NEW ZEALAND
DEPARTMENT OF
SCIENTIFIC AND
INDUSTRIAL
RESEARCH

REGIONAL NATURAL DISASTER REDUCTION PLAN - SEISMIC HAZARD

Earthquake Ground Shaking Hazard Assessment of the Kapiti Coast, New Zealand

(Part 7 of 1991/92 Study)

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REGIONAL NATURAL DISASTER REDUCTION PLAN
SEISMIC HAZARD

Part 1	Frequency Dependent Amplification of Weak Ground Motions in Wellington City and the Kapiti Coast
Part 2	Report on Cone Penetrometer and Seismic Cone Penetrometer Probing in Wellington City, Kapiti Coast and Upper Hutt Valley
Part 3	Compilation of Geological Data, Wellington Area
Part 4	Geology of the Kapiti Coast (Pukerua Bay to Otaki), Wellington
Part 5	Geology and Earthquake Ground Shaking Hazard Assessment of the Upper Hutt Basin, New Zealand
Part 6	Earthquake Ground Shaking Hazard Assessment of the Wairarapa, New Zealand
Part 7	Earthquake Ground Shaking Hazard Assessment of the Kapiti Coast, New Zealand
Part 8	Earthquake Ground Shaking Hazard Assessment for Wellington City and Suburbs, New Zealand

Frontispiece: View of Otaki area, Kapiti Coast, New Zealand.
Photo: D. L. Homer, DSIR Geology & Geophysics

EARTHQUAKE GROUND SHAKING HAZARD ASSESSMENT for the KAPITI COAST, NEW ZEALAND

DSIR Geology & Geophysics
CONTRACT REPORT 1992/23

Prepared for

The Wellington Regional Council

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June 1992

CONTENTS

SUMMARY 1

1. INTRODUCTION 2

2. METHODOLOGY 3

    2.1 Earthquake Scenarios 3

3. RESULTS 8

    3.1 Identification of Ground Shaking Hazard Zones 8

    3.2 Geological Description of Hazard Zones 12

    3.3 Quantification of Ground Shaking Hazard Zones 12

        3.3.1 Modified Mercalli intensity 13
        3.3.2 Peak horizontal ground acceleration 15
        3.3.3 Duration of strong shaking 15
        3.3.4 Amplification of ground motion spectrum 16

    3.4 Some Comparisons with a Recent California Zonation 18

4. ASSUMPTIONS, LIMITATIONS, AND RECOMMENDATIONS 22

5. CONCLUSIONS AND IMPLICATIONS 26

6. ACKNOWLEDGEMENTS 26

7. REFERENCES 27

APPENDIX A
Modified Mercalli Intensity Scale

SUMMARY

This report identifies and quantifies the geographic variations in strong ground shaking expected during damaging earthquakes impacting on the Kapiti Coast study area (Pukerua Bay to Otaki), New Zealand. Three Ground Shaking Hazard Zones have been identified in the Kapiti Coast area: Zones 1, 2, and 3-4. These zones are defined based on geological and microseismic inputs. In general, Zone 1 areas are expected to experience very low to low amplifications of ground shaking during an earthquake. In contrast, Zone 3-4 areas are expected to experience moderate to high ground motion amplifications, and are thus subject to a greater ground shaking hazard. Zone 2 areas are expected to experience low to moderate amplifications, and are subject to an intermediate shaking hazard, relative to Zones 1 and 3-4.

Zone 1 is typically underlain by moderately weak to very strong sandstone and siltstone bedrock, and includes much of the hill country of the study area. Zone 2 is generally underlain by interbedded compact gravel and sand of late Pleistocene age (c. 10,000 to 250,000 years). These sediments include interglacial and previous glacial deposits and comprise much of the coastal portion of the study area east of S.H. 1. Zone 3-4 is typically underlain by geologically young (less than 10,000 years old) loose beach and dune sand, and peat, and comprises much of the coastal portion of the study area west of S.H. 1.

The response of each Ground Shaking Hazard 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 response characterisation for each zone comprises: expected Modified Mercalli intensity; peak horizontal ground acceleration; duration of strong shaking; and 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.

1. INTRODUCTION

Local geological deposits, or ground conditions, are well known for their ability to influence the level 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, "flexible" material experience greater shaking than nearby sites underlain by firmer, "stiff" material. This relationship has been recently documented in the Lower Hutt, Porirua, and Wellington areas during non-damaging shaking (see Van Dissen 1991, Van Dissen et al. 1992a), and in the San Francisco Bay area during both damaging and non-damaging shaking (Borcherdt 1991). Recent earthquakes affecting Mexico City, Leninakan, and Newcastle also 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 (e.g. Seed et al. 1988, Borcherdt et al. 1989, Rynn et al. 1992).

