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REGIONAL NATURAL DISASTER REDUCTION PLAN - SEISMIC HAZARD

Ground Shaking Hazard Map for the Lower Hutt and Porirua Areas: A Summary Report

(Part 8 of 1990 Study)

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GROUND SHAKING HAZARD MAP FOR LOWER HUTT AND PORIRUA AREAS: A SUMMARY REPORT

CONTRACT REPORT NO. 1991/42

Prepared for

THE WELLINGTON REGIONAL COUNCIL

by

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SUMMARY

This report, including maps and legend, identifies and quantifies the variation in ground shaking expected during damaging earthquakes impacting on the Lower Hutt and Porirua areas. Four ground shaking hazard zones have been identified in the Lower Hutt area, and three in Porirua. These hazard zones are defined based on geological, microseismic, and strong motion inputs, and are graded from 1 to 5. In general, areas within Zone 5 are expected to experience the greatest amount of shaking during an earthquake event, whereas areas within Zone 1 are expected to experience the least amount of shaking.

The accompanying Ground Shaking Hazard Maps (figures 1, 2 & 3) show the ground shaking hazard zones. The response of each zone is assessed for two earthquake scenarios. Scenario 1 is for a moderate to large, distant earthquake that results in regional Modified Mercalli intensity (MM) V-VI shaking on bedrock. Scenario 2 is for a large, local, yet rarer, Wellington fault earthquake. The map legend (Appendix A) provides geological descriptions of the ground shaking zones, and quantifies the expected shaking response for each zone during the two earthquake scenarios. The response characterisation for each zone comprises: expected Modified Mercalli intensity; peak horizontal ground acceleration; duration of strong shaking; amplification of ground motion with respect to bedrock, expressed as a Fourier spectral ratio, including the frequency range over which the most pronounced amplification occurs; amplification of the peak of the 5% damped acceleration response spectrum relative to the peak at a bedrock site; representative maximum 5% damped spectral acceleration and velocity, and the periods for which these occur.

1. INTRODUCTION

Local geological deposits are well known for their ability to influence profoundly the amount of shaking a site experiences during an earthquake. Following the great San Francisco earthquake of 1906, H.O. Wood noted that damage in the city "... depended chiefly on the geologic character of the ground. Where the surface was of solid rock, the shock produced little damage; whereas upon made ground [man-made fill] great violence was manifested...." (Wood 1908). In general, sites underlain by softer, more "flexible" material experience greater shaking than near-by sites underlain by firmer material. Recent earthquakes affecting Mexico City, Leninakan, and the San Francisco Bay area serve to illustrate this point, and underscore the important role that local geological conditions can have in influencing property damage and life loss during earthquakes (eg. Seed et al. 1988, Borcherdt et al. 1989, U.S. Geological Survey Staff 1990).

If areas of increased shaking hazard can be identified, then the potential exists to reduce the vulnerability, and risk, of the community to earthquake shaking. The Wellington microzoning study (Grant-Taylor et al. 1974) attempted to do just this. Areas of increased shaking hazard were identified, and quantified in terms of variations in Modified Mercalli intensity (MM) units, relative to bedrock, expected during an earthquake (the MM intensity scale is described in Appendix B). While intensity is widely used for the evaluation and prediction of earthquake damage (eg. Evernden and Thomson 1988), it is not the "final word" on ground shaking response. Intensity is not always well correlated with peak ground acceleration. Peak ground accelerations attributed to the same intensity can differ by an order of magnitude. Nor does intensity always provide information regarding the frequencies over which site-related shaking amplification (or attenuation) occurs. Peak accelerations and frequency content, as well as others parameters (including intensity), are required if the variation in shaking hazard within a region is to be adequately defined. Such quantification is vital if seismic hazard maps are to offer the widest applicability and greatest use to both planners and engineers.

This and contributing DSIR reports[1] form part of an overall study of seismic hazard for the Wellington Regional Council's Natural Disaster Reduction Plan. Fault rupture and Tsunami hazards in the Wellington region have previously been addressed by Berryman and Fellows (1989), and Gilmour and Stanton (1990) respectively. The focus of this years work has been the identification and quantification of the earthquake ground shaking hazard in the Lower Hutt and Porirua areas (figure 1).

1

Berryman, K., Fellows, D. 1989. Fault displacement hazards in the Wellington region. New Zealand Geological Survey Contract Report 89/17 (prepared for Wellington Regional Council).

Dellow, G.D., Read, S.A.L., Van Dissen, R.J., Perrin, N.D. 1991. Geological setting of the Porirua Basin, including distribution of materials and geotechnical properties. DSIR Geology & Geophysics Contract Report 1991/46 (prepared for Wellington Regional Council).

Gilmour, A., Stanton, B. 1990. Tsunami hazards in the Wellington region. DSIR Division of Water Sciences Contract Report (prepared for Wellington Regional Council).

Read, S.A.L., Begg, J.B., Van Dissen, R.J., Perrin, N.D., Dellow, G.D. 1991. Geological setting of the Lower Hutt Valley and Wainuiomata, including distribution of materials and geotechnical properties. DSIR Geology & Geophysics Contract Report 1991/45 (prepared for Wellington Regional Council).

Smith, E., Berryman, K. 1990. Return times of strong shaking in the Wellington region. DSIR Geology & Geophysics Contract Report 1990/14 (prepared for Wellington Regional Council).

Sritharan, S., McVerry, G.H. 1991. Quantifying microzone effects in the Hutt Valley using strong motion earthquake records. DSIR Physical Sciences Contract Report (prepared for Wellington Regional Council).

Sritharan, S., McVerry, G.H. 1990. Analysis of strong motion earthquake records for microzoning central Wellington. DSIR Physics and Engineering Laboratory Contract Report (prepared for Wellington Regional Council).

Stephenson, W.R., Barker, P.R. 1991. Report on cone penetrometer and seismic cone penetrometer probing in Wainuiomata, Eastern Harbour Bays, Stokes Valley, Kura Park (Titahi Bay), and Whitby. DSIR Land Resources Contract Report 91/21 (prepared for Wellington Regional Council).

Stephenson, W.R., Barker, P.R., Mew, G. 1990. Report on resonant alluvium conditions for part of Porirua Basin. DSIR Land and Soil Sciences Contract Report 90/5 (prepared for Wellington Regional Council).

Taber, J. 1991. Frequency dependent amplification of seismic waves at characteristic sites in the Lower Hutt Valley. Institute of Geophysics, Victoria University of Wellington (report prepared for Wellington Regional Council).

Taber, J.J., Smith E.G.C. 1991. Frequency dependent amplification of seismic waves at characteristic sites in the Porirua Basin. DSIR Geology & Geophysics Contract Report 91/32 (prepared for Wellington Regional Council).

Van Dissen, R.J., Berryman, K.R. 1990. Seismic hazard assessment of the Wellington-Hutt Valley segment of the Wellington Fault. DSIR Geology & Geophysics Contract Report 90/24 (prepared for Wellington Regional Council).

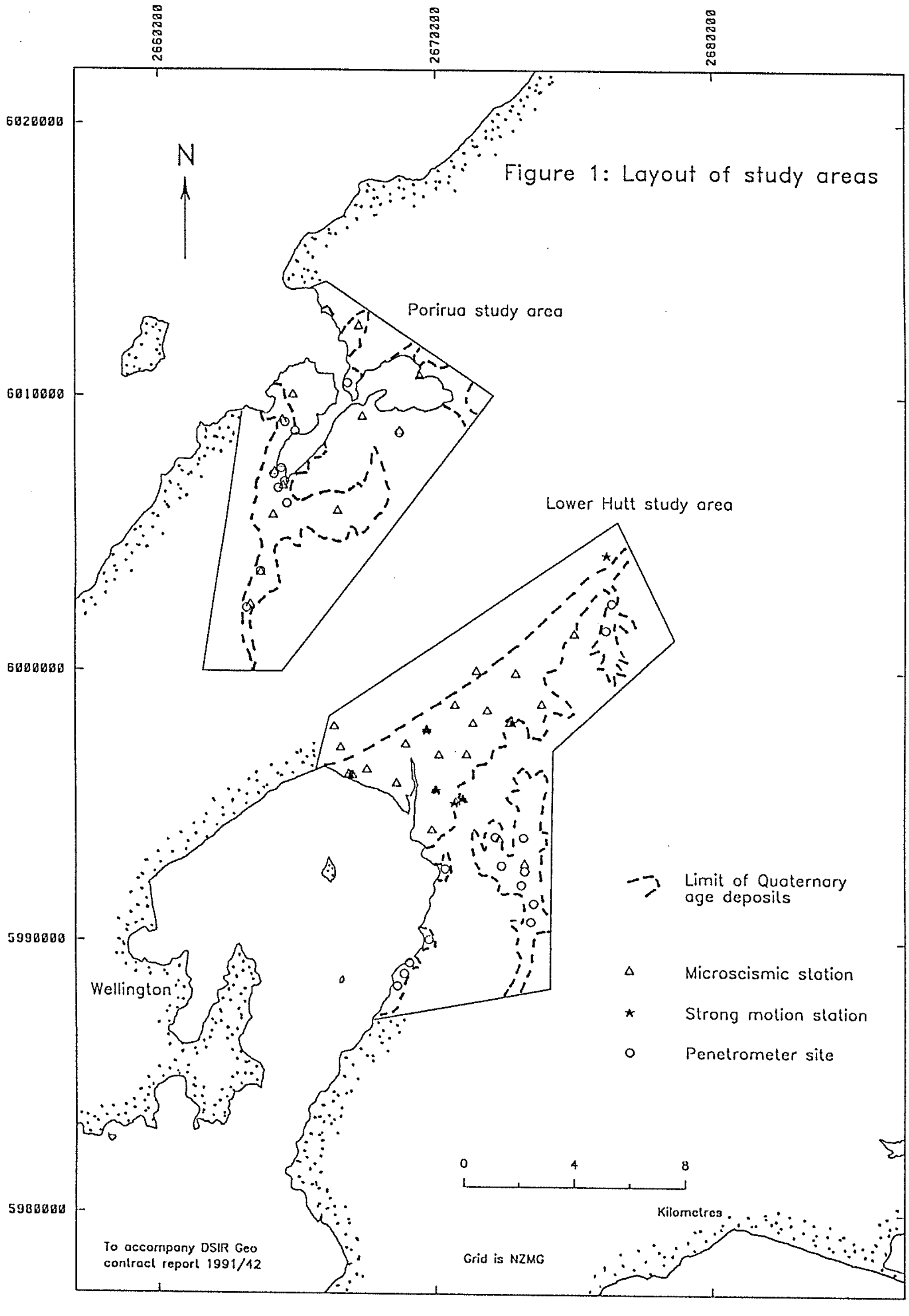

Figure 1. Layout of study areas.

The purpose of this report is to: 1) summarize and integrate the findings of the various DSIR studies that have been carried out to help define the ground shaking hazard in the Lower Hutt and Porirua areas; and 2) provide the documentation needed to justify the ground shaking zonation presented in the maps and legend. In doing so, this report provides a stand-alone technical document to accompany the Ground Shaking Hazard Maps for Lower Hutt and Porirua Areas (figures 2 & 3, and Legend).

2. METHODOLOGY

A number of techniques were employed to identify and define the shaking hazard zones in the Lower Hutt and Porirua areas (Table 1).

In Porirua, the distribution of geological materials, and their description is given in Dellow et al. (1991). Stephenson et al. (1990) provide results from cone- and seismic-cone penetrometer probings, and use numerical techniques to model the seismic response of the mapped soft "flexible" sediments[2] in the Porirua Basin. An array of 12 digital seismographs was also used to measure the ground response of these and other geological materials during microearthquakes (Taber and Smith 1991) (figure 1).

The distribution of the geological materials in the Lower Hutt area (Wainuiomata, Eastbourne, Lower Hutt Valley), and their description, is given in Read et al. (1991). Stephenson and Barker (1991) further quantify the properties of these materials at Wainuiomata and Eastbourne using 14 cone- and two seismic-cone penetrometer probings. They also model the seismic response of the "flexible" sediments at Wainuiomata. The ground response of the geological materials is assessed at 23 sites in the Lower Hutt area using records from 33 microearthquakes (Taber 1991), and at seven sites in the Lower Hutt Valley using strong motion earthquake records from up to 14 events (Sritharan and McVerry 1991) (figure 1).

