximate duration of shaking, and a very approximate indication of frequency content. To quantify the relative motion at the six sites, two different techniques were used. The first was to calculate Fourier spectra of each of the seismograms for each of the sites and then to compare the sites using spectral ratios. The second technique involved the calculation of damped acceleration response spectra from the same seismograms and then site comparisons via response spectral ratios. The two techniques provide different parameterisations of the data and thus it is possible for sites with similar weak- and strong-motion Fourier spectra to have different response spectra. Fourier spectra are used by the seismological community because they are a complete representation of the ground

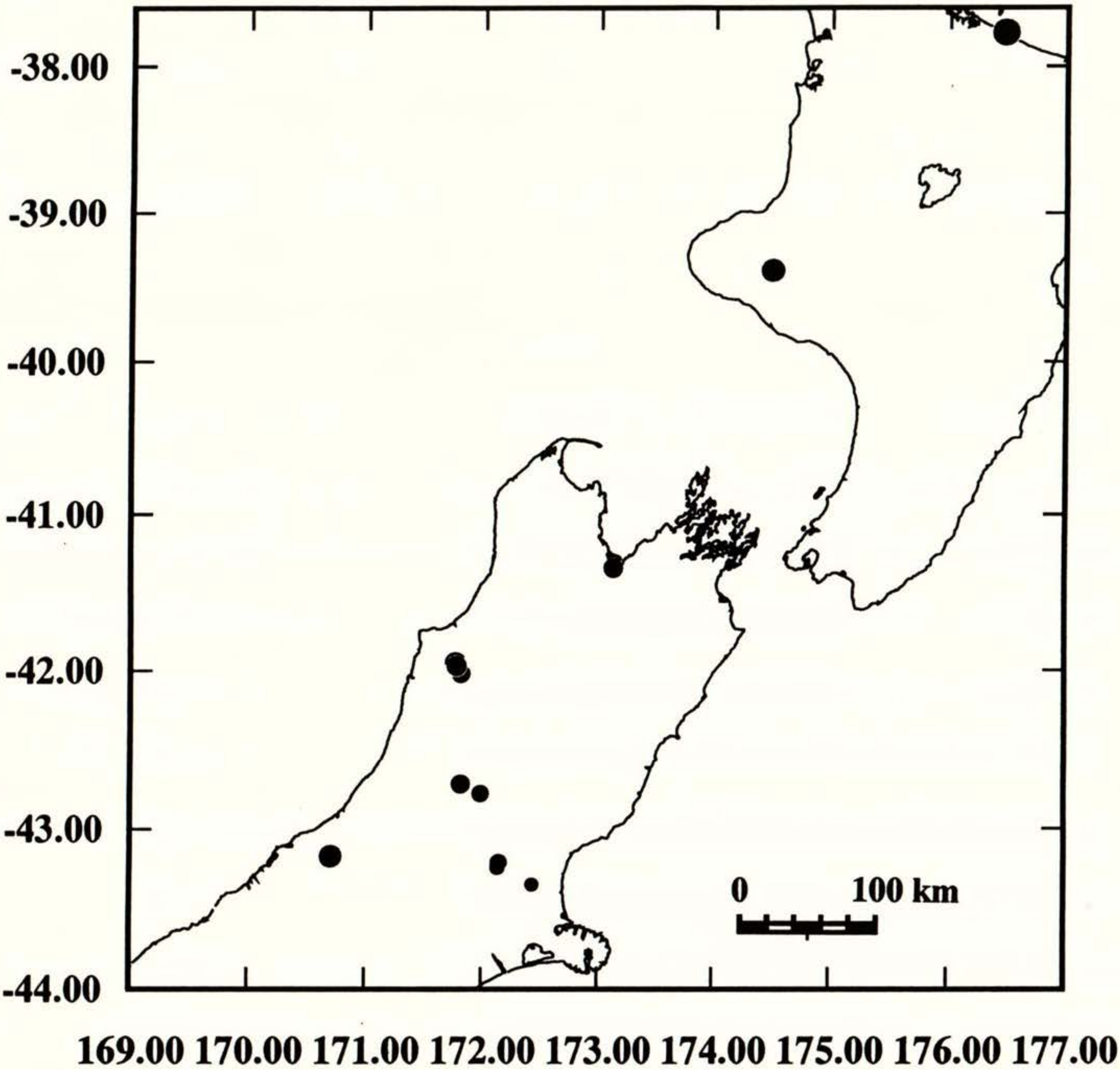

Figure 3. Locations of the 12 earthquakes used in the study. The symbol size is scaled by magnitude.

motion (when phase is included). Response spectra are preferred by the engineering community because they provide better information about the response of buildings to the ground motion.

The recorded seismograms for an earthquake centred 45 km from Christchurch are shown in Figure 4. The plot shows the *S* wave arrival on the north-south (horizontal) components, and is essentially a recording of ground velocity. The scaling is the same for all the traces and each trace is labeled with its station name. The highest amplitudes for this earthquake were recorded at stations C02 (Christchurch Womens Hospital), followed by C01 (Latimer Square). The other three sites in the central city (C03-Guthrie Centre, C04-Regent Centre and C05-Arts Centre) showed similar amplitudes to each other. All five central city sites exhibited amplified motion relative to the rock reference site at Cashmere.

Figure 5 shows an example for an earthquake 110 km from Christchurch. This earthquake occurred near the Hope fault, which is one of the faults contributing to the risk in Christchurch. Once again there is a very high level of shaking at Christchurch Womens hospital and a moderate amount of shaking at the Arts Centre relative to the reference site at Cashmere.

3.1 Fourier Spectral Ratios

Fourier spectra were calculated for 37 seismograms for the Christchurch study. The amplification effect is primarily in the horizontal plane; hence a 25 second window, starting 0.5 second before the S wave arrival, was selected from the horizontal components of each seismogram. A 4% Hanning taper was applied to the window before the Fourier amplitude spectra were calculated. The resulting spectra were then smoothed with a 0.5 Hz triangular moving window.

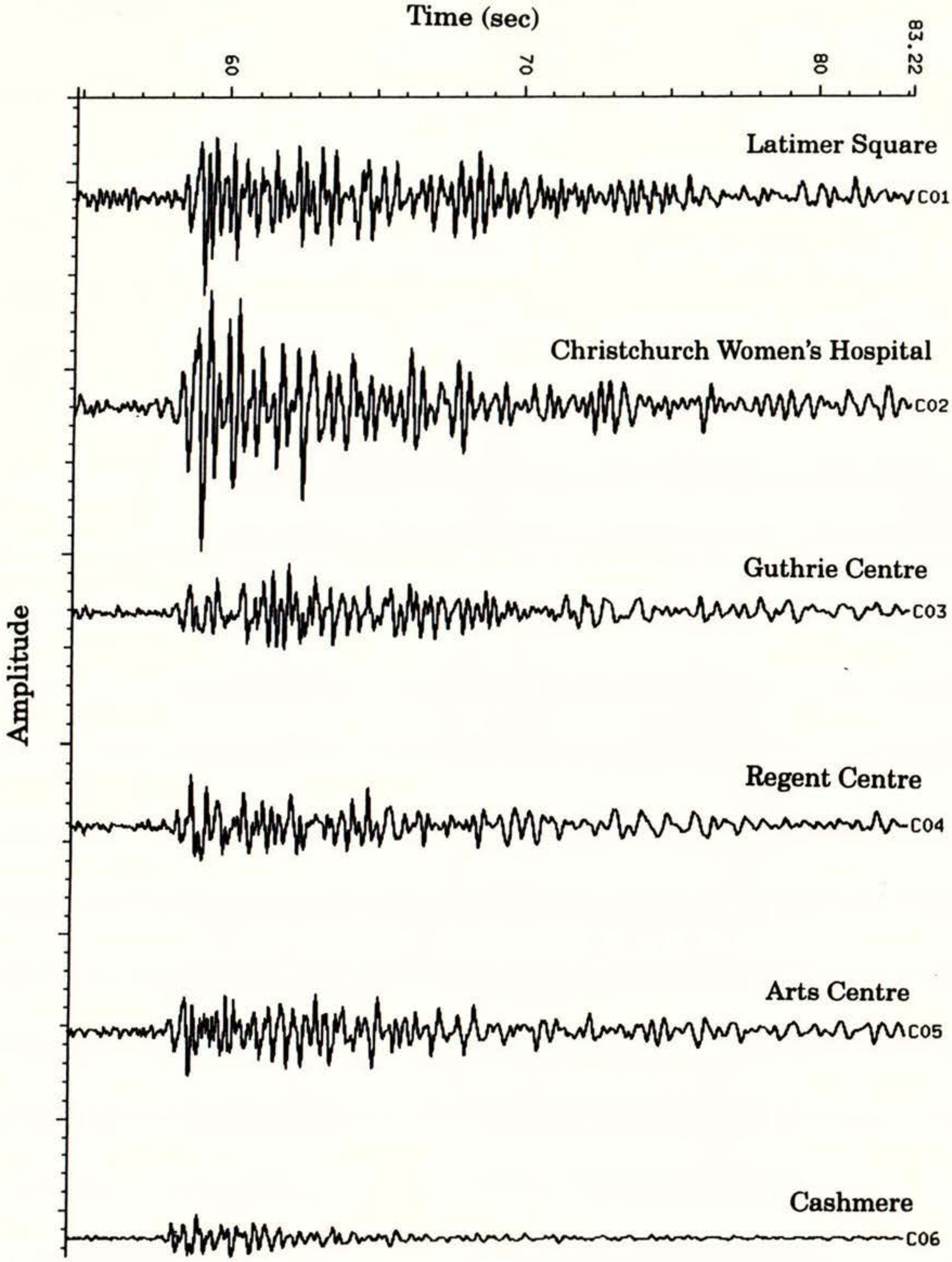

Figure 4. Seismograms recorded at six sites in Christchurch during a magnitude 3.6 earthquake on 1/11/92 that occurred approximately 45 km from the city. The S wave from the North-South component at each site is shown.