Strong ground shaking is the most pervasive earthquake hazard, and accounts, either directly or indirectly, for most of the damage, and consequent life loss, resulting from an earthquake. If areas of increased shaking hazard can be identified, then the potential exists to reduce the vulnerability, and risk, of the community to strong earthquake shaking. In Wellington City, the microzoning study of 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 A). While intensity is widely used for the evaluation and prediction of earthquake damage (e.g. Evernden & Thomson 1988), it is not the "final word" on ground shaking response. For example, intensity is not always well correlated with peak ground acceleration. In extreme cases, peak ground accelerations attributed to the same intensity can differ by close to an order of magnitude (e.g. Murphy & O'Brien 1977). 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 other 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 report forms part of a comprehensive study of seismic hazard for the Wellington Regional Council's Natural Disaster Reduction Plan. A primary aim of the Plan is the identification and reduction of the vulnerability of the community to seismic hazards. Fault rupture and Tsunami hazards in prescribed parts of the Wellington region have been addressed by Berryman & Fellows (1989), and Gilmour & Stanton (1990) respectively. In 1991, the earthquake ground shaking hazard in the Lower Hutt and Porirua areas was assessed (see Van Dissen 1991, and DSIR reports cited therein). A focus of this year's work has been the identification and quantification of the earthquake ground shaking hazard in the Kapiti Coast study area (Pukerua Bay to Otaki).

The purpose of this report is: 1) to summarize and integrate the findings of the various DSIR and University studies that have been carried out to help define the ground shaking hazard in the Kapiti Coast area; and 2) to provide the documentation needed to justify the presented ground shaking hazard zonation. In doing so, this report provides a stand-alone technical document to accompany the Ground Shaking Hazard Map for the Kapiti Coast (Fig. 1).

2. METHODOLOGY

A number of techniques were employed to identify and define geographic variations in earthquake ground shaking in the Kapiti Coast area. The distribution of the geological materials in the study area is summarized in Heron & Van Dissen (1992). Taber & Richardson (1992) assess the shaking response of a representative suite of these materials at 10 sites using records from 16 microearthquakes. Stephenson & Barker (1992) further quantify the properties of younger, "flexible", geological materials using ten cone- and two seismic-cone penetrometer probings.

A workshop held in mid-March, 1992, facilitated the compilation of the separate studies into a single integrated, multi-disciplinary ground shaking hazard assessment. At the workshop the findings of each study were critically compared to those of other studies, and were iteratively used to quantify the expected geographic variations in strong earthquake ground shaking in the Kapiti Coast area. The agreement found amongst the studies is the strength from which the Ground Shaking Hazard Zonation of the Kapiti Coast is presented. This zonation is described fully in section 3.

2.1 Earthquake Scenarios

The Wellington region is cut by several major active faults, and is not infrequently shaken by moderate to large earthquakes (Figs. 2 & 3, Van Dissen & Berryman 1991, Smith & Berryman 1986, 1990). At the beginning of this study, it was recognised that no single earthquake scenario adequately describes the potential ground shaking hazard facing the Kapiti Coast. The Pukerua, and Ohariu faults are within the study area; the Wairau, and Wellington faults are within 20 km of the study area. A large earthquake centred on any of these proximal faults will certainly be