A workshop, held in early March 1991, facilitated the compilation of the separate studies into a single integrated, multi-disciplinary ground shaking hazard report. At the workshop the findings of each study were critically compared to those of other studies, and were iteratively used to identify and define the variations in earthquake ground response in the Lower Hutt and Porirua areas. The agreement found amongst the studies is the strength from which the Ground Shaking Hazard Maps for the Lower Hutt and Porirua Areas are presented (figures 2 & 3). These maps, including legend, were drafted at the workshop, subsequently refined during the report preparation and review process, and are described fully in section 3.

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[2] Soft sediments refer collectively to normally consolidated fine-grained engineering soils (sands, silts and clays with SPT values less than 20 blows/300 mm). Where these materials have low shear wave velocities (in the order of 200 m/s or less), they are also referred to in this report as "flexible" sediments.

GROUND SHAKING HAZARD MAP
FOR THE PORIRUA AREA

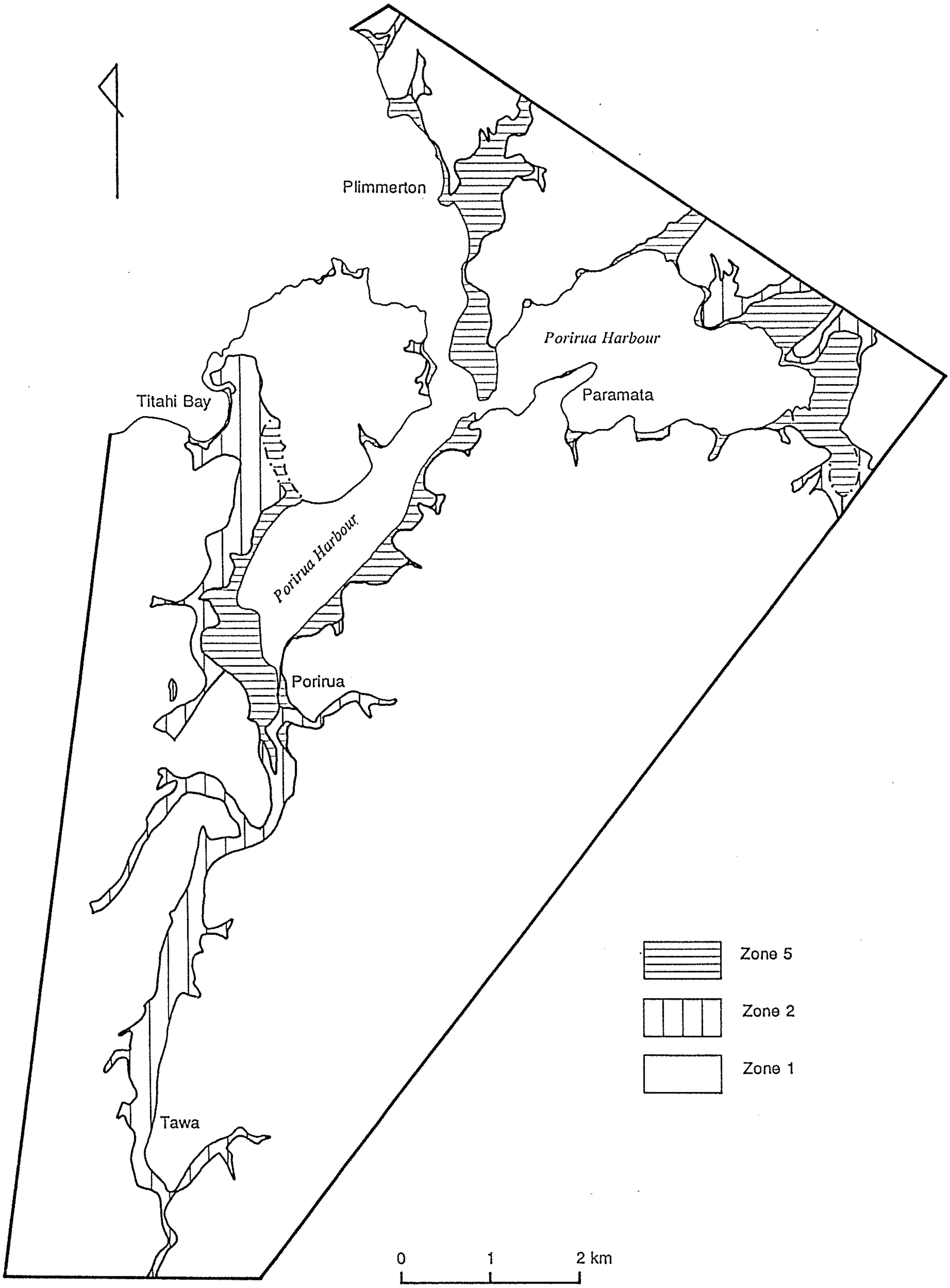

Figure 2. Ground shaking hazard map for the Porirua area.

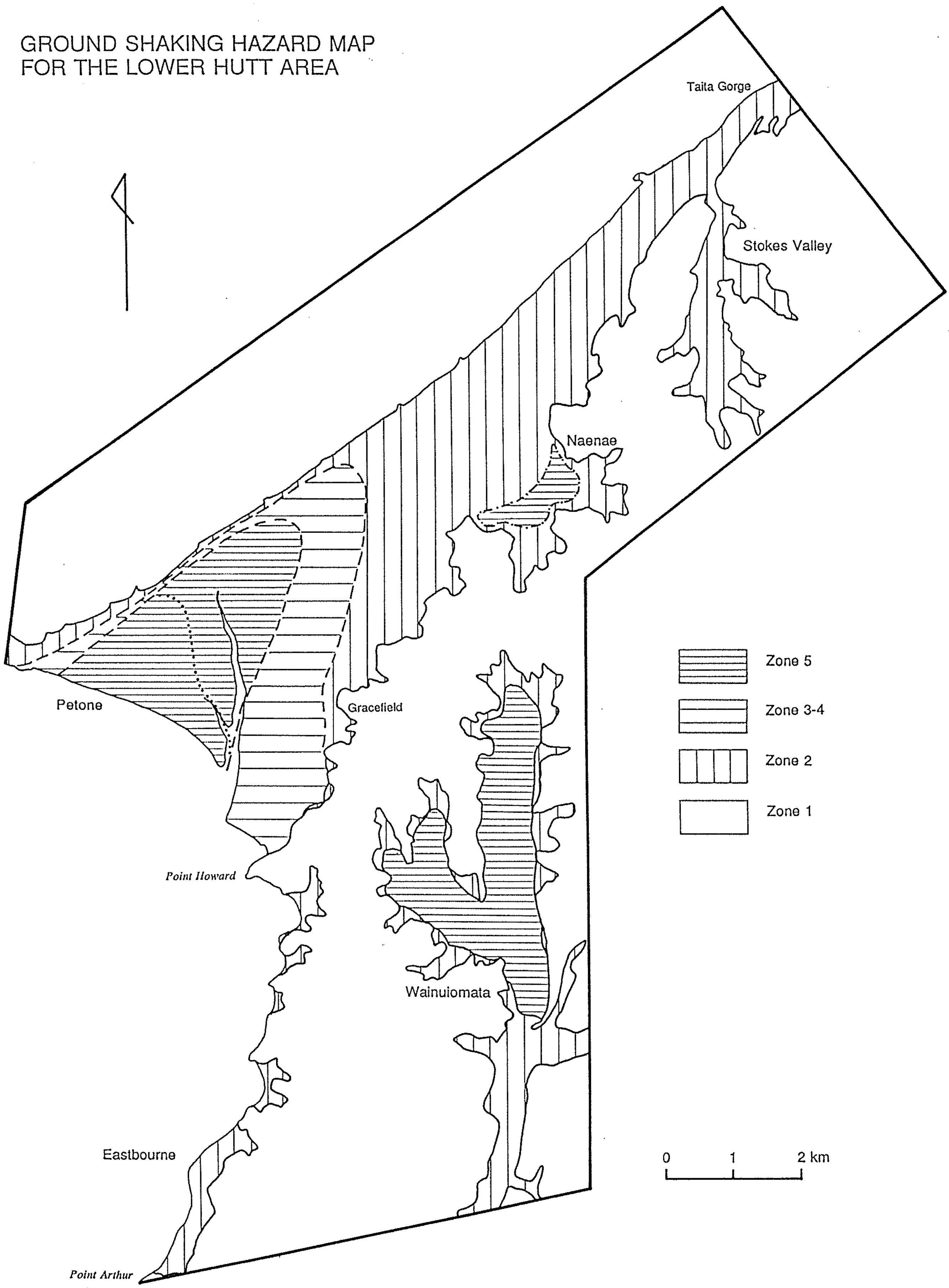

Figure 3. Ground shaking hazard map for the Lower Hutt area.

Table 1. Reports and methods used to define the Ground Shaking Hazard zones in the Lower Hutt and Porirua areas

	LOWER HUTT	PORIRUA
Geological mapping	Read et al. (1991)	Dellow et al. (1991) Stephenson et al. (1990)
Penetrometer probing	Stephenson and Barker (1991)	Stephenson et al. (1990)
Strong motion records	Sritharan and McVerry (1991)	
Microearthquake recordings	Taber (1991)	Taber and Smith (1991)
Numerical modelling	Stephenson and Barker (1991)	Stephenson et al. (1990)

2.1 Earthquake Scenarios

In a global tectonic context, the Wellington region is located within the obliquely-convergent boundary between the Pacific and Australian plates. As a consequence, the region is cut by several major active faults (figure 4), and is not infrequently shaken by moderate to large earthquakes (figure 5, Smith and Berryman 1990). At the beginning of this study, it was recognised that no single earthquake scenario adequately describes the whole range of ground shaking hazard facing the Lower Hutt and Porirua areas. A large local earthquake will certainly be devastating, yet significant localized damage is also expected from large, more frequent, distant earthquakes.

Variations in ground shaking response resulting from local geological conditions are thus assessed for two distinct earthquake scenarios. Scenario 1 is for a large, distant, shallow (<60 km) earthquake that produces MM V-VI shaking intensities in bedrock over the Wellington region. It is expected that this type of earthquake will produce the largest variations in ground response, that is, the greatest difference between the shaking of the best areas and the worst. This scenario implies little damage to structures founded on the best sites, yet significant damage to certain structures on the worst. An example of such an event would be a M_s 7 earthquake centred about 100 km from the study area at a depth of 15-60 km, perhaps similar to the 1942 south Wairarapa earthquakes[3] (Hayes 1943). The larger 1848 Marlborough earthquake (Eiby 1980, Dowrick and Smith 1990) would also have resulted in significant, and predictable, variations in ground response.

The return time of MM VI or greater shaking at bedrock sites of low topographic relief in the Wellington region is about 20 years (Smith and Berryman 1990). This return time is derived from the historical occurrence of both large earthquakes, and moderate sized local events. While 20 years is the return time for MM VI shaking at bedrock sites in the Wellington region, not all earthquakes that produce MM VI will result in the pronounced variations in ground response expected during a scenario 1 event. For example, the local M5 1968 earthquake documented in the Wellington microzoning study (Grant-Taylor et al. 1974) produced MM VI shaking on firm sites in Wellington, but did not cause significant damage to structures sited on softer material. Thus 20 years is a minimum estimate for the return time of a scenario 1 event. A reasonable maximum estimate is about 80 years; the return time of MM VII or greater shaking at bedrock sites in the Wellington region resulting from large earthquakes (Smith and Berryman 1990).

Scenario 2 is for a large earthquake centred on the Wellington-Hutt Valley segment of the Wellington fault which extends through Wellington and the Hutt Valley. Rupture of this 75 km long segment is expected to be associated with a c. M_s 7.5 earthquake at a depth less than 30 km, and up to 5 m of right-lateral and 1 m of

[3] It is a recommendation of this report (section 4) that the variations in ground response in the Lower Hutt and Porirua areas resulting from these earthquakes be investigated.