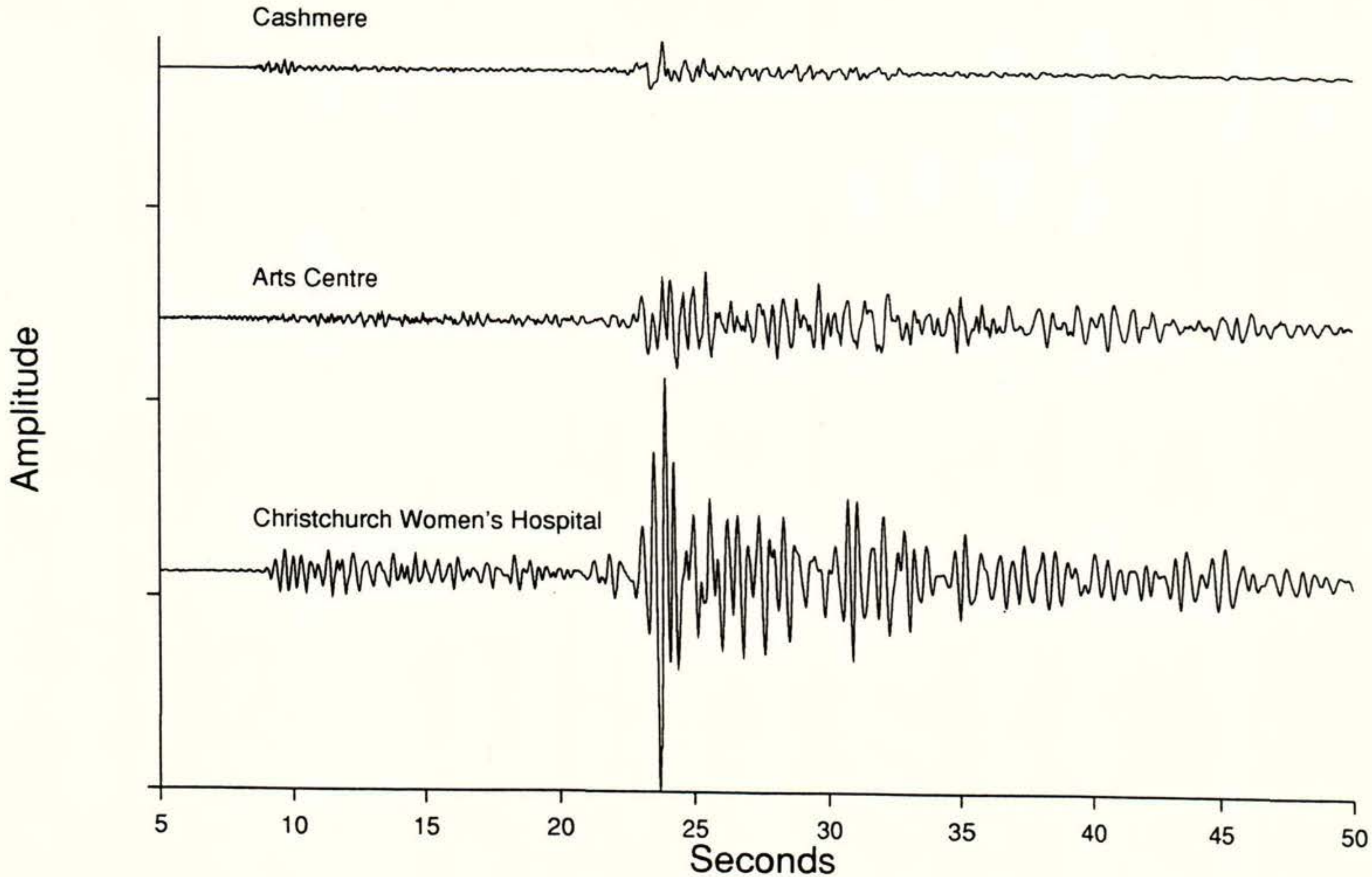

Figure 5. Seismograms recorded at three sites in Christchurch from a magnitude 4.0 earthquake on 27/9/92 that occurred approximately 110 km from the city. The North-South horizontal component is shown.

To find the average response of each site, the spectra of the north-south and east-west components were combined into an average horizontal amplitude spectrum. This average spectrum was computed by taking the sum of the squares of the spectra of the north-south and east-west components, dividing by 2, and taking the square root. This technique has been shown to result in a more stable and reliable spectral ratio than using components individually (Jarpe *et al.*, 1988; Huang, 1982). Spectral ratios were then calculated by dividing each spectrum by the spectrum for the rock reference site (C06, Cashmere)

The spectra refer to ground velocity because the seismograms are a measure of ground velocity. However, the spectral ratios are the same whether the initial spectra are calculated for velocity, acceleration or displacement. The frequency response of the seismometer is one potential limitation, but that is overcome by dividing each station spectra by the reference site spectra; this is permissible as all the seismometers were of the same type and had nearly identical characteristics. Effects due to the earthquake source or variations in the path between the source and the receiver are similarly reduced through the use of spectral ratios.

There are limitations to the spectral ratio technique, however. The reference spectrum may not be as flat as predicted by simple source theory (*e.g.* Aki and Richards, 1980), perhaps due to interference between signals arriving via slightly different paths. Low or high points in the reference spectrum may create spurious high or low ratios not inherent in the original spectrum. The additional noise caused by this problem can be reduced either by further smoothing or by averaging many spectral ratios observed for a station. Here we have chosen to average the spectral ratios, as some useful frequency information may be lost by too much smoothing.

It is also necessary to determine the frequency limits outside which the spectral ratios are not meaningful. At both high and low frequencies the amplitude spectrum of the signal approaches the spectral level of the background noise. The ratio values below about 0.5 Hz are not meaningful here because of the limited response of the seismometers at low frequencies and the smoothing that has been applied to the spectra. For some of the small events used in the calculation of the mean ratio for C02, the signal to noise ratio drops below 4 at frequencies below 1 Hz. Therefore the average ratio for C02 may be contaminated by noise below 1 Hz. However for the larger events, the signal to noise ratio remains high down to 0.5 Hz. At the high frequency end, the signal to noise ratio for several of the sites was found to drop below 4 above 10 Hz so that is the cutoff frequency that was adopted for the plots. Note that high ratios at high frequencies do not necessarily mean large signal amplitudes; they can instead be due simply to a low level in the reference spectrum. In general, ratio peaks at frequencies above 6 Hz are not important, particularly because they are likely to be more attenuated during large motions.

The spectral ratio can not be directly correlated with peak acceleration or velocity since the spectral ratio is strongly influenced by the duration of the shaking. In general the spectral ratio is higher than the ratio of peak velocity or acceleration. For example, the peak spectral ratio for C02 (C02 divided by C06) for the earthquake plotted in Figure 4 is 14.5 whereas the ratio of peak ground velocity is only 6.9. Many cycles of moderate motion (as shown in the seismic traces in Figures 4 and 5) may excite resonances in buildings with the same natural period. Thus a high spectral ratio may be more important than a small increase in peak acceleration.

The response spectrum is more affected by the amplitude than the duration. A site with a long duration but low amplitude at a particular frequency can have a high Fourier spectral ratio but a lower response spectral ratio. Thus strongly resonant sites are likely to have higher Fourier spectral ratios than response spectral ratios.

The Fourier spectral ratios for the five sites in Christchurch are shown in Figures 6-8. The average of the north and east horizontal component as described above is plotted in these figures. The number of events at each site varies from 1 at C03 to 12 at C02. Figure 6 (bottom) shows the wide variation in the site response at site C02 due to different micro-earthquakes. Note the wide range of values for individual earthquakes about the mean (shown by the dark lines). All events show a higher ratio in the 2-4 Hz frequency band, but the maximum ratio for a particular earthquake can vary from 9 to 30. Thus there is a wide range of values about the mean, and an individual earthquake can produce a response significantly different from the average. Different frequencies, corresponding to different soil layers, can be preferentially excited by particular earthquakes. It is because of this scatter that the average site response is best determined by recording many earthquakes at each site. Unfortunately, too few earthquakes were recorded at some of the sites to demonstrate the range of values that might be expected. From previous surveys, it appears the the scatter is such that one standard deviation is approximately +/- 1/2 the value of the mean (Taber and Smith, 1992). This means that the larger the mean ratio, the larger the scatter in the ratios for different earthquakes. When only one or two events have been recorded at a site, as in the case of C01, C03, and C04, it is not known if peaks at particular frequencies are likely to occur for all earthquakes, but an approximate estimate of the range of amplification can be made.