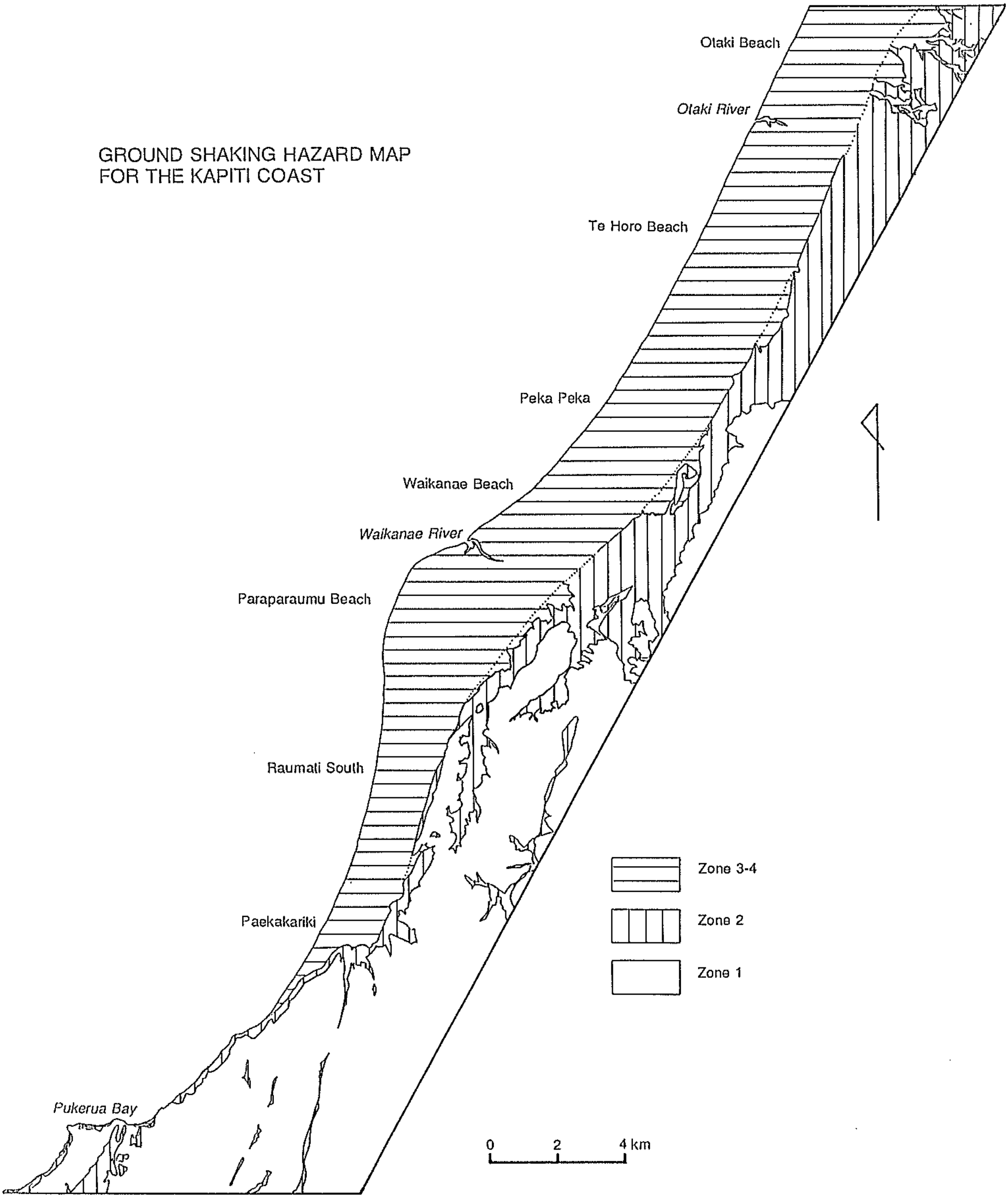

Figure 1. Ground Shaking Hazard Map for the Kapiti Coast.

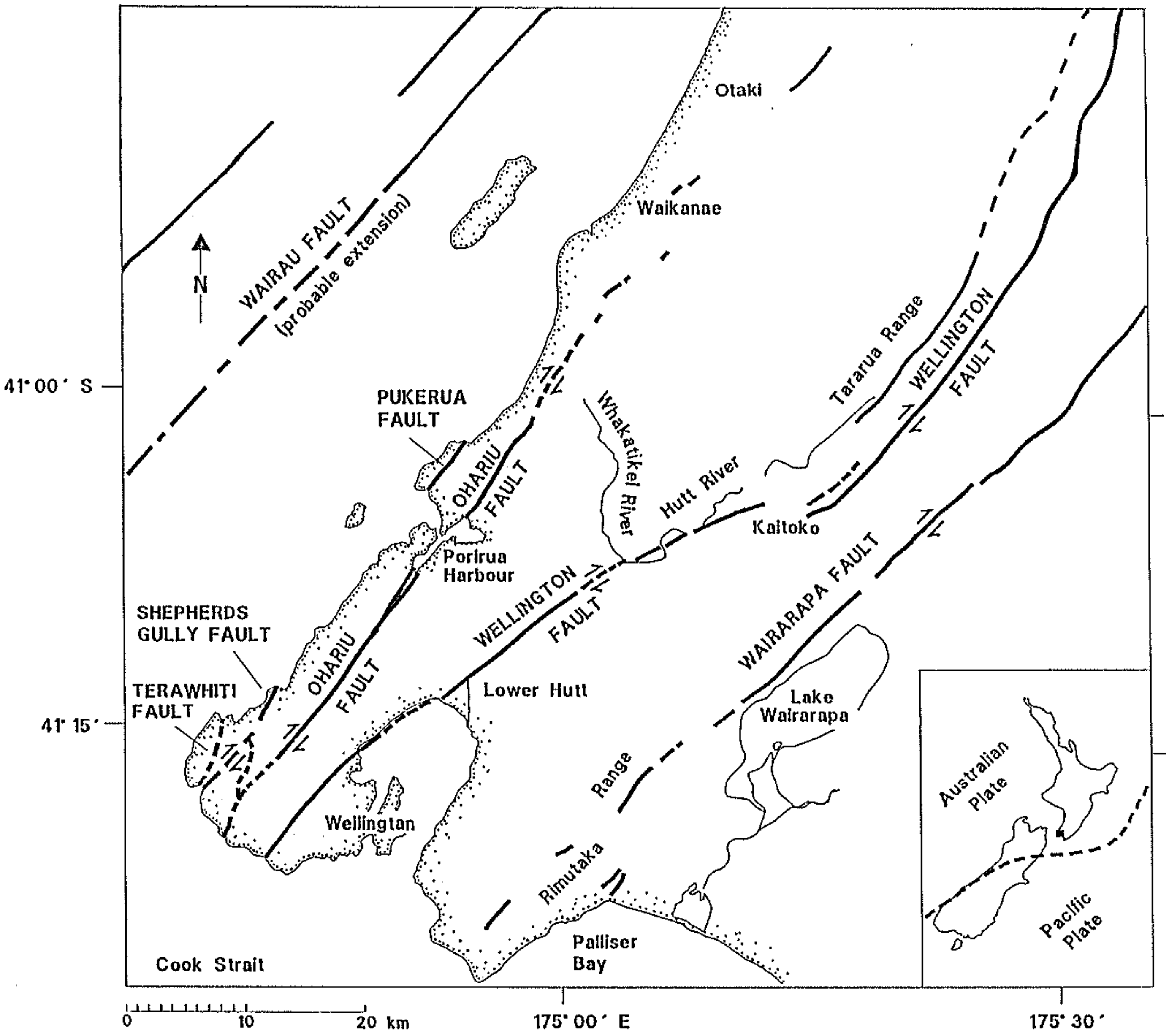

Figure 2. Active faults in the Wellington region.