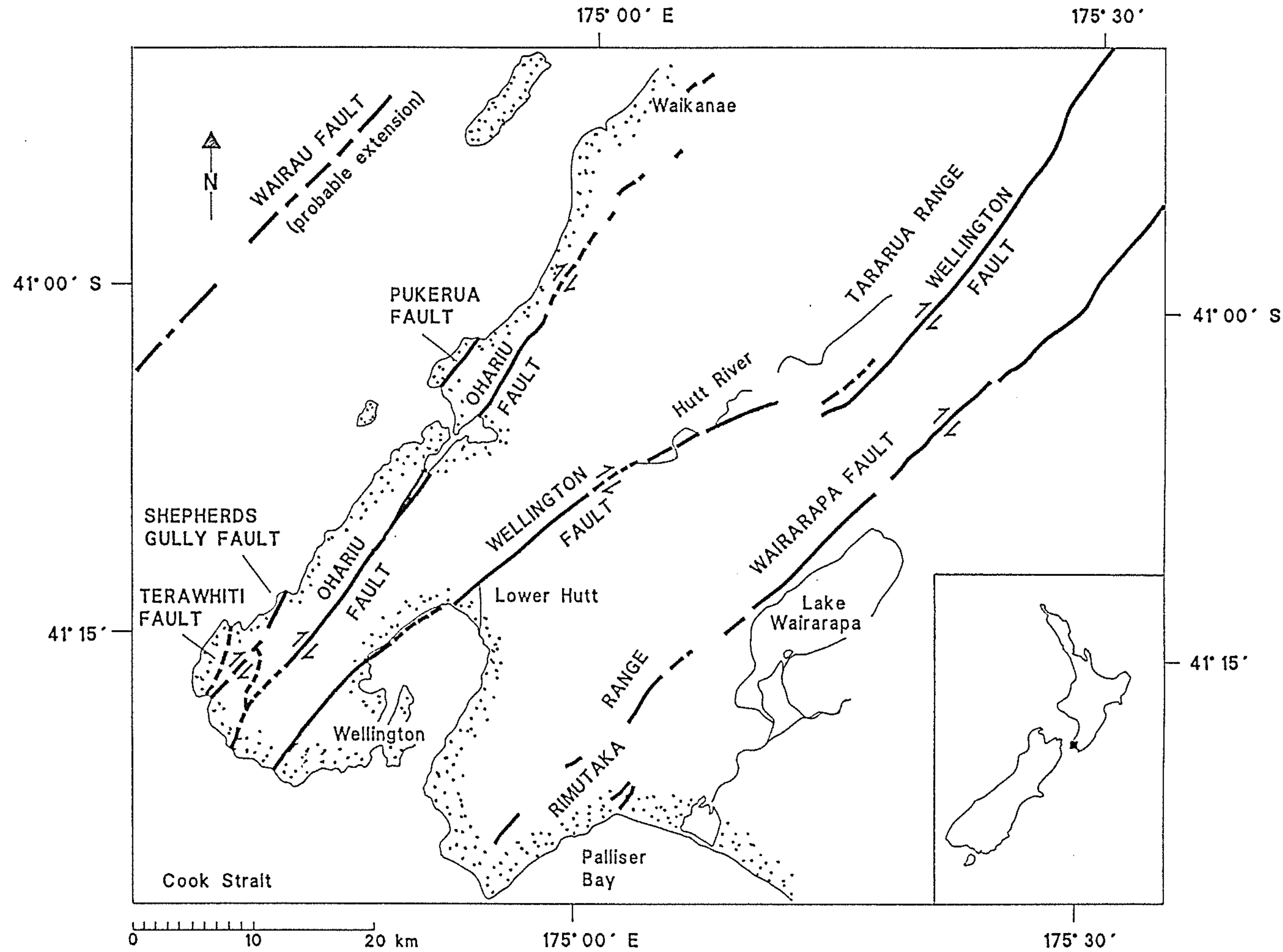

Figure 4. Active strike-slip faults in the Wellington region.

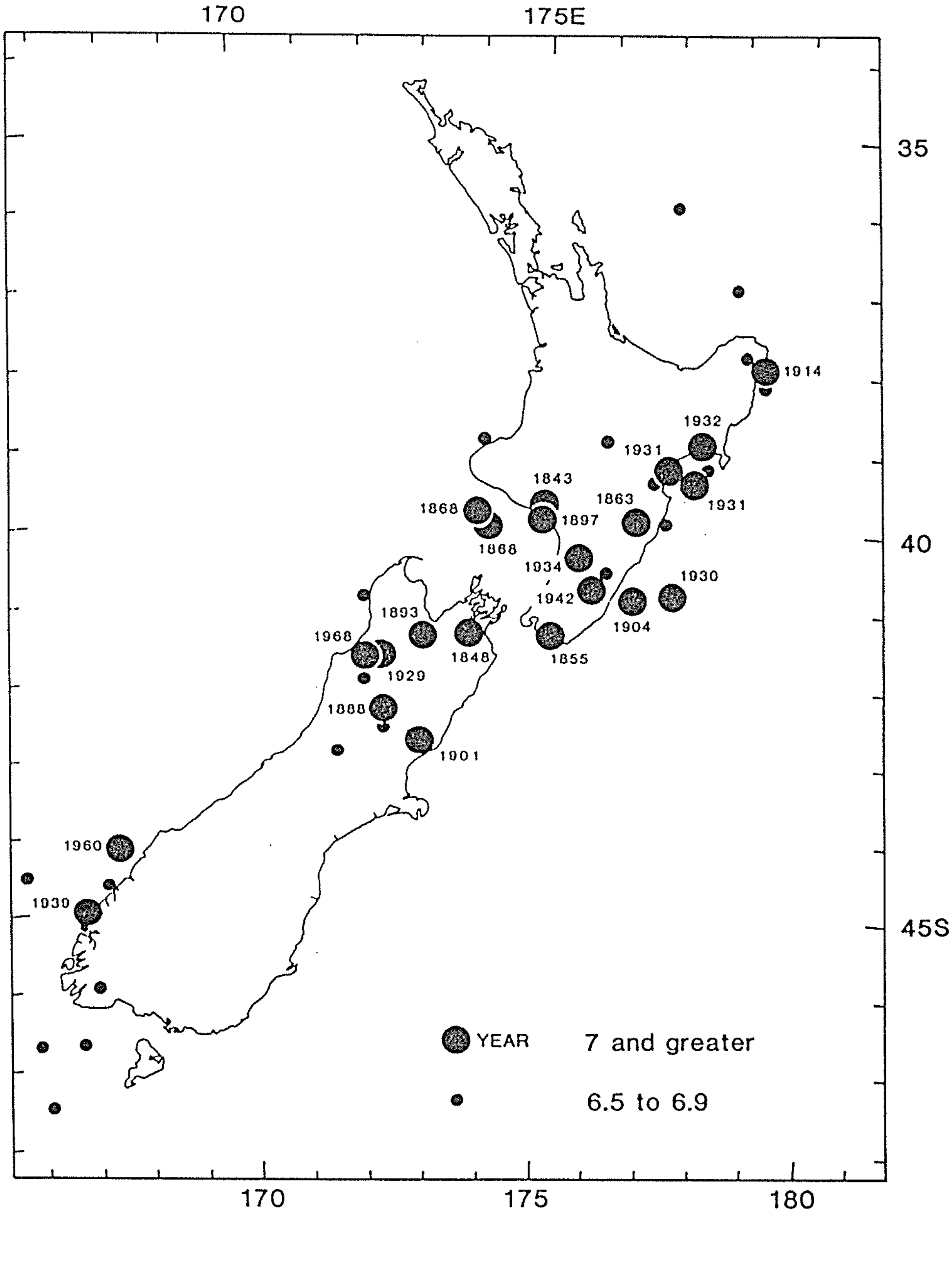

Figure 5. Epicentres of shallow earthquakes of magnitude 6.5 and greater since 1840 [from figure 2 of Smith and Berryman (1986)].

vertical displacement at the ground surface (Berryman 1990). The mean recurrence interval for such an event is about 600 years (Van Dissen and Berryman 1990), and the probability of this event occurring in the next 30 years is estimated to be in the order of 10%.

In comparison with scenario 1, it is more difficult to predict the ground shaking resulting from a scenario 2 earthquake. This is because there are so few near-source[4] ground motion data from large earthquakes, and because factors such as proximity to local asperities along the rupture plane, and random cancellation and reinforcement of seismic waves can locally overwhelm the effects caused by near-surface geological deposits. Also, a portion of the ground shaking during such an event will probably be at frequencies and strengths that some local geological deposits, such as thick soft sediment, will not amplify.

3. RESULTS

The results from the techniques used to define the shaking response of the geological materials in the Porirua and Lower Hutt Valley areas, and how they relate to the ground shaking zonation of these areas are summarized below. More detail regarding specific techniques and findings is contained in the cited reports.

3.1 Identification of Ground Shaking Hazard Zones

3.1.1 Porirua ground shaking zonation

Stephenson et al. (1990) documented a significant "hazardous" thickness of soft "flexible" sediment in the Porirua Basin that is capable of strongly amplifying certain earthquake motions. They mapped the boundary of these sediments [also shown on the geological map in Dellow et al. (1991)], measured their shear wave velocity (in the order of 110 m/s), and modeled the seismic response of the basin. Three seismograph sites of Taber and Smith (1991) showed greatly increased shaking, two of which were "flexible" sediment sites, while the third was just outside of the mapped boundary. The recorded ground shaking at these sites, expressed as an averaged Fourier spectral ratio (Fsr), is 10-20 times stronger than that of a reference bedrock site, and occurs over a narrow frequency band, 1-3 Hz. The frequency and approximate amplification were as modeled by Stephenson et al. (1990). Spectral ratios of Fsr=10-20 have also been measured for soft "flexible" sediment in Wainuiomata and the Lower Hutt Valley (see below, Taber 1991).

[4] Near-source refers to areas within several tens of kilometres from the epicentre of a M7.5 earthquake (e.g. Krinitzsky and Chang 1977).

Taber and Smith (1991) also measured the ground response on firm sites, including bedrock sites and sites where bedrock is overlain by >10 m of deeply weathered gravel and loess (Dellow et al. 1991). With the exception of one site, the spectral ratios for firm sites varied from no amplification to factors of about 3 relative to the hard rock reference site, consistent with results from the Lower Hutt area (see below; Sritharan and McVerry 1991, Taber 1991). The exception was a firm site on a small ridge at Whitby which showed a spectral ratio of nearly 10 at 5.5 Hz. The amplification at this site could in part be due to topographic effects since spectral ratios of up to 8 have been recorded at hard rock ridge-crest sites (Tucker et al. 1984). Cone penetrometer results discount the possibility of a significant thickness of soft sediment near this site (Stephenson and Barker 1991).

Dellow et al. (1991) shows the distribution of near-surface Quaternary age deposits of gravel and "compact" sand deposits (eolian, alluvial and marine) in the Porirua area, including extremely weak sandstones at Titahi Bay. Stephenson et al. (1990) presents cone penetrometer results from sites underlain by most of the above deposits. The one seismograph sited on these deposits shows an amplification of Fsr=5 (Taber and Smith 1991), consistent with the response measure on similar materials in the Lower Hutt area (see below, Taber 1991).

The Porirua area is mapped into three Ground Shaking Hazard Zones (figure 2), based on the distribution of geological materials and the measured and modeled response of these materials to seismic waves. Zone 1 is characterized by areas underlain by firm geological material (eg. bedrock), and little if any amplification of seismic waves. However, localised yet potentially significant topographic amplifications are possible. Zone 2 is characterized by areas underlain by 10+ m of gravel and "compact" sand, and only slight amplification of seismic waves. Areas underlain by a significant thickness (about 10-30 m) of soft "flexible" sediment show greatly amplified shaking, and are mapped as Zone 5.