It is important to consider whether there is a correlation between the amplitude of the incoming signal and the size of the ratio. A possible correlation would suggest non-linearity even at this low level of motion. Consider the ratios of the

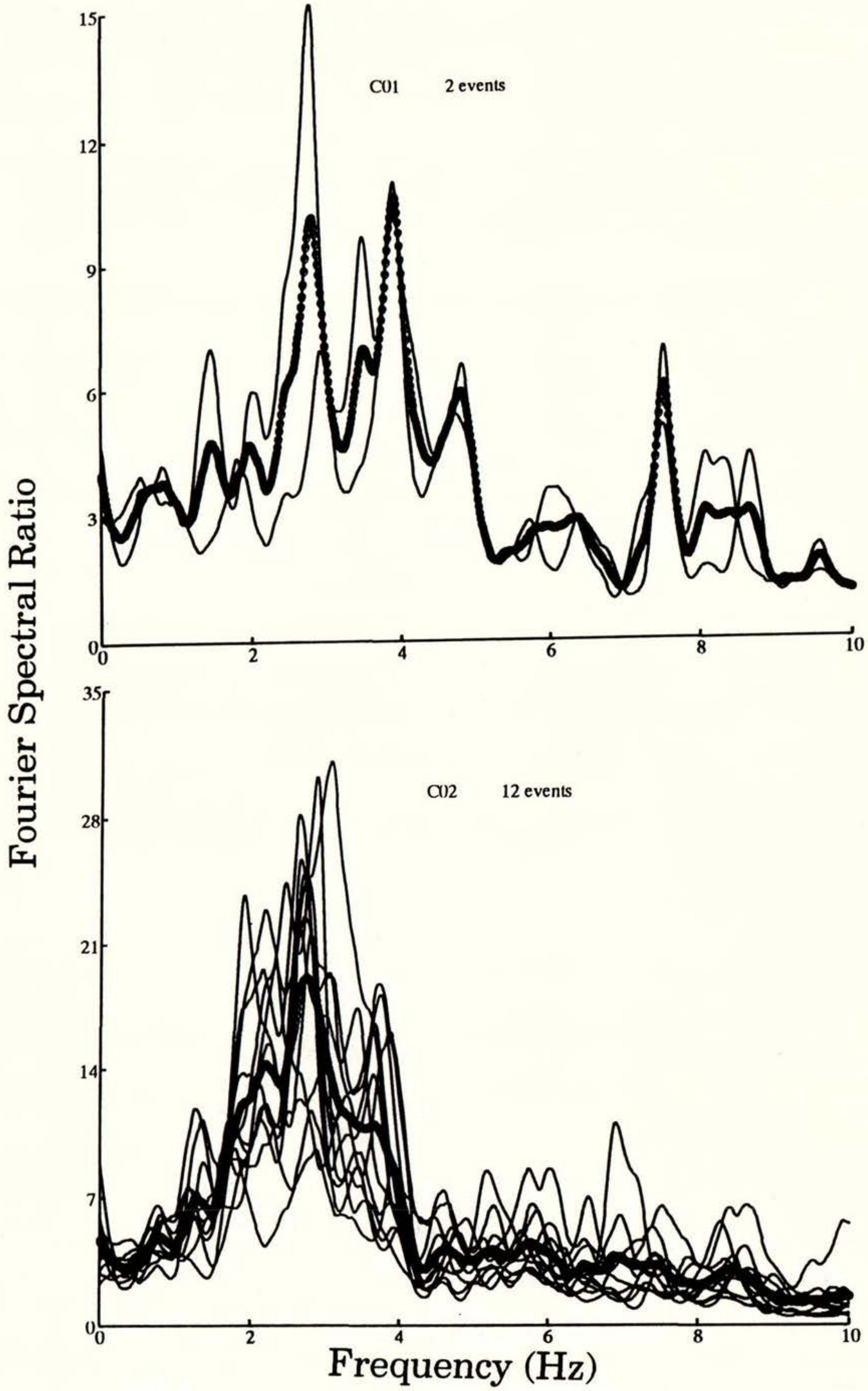

Figure 6. Top: Fourier spectral ratios (C01 divided by C06) of the average horizontal spectrum for the two events recorded at site C01. The thick line shows the mean of the spectral ratios. Bottom: Spectral ratios for the 12 events recorded at site C02.

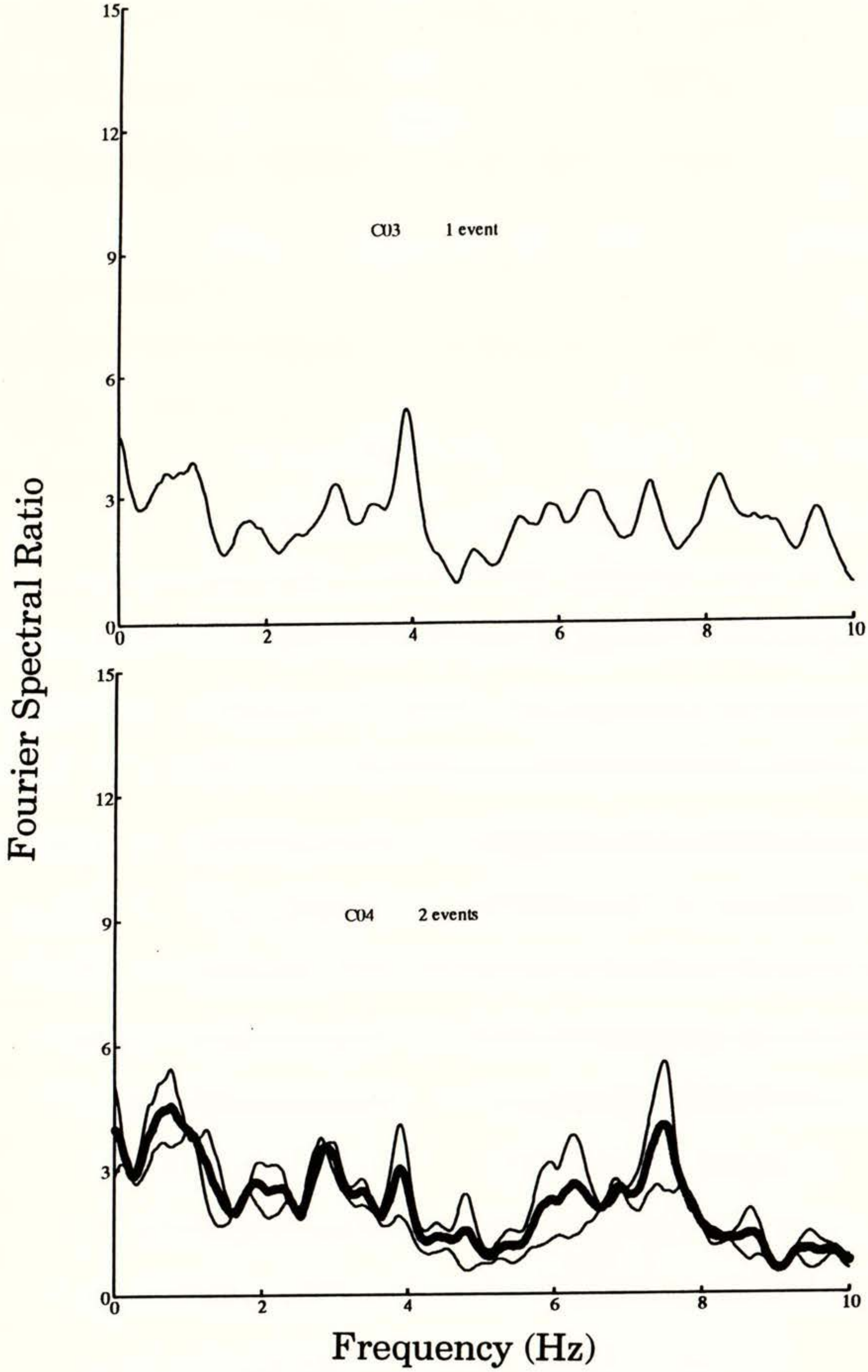

Figure 7.Top: Fourier spectral ratio for the only event recorded at C03. Bottom: Spectral ratios for the 2 events recorded at site C04.

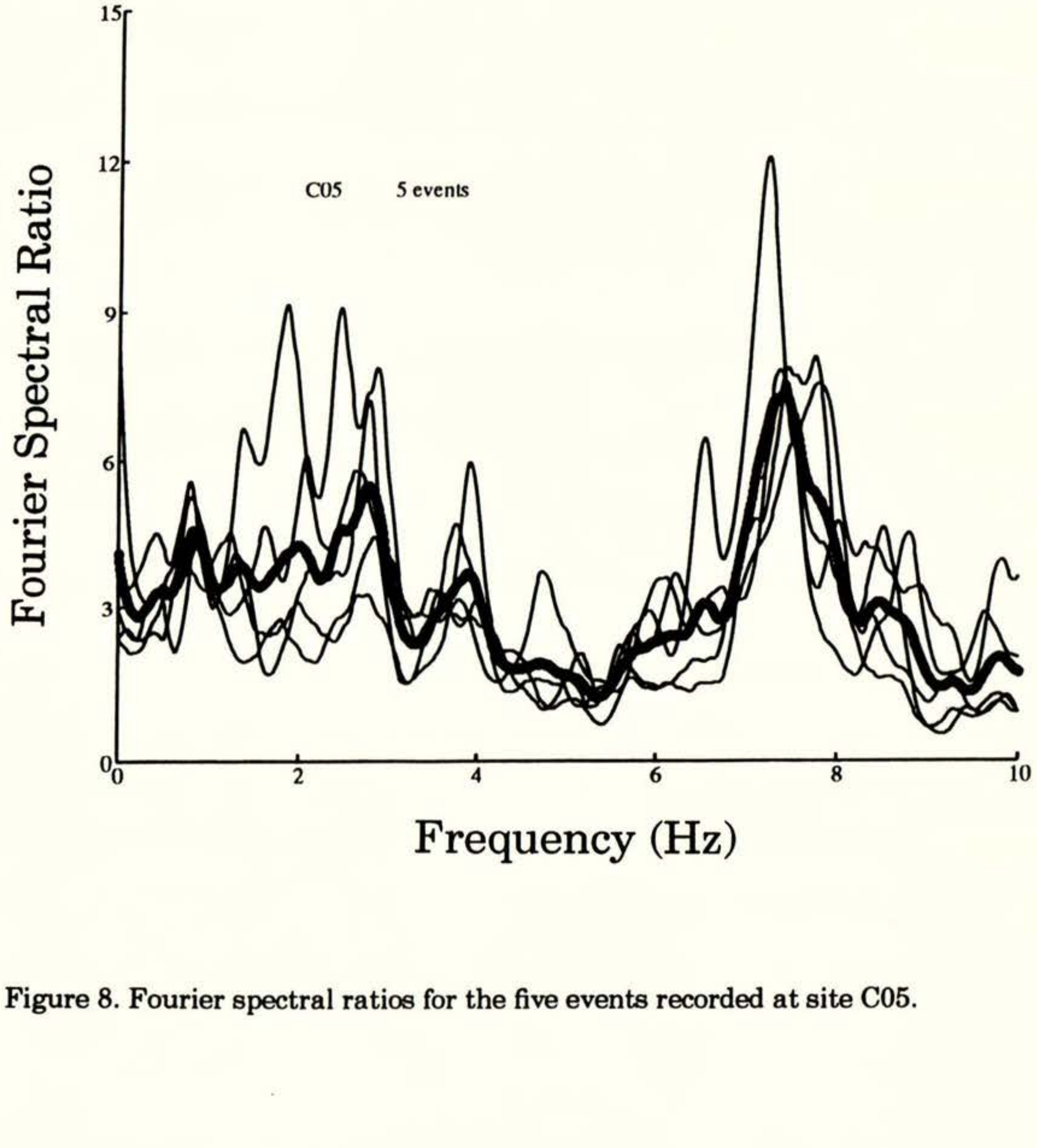

Figure 8. Fourier spectral ratios for the five events recorded at site C05.

events with the four largest and four smallest amplitudes at C02 (Figure 9). The largest event had the smallest ratio of all recorded earthquakes, and the mean of the four largest events is less than the mean of the four smallest. However, the second largest event generated amplifications as large as any of the four smallest events. Thus the existence of non-linearity is neither proven nor disproven by this data set.