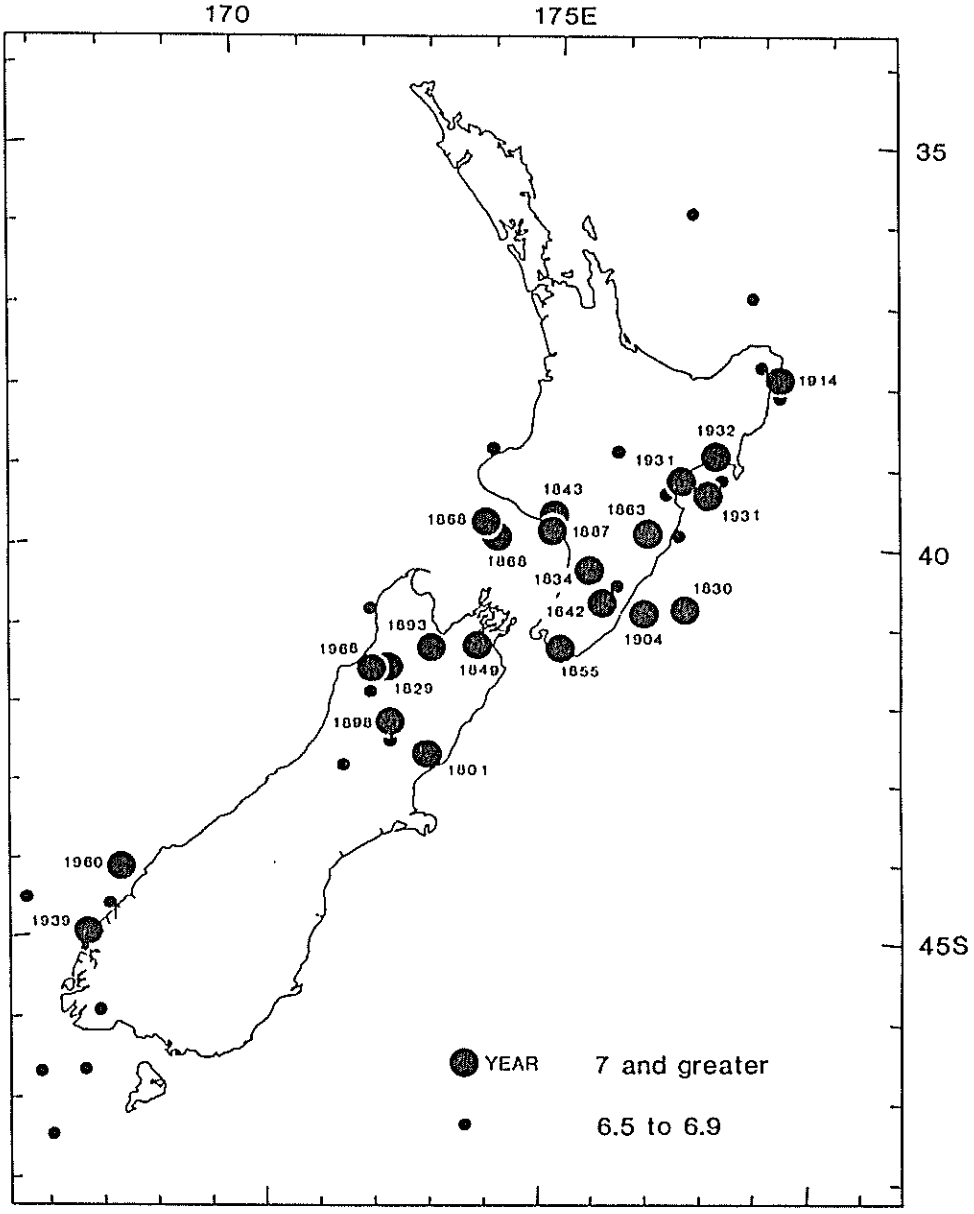

Figure 3. Epicentres of shallow earthquakes of magnitude 6.5 and greater since 1840. From Figure 2 of Smith and Berryman (1986).

devastating, yet significant localized damage is also expected from large, more frequent, distant earthquakes.

Recent assessments of ground shaking hazard in Wellington, Lower Hutt, and Porirua (Van Dissen 1991, Van Dissen et al. 1992a) have characterized shaking response based on two earthquake scenarios, a distant earthquake that results in regional MM V-VI shaking on bedrock, and a large Wellington fault earthquake. These two scenarios are also used in this report to characterize the shaking response of the Kapiti Coast study area. This is done, not to downplay the hazard represented by the active faults within the study area, but to provide a consistent frame of reference with the above cited Wellington region hazard assessments. Also of note, the mean earthquake recurrence interval for a large Wellington fault earthquake is about 600 years (Van Dissen et al. 1992b) which is several hundred to a few thousand years shorter than the estimated recurrence interval of the Wairau, Pukerua, or Ohariu faults (Van Dissen & Berryman 1991). The two earthquake scenarios are described below.

Scenario 1 is for a large, distant, shallow earthquake that produces MM V-VI shaking intensities in bedrock over the Kapiti Coast area. 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 (see Stephenson 1991). 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 7 earthquake centred about 100 km from the study area at a depth of less than c. 30 km, perhaps similar to the 1942 south Wairarapa earthquakes (Hayes 1943). The larger 1848 Marlborough earthquake (Eiby 1980, Dowrick & Smith 1990) would also have resulted in significant, and predictable, variations in ground shaking.