3.1.2 Lower Hutt ground shaking zonation

3.1.2.1 Wainuiomata

The highest spectral amplifications recorded in the Lower Hutt area are from two sites in Wainuiomata (Taber 1991). Both sites have spectral ratios of Fsr=16-18 relative to a hard rock reference site, and are underlain by up to 35 m of soft "flexible" sediment with shear wave velocities in the order of 90-150 m/s (Read et al. 1991, Stephenson and Barker 1991). The site underlain by the greatest thickness of sediment (about 60 m) exhibits a broad band frequency response over 0.5-3 Hz, with a peak at 1 Hz. This peak is also modeled by Stephenson and Barker (1991). The site underlain by a lesser thickness of sediment (less than 20 m) exhibits a narrow frequency response at 2 Hz. The area underlain by soft "flexible" sediments in Wainuiomata corresponds closely to Zone 5 on the Ground Shaking Hazard Map (figure 3).

As with Porirua, areas in Wainuiomata underlain by bedrock, or less than 10 m of weathered gravel and loess are characterized as firm sites. These sites, as for similar sites with measured ground motions in Porirua and the Lower Hutt Valley, are expected to experience little if any amplification of ground shaking, and are mapped as Zone 1 on the Ground Shaking Hazard Map.

Areas of alluvial gravels and fan alluvium are shown by Read et al. (1991). As discussed in sections 3.1.1 and 3.1.2.3, sites underlain by a significant thickness of near-surface dense gravel (generally greater than 10 m) are expected to experience only slight amplifications of ground shaking relative to bedrock, and are mapped as Zone 2 on the Ground Shaking Hazard Map. In Wainuiomata, fan gravels interfinger with "flexible" sediment along the valley sides. The "flexible" sediments will dominate the ground response where they comprise a major portion of the material at depth.

3.1.2.2 Eastbourne

The distribution of geological materials in Eastbourne (Point Howard to Point Arthur) is not well constrained (Read et al. 1991). In order to locate possible deposits of soft "flexible" sediment, five cone penetrometer tests were carried out at likely locations (Stephenson and Barker 1991). No significant soft or weak layers were identified below about three metres depth. All probes reached refusal in dense sand or gravel, except at one site where probing was stopped in very stiff clayey silty sand. From these results, Stephenson and Barker (1991) conclude that the areas investigated in Eastbourne are not likely to greatly amplify earthquake shaking. Based on this conclusion, the non-bedrock areas of Eastbourne are mapped as Zone 2, and are expected to only slightly amplify ground shaking. The bedrock areas (firm sites) of Eastbourne are mapped as Zone 1. It is important to note that there may be as yet unidentified localized deposits of soft material in Eastbourne that could amplify earthquake motions, though probably not to the extent as in Zone 5 areas in Porirua or Wainuiomata (see section 4).

3.1.2.3 Lower Hutt Valley

In the Lower Hutt Valley there is both a general increase in total sediment thickness (Quaternary age deposits) and thickness of near-surface soft sediment down valley and across valley (Taita gorge to Petone, and from Gracefield to Petone, Read et al. 1991). The hills bounding these sediments are composed of greywacke bedrock.

Five stations studied by Taber (1991) were sited on bedrock, or deeply weathered gravel and loess underlain by bedrock. These stations show little if any amplification of microearthquake ground motions relative to a hard rock reference site, the spectral ratios are all less than Fsr=4. Three strong motion instruments are sited on bedrock or deeply weathered bedrock. Compared to the response spectra of the reference site, one site shows slightly amplified ground motion, the other slightly attenuated motion (Sritharan and McVerry 1991). In the Lower Hutt Valley areas underlain by bedrock, deeply weathered bedrock, or less than 10 m of deeply weathered gravel and loess are characterized as firm sites. These sites exhibit little if any amplification of earthquake motions, and are mapped as Zone 1 on the Ground Shaking Hazard Map (figure 2).

Much of the sediment in the Hutt Valley is composed of fine to coarse alluvial gravel. The thickness of this sediment increases from about 10-20 m near the Taita gorge to over 300 m at Petone. A significant thickness of near-surface "flexible" sediment is found southwest from about Melling. Its thickness also increases towards Petone (Read et al. 1991). Of the 16 seismographs sited on the unconsolidated sediments in the Lower Hutt Valley, six had spectral ratios of less than about Fsr=5 (Taber 1991). These sites are all underlain by less than 200 m of gravel, and some sites are underlain by as little as about 10 m of gravel. Also, none of these sites are underlain by more than about 5 m of near-surface "flexible" sediment. Areas with the above characteristics are mapped in the Lower Hutt Valley as Zone 2 on the Ground Shaking Hazard Map. The near five-fold amplification of the Zone 2 site in Porirua (Taber and Smith 1991) is consistent with the response of the Zone 2 sites in Lower Hutt. The strong motion instrument sited within Zone 2 shows an intermediate response compared to bedrock sites, and sites located in the deepest part of the valley where the strongest motions are recorded (Sritharan and McVerry 1991).

The highest amplifications recorded by Taber (1991) in the Lower Hutt Valley are at Petone where total sediment thickness, and thickness of soft near-surface sediment are at their maximum (Read et al. 1991). Here, two sites have averaged spectral ratios of Fsr=12-15 relative to a hard rock reference site. For sites near the Hutt River, and further northeast and east from Petone, averaged spectral ratios are less than 8. As discussed in sections 3.1.1 and 3.1.2.1, sites in Porirua and Wainuiomata that exhibit spectral ratios of greater than Fsr=10 are mapped as Zone 5. This implies that the Zone 5 boundary in the Lower Hutt Valley should be located southwest of the Hutt River, the dotted line on Ground Shaking Hazard Map (figure 2). However, the few strong motion records available suggest that the maximum amplification measured at the Petone site is similar to that measured at the central Lower Hutt site (Sritharan and McVerry 1991), though the two sites have a different frequency response (Sritharan and McVerry 1991, Taber 1991). This suggests that the northeastern extent of Zone 5 should include central Lower Hutt. Where differing interpretations arise, it is considered more appropriate to adopt the conservative interpretation. Therefore, central Lower Hutt is included in Zone 5. In doing so, the uncertainty regarding the northeastern extent on the Zone 5 boundary is acknowledged. Additional work is needed to confidently locate this boundary, whether this be northeast of central Lower Hutt or southwest of the Hutt River (see section 4).

A spectral ratio of near 15 is recorded for a site in Naenae (Taber 1991). This site corresponds to an area of locally thick, 10-20 m, soft sediment (Read et al. 1991), and is mapped as Zone 5.

The general increase in sediment thickness in the Lower Hutt Valley is reflected in the measured ground motions as a gradual down-valley increase in shaking (Sritharan and McVerry 1991, Taber 1991). There is no distinct boundary between sites that show only slight amplification of ground shaking (Zone 2), and sites that exhibit high amplification (Zone 5). This transitional area between Zones 2 and 5 is mapped as Zone 3-4. The 3-4 distinction is chosen to emphasize the transitional character of this zone, and to highlight the greater shaking measured, and expected, in Zone 5 relative to that in Zones 1 and 2.

3.2 Geological Description of Ground Shaking Hazard Zones

Descriptions of the geological materials that typify each Hazard Zone are summarized below.

Zone 1: Greywacke bedrock, including areas overlain by less than 10 m of deeply weathered gravel and loess, or well engineered fill.

Zone 2: Alluvial gravel and fan alluvium; fine to coarse gravel, up to 200 m thick, with some beds and lenses of finer grained sediment (sand, silt, clay, and peat) usually less than 5 m thick. The coarser sediments typically have moderate to high SPT values, N=20->60. At Titahi Bay, 10-20 m thickness of extremely weak silty sandstone with lenses of gravel, or about a 5-10 m thickness of windblown sand.

Zone 3-4: Up to 15 m of fine grained sediment (fine sand, silt, clay, and peat) within the top 20 m or so of alluvial gravel, underlain by up to 250 m of alluvial gravels and finer grained sediment. Near-surface fine grained sediments typically have low SPT values, N=<20, whereas the coarser consolidated sediments generally have moderate to high SPT values, N=20->60.

Zone 5: Soft sediment (fine sand, silt, clay, and peat), up to 10-30 m thick, at or very near the surface, underlain by bedrock or a variable thickness of gravel and other finer grained sediment. Shear wave velocities for these "flexible" sediments at Lower Hutt, Wainuiomata, and Porirua are in the order of 175 m/s, 90-150 m/s, and 110 m/s respectively (Stephenson 1989, Stephenson and Barker 1991, Stephenson et al. 1990).

3.3 Quantification of Ground Shaking Hazard Zones

The shaking response of the Ground Shaking Hazard Zones (Zones 1 through 5) is assessed for the two earthquake scenarios described in section 2. The response of each Zone is expressed as a suite of ground motion parameters, comprising: expected Modified Mercalli intensity (MM); peak horizontal ground acceleration (pga); duration of strong shaking; amplification of ground motion with respect to bedrock, expressed as a Fourier spectral ratio (Fsr), including the frequency range over which the greatest amplification occurs; amplification of the peak of the 5% damped acceleration response spectra relative to the peak at a reference bedrock site;

representative maximum 5% damped spectral acceleration (SA $max_{(rep)}$) and velocity (SV $max_{(rep)}$), and the periods over which these occur. Some of these parameters have been measured directly, others have been estimated using comparisons found in the published scientific and engineering literature.

The recent Loma Prieta earthquake is significant with respect to this report because of the recorded variations in ground motion related to local geological conditions, and because its magnitude is similar to that of the scenario 1 earthquake. Thus, the values calculated for the above ground motion parameters are often compared with those measured for the Loma Prieta event.

3.3.1 Modified Mercalli intensity (MM)

Scenario 1: The scenario 1 earthquake (a large, distant, shallow earthquake, resulting in MM V-VI shaking on bedrock) will be of sufficient duration and contain sufficient long period energy to allow strong long-period response to develop at deeper sediment sites. The shallow focal depth will allow strong surface wave effects. The result is a marked difference between the shaking of the "worst" sediment site and the "best" firm site. It is not uncommon during an earthquake to have a spread of three to four units of MM intensity separating the response of the "best" site from the response of a near-by "worst" site (eg. Evernden and Thomson 1988, Lowry et al. 1989, Plafker and Galloway 1989). A difference of three to four MM units is thus expected between the response of Zone 1 and Zone 5 (see Appendix B for a description of the MM intensity scale). The response of Zones 2 and 3-4 is expected to be slightly stronger than Zone 1, comparable to estimates made in the Wellington microzoning study (Grant-Taylor et al. 1974).

Thus, in terms of MM intensity the response of Zone 1 is expected to be MM V with some VI, Zone 2 is MM VI, Zone 3-4 is MM VI-VII, and Zone 5 is MM VIII-IX (Table 2, and Legend).

Scenario 2: The effects of a scenario 2 event, a large local Wellington fault earthquake, will be a marked increase in the shaking throughout the region, relative to scenario 1; a decrease in the average difference in shaking between Zone 1 and Zone 5; and an increase in the variability of shaking within each zone.

Another important factor influencing ground shaking for this event is distance from the earthquake source. In general, shaking decreases with increased distance away from the source. The entire Hutt Valley is within 4 km of the Wellington fault; Wainuiomata and Porirua are about 6-11 km from the fault. Thus sites in Wainuiomata and Porirua are expected to shake less than similar sites in the Lower Hutt Valley. Epicentral intensities for the 1989 Loma Prieta earthquake were MM VIII (Plafker and Galloway 1989); however, the Loma Prieta earthquake was smaller than the scenario 2 event (M 7.1 compared to 7.5). Epicentral intensities for similarly sized New Zealand earthquakes are MM IX, MM IX-X, and MM VIII-IX for the 1848 Marlborough, 1931 Hawkes Bay, and 1968 Inangahua earthquakes respectively (Eiby 1980, Smith 1981).