The spectral ratio values are dependent on the response of the reference site. Rocks sites used in separate surveys in the Wellington regions show that ratios can vary by up to a factor of 3 depending on the rock site chosen (Taber and Smith, 1992). Thus the relative ratios of the central city sites are more important than the absolute values. Ideally the reference site would be calibrated against other reference sites so that a direct comparison could be made between surveys.

The ground shaking hazard at a site is best defined by determining the average response from a number of earthquakes, because there can be a wide range of responses at each site, depending on such parameters as the earthquake location, mechanism and size. Fewer earthquakes than expected were recorded during the experiment, so the average response can be determined for 2 sites while the response from one or two earthquakes is presented for the other 3 sites. The mean spectral ratios for all Christchurch sites relative to reference site C06 are plotted in Figure 10. Thus these are averages of up to 12 earthquakes. The sites fall into three basic groups. Site C02 has by far the greatest amplification, reaching a maximum near 20 at 3 Hz. The greatest amplification is in the 1-4 Hz range. Site C01 shows the next highest response, with strong peaks at 2.5 and 4 Hz. Sites C03, C04 and C05 are similar to each other, with maximum ratios near 4. C05 has slightly higher ratios between 1 and 3 Hz, while C03 has a higher peak at 4 Hz. Only one or two earthquakes were recorded at C03 and C04, so the differences between these sites shown in Figure 10 are probably not significant.

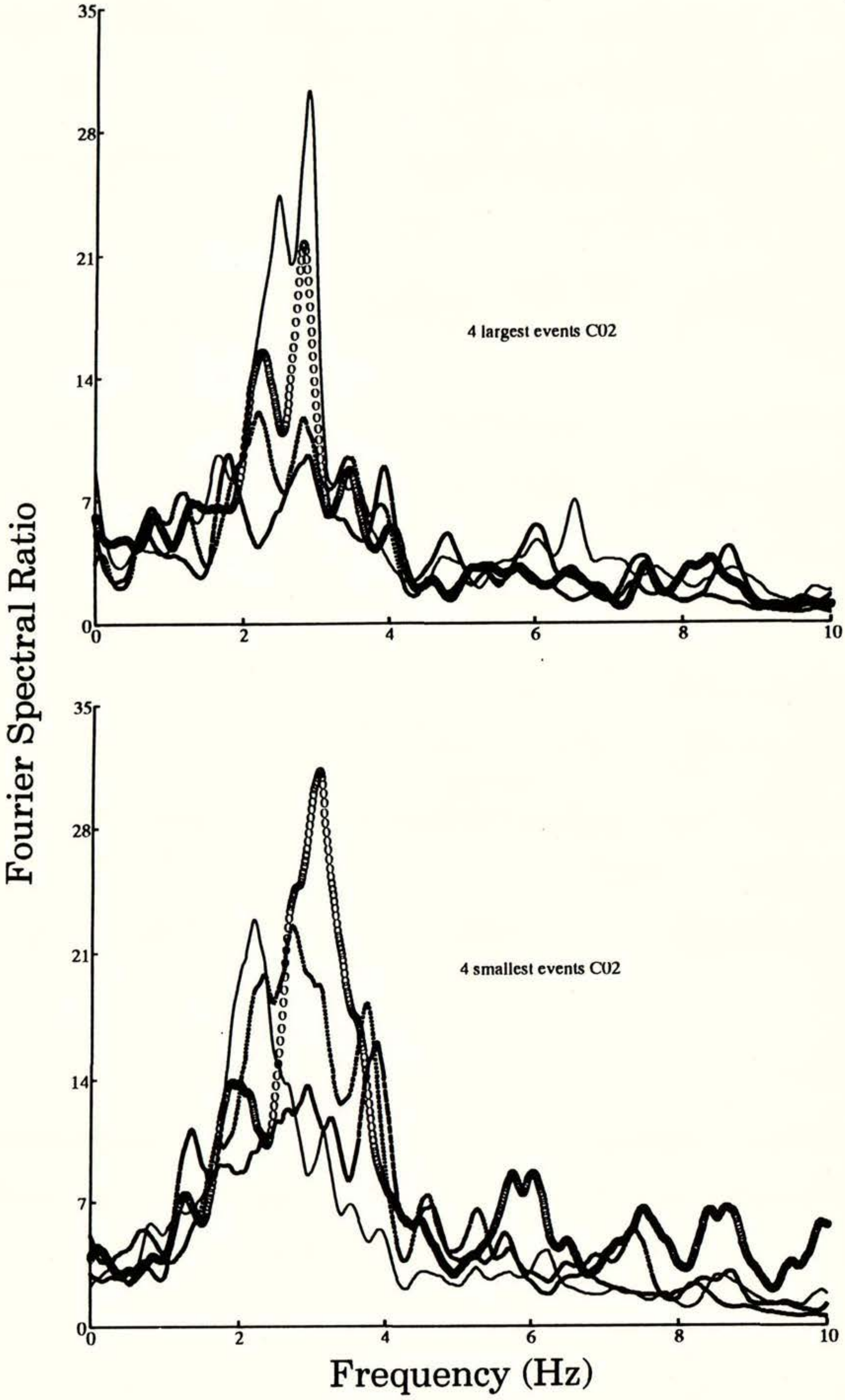

Figure 9. Comparison of the spectral ratios at site C02 for the events with the four largest and four smallest amplitudes.

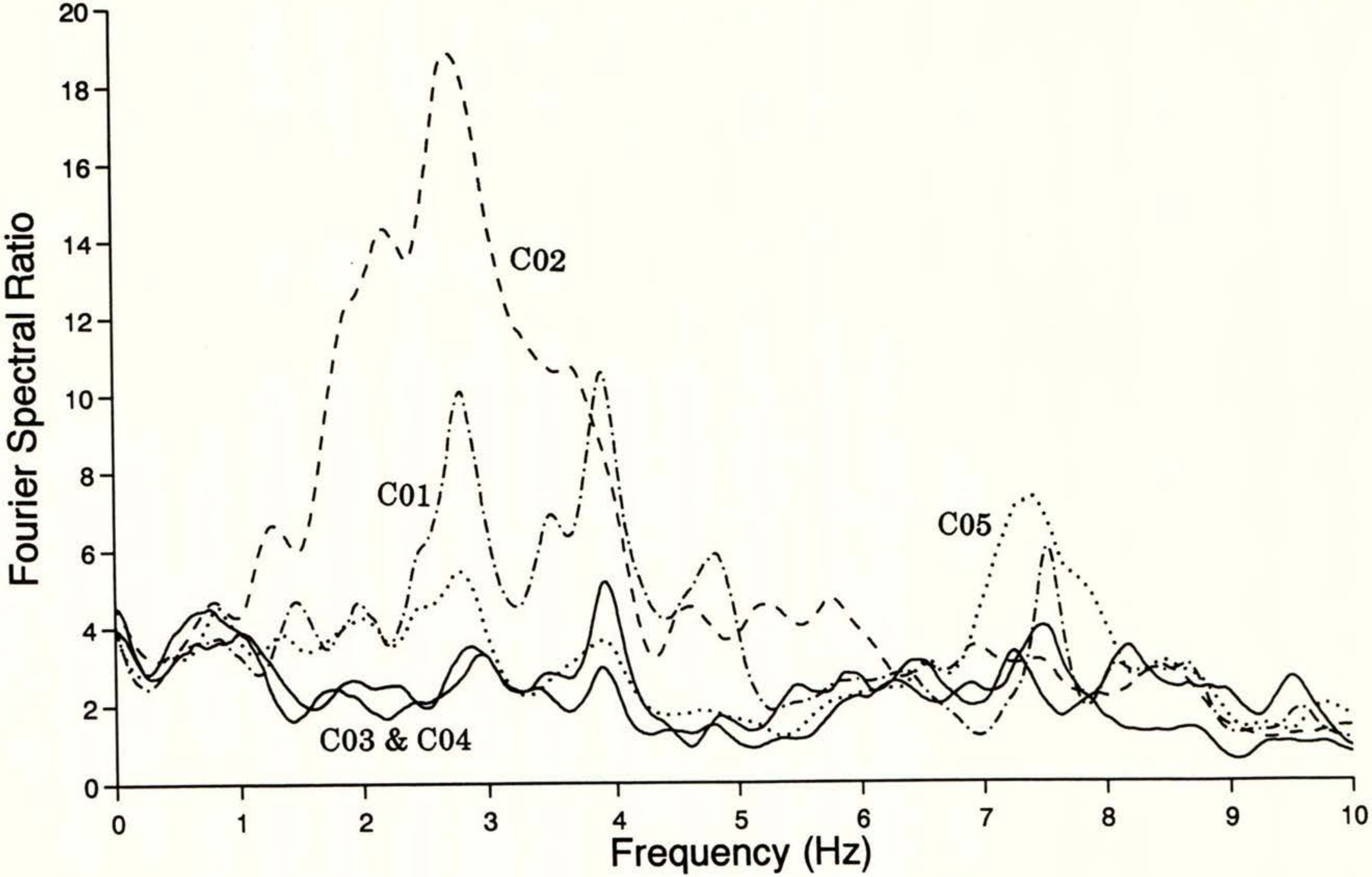

Figure 10. Mean Fourier spectral ratios for each of the five central city sites.