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 & Berryman 1990). This return time is derived from the historical occurrence of both large earthquakes, and moderate sized local events. While these local events resulted in MM VI on bedrock, they did not generally cause significant damage [e.g. the 1968 earthquake documented in the Wellington microzoning study (Grant-Taylor et al. 1974)]. Twenty years is thus a minimum estimate for the return time of a scenario 1 event. A reasonable maximum estimate is about 80 years, which is the return time of MM VII or greater shaking at bedrock sites in the Wellington region resulting from large earthquakes (Smith & Berryman 1990).

Scenario 2 is for a large earthquake centred on the Wellington-Hutt Valley segment of the Wellington fault. The closest distance from the Wellington-Hutt Valley segment to Pukerua Bay and Otaki is 15 km and 35 km respectively. 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 vertical displacement at the ground surface (Berryman 1990). This segment last ruptured 340-490 years ago (Van Dissen et al. 1992b), and the probability of a scenario 2 event occurring in the next 30 years is estimated to be about 10%.

It is with less certainty that the values for near-source[1] shaking resulting from a scenario 2 earthquake are reported. This is particularly the case for the southern portion of the study area because there are so few near-source 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 Kapiti Coast study area, and how they relate to the ground shaking zonation of this area are summarized below. More detail regarding specific techniques and findings is contained in the cited reports.

3.1 Identification of Ground Shaking Hazard Zones

Heron & Van Dissen (1992) have identified, and mapped, 15 geological units in the Kapiti Coast study area. These units range from hard rock (greywacke and quartzite), many millions of years old, to unconsolidated beach and peat deposits which are still accumulating today. The geological deposits in the Kapiti Coast area can be broadly grouped into three strength classes, the distributions of which can be described by the position of two distinct physiographic features in the study area: the hill country to the east, and coastal plain to the west.

The hill country of the study area is underlain by bedrock, typically composed of moderately

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[1] As defined by Krinitzsky & Chang (1977), near-field, when applied to intensity, refers to areas within a 45 km radius from the epicentre of a M 7.5 earthquake. For comparison, the epicentral, or near-source, region of the M 7.1 Loma Prieta earthquake, as defined by the MM VIII isoseismal, has a 10-15 km radius about the rupture plane at the ground surface (Plafker & Galloway 1989).

strong[2] to very strong greywacke, argillite, and quartzite, and weak to moderately strong sandstone, siltstone and greensand. These deposits are generally overlain by less than 3 m of scree, slopewash, and loess.

The coastal plain is divided into the Postglacial wedge, to the west, and the Pleistocene wedge, to the east, based on sediment age and the position of the Postglacial cliff (Fig. 4). The Postglacial cliff was formed about 6500 years ago when sea level reached a maximum and cut (eroded) a low cliff into the Pleistocene wedge. As sea level stabilized, or fell slightly, the coast prograded and the Postglacial wedge was formed. The Postglacial wedge is composed of beach and dune sand, interdune peat, and river and fan alluvium deposited in the last 6500 years. These sediments are classified as very weak to extremely weak rock (i.e., they are soils). Similar, but older and more consolidated materials comprise the Pleistocene wedge. The sand and gravel in the Pleistocene wedge is generally compact, and can be classified as weak to very weak rock.

Both the Postglacial and Pleistocene wedges presumably thicken towards the present-day coast. A drillhole at Te Horo indicates that the Postglacial wedge is composed of 40 m of unconsolidated sand, silt, and peat, and the Pleistocene wedge is composed of at least 120 m of compact gravel and sand.

Weak ground motions, resulting from microearthquakes, were measured at 10 sites in the Kapiti Coast study area (Taber & Richardson 1992). One site, the reference site, was located on bedrock. Two sites were located on the Pleistocene wedge, and seven sites were located on the Postglacial wedge.

The relative shaking response of each site is expressed as an averaged ratio of the Fourier spectra of the seismograms compared to a reference bedrock site. The ratios are reported as either peak values within the 0.5-4 Hz frequency band, or mean values averaged over the 0.5-2.5 Hz frequency band. In the following discussion, only peak values are noted; the mean values, though different in magnitude, yield a similar result. Relative to the reference bedrock site, the lowest ground motion amplifications were recorded at the two Pleistocene wedge sites. These sites are underlain by compact sand and gravel, and have peak Fourier spectral ratios (FSR) of 3.1 and 4.0. The remaining sites were located on the Postglacial wedge, composed of loose silt, sand, and fine gravel, and peat, and exhibit higher amplifications ranging from FSR=7.5-21, relative to the reference site. In the Paraparaumu area, shaking appears to increase towards the coast where sediment thickness is presumably greatest.

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[2] Soil and rock strength terminology follows that of New Zealand Geomechanics Society (1988).