Table 2. Ground motion parameters, and values, for the Ground Shaking Hazard Zones in the Porirua and Lower Hutt areas

SCENARIO 1

<table>
<tr><th colspan="2">ZONES</th><th>MM Intensity</th><th>Peak ground acceleration (g)</th><th>Duration</th><th colspan="2">Amplification of ground motion (Fsr) and frequency</th><th>Amplification of peak of acceleration response spectra (5% damped)</th><th>SA max* (g) and period</th><th>SV max* (m/s) and period</th></tr>
<tr><td colspan="2">1</td><td>V-VI</td><td>0.02-0.06</td><td><5 sec</td><td colspan="2">1-3 × @ >1 H_z</td><td></td><td>0.1 @ 0.2-0.3 sec</td><td>0.06 @ 0.3-0.4 sec</td></tr>
<tr><td colspan="2">2</td><td>VI</td><td>0.02-0.1</td><td>2-3 ×</td><td colspan="2">2-5 × @ 0.5-5 H_z</td><td><5×</td><td>0.4 @ 0.3-0.4 sec</td><td>0.3 @ 0.4 sec</td></tr>
<tr><td colspan="2">3-4</td><td>VI-VII</td><td>0.02-0.1</td><td>2.3 ×</td><td colspan="2">5-10 × @ 0.5-3 H_z</td><td>2-5×</td><td>0.5 @ 0.4 sec</td><td>0.4 @ 1.0 sec
0.3 @ 0.4 sec</td></tr>
<tr><td rowspan="5">5</td><td>Porirua</td><td rowspan="5">VIII-IX</td><td rowspan="4"><0.3 generally between 0.1-0.2</td><td rowspan="5">>3 ×</td><td rowspan="5">10-20×</td><td>@ 2 H_z</td><td rowspan="3">>4 ×</td><td>not calculated</td><td>not calculated</td></tr>
<tr><td>Naenae</td><td>@ 1 H_z</td><td>0.4 @ 0.8 sec</td><td>0.6 @ 0.9 sec</td></tr>
<tr><td>Wainuiomata (shallow)</td><td>@ 2 H_z</td><td>1.0 @ 0.5 sec &
0.7 @ 0.3 sec</td><td>0.7 @ 0.5 sec</td></tr>
<tr><td>Wainuiomata (deep)</td><td>0.5-3 H_z with a peak at 1 H_z</td><td>>5 ×</td><td>0.9 @ 0.3 sec &
0.7 @ 0.4 sec</td><td>0.7 @ 1.1 sec</td></tr>
<tr><td>Lower Hutt</td><td><0.2 generally around 0.05-0.1</td><td><3 H_z down to at least 0.5 H_z</td><td>2-5 ×</td><td>0.3 with several peaks between 0.5 - 1.5 sec</td><td>0.4-0.5 with several peaks between 0.5-1.8 sec</td></tr>
</table>

* These values were estimated for specific sites within a Hazard Zone, and may not be general enough to characterise the response of the Zone as a whole

SCENARIO 2

<table>
<tr><th colspan="2">ZONE</th><th>MM Intensity</th><th>Peak ground acceleration (g)</th><th>Duration</th><th>Amplification of peak of acceleration response spectra (5% damped)</th></tr>
<tr><td rowspan="2">1</td><td>near fault</td><td>IX</td><td>0.5-0.8</td><td rowspan="2">15-40 sec</td><td rowspan="2"></td></tr>
<tr><td>Porirua & Wainuiomata</td><td>VIII</td><td>0.3-0.6</td></tr>
<tr><td rowspan="2">2</td><td>near fault</td><td>IX-X</td><td>0.5-0.8</td><td rowspan="2">1-2 ×</td><td rowspan="2"><5 ×</td></tr>
<tr><td>Porirua & Wainuiomata</td><td>VIII-IX</td><td>0.3-0.6</td></tr>
<tr><td>3-4</td><td></td><td>IX-X</td><td>0.5-0.8</td><td>1-2 ×</td><td>2-5 ×</td></tr>
<tr><td rowspan="2">5</td><td>near fault</td><td rowspan="2">X-XI</td><td>0.6-0.8</td><td rowspan="2">>2 ×</td><td rowspan="2">>5 ×</td></tr>
<tr><td>Porirua & Wainuiomata</td><td>0.5-0.8</td></tr>
</table>

Using the above relationships and constraints, MM IX is expected near the fault in Zone 1 (Table 2). Further from the fault, MM VIII is anticipated in Wainuiomata and Porirua for Zone 1. MM IX-X is expected near the fault for Zone 2, MM VIII-XI further away in Wainuiomata and Porirua. The expected Zone 3-4 response, found only near the fault, is MM IX-X. Violent shaking, MM X-XI, is expected in Zone 5 both near the fault, and in Wainuiomata and Porirua.

Some of the possible ground damage effects that are likely in the various Hazard Zones for the two earthquake scenarios are presented in Table 3. These are based largely on the expected MM intensities, and knowledge of past damaging earthquakes in the Wellington region and elsewhere. With the cost of repairs to certain lifelines, such as cast iron pipeline systems, going up by a factor of ten for each MM unit increase (O'Rourke et al. 1991), these effects have important implications with respect to earthquake damage evaluation and prediction, and warrant further investigation.

3.3.2 Peak horizontal ground acceleration

For both scenarios, peak horizontal ground acceleration is estimated based on comparisons with a number of appropriate attenuation relations (eg. Campbell 1981; Joyner and Boore 1981; Idriss 1985, 1990; Fukushima and Tanaka 1990). In general, the peak ground accelerations presented below (Table 2, and Legend) are within one standard deviation of the values predicted using any of the appropriate attenuation relations [see Sritharan and McVerry (1991) for more detail]. Values for scenario 1 are also compared to those recorded during the Loma Prieta earthquake (Plafker and Galloway 1989, Borcherdt and Glassmoyer 1990).

Scenario 1: Peak ground acceleration for Zone 1 is expected to be in the order of 0.02-0.06 g. This compares to the 0.06 g recorded during the Loma Prieta earthquake at a hard rock site 95 km from the epicentre (Yerba Buena Island). Accelerations of 0.02-0.1 g are expected in Zones 2 and 3-4. For Zone 5, in Porirua, Wainuiomata, and Naenae, average accelerations of 0.1-0.2 g are expected, though these could be as high as 0.3 g, based on the 0.29 g acceleration recorded 97 km from the Loma Prieta epicentre on a "soil site" at Emeryville. Strong long period response is anticipated for the deepest sediment sites in the Lower Hutt Valley, Zone 5 (Sritharan and McVerry 1991). However, strong long-period response is not well characterized by ground acceleration (eg. Borcherdt 1985). Thus the Lower Hutt Valley Zone 5 accelerations are lower than the accelerations expected for the "thinner" sediment Zone 5 areas in Porirua and Wainuiomata. Accelerations of less than 0.2 g, probably in the order of about 0.05 g, are expected for Zone 5 in the southern Lower Hutt Valley.

Scenario 2: The average peak ground accelerations expected for scenario 2, based on the above attenuation relations and geological (site) considerations are as follows: Zone 1, 0.5-0.8 g in Lower Hutt Valley (near fault), 0.3-0.6 g in Porirua and Wainuiomata; Zone 2, 0.5-0.8 g in Lower Hutt Valley, 0.3-0.6 g in Porirua and

Table 3. Ground damage effects likely in the various Hazard Zones for the two earthquake scenarios.

SCENARIO 1 EARTHQUAKE		
Hazard Zones	MM intensity	Ground conditions and likely effects
1	V - VI	**"Greywacke"/argillite bedrock:** Little ground damage. Small (<100 m^3) local failures on steep slopes and unsupported cut batters. Small local failures on cuts in weathered gravels.
2	VI	**Alluvial deposits:** Little or no significant damage likely. Small local failures on river banks possible.
3-4	VI - VII	**Thicker alluvial deposits:** Little widespread damage expected. Small localised failures of banks adjacent to rivers, streams, or cuts. Some local cracking and sand ejection possible at MM VII.
5	VIII - IX	**Soft sediments:** Widespread minor slumping of steep banks (>2 m high). Localised lateral spreading of ground adjacent to river and stream banks with sand ejection (liquefaction effects). Differential settlement and collapse possible in some areas - especially in areas where the water table is close to the ground surface and adjacent to river banks.

SCENARIO 2 EARTHQUAKE		
Hazard Zones	MM intensity	Ground conditions and likely effects
1	VIII - IX	**"Greywacke" bedrock:** Small failures of bedrock and surficial deposits. Widespread on steep slopes, and on steep unsupported cuts (>2 m high).
2	VIII - X	**Alluvial deposits:** Only little significant ground damage expected. Small localised failures of river banks and cuts. Cracking and lateral spreading likely adjacent to river and stream channels with sand ejection due to liquefaction. Minor settlement and collapse of saturated materials in most places.
3-4	IX -X	
5	X - XI	**Soft sediments:** Effects as for Zones 2, and 3-4 - except that damage will be widespread and at a greater scale. Liquefaction effects (sand ejection, cracking, lateral spreading, and settlement) would be widespread and seriously damaging in some places, especially areas adjacent to river and stream courses.

Wainuiomata; Zone 3-4, 0.5-0.8 g; Zone 5, 0.6-0.8 g in Lower Hutt Valley, 0.5-0.8 g in Porirua and Wainuiomata.

3.3.3 Duration of strong shaking

This parameter provides a qualitative estimate of the effects that local geological deposits can have in increasing the length of time a site will experience strong shaking. In general, amplitudes and durations of shaking increase with decreasing firmness of the underlying sediment. This has been observed for microearthquakes (eg. Taber and Smith 1991, Taber 1991) and for larger damaging earthquakes (eg. Borcherdt and Glassmoyer 1990). In this report, duration refers to the time between the first and last accelerations that exceed 0.05 g.

Scenario 1: The expected duration of strong shaking in Zone 1 during a scenario 1 event is less than 5 sec (Table 2). The expected increase in duration of shaking relative to bedrock is 2-3 times in Zones 2 and 3-4, and more than 3 times in Zone 5. These values are broadly consistent with the intensity based increases in duration reported in Krinitzsky and Chang (1988).

Scenario 2: Length of fault rupture is a controlling factor regarding the duration of near-source ground shaking. The Loma Prieta earthquake produced about 10 seconds of strong shaking, resulting from a bilateral rupture of a roughly 40 km long fault plane (U.S. Geological Survey Staff 1990). Had the rupture been unilateral, that is, propagating from one end of the fault to the other, instead of bilateral, propagating from the centre of the fault to the ends, the shaking would have lasted much longer, perhaps up to about 20 sec. Rupture of the Wellington fault in scenario 2 is expected to be about twice as long as the fault rupture that produced the Loma Prieta earthquake. The duration of shaking for Zone 1 during scenario 2 is expected to be in the order of 15-40 sec, by comparison with the Loma Prieta event and depending on whether the rupture propagates bilaterally or unilaterally. This compares with the 30 sec duration predicted for a M 7.5 earthquake using figure 27 in Hays (1980). The increase in duration, relative to Zone 1, is 1-2 times for Zones 2 and 3-4, and >2 times for Zone 5 (Table 2).

3.3.4 Amplification of ground motion spectrum

The relative ground response at 35 sites through out Porirua and the Lower Hutt areas due to microearthquakes has been measured (figure 1, Taber and Smith 1991, Taber 1991). Results are expressed as averaged ratios of Fourier spectra of the seismograms. Spectral ratios vary from 1-3 for firm sites up to about 20 for "flexible" sediment sites. Amplification at most of the sites occurs over a broad frequency band from 0.5 to 5 Hz; however, some sites exhibit a very narrow frequency response. Results from other areas (eg. Borcherdt et al. 1989) suggest that the frequency of amplified shaking during small earthquakes remains the same for larger damaging earthquakes. Thus the results of Taber and Smith (1991) and Taber (1991) are not only useful for determining relative shaking but also for identifying the frequencies over which this shaking will be most strongly amplified.

Characteristic Fourier spectral ratios (Fsr) for each of the mapped Hazard Zones, including the frequencies over which the strongest amplifications occurs, are as follows (Table 2): Zone 1, Fsr=1-3 at >1 Hz; Zone 2, Fsr=2-5 at 0.5-5 Hz; Zone 3-4, Fsr=5-10 at 0.5-3 Hz; Zone 5, Fsr=10-20 at <3 Hz (down to at least 0.5 Hz) in the southern Lower Hutt Valley, at 2 Hz in Porirua, at 1 Hz in Naenae, at 2 Hz in the shallower parts of Wainuiomata, and 0.5-3 Hz (with a peak at 1 Hz) in the deeper parts of Wainuiomata.