Large amplifications in a narrow frequency band (i.e. resonance) appear most common on relatively thin (<30 m), flexible, low velocity sediments overlying much firmer material. The resonant frequency is a function of the thickness and velocity of the flexible sediments. The existence of multiple high and low velocity layers beneath Christchurch, means that a number of different resonances could be excited, but the predominant frequency may vary between earthquakes. Thus the mean ratio tends to show a broad peak, whereas the peaks for individual earthquakes can be quite sharp.

3.2 Response Spectral Ratios

A similar approach to the data processing was taken in the preparation of the data for the calculation of response spectral ratios. The instrument response was first removed from the seismometer signal and then the resulting ground displacement was converted to acceleration, after appropriate filtering and tapering of the signal. The 5% damped response spectra were then calculated for the same 25 second window that was used to calculate the Fourier spectral ratios.

The average response spectral ratios for the five central city sites are shown in Figure 11. The overall comparison of the sites is similar to the Fourier spectral ratios, though differences at longer period are clearer in Figure 11. The response spectra are more sensitive to peak acceleration while the Fourier spectra are more sensitive to duration. The response at the site on the softest material, C02, is dominated by the large amplification between 0.3 and 0.6 sec. Site C01 has closely spaced peaks at approximately 0.25 and 0.35 sec. As in the Fourier spectral ratios, sites C03, C04, and C05 have similar responses, with site C05 having a higher response in the 0.3 to 0.8 sec range. The response spectral ratios for all events for the 5 sites are shown in Figures 12-14. As with the Fourier spectral ratios, there is

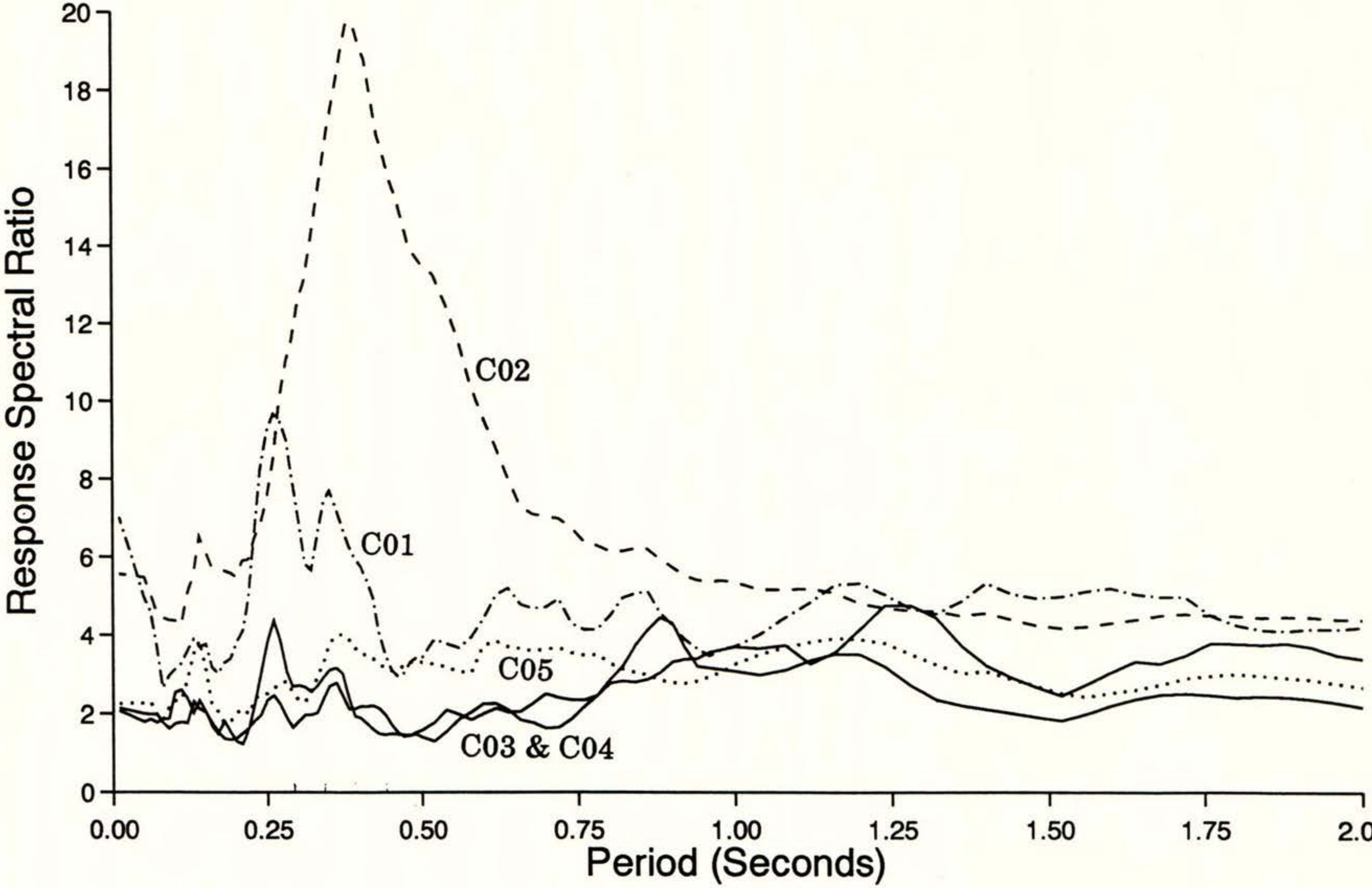

Figure 11. Mean response spectral ratios (5% damping) for each of the five central city sites.

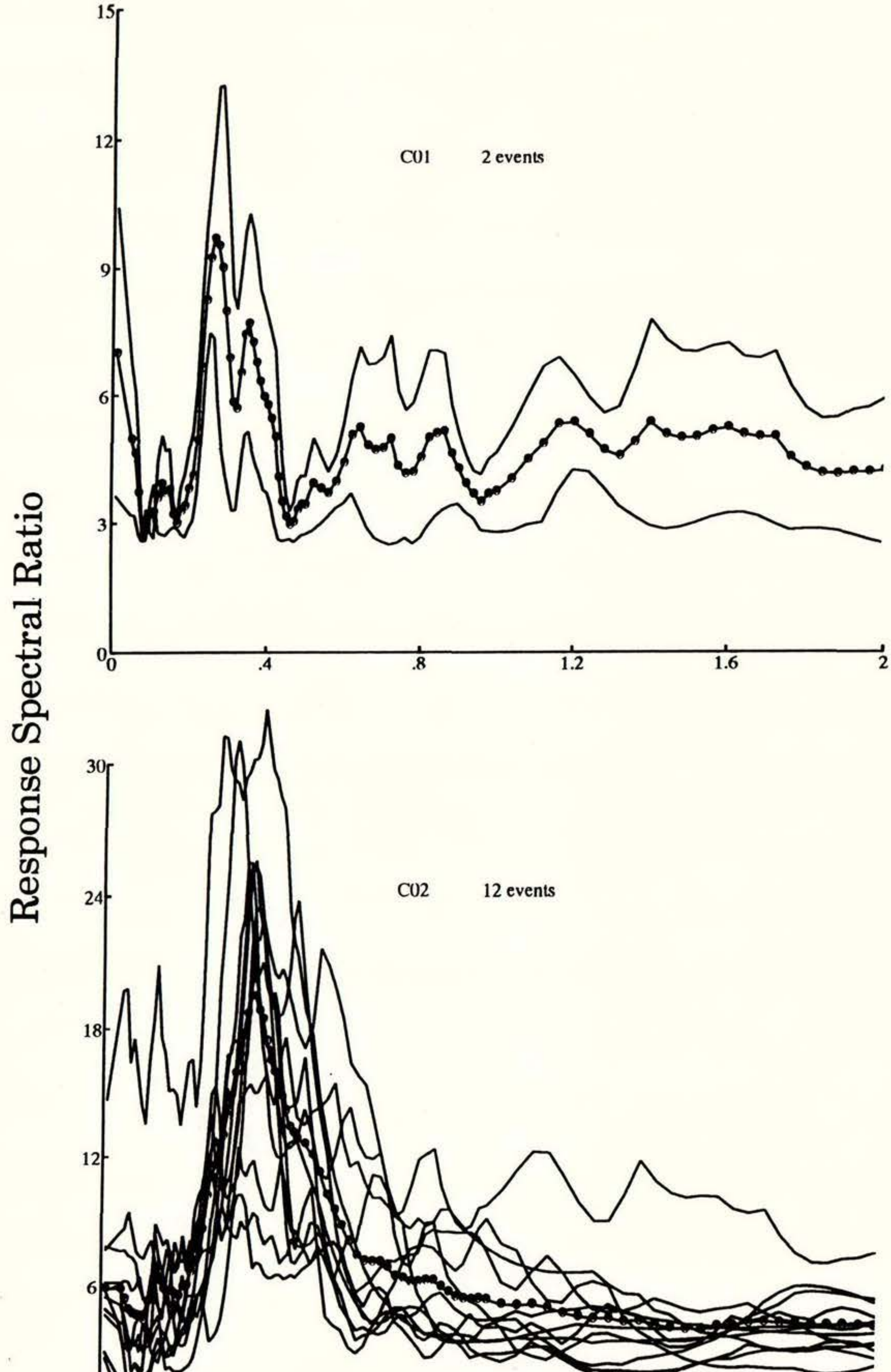

Figure 12. Top: Response spectral ratios (5% damping) for the two events recorded at site C01. The thick line shows the mean of the two events. Bottom: Response spectral ratios for the 12 events recorded at site C02.