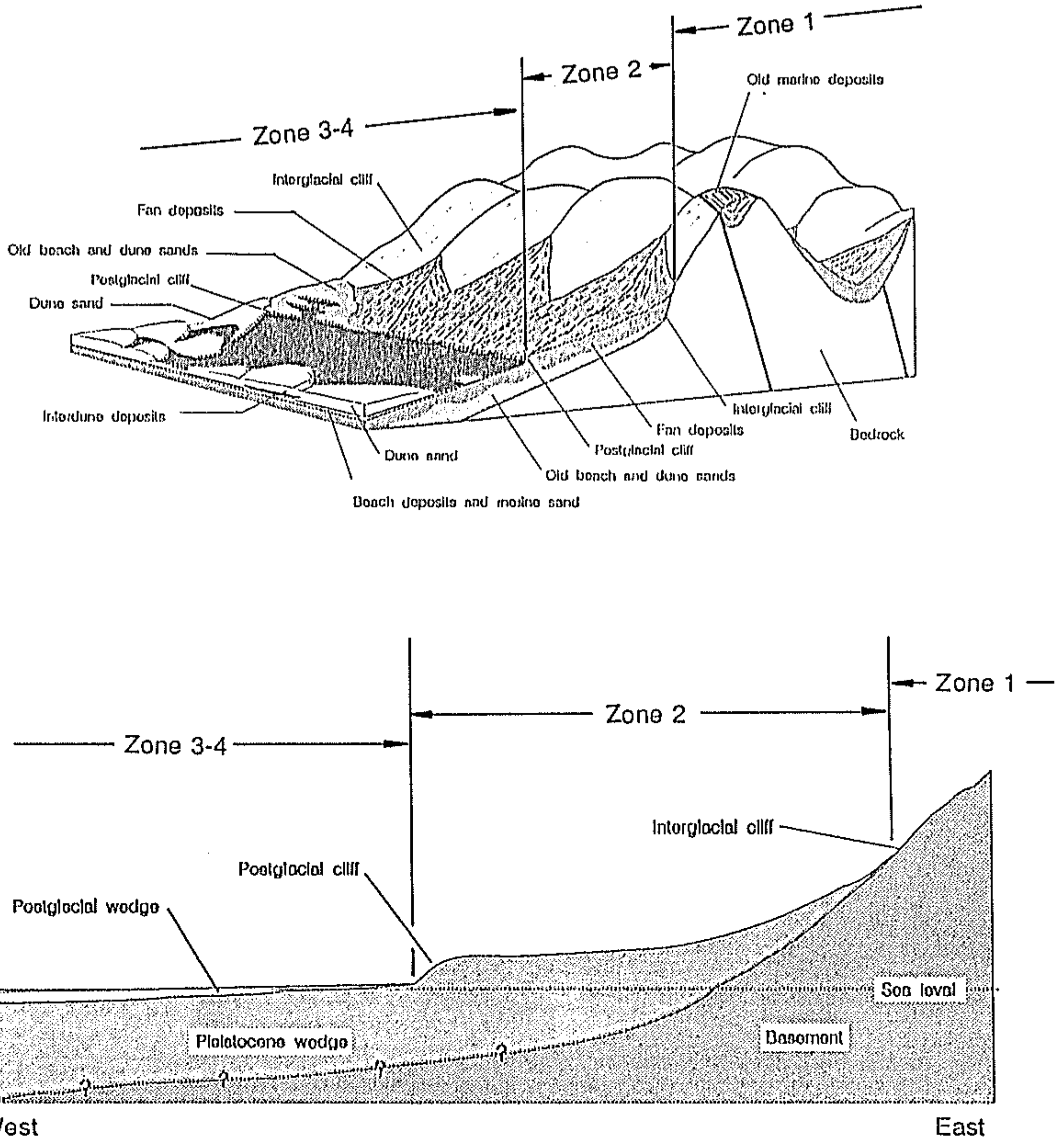

Figure 4. Diagrammatic cross-sections near Paraparaumu showing typical relations between the geological materials present in the Kapiti Coast area and the mapped Ground Shaking Hazard Zones. There is a general increase in ground shaking hazard and amplification from Zone 1 to Zone 3-4.

Stephenson & Barker (1992) further define the nature of the near-surface material at ten Postglacial wedge sites using cone- and seismic-cone penetrometer probing. At all sites probing was terminated at less than 10 m depth due to the inability of the cone to advance under the three tonne maximum load, indicating material that is strong in shear was encountered. The materials were generally loose to medium dense sand, and some peat and loose gravel. Using the seismic probe, shear wave velocities in the order of 130-200 m/s were measured at two sites for the upper 5 to 10 m. It is significant to note that during probing, no reflected seismic energy was observed. This suggests that shear wave velocity gradually increases with depth, at least to a depth below which a reflected signal could not be detected, in the order of 15 m.

Based on the distribution of geological materials along the Kapiti Coast, and the measured response of these materials to seismic waves, the Kapiti Coast study area is mapped into three Ground Shaking Hazard Zones: Zones 1, 2, and 3-4 (Fig. 1). The least hazardous zone, Zone 1, is characteristically underlain by bedrock. It is anticipated that this zone will exhibit very low to low amplifications of seismic waves. Zone 2 areas are directly underlain by the Pleistocene wedge composed of "stiff" material, including compact gravel and sand interbedded with weaker silt and peat. Relative to Zone 1, low to moderate ground motion amplifications are expected in Zone 2. With respect to ground shaking, Zone 3-4 represents the most hazardous zone in the study area. Zone 3-4 areas are typically underlain by the Postglacial wedge composed of loose material, including geologically young beach and dune sand, river and fan alluvium, and peat. Moderate to high ground motion amplifications are anticipated in Zone 3-4, relative to Zone 1. Figure 4 diagrammatically illustrates some of relationships between the above zonation and the underlying geology.