These spectral ratios were measured during earthquakes that produced no damage in the Wellington region. The amount of amplification for large ground motions is an unresolved question. An amplification of near 20 in Zone 5 is unlikely to persist to very large motions (Jarpe et al. 1989) because the weak sediments may attenuate ground motions as shearing stresses approach shear strengths and high energy dissipation occurs. Nevertheless, high amplification of small ground motions, such as the scenario 1 bedrock motions, means that significant local damage in Zone 5 could result from an earthquake that would cause little or no damage in Zone 1. It is amplifications at smaller ground motions that the measured spectral ratios best characterize, thus they are given only for scenario 1.

3.3.5 Spectral acceleration and velocity

To illustrate again the difference that is expected in ground response during the scenario 1 event between identified Hazard Zones, spectral accelerations and velocities were derived by Sritharan and McVerry (1991) for selected sites within each Zone in the Lower Hutt Area. In brief, a response spectrum was estimated for the bedrock reference site using a smoothed response spectra shape obtained from several recorded earthquakes, which was then scaled by the peak horizontal ground acceleration expected for bedrock during scenario 1. Response spectra amplification relative to the bedrock reference site were estimated for one to five sites within each Hazard Zone, based largely on the results of Sritharan and McVerry (1991) but drawing from those of Taber (1991). From these, acceleration response spectra were estimated. In terms of spectral accelerations, the Wainuiomata sites in Zone 5 stand out for their strong response, with response peaks reaching 0.8 to 1 g for the input rock motion with a peak ground acceleration of 0.03 g. The ratio between the maximum spectral acceleration estimated for the Hazard Zone sites, and the maximum acceleration for the bedrock reference site is also presented in Table 2 (and Legend).

To emphasize the strong long period response of some of the deep sediment sites, a general estimate of relative velocity response spectra was obtained by dividing the acceleration response spectra by the angular frequency. The approximate relative velocity spectra show the distinct long period amplification at sites like Naenae, and the Zone 5 deep sediment sites in the southern Lower Hutt Valley that was not clear on the acceleration response spectra. Table 2 presents representative values for both 5% damped maximum spectral acceleration (SA $max_{(rep)}$), and spectral velocity (SV $max_{(rep)}$) for the selected sites within the Hazard Zones, also included are the periods at which these maxima occur.

The response spectrum values included in the Legend (and Table 2) are intended only to illustrate the range of values (motions) that may be expected for certain sites within the Hazard Zones during a scenario 1 event. It is important to note that while the amplifications used to derive the response spectra all have basis in earthquake motions recorded in the Lower Hutt area, the procedure used to derive these response spectra is not analytically rigorous. The response spectra values in Table 2 were calculated for specific sites within a Hazard Zone, and may not be general enough to characterize the response of the Zone as a whole, and there may be significant local variations from the listed values. However, at present these response spectrum values provide the best estimate available for assessing the response of structures in the Hazard Zones.

Response spectra ratios for certain strong motion instrument sites in the Lower Hutt Valley show amplifications, in one or more narrow frequency bands, that exceed the values derived from the Katayama (1982) empirical model, in some bases by a factor of two or more [see Sritharan and McVerry (1991) for further discussion].

4. ASSUMPTIONS, LIMITATIONS, AND RECOMMENDATIONS

Important assumptions that limit the certainty with which the Ground Shaking Hazard Zones have either been identified or quantified are discussed below. Recommendations are also given for further work that would resolve some of these uncertainties.

a) Scenario 2 ground motion parameters are defined with less certainty. There is a world-wide lack of near-source ground motion data recorded during large earthquakes. Moreover, during a large local earthquake, near-source seismic wave propagation will be complex and non-uniform, and ground strains will be large enough to cause some sediments to exhibit non-linear response (attenuation of ground motions). These effects will tend to increase the variability of shaking within a zone, decrease the average difference in shaking between zones, and decrease the certainty with which expected ground motions can be characterized. Also, near-source ground motions for an earthquake associated with a long fault rupture, such as scenario 2, may be more correlated with proximity to local asperities along the fault rupture, rather than proximity to the fault itself. It is conceivable that two sites on similar materials could be equal distant from the fault, yet one site could be next to an asperity while the other site could be tens of kilometres away. Ground motions at these two sites would probably not be the same. At present, it is not possible locate all the major asperities along the expected scenario 2 fault rupture.

b) Amplification of ground motions due to topographic effects has not been addressed in this study. Though probably quite localized, these effects can nevertheless be pronounced. Spectral ratios of up to 8 have resulted from topographic amplifications at hard-rock sites (Tucker et al. 1984). It is possible that the high amplification at a firm site in Whitby is also in part the result of topographic effects (Taber and Smith 1991).

Recommendation:

Detailed assessment of previous case histories, instrumentation of characteristic topographic shapes, and/or sophisticated modelling should be carried out to develop a systematic approach for the identification and quantification of "higher risk" topographic shapes and orientations.

c) Within each Hazard Zone there are isolated occurrences of materials that may cause ground motions that are not typical of the Zone as a whole. In the western Hutt hills there are small terrace remnants, and local areas of deeply weathered bedrock. These have been included in Zone 1, but it is possible their response could be closer to that of Zone 2.

Much of what is mapped as Zone 2 in the Lower Hutt Valley is underlain by a thin near-surface layer of alluvial silt (Read et al. 1991). Usually these fine grained sediments are less than 5 m thick, and are underlain by coarser alluvial gravels. However, locally they are up to 10 or more metres thick, an extreme example is at Naenae. At these "thicker" localities a less favourable response is expected.

The mapped fills in Porirua East are placed on bedrock (Dellow et al. 1991), and are included with Zone 1. However, these fills are over 20 m thick in places, and may respond more like Zone 2. In Eastbourne, the spacing of penetrometer probings does not preclude the existence of isolated pockets of "flexible" sediment. If thick enough, these sediments would respond less favourably than the general Zone 2 response expected for most of Eastbourne. Conversely, some areas mapped in Porirua as Zone 5 may not be underlain by enough sediment to cause high amplifications of ground motion. At these "thinner" sites a more favourable response may result.

Recommendation:

Detailed geological mapping, supplemented by penetrometer probing and seismograph instrumentation would resolve some of these questions.

d) High amplifications have been recorded at Titahi Bay and Naenae (Taber 1991, Taber and Smith 1991), but the distribution of the materials causing these amplifications is not well defined. The poorly resolved boundary around these Zone 5 areas is denoted as a dot-dash line on the Ground Shaking Hazard Map (figures 2 & 3).

Recommendation:

Additional work should be carried out to define the extent of the geological materials present at these and similar sites. This would result in a better resolved, and more accurately located boundary.

e) The Zone 5 and Zone 3-4 boundaries in the southern Lower Hutt Valley are gradational (see section 3.1.2.3), reflecting the gradual down-valley increase in both total sediment thickness and thickness of soft near-surface "flexible" sediment. These boundaries are marked on the Ground Shaking Hazard Map as dashed lines. The change in response from one zone to the other is expected to occur over distances of about 300 m perpendicular to the boundary (roughly the depth to bedrock). The boundary as shown on the map is accurate to within about 200-800 m, depending on the spacing and quality of the constraining data.

Recommendation:

Additional work should be undertaken to define with certainty the location of the Zone 5 boundary in the southern Lower Hutt Valley (see section 3.1.2.3). Additional geological constraints regarding shear wave velocities and depths of flexible layers, deployment of a dense array of seismographs, an increase in the number of strong motion records, and further detailed comparisons between strong and weak motion data are required.

f) The response spectra calculated by Sritharan and McVerry (1991), maximum values presented in Table 2 and the Legend) are derived for specific sites within a Hazard Zone. They help illustrate the differing response expected between each Zone, and highlight the strong long period response expected in the southern part of the Lower Hutt Valley. However, they may not be general enough to adequately characterize the range of response of each Zone.

Recommendation:

Instrumentation of additional sites within each Hazard Zone, and analysis of more strong motion records is necessary before characteristic response spectra for each Hazard Zone can be developed.

g) There is a marked directionality in the response of some strong motion sites during some earthquakes. However, the direction of strongest response is not consistent for different events (Sritharan and McVerry 1991).

h) The ground damage effects presented in Table 3 are estimated from a general knowledge of past earthquakes in the Wellington region and elsewhere. However, further detailed studies of these aspects should be carried out to provide a comprehensive evaluation of the likely extent and variability of ground damage that can be expected to occur in the mapped Hazard Zones. With the cost of repairs to certain lifelines going up by a factor of ten for each MM unit increase (O'Rourke et al. 1991), these effects have important implications with respect to earthquake damage evaluation and prediction.

i) It is recommended that a detailed investigation be undertaken to document the variations in ground response produced by the 1942 south Wairarapa earthquakes.

j) This report, including maps (figures 2 & 3) and Legend, is the result of a regional multi-disciplinary study of ground shaking hazard. It provides useful information for the mitigation of this hazard, but should not be used to replace site specific studies.

5. CONCLUSIONS AND IMPLICATIONS

Four Ground Shaking Hazard Zones have been identified in the Lower Hutt area, and three in Porirua (figures 2 & 3). These zones are graded from 1 to 5, with Zone 5 expected to experience the strongest shaking during an earthquake event, and Zone 1 the least. The expected response of each of these Zones is assessed for two earthquake scenarios and summarized in Table 2 and the Legend.

During a scenario 1 earthquake, areas underlain by a greater than 10 m thickness of soft "flexible" sediment are expected to strongly amplify earthquake ground motions. These areas are mapped as Zone 5. The high amplifications that characterize this Zone imply that significant local damage in Zone 5 could result from an earthquake that would cause little or no damage at a near-by firm site (Zone 1).

Within Zone 5, sites underlain by a relatively simple sequence of "flexible" sediment, such as a 10-30 m thickness over bedrock, tend to show high amplifications over a narrow frequency range; whereas sites underlain by a more complex sequence, such as more than 10 m of "flexible" sediment over some appreciable thickness of coarser sediment (greater than about 50 m), tend to show high amplifications over a broader frequency range. Thus any building with a natural period within the range of measured amplified frequencies (Table 2, Legend) is potentially at greater risk relative to a near-by building sited on similar materials but with a different natural period.

The most marked difference in shaking between Zones is expected during a large, distant, shallow earthquake (scenario 1). During this earthquake an increase of up to three MM intensity units is expected between the shaking of Zone 1 and the shaking of Zone 5.

The Katayama (1982) empirical model does not satisfactorily predict the amount of amplification, relative to the bedrock reference site spectra, exhibited by the strong motion sites in the Lower Hutt Valley that are underlain by a greater than 20 m thickness of sediment. During a specific earthquake, these sites have one or several period bands in which they exceed the broad band amplifications given by the Katayama model for the appropriate ground class [see Sritharan and McVerry (1991) for further discussion].

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APPENDIX A

GROUND SHAKING HAZARD MAPS
for the
LOWER HUTT AND PORIRUA AREAS

LEGEND

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part of
Wellington Regional Council's
Regional Natural Disaster Reduction Plan - Seismic Hazard

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Introduction

These maps (figures A1 & A2) depict, and quantify, the variation in ground shaking expected during damaging earthquakes impacting on the Lower Hutt and Porirua areas. Three ground shaking hazard zones are identified in Porirua, and four in the Lower Hutt area. These zones are graded from 1 to 5. In general, areas within Zone 5 are expected to experience the strongest shaking during an earthquake event; areas within Zone 1 are expected to experience the weakest shaking. The response of each zone is assessed for two earthquake scenarios. Scenario 1 is for a large, distant earthquake, and scenario 2 is for a local Wellington fault earthquake.