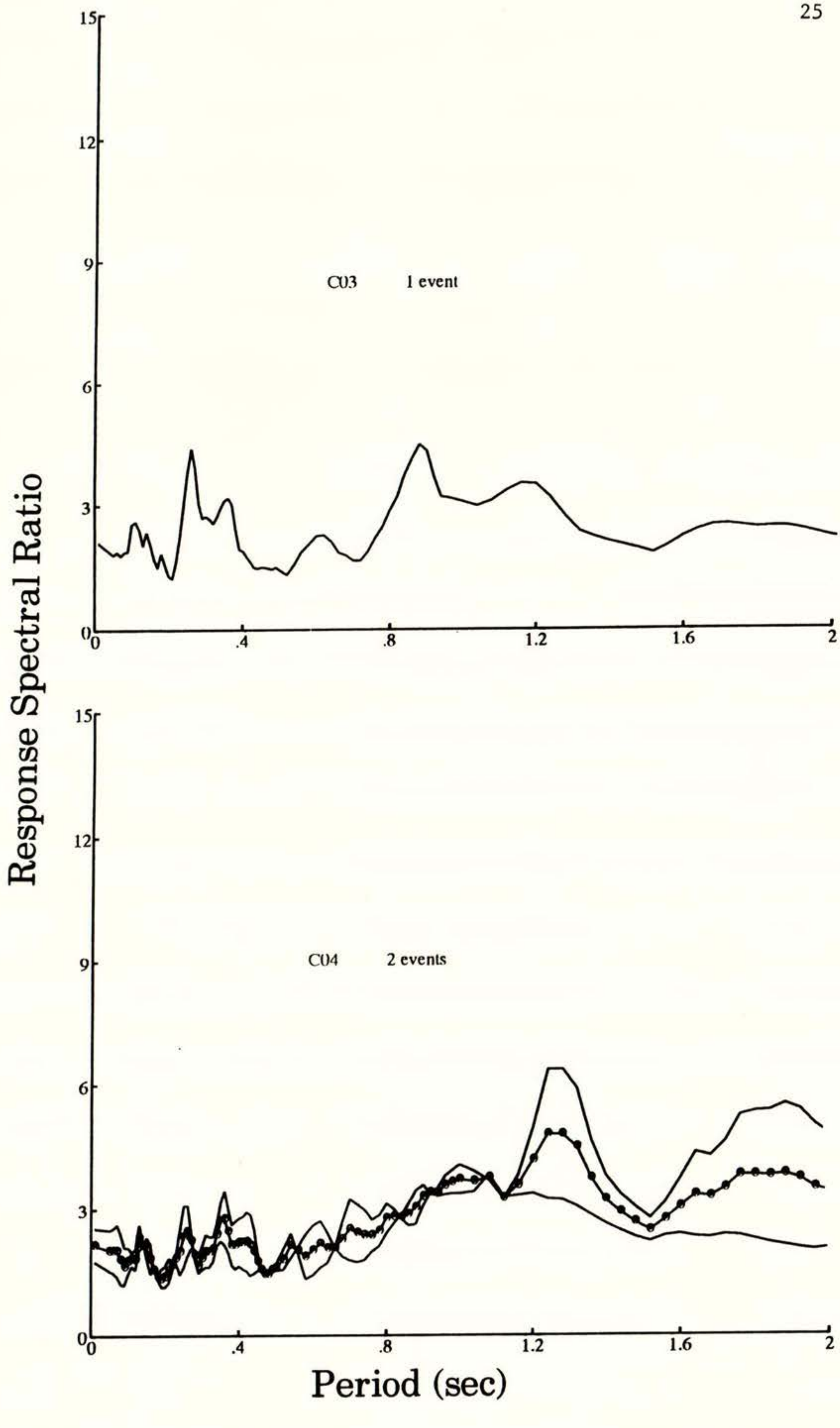

Figure 13. Top: Response spectral ratios for the one event recorded at site C03. Bottom: Response spectral ratios for the two events recorded at site C04.

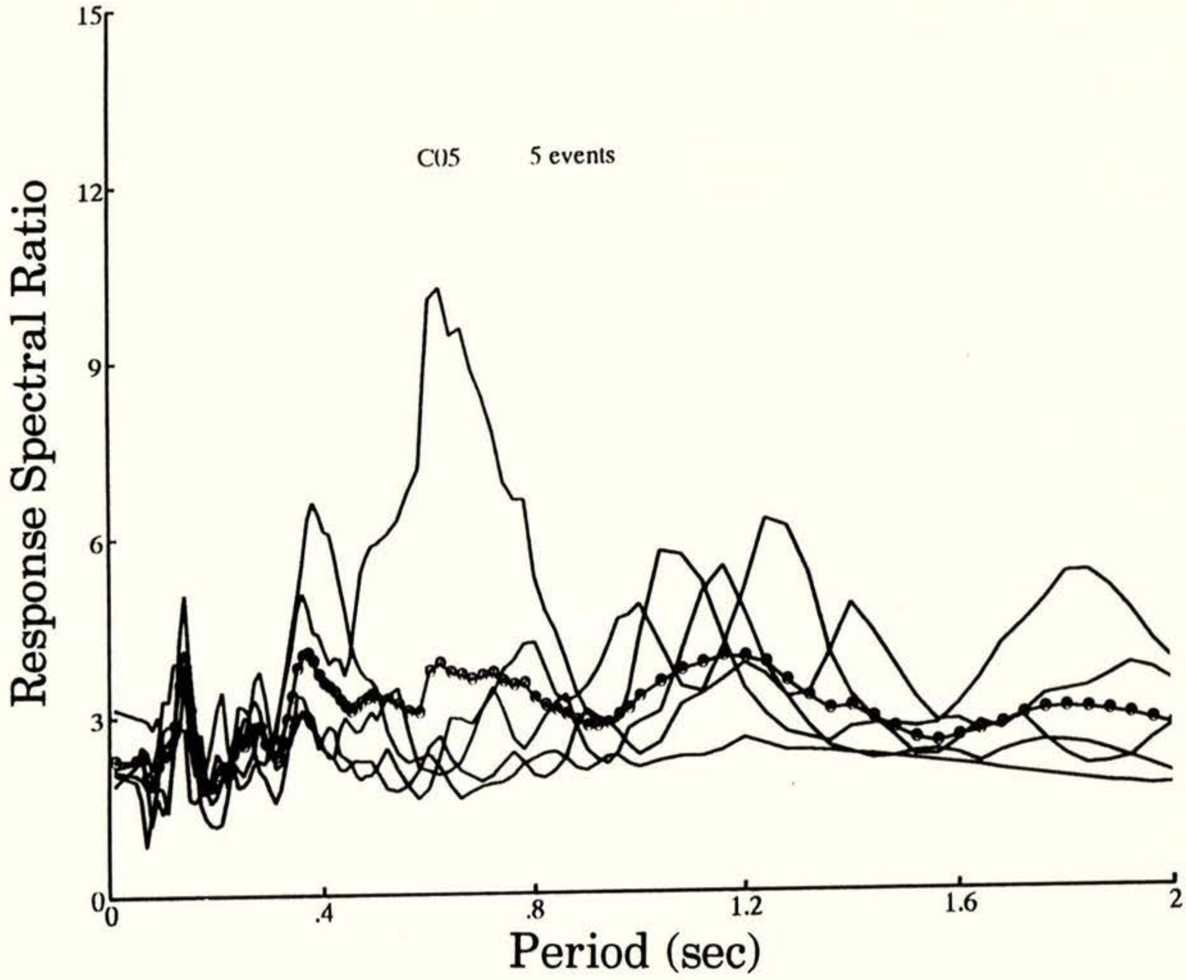

Figure 14. Response spectral ratios for the five events recorded at site C05.

a wide scatter of ratios about the mean ratio at sites with a sufficient number of recordings.

4. Discussion

It is important to determine the extent to which the relative weak motion responses can be extrapolated to the strong motions that can cause damage. Other studies have presented strong cases for both linear and non-linear behaviour, so that one paper concluded that it is unknown whether non-linear behaviour is pervasive or occasional (Yu *et al.*, 1993). Therefore the sites most at risk are likely to be those where both linear and non-linear approaches predict high levels of shaking. Peak frequencies and relative amplifications for strong and weak ground motions have been correlated in other areas. Peak frequencies determined from spectral ratios for aftershocks of the 1988 Armenian earthquake were similar to the natural period of the buildings most heavily damaged in Leninakan (Borcherdt *et al.*, 1989). Greater damage also occurred in the regions with the highest spectral ratios. There was significant amplification to periods as short as 0.5 sec.

Intensity maps based on weak motion data in the San Francisco area anticipated all the areas that experienced strong shaking during the 1989 Loma Prieta earthquake (Borcherdt, 1991). However, the absolute levels of strong and weak motions do not always correlate. Small amplifications (factors of 2-3) have been shown to persist to 0.7g in soft soils in California (Jarpe *et al.*, 1988) and to 0.2g in Garm, USSR (Tucker and King, 1984), but ground motion amplifications were greater for the aftershocks of the 1989 Loma Prieta earthquake in California than for the mainshock at some sites. For one pair of sites, the maximum spectral ratio was 8 for the aftershocks but only 3 for the mainshock (Jarpe et al, 1989). This is an extreme example of non-linear behaviour as the soils liquified after 5 seconds of shaking.

Borcherdt (1991) found that the correlation of average spectral ratio to shear wave velocity was nearly the same for strong and weak motions, when a broadband average from 0.5 to 2.5 Hz was considered. This is the frequency range most important for larger engineered structures. Averaging over a range of frequencies reduces the effect of narrow resonance peaks and enhances the importance of low frequency shaking.