With respect to strong earthquake ground shaking, recent studies both in New Zealand and in California have found that the most "hazardous" site condition is typified by a greater than 10 m thickness of geologically young (usually less than about 10,000 years old), unconsolidated, often water saturated, fine-grained sediment with shear wave velocities in the order of 200 m/s or less. These materials, often referred to as "soft soil" or "flexible sediment", have the potential to greatly amplify earthquake ground shaking. Zone 3-4 materials in the Kapiti study area have near-surface shear wave velocities in the order of 200 m/s or less; however, there does not appear to be any appreciable mappable extent of such materials with thicknesses greater than 10 m. This contrasts with other parts of the Wellington region, such as the low-relief coastal areas in Wellington, Lower Hutt, and Porirua that are typically underlain by thick "soft soil" or "flexible sediment".

3.2 Geological Description of Hazard Zones

Zone 1: Bedrock. Moderately strong to very strong quartzite, and sandstone and argillite (collectively referred to as greywacke). Also included are weak to moderately strong siltstone, sandstone, and greensand. These rocks are typically moderately weathered, but in places are highly weathered. Rock defects are common, and most closely spaced adjacent to major faults. Areas within Zone 1 are often overlain by less than 3 m of scree, slopewash, and loess.

Zone 2: Stiff sediment. Compact to very compact granular material composed primarily of Pleistocene gravel and sand. These materials are interbedded with weaker layers of silt and peat, and are collectively referred to as the Pleistocene wedge. The maximum sediment thickness beneath this zone is unknown, but probably exceeds 100 m in places.

Zone 3-4: Loose sediment. Loose to moderately dense granular material composed of geologically young (less than 6500 years old) beach and dune sand, and river and fan alluvium. Interdune peat, up to about 5 m thick, is also present. Collectively these sediments comprise the Postglacial wedge, and have near-surface shear wave velocities in the order of 200 m/s or less that probably gradually increase with depth. From the Postglacial cliff, these sediments almost certainly thicken to the west, towards the present-day coast. At Te Horo they are 40 m thick.

3.3 Quantification of Ground Shaking Hazard Zones

The shaking response of the Ground Shaking Hazard Zones (Zones 1, 2, and 3-4) is assessed for the two earthquake scenarios described in section 2.1. 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; and 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. 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 expected for 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

Scenario 1: The scenario 1 earthquake will be of sufficient duration and contain sufficient long period energy to allow strong long-period response to develop at 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" rock 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 (e.g. Evernden & Thomson 1988, Lowry et al. 1989, Plafker & Galloway 1989). However, it is again important to note that there does not appear to be an appreciable, mappable extent of thick (in the order of 10 m or more), near-surface "soft soil" or "flexible sediment" in the study area. Thus a spread of three to four MM units, resulting from geographic variation in near-surface geology, is not anticipated for earthquakes impacting the Kapiti Coast. The response of Zone 3-4 is expected to be in the order of 1 to 2 MM intensity units stronger than Zone 1 (Table 1, Fig. 5). The Zone 2 response is expected to be one MM intensity unit stronger than Zone 1, similar 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, and Zone 3-4 is MM VI-VII (Table 1).

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, and an increase in the variability of shaking within each zone, owing in part to differing source to site distances between the southern and northern part of the study area. In general, shaking decreases with increased distance from the source. Pukerua Bay is about 15 km from the Wellington-Hutt Valley segment; Otaki is about 35 km from the northern-most portion of the segment. Thus sites near Otaki are expected to shake less than similar sites near Pukerua Bay. The shaking in Paraparaumu and Waikanae is expected to be intermediate between that of Pukerua Bay and Otaki.

Epicentral intensities for the 1989 Loma Prieta earthquake were MM VIII (Plafker & 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).

Using the above relationships, MM VIII is expected in Zone 1 in the southern portion of the study area (Table 1). Further from the fault, near Otaki, MM VII is expected. MM VIII-IX is expected in

Table 1. Ground motion parameters, and values, for the Ground Shaking Hazard Zones in the Kapiti Coast area.

Scenario 1

Zones	MM Intensity	Peak ground acceleration (g)	Duration	Amplification of ground motion (FSR)
1	V-VI	0.02-0.06	<5 sec	c. 1
2	VI	0.02-0.1	2-3x	<5x
3-4	VI-VII	0.02-0.1	2-3x	>5x, generally 8-15x

Scenario 2

Zones		MM Intensity	Peak ground acceleration (g)	Duration
1	Pukerua Bay	VIII	0.3-0.6	15-40 sec
	Otaki	VII	0.1-0.3	10-30 sec
2	Pukerua Bay	VIII-IX	0.3-0.6	1-2x
	Otaki	VII-VIII	0.1-0.3	1-2x
3-4	Pukerua Bay	IX-X	0.3-0.6	2x
	Otaki	VIII-IX	0.1-0.3	2x

Zone 2 near Pukerua Bay, and MM VII-VIII further afield, near Otaki. In Zone 3-4, MM IX-X is anticipated in the southern portion of the study area, and MM VIII-IX in the northern portion.

3.3.2 Peak horizontal ground acceleration (pga)

For both scenarios, peak horizontal ground acceleration is estimated based on comparisons with a number of appropriate attenuation relations (e.g. Campbell 1981; Joyner & Boore 1981; Idriss 1985, 1990; Fukushima & Tanaka 1990). In general, the peak ground accelerations presented below (Table 1) are within one standard deviation of the values predicted using any of the above relations [see Sritharan & McVerry (1991) for more detail]. Values for scenario 1 are also compared to those recorded during the Loma Prieta earthquake (Plafker & Galloway 1989, Borcherdt & 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 both Zones 2, and 3-4.