Scenario 1

A large, distant, shallow (<60 km) earthquake that produces MM V-VI shaking intensities in bedrock over the Wellington region. An example of such an event would be a M_s 7 earthquake centred roughly 100 km from the study area at a depth of 15-60 km, perhaps similar to the 1942 south Wairarapa earthquakes (Hayes 1943). The larger 1848 Marlborough earthquake (Eiby 1980, Dowrick and Smith 1990) produced MM VI-VII intensities in bedrock over the Wellington region. The return time of MM VI or greater shaking at bedrock sites of low topographic relief in the Wellington region is about 20 years (Smith and Berryman 1990).

Shaking Hazard Zones

(1) Greywacke bedrock, including areas overlain by less than 10 m of deeply weathered gravel and loess, or well engineered fill.

Moderate shaking, MM V with some VI

Peak horizontal ground acceleration (pga), 0.02-0.06 g.

Duration of strong shaking, <5 sec.

Frequency range of strongest ground response, >1 Hz

Representative 5% damped maximum spectral acceleration (SA $max_{(rep)}$),

and period (T) over which it occurs;

0.1 g at 0.2-0.3 sec (3-5 Hz).

Representative 5% damped maximum spectral velocity (SV $max_{(rep)}$),

and period (T) over which it occurs;

0.06 m/s at 0.3-0.4 sec (2.5-3 Hz).

(2) Alluvial gravel and fan alluvium; fine to coarse gravel, up to 200 m thick, with some beds and lenses of finer grained sediment (sand, silt, clay, and peat) usually less than 5 m thick. Moderate to high SPT values, N=20->60. At Titahi Bay, 10-20 m thickness of extremely weak silty sandstone with lenses of gravel, or about a 5-10 m thickness of windblown sand.

Moderate shaking, MM VI

Peak ground acceleration (pga), 0.02-0.1 g.

Duration of shaking with respect to bedrock, 2-3×

Amplification with respect to bedrock (Fourier spectral ratio, Fsr), 2-5×

Frequency range of strongest ground amplification, 0.5-5 Hz

For sites underlain by <50-75 m of sediment, maximum amplification is expected in the higher frequency range (>2 Hz).

Amplification with respect to bedrock of peak of 5% damped acceleration response spectra, weak to moderate (<5×)

SA $max_{(rep)}$ and T, 0.4 g at 0.3-0.4 sec (2.5-3 Hz).

SV $max_{(rep)}$ and T, 0.3 m/s at 0.4 sec (2.5 Hz).

(3-4) Lower Hutt Valley only; up to 5-15 m of fine grained sediment (fine sand, silt, clay, and peat) within the top c. 20 m of alluvial gravel, underlain by up to 250 m of alluvial gravels and finer grained sediment. Near-surface fine grained sediments typically have low SPT values, N=<20, whereas the coarser consolidated sediments generally have moderate to high SPT values, N=20->60.

Moderate to strong shaking, MM VI-VII

Peak ground acceleration (pga), 0.02-0.1 g.

Duration of shaking with respect to bedrock, 2-3×

Amplification with respect to bedrock (Fsr), 5-10×

Frequency range of strongest ground amplification, 0.5-3 Hz

Amplification with respect to bedrock of peak of 5% damped response spectra, moderate (2-5×)

SA $max_{(rep)}$ and T, 0.5 g at 0.4 sec (2.5 Hz).

SV $max_{(rep)}$ and T, 0.4 m/s at 1.0 sec (1.1 Hz), and 0.3 m/s at 0.4 sec (2.5 Hz).

(5) Soft sediment (fine sand, silt, clay, and peat) at or very near the surface, typically with low to very low SPT values (N=<10-20). Shear wave velocities for these "flexible" sediments at Porirua, Wainuiomata, and Lower Hutt are in the order of 110 m/s, 90-150 m/s, and 175 m/s respectively.

a) Porirua, Naenae, and Wainuiomata: Soft "flexible" sediment 10-30 m thick, underlain by bedrock or a thin layer of coarser sediment (less than 10 m thick) over bedrock.

Very strong shaking, MM VIII-IX

Peak ground acceleration (pga), <0.3 g, generally between 0.1-0.2 g.

Duration of shaking with respect to bedrock, >3×

Amplification with respect to bedrock (Fsr), 10-20×

Resonant frequencies; Naenae, 1 Hz

Wainuiomata, 2 Hz

Porirua, 2 Hz

Amplification with respect to bedrock of peak of 5% damped response spectra, moderate to strong (>4×)

SA $max_{(rep)}$ and T; Naenae, 0.4 g at 0.8 sec (1.25 Hz).

Wainuiomata, 1.0 g at 0.5 sec (2.2 Hz), and 0.7 g at 0.3 sec (4 Hz).

SV $max_{(rep)}$ and T; Naenae, 0.6 m/s at 0.9 sec (1.22 Hz)

Wainuiomata, 0.7 m/s at 0.5 sec (2.2 Hz).

b) Wainuiomata: Soft "flexible" sediment 20-35 m thick, underlain by a thickness (about 30 m) of gravel and other finer grained sediment.

Very strong shaking, MM VIII-IX

Peak ground acceleration (pga), <0.3 g, generally between 0.1-0.2 g.

Duration of shaking with respect to bedrock, >3×

Amplification with respect to bedrock (Fsr), 10-20×

Frequency range of strongest ground amplification; 0.5-3 Hz, with a peak at 1 Hz

Amplification with respect to bedrock of peak of 5% damped response spectra, strong (>5×)

SA $max_{(rep)}$ and T, 0.9 g at 0.3 sec (3.3 Hz), and 0.7 g at 0.4 sec (2.5 Hz).

SV $max_{(rep)}$ and T, 0.7 m/s at 1.1 sec (0.9 Hz).

c) Lower Hutt Valley: Soft "flexible" sediment 10-30 m thick underlain by more than 200 m (up to 300+ m) of gravel and other finer grained sediment.

Very strong shaking, MM VIII-IX

Peak ground acceleration (pga), <0.2 g, generally around 0.05-0.1 g.

Duration of shaking with respect to bedrock, >3×

Amplification with respect to bedrock (Fsr), 10-20×

Frequency range of strongest ground amplification; <3 Hz, down to at least 0.5 Hz

Amplification with respect to bedrock of peak of 5% damped response spectra, moderate (2-5×)

SA $max_{(rep)}$ and T, 0.3 g with several peaks between 0.5-1.5 sec (0.7-2 Hz).

SV $max_{(rep)}$ and T, 0.4-0.5 m/s with several peaks between 0.7-1.8 sec (0.6-1.4 Hz).

Scenario 2

Rupture of the 75 km long Wellington-Hutt Valley segment of the Wellington fault that extends from Cook Strait through Wellington and the Hutt Valley to Kaitoke. This is expected to be associated with a c. M_s 7.5 earthquake at a depth less than 30 km, with fault rupture producing up to 5 m of right-lateral and 1 m of vertical displacement at the ground surface (Berryman 1990). The mean recurrence interval for such an event is about 600 years (Van Dissen and Berryman 1990), and the probability of this event occurring in the next 30 years is estimated to be in the order of 10%.

Shaking Hazard Zones

(1) Greywacke bedrock, including areas overlain by less than 10 m of deeply weathered gravel and loess, or well engineered fill.

Very strong shaking (depending on proximity to source and local asperities, and attenuation of seismic energy)

Near fault (Lower Hutt Valley), MM IX

Porirua & Wainuiomata, MM VIII

Peak horizontal ground acceleration (pga),

Near fault (Lower Hutt Valley), 0.5-0.8 g.

Porirua & Wainuiomata, 0.3-0.6 g.

Duration of strong shaking, 15-40 sec.

(2) Alluvial gravel and fan alluvium; fine to coarse gravel, up to 200 m thick, with some beds and lenses of finer grained sediment (sand, silt, clay, and peat) usually less than 5 m thick. Moderate to high SPT values, N=20->60. At Titahi Bay, 10-20 m thickness of extremely weak silty sandstone with lenses of gravel, or about a 5-10 m thickness of windblown sand.

Very strong to violent shaking

Lower Hutt Valley, MM IX-X

Porirua & Wainuiomata, MM VIII-IX

Peak ground acceleration (pga)*

Lower Hutt Valley, 0.5-0.8 g.

Porirua & Wainuiomata, 0.3-0.6 g.

Duration of shaking with respect to bedrock, 1-2×

Frequency range; broad frequency response, permanent ground deformation becomes more a controlling factor with stronger shaking.

Amplification with respect to bedrock of peak of 5% damped acceleration response spectra, weak to moderate (<5×)

(3-4) Lower Hutt Valley only; up to 5-15 m of fine grained sediment (fine sand, silt, clay, and peat) within the top c. 20 m of alluvial gravel, underlain by up to 250 m of alluvial gravels and finer grained sediment. Near-surface fine grained sediments typically have low SPT values, N=<20, whereas the coarser consolidated sediments generally have moderate to high SPT values, N=20->60.

Very strong to violent shaking, MM IX-X

Peak ground acceleration (pga)*, 0.5-0.8 g.

Duration of shaking with respect to bedrock, 1-2×

Frequency range, broad frequency response

Amplification with respect to bedrock of peak of 5% damped response spectra,
moderate (2-5×)

(5) Soft sediment (fine sand, silt, clay, and peat), up to 10-30 m thick, at or very near the surface, underlain by bedrock or a variable thickness of gravel and other finer grained sediment. Shear wave velocities for "flexible" sediments at Lower Hutt, Wainuiomata, and Porirua are on the order of 175 m/s, 90-150 m/s, and 110 m/s respectively.

Violent shaking, MM X-XI

Peak ground acceleration (pga)*

Near fault, 0.6-0.8 g.

Porirua & Wainuiomata, 0.5-0.8 g.

Duration of shaking with respect to bedrock, >2×

Frequency range; pronounced non-linear effects, lack of high frequency peaks, less marked in Porirua and Wainuiomata.

Amplification with respect to bedrock of peak of 5% damped response spectra,
moderate to strong (2->5×)

* Assuming a near linear response of the underlying sediment, though at high accelerations (>0.4-0.6 g) this assumption may not be valid. When ground strains cause sediments to exhibit non-linear response, peak horizontal accelerations may have a maximum value of about 0.6 g.

These maps are the result of a regional multi-disciplinary study of ground shaking hazard. They provide useful information for the mitigation of this hazard, but should not be used to replace site specific studies