A calculation of the broadband spectral ratio allows us to compare the Christchurch sites to those in the San Francisco area. The broadband ratios for Christchurch are overlayed on the San Francisco data in Figure 15 (top). The sites are shown as a band, since there are only estimates of the velocity at each site. The much higher amplification and lower estimated velocity at site C02 correlates reasonably well with the California data. Sites C01 and C05 have similar broadband values even though individual peaks are much higher for site C01 (Figure 10), because the higher level of shaking at site C01 occurs at higher frequencies. Thus the site is a greater risk only for smaller buildings. Sites C03 and C04 have the lowest broadband ratios but these values are still 2 to 3 times that expected at a rock site. The California strong and weak motion data show similar amplifications for similar shear wave velocities. The same correlation between strong and weak motion may exist in Christchurch for a large distant earthquake.

Micro-earthquake surveys similar to the Christchurch survey have been carried out recently at four different locations in the Wellington region (Taber and Smith, 1992; Taber and Richardson, 1992). Those surveys were part of a multi-disciplinary ground shaking hazard project for the Wellington region. A direct comparison of the Fourier spectral ratios is difficult because different reference sites were used for each survey, but a general comparison can be made by also considering the ground classes defined in those surveys and the Christchurch soil profiles.

The Wellington region was divided into 4 zones based on the potential ground shaking hazard. The zones were classified according to the geology and the measured response to strong and weak seismic shaking. Zone 1 areas are underlain by bedrock or weathered bedrock, Zone 2 areas are typically underlain by compact alluvial and fan gravel, Zone 3-4 is underlain to a depth of 20 m by interfingered layers of flexible sediment and compact gravel and sand, and Zone 5 is generally underlain by more than 10 m of flexible sediment of low shear-wave velocity. The estimated amplification of the ground motions range from none for the rock sites (Zone 1) to increases in the peak ground acceleration (pga) of factors of 3 to 4 for Zone 5 for a large, shallow, distant earthquake (Van Dissen *et al.*, 1992a,b).

The two softest sites in Christchurch (C01 and C02) appear to fit the Zone 5 criteria both in terms of ground condition and measured ground motion amplification though as mentioned above, the broadband average for site C01 (Figure 15) is only slightly higher than site C05. The other three sites (C03, C04, and C05) could probably be classified as Zone 3-4 due to the thick column of stiff sands and gravels. Thus all the sites could experience much greater shaking than a site on rock, particularly for large, distant earthquakes.

One of the purposes of this study was to compare the measured microearthquake response to Christchurch modelling studies. The motions in the present study are very small (0.1%g or less) and thus represent the linear response of the subsurface materials. Some non-linear motion will occur in large, damaging earthquakes, but as mentioned above, there has been considerable debate over the extent of the non-linearity.

The ground shaking response for Christchurch has been calculated using both linear and non-linear models. Haines (1993a,b) modelled central Christchurch using

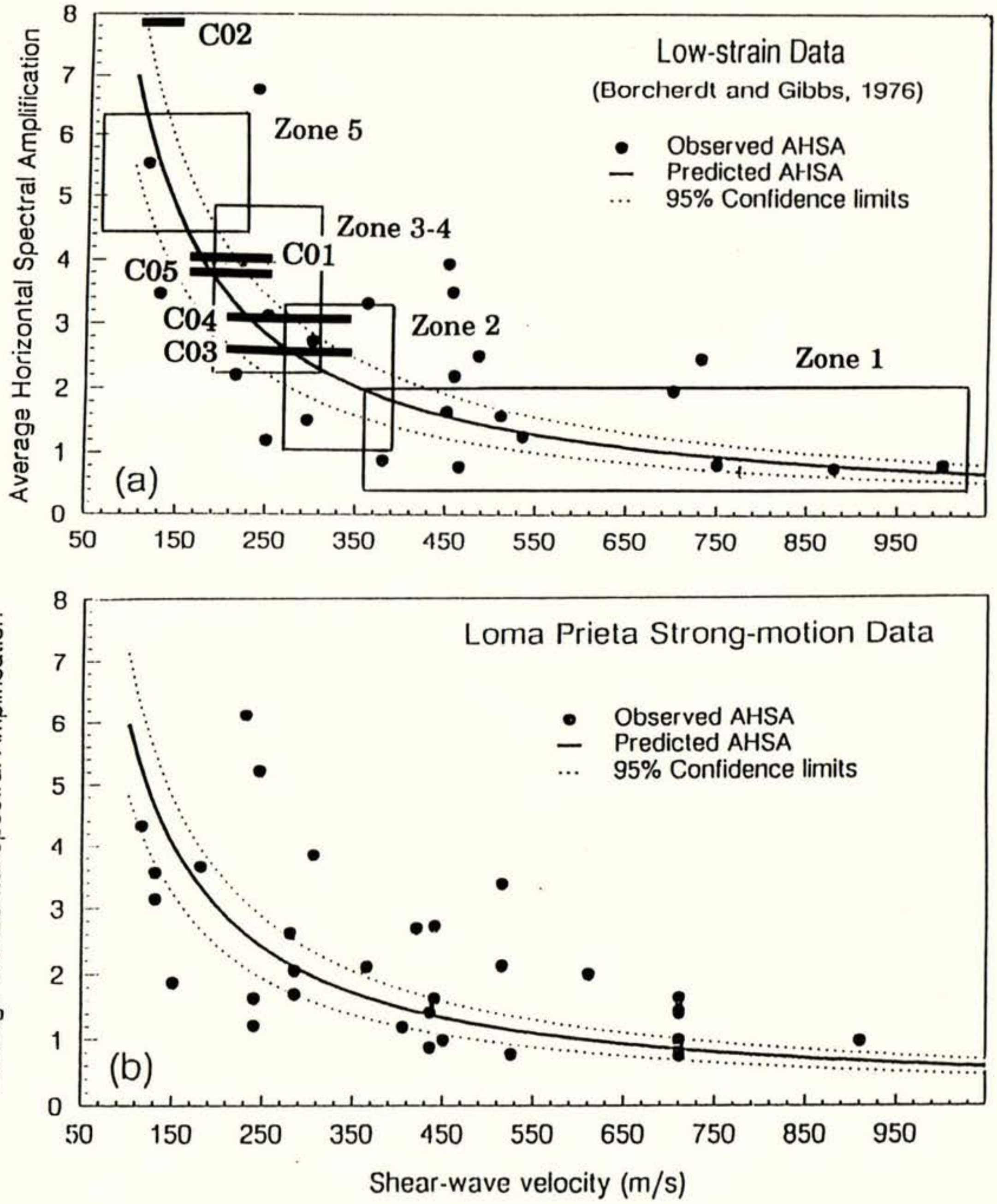

Figure 15. Top: Comparison of weak motion data in California to Wellington and Christchurch data. Bold lines are the average horizontal spectral amplification (ASHA) for the five Christchurch sites. The sites are shown as a line because the velocities have been estimated instead of measured. Boxes on the upper plot represent the ranges of AHSA for sites in each of four ground shaking hazard zones in the Wellington region. Bottom: California strong motion data. Note the similarity between weak and strong motion amplification.

a 3 dimensional linear technique. There is reasonable agreement between his calculated frequencies and amplitudes and the recorded responses at sites C01, C03 and C04, though there is less difference between C03 and C04 than predicted by the model. His modelling also predicts a wide range of amplifications depending on the direction of the incoming seismic energy, similar to the scatter in the recorded data. Such directional effects are evident when comparing the north-south and east-west response at some sites (Figure 16). The response at 4 Hz on the north-south component is approximately twice the response at that frequency on the east-west component. Thus at some sites structures may be subjected to more shaking in one direction than the other.

There is a much larger difference between the micro-earthquake results and the modelling of Berril *et al.* (1993). They used a 1-dimensional non-linear technique that incorporates strain softening and hysteretic attenuation. A comparison of the calculated response spectra of Berril *et al.* (1993) and the largest recorded micro-earthquake response spectra for the two sites in common is shown in Figure 17. The Berril *et al.* response spectra have been converted to ratios to allow a direct comparison to the weak motion spectra. Note that the non-linear modelling damps out almost all of the short period amplification, while the long period amplification is higher than in the micro-earthquake case. In the linear case, the softer the near surface layers, the higher the amplification at short periods, while the reverse is true in the non-linear model.

There are several possible explanations for the differences. The micro-earthquake source spectra have relatively less long period energy than do the assumed spectra for the Berril *et al.* model, so the micro-earthquakes may not be exciting resonances in the deeper layers. The Berril *et al.* model relies on estimated velocities and damping values determined from lab experiments, so under- or over-

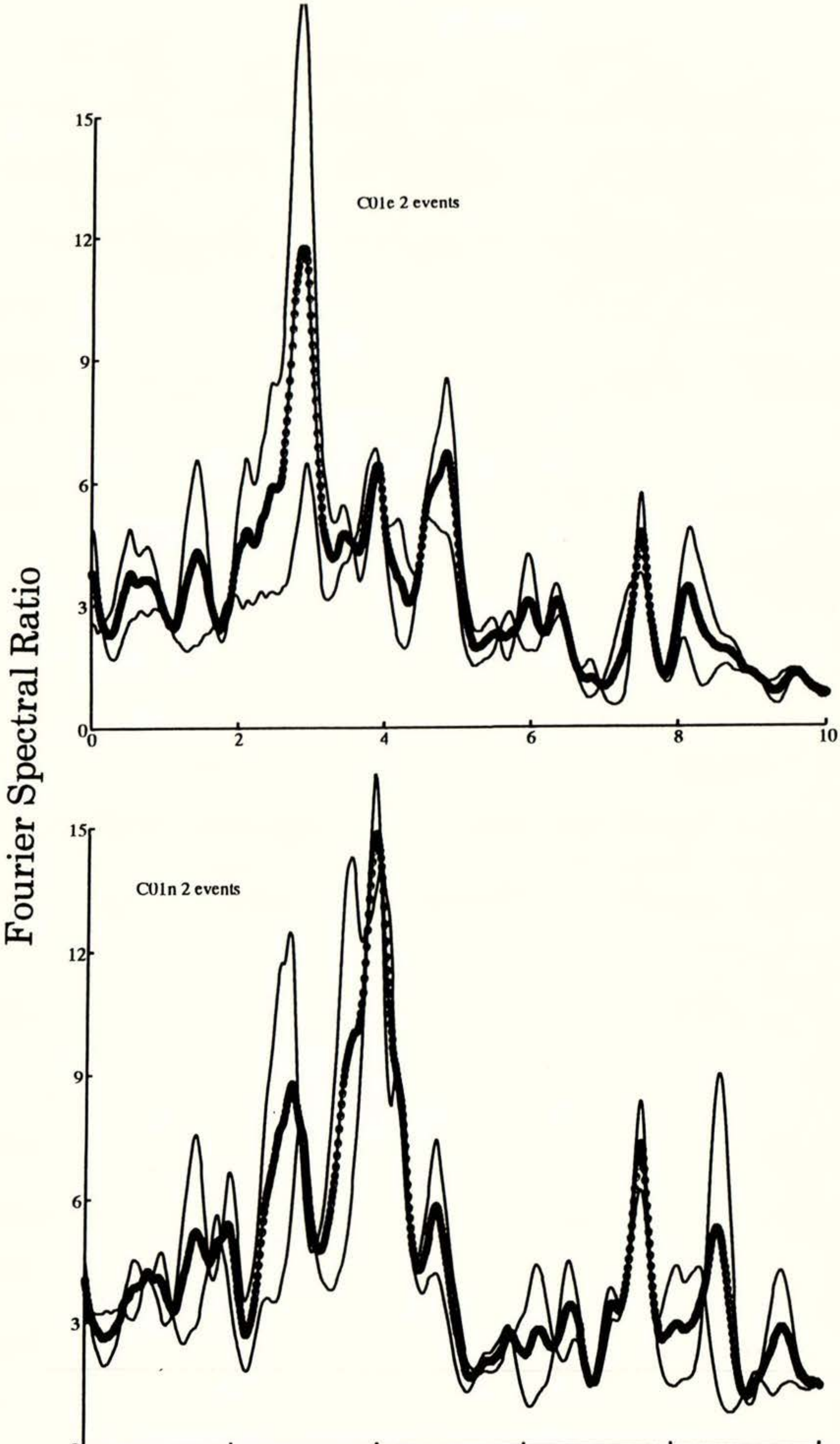

Figure 16. Comparison of the Fourier spectral ratios of the east-west (top) and north-south (bottom) components at site C01.

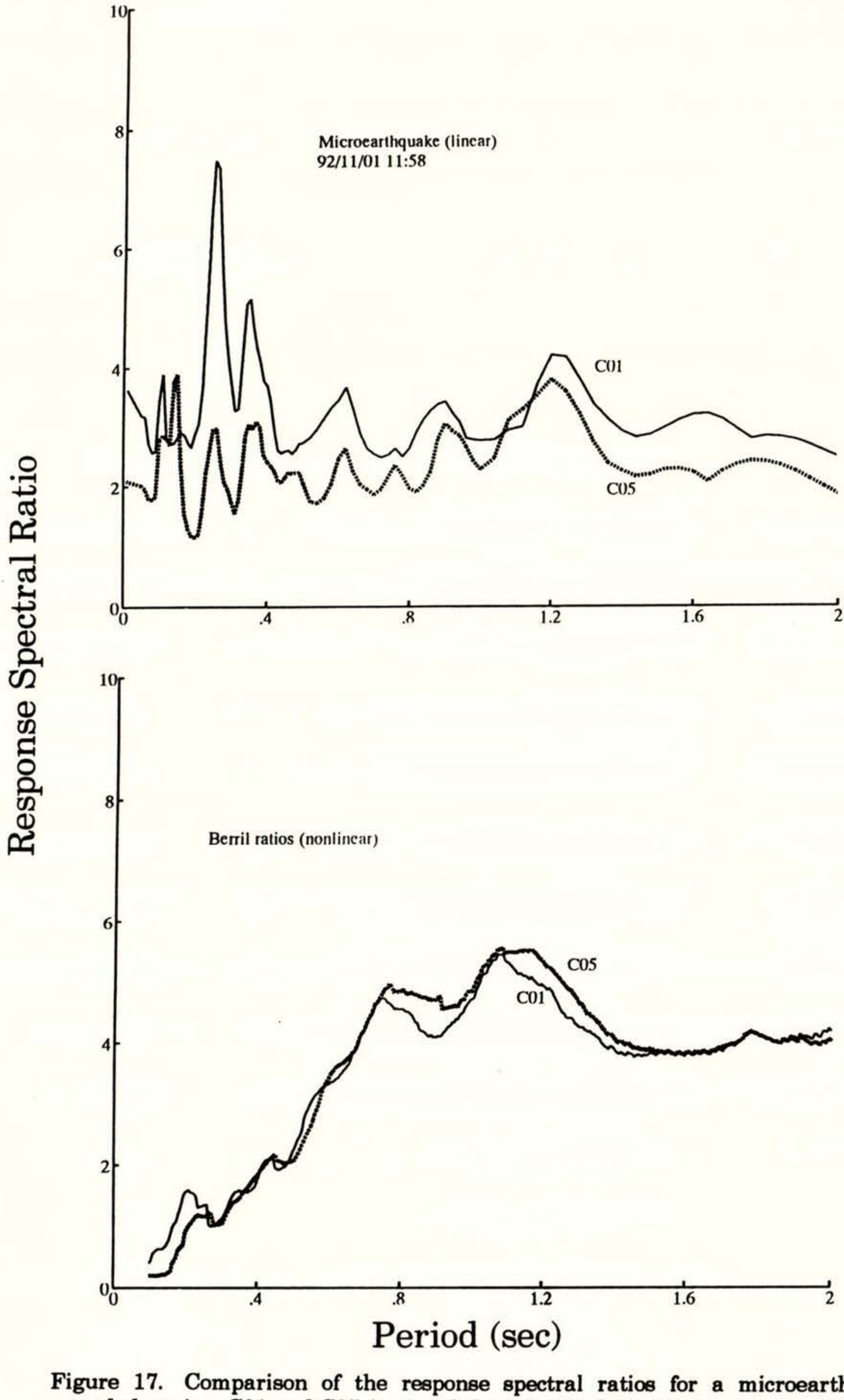

Figure 17. Comparison of the response spectral ratios for a microearthquake recorded at sites C01 and C05 (top) and the calculated non-linear response (Berril *et al.*, 1993) based on the soil profile (bottom).

estimates of the velocity or the damping could have a significant effect on the results. The actual ground response during a distant earthquake capable of causing moderate damage, is likely to lie somewhere between these two extremes.

A comparison of strong and weak ground motions in Wellington and Lower Hutt (Taber *et al.*, 1993) showed that the weak motion frequency responses and amplification levels were similar to the strong motion recordings. In that study the largest motions were only 0.1 g, so they may still have been in the linear range, and the soils were not as soft as at some of the Christchurch sites. However the 0.1 g motions were large enough to cause some damage.

The large amplifications recorded at site C02 are consistent with the modelling of Elder *et al.* (1991), though the peak recorded periods are shorter than those predicted. They predicted high amplifications in the 0.7 to 1.5 sec range whereas the peak for the weak motion was in the 0.3 to 0.5 sec range. The relative amplitudes of the other weak motion sites are similar to the spatial variations in their modelled 0.7 sec period spectral acceleration. Thus while the predicted spectral shape (the relative importance of short and long periods) of Elder *et al.* is more in accord with the modelling of Berril *et al.* than the recorded weak motions, the variation in amplitude between sites is similar to the weak motion results. Elder *et al*'s predicted increase in intensity of up to 2 units is also consistent with the weak motion results, though based on a comparison with the Wellington studies, there could be an increase of up to 3 intensity units at the softest site for a large distant earthquake.

5. Conclusions

The large variations in ground shaking in Christchurch predicted by modelling studies, have been verified by recording the response due to micro-earthquakes. The five recording sites in central Christchurch all experienced considerably greater shaking than a rock site in the Cashmere Hills. The greatest shaking was recorded at Christchurch Womens Hospital, where the response spectral ratio was 10-20 in the period range 0.3 to 0.6 sec. This is also one of the areas of Christchurch where the greatest shaking was predicted by Elder *et al.* (1991). A site at Latimer Square produced ratios of 4 to 10 times the rock site at short periods while three other sites showed 2-4 times the shaking of the rock site.

A high amplification of small ground motions means significant local damage could result from a moderate earthquake that would cause no damage at a firm site. If the comparison of strong and weak motions in other areas can be applied to Christchurch, moderate amplification factors may remain the same for strong ground motion, while the large amplifications at short period measured for microearthquakes at the softest site are likely to be decreased for the larger earthquakes. Thus the high amplifications at short period for these sites must be considered as an upper bound on the shaking to be expected during a large earthquake. Both the micro-earthquake motions and the non-linear modelling predicted significant amplifications at long periods.

Microearthquake recording of ground motion is best for determining regions of greater shaking hazard, rather than predicting absolute levels. The technique has the advantage that variations in ground motion can be measured directly at little expense and with little disruption of the soil. This is particularly useful in areas where drilling is not feasible. A reconnaissance survey can also determine areas where more detailed study is required.

There appears to be a correlation between the shear wave velocity of the shallow soil layers and a broadband spectral ratio of the weak and strong motions (Borcherdt, 1991). Establishing this correlation in Christchurch is more difficult because of the lack of velocity information. Field experiments where the shallow shear wave velocities are measured directly would help test the possible correlation, as well as being of great benefit to modelling studies.

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