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GROUND SHAKING HAZARD MAP
FOR THE PORIRUA AREA

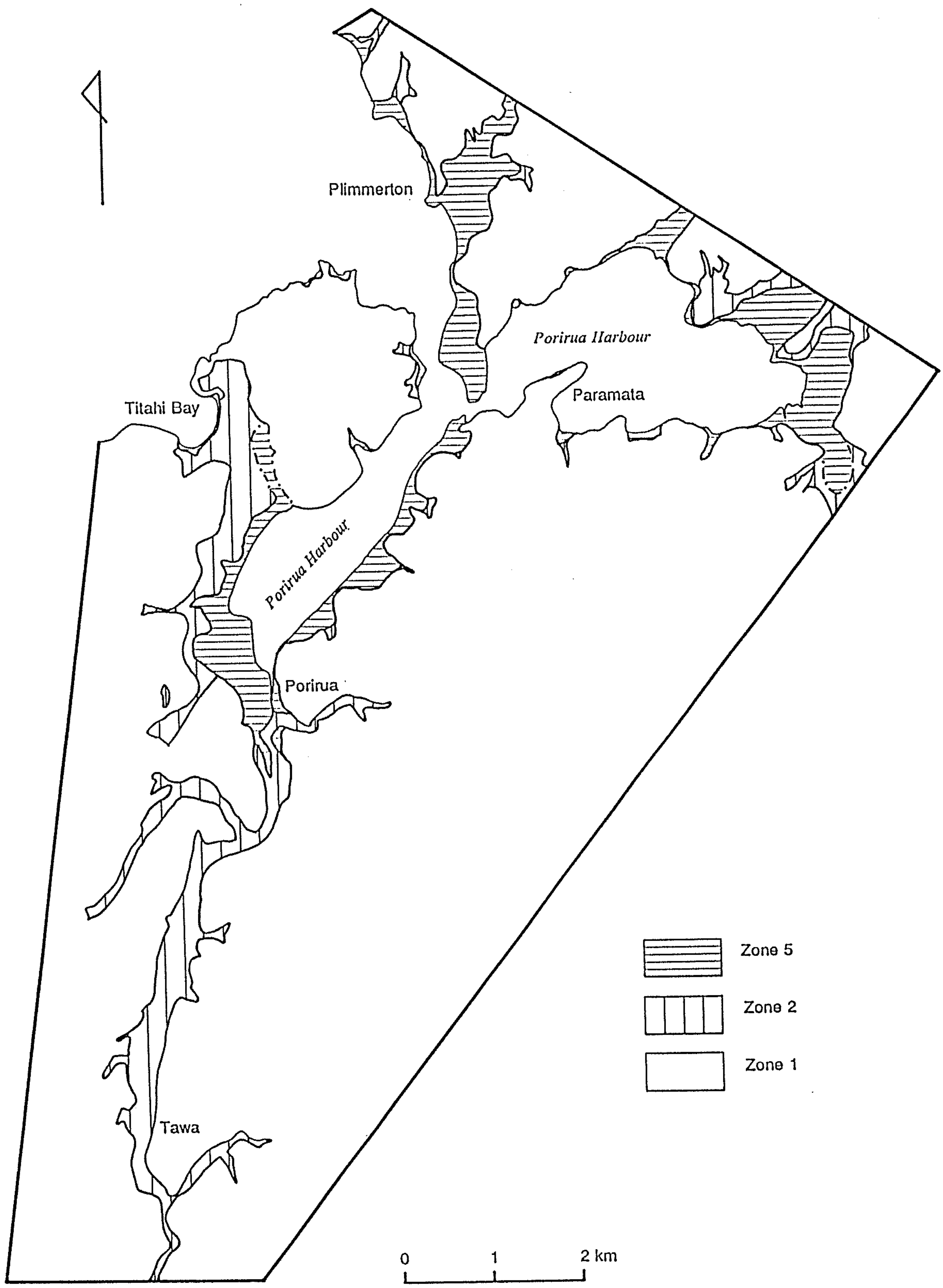

Figure A1. Ground shaking hazard map for the Porirua area.

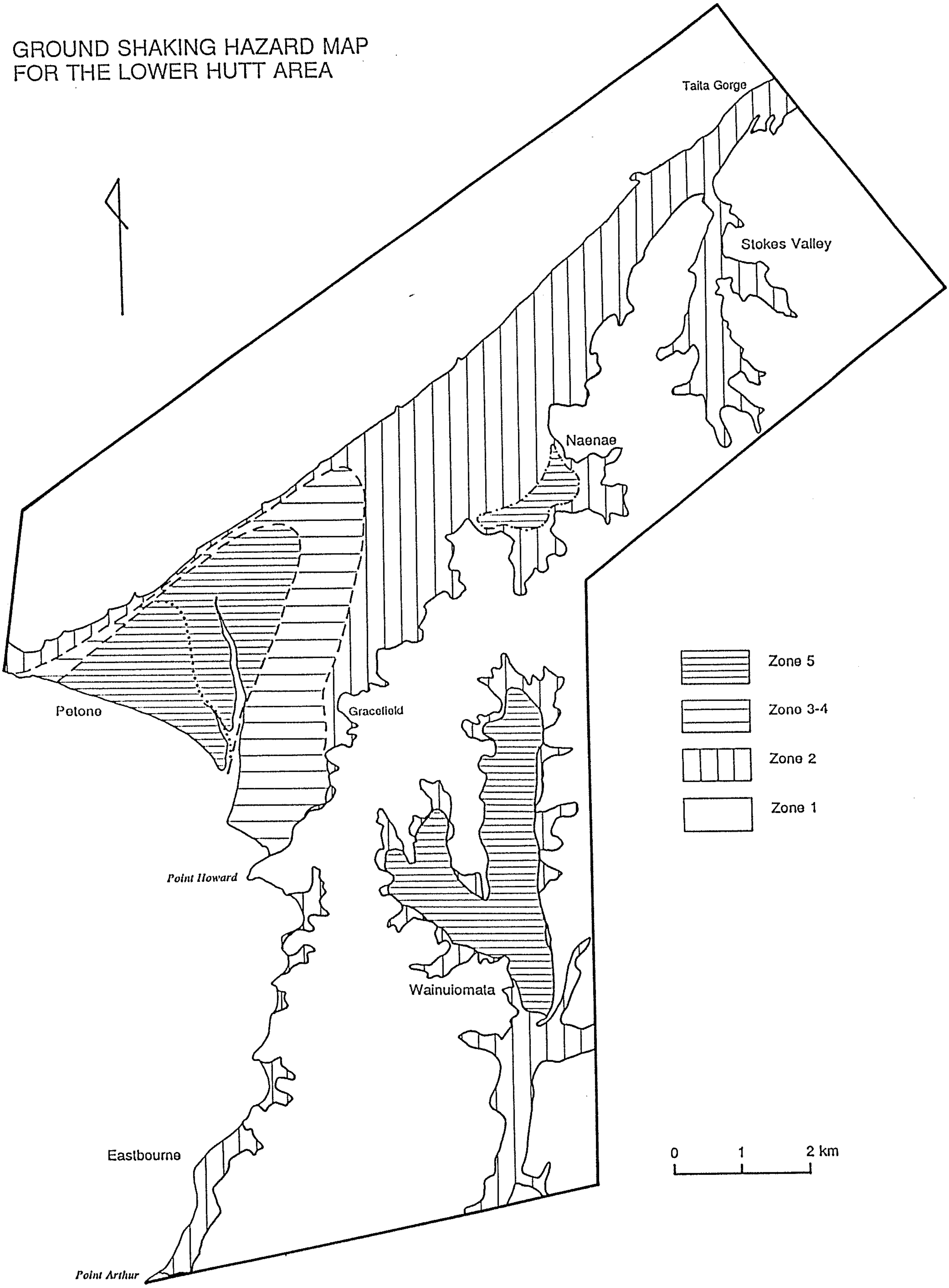

Figure A2. Ground shaking hazard map for the Lower Hutt area.

MODIFIED MERCALLI SCALE OF INTENSITY OF EARTHQUAKE SHAKING (NZ Version 1965)

MM I

Not felt by humans, except in especially favourable circumstances, but birds and animals may be disturbed.
Reported mainly from the upper floors of buildings more than 10 storeys high.
Dizziness or nausea may be experienced.

Branches of trees, chandeliers, doors, and other suspended systems of long natural period may be seen to move slowly.
Water in ponds, lakes, reservoirs, etc., may be set into seiche oscillation.

MM II

Felt by a few persons at rest indoors, especially by those on upper floors or otherwise favourably placed.

The long-period effects listed under MMI may be more noticeable.

MMIII

Felt indoors, but not identified as an earthquake by everyone.
Vibration may be likened to the passing of light traffic.

It may be possible to estimate the duration, but not the direction.
Hanging objects may swing slightly.
Standing motorcars may rock slightly.

MM IV

Generally noticed indoors, but not outside.
Very light sleepers may be wakened.
Vibration may be likened to the passing of heavy traffic, or to the jolt of a heavy object falling or striking the building.

Walls and frame of buildings are heard to creak.
Doors and windows rattle.
Glassware and crockery rattles.
Liquids in open vessels may be slightly disturbed.
Standing motorcars may rock, and the shock can be felt by their occupants.

MM V

Generally felt outside, and by almost everyone indoors.
Most sleepers awakened.
A few people frightened.

Direction of motion can be estimated.
Small unstable objects are displaced or upset.
Some glassware and crockery may be broken.
Some windows cracked.
A few earthenware toilet fixtures cracked.
Hanging pictures move.
Doors and shutters may swing.
Pendulum clocks stop, start, or change rate.

MM VI

Felt by all.
People and animals alarmed.
Many run outside.
Difficulty experienced in walking steadily.

Slight damage to Masonry D.
Some plaster cracks or falls.
Isolated cases of chimney damage.

Windows, glassware, and crockery broken.
Objects fall from shelves, and pictures from walls.
Heavy furniture moved. Unstable furniture overturned.

Small church and school bells ring.
Trees and bushes shake, or are heard to rustle.
Loose material may be dislodged from existing slips, talus slopes, or shingle slides.

MM VII

General alarm.
Difficulty experienced in standing.
Noticed by drivers of motorcars.
Trees and bushes strongly shaken.
Large bells ring.

Masonry D cracked and damaged.
A few instances of damage to Masonry C.

Loose brickwork and tiles dislodged.
Unbraced parapets and architectural ornaments may fall.
Stone walls cracked.
Weak chimneys broken, usually at the roof-line.
Domestic water tanks burst.
Concrete irrigation ditches damaged.

Waves seen on ponds and lakes.
Water made turbid by stirred-up mud.
Small slips, and caving-in of sand and gravel banks.

MM VIII

Alarm may approach panic.
Steering of motorcars affected.

Masonry C damaged, with partial collapse.
Masonry B damaged in some cases.
Masonry A undamaged.

Chimneys, factory stacks, monuments, towers, and elevated tanks twisted or brought down.
Panel walls thrown out of frame structures.
Some brick veneers damaged.
Decayed wooden piles broken.
Frame houses not secured to the foundation may move.
Cracks appear on steep slopes and in wet ground.
Landslips in roadside cuttings and unsupported excavations.
Some tree branches may be broken off.

Changes in the flow or temperature of springs and wells may occur.
Small earthquake fountains.

APPENDIX (continued)

MM IX

General panic.

Masonry D destroyed.
Masonry C heavily damaged, sometimes collapsing completely.
Masonry B seriously damaged.
Frame structures racked and distorted.

Damage to foundations general.
Frame houses not secured to the foundations shifted off.
Brick veneers fall and expose frames.

Cracking of the ground conspicuous.
Minor damage to paths and roadways.
Sand and mud ejected in alluviated areas, with the formation of earthquake fountains and sand craters.
Underground pipes broken.
Serious damage to reservoirs.

MM X

Most masonry structures destroyed, together with their foundations.
Some well built wooden buildings and bridges seriously damaged.
Dams, dykes, and embankments seriously damaged.
Railway lines slightly bent.
Cement and asphalt roads and pavements badly cracked or thrown into waves.

Large landslides on river banks and steep coasts.

Sand and mud on beaches and flat land moved horizontally.
Large and spectacular sand and mud fountains.
Water from rivers, lakes, and canals thrown up on the bank.

MM XI

Wooden frame structures destroyed.
Great damage to railway lines.
Great damage to underground pipes.

MM XII

Damage virtually total. Practically all works of construction destroyed or greatly damaged.

Large rock masses displaced.
Lines of sight and level distorted.
Visible wave-motion of the ground surface reported.
Objects thrown upwards into the air.

Categories of Non-wooden Construction

Masonry A. Structures designed to resist lateral forces of about 0.1 g, such as those satisfying the New Zealand Model Building Bylaws, 1955. Typical buildings of this kind are well reinforced by means of steel or ferro-concrete bands, or are wholly of ferro-concrete construction. All mortar is of good quality and the design and workmanship is good. Few buildings erected prior to 1935 can be regarded as in category A.

Masonry B. Reinforced buildings of good workmanship and with sound mortar, but not designed in detail to resist lateral forces.

Masonry C. Buildings of ordinary workmanship, with mortar of average quality. No extreme weakness, such as inadequate bonding of the corners, but neither designed nor reinforced to resist lateral forces.

Masonry D. Buildings with low standards of workmanship, poor mortar, or constructed of weak materials like mud brick and rammed earth. Weak horizontally.

Windows

Window breakage depends greatly upon the nature of the frame and its orientation with respect to the earthquake source. Windows cracked at MM V are usually either large display windows, or windows tightly fitted to metal frames.

Chimneys

The "weak chimneys" listed under MM VII are unreinforced domestic chimneys of brick, concrete block, or poured concrete.

Water tanks

The "domestic water tanks" listed under MM VII are of the cylindrical corrugated-iron type common in New Zealand rural areas. If these are only partly full, movement of the water may burst soldered and riveted seams.

Hot-water cylinders constrained only by supply and delivery pipes may move sufficiently to break the pipes at about the same intensity.