Scenario 2: The average peak ground accelerations expected for scenario 2, based on the cited attenuation relations and geological (site) considerations are as follows: Zone 1, 0.3-0.6 g near Pukerua Bay, 0.1-0.3 g near Otaki; Zones 2, and 3-4, 0.3-0.6 g near Pukerua Bay, 0.1-0.3 g near Otaki (Table 1).

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, amplitude and duration of shaking increases with decreasing firmness of the underlying sediment. This has been observed in the Kapiti Coast area for non-damaging earthquakes (Taber & Richardson 1992) and elsewhere for larger damaging earthquakes (e.g. Borcherdt & 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 1). The expected increase in duration of shaking relative to bedrock is 2-3 times in Zones 2, and 3-4. These values are broadly consistent with the intensity based increases in duration reported in Krinitzsky & 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, close to Pukerua Bay, 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). Zone 1 shaking near Otaki would be expected to be in the order of 10-30 sec. The anticipated increase in duration, relative to Zone 1, is 1-2 times for Zones 2, and 2 times for Zone 3-4 (Table 1).

3.3.4 Amplification of ground motion spectrum

Taber & Richardson (1992) measured the relative shaking response at 10 sites throughout the Kapiti Coast area due to microearthquakes. Their results are expressed as both peak values, over the frequency band of 0.5-4 Hz, and mean values, over the frequency band of 0.5-2.5 Hz, of averaged ratios of Fourier spectra of the seismograms compared to a reference site on bedrock. Peak ratios vary from less than 5 for "stiff" sediment sites to greater than 20 for thick, loose sediment sites.

Characteristic peak Fourier spectral ratios (FSR), within the frequency band of 0.5-4 Hz, for each of the mapped Hazard Zones are as follows (Table 1): Zone 1, very low to low amplifications with FSR near 1; Zone 2, low to moderate amplifications with FSR less than 5; Zone 3-4, moderate to high amplifications with FSR greater than 5, generally about 8 to 15.

Fourier spectral ratios have previously been determined in Lower Hutt, Porirua, and Wellington (Taber & Richardson 1992, Taber & Smith 1991, Taber 1991). When comparing the Lower Hutt and Porirua ratios with those determined in the Kapiti Coast area, the Kapiti Coast ratios need to be scaled by a factor of 0.5, due to the relatively quiet reference site used in the Kapiti Coast study compared to the reference site in Lower Hutt or Porirua. When comparing the Wellington ratios with those of the Kapiti study, the Kapiti ratios need to be scaled by a factor of 0.33, again due to the relatively quite Kapiti reference site compared to the Wellington reference site.

Taber & Richardson (1992) suggest that their results are not only useful for determining relative shaking, but also for identifying the frequencies over which this shaking will be most strongly amplified during certain earthquakes, specifically scenario 1 type events. This is supported by the findings of Borcherdt et al. (1989) who concluded that the frequency of amplified shaking in Leninakan during aftershocks of the 1988 Armenian earthquake was similar to the natural period of the buildings most heavily damaged in the larger damaging main shock, a M 6.8 event about 35 km distant from Leninakan.

Ground motion amplification at most sites in the Kapiti Coast study area occurs over a broad frequency band. Some Zone 3-4 sites exhibit a notable high frequency response. Two sites in particular show a narrow (resonant) frequency response at about 9 Hz. Resonant response appears most common when relatively thin (less than about 30 m), "flexible", low velocity sediment overlies much firmer material; the resonant frequency is a function of the thickness and velocity of the "flexible" layer. Site resonance is of most concern where man-made structures exist with natural periods that coincide with the resonant period band(s) of strong ground shaking. The resonant response in the above two cases is attributed to a thin (in the order of 4 m or less) layer of peat and silty sand. The lack of resonance at the other Kapiti sites probably indicates that the increase with depth of shear wave velocity and stiffness is gradual instead of occurring at an abrupt layer boundary.

Even though the ground motion amplifications measured in the Kapiti Coast study area were recorded during non-damaging earthquakes (low-strain shaking), it is significant to note that intensity maps prepared in the 1970's for the San Francisco Bay area, based on low-strain amplification, anticipated all of the areas that experienced high intensity shaking during the damaging 1989 Loma Prieta earthquake (Borcherdt 1991). However, the level of amplification during even larger ground motions, that is, the level of shaking at near-source sites during large or great earthquakes is an unresolved question. An amplification of near FSR=20 at Paraparaumu is unlikely to persist to extreme motions (e.g. Jarpe et al. 1989) because at high strain levels weak sediments begin to behave in a nonlinear fashion, i.e. they begin to lose strength and increase wave attenuation or damping. This is particularly the case for the relatively non-cohesive sediments that typify the materials that comprise the Postglacial wedge. Nevertheless, variations in the nature of seismic response can still be expected from one zone to another. High amplification of small bedrock ground motions, such as the scenario 1 bedrock motions, means that significant local damage at the "worst" sites in Zone 3-4 could result from an earthquake that would cause little or no damage in Zone 1. It is amplification of small bedrock ground motions that the measured spectral ratios best characterize, thus they are given only for scenario 1.

3.4 Some Comparisons with a Recent California Zonation

Borcherdt (1991) takes advantage of the relatively complete geologic, geotechnical, and seismic data sets available for the San Francisco Bay area to develop empirical relationships regarding the shaking response characteristics of the wide spectrum of geological deposits in the area. The data sets include detailed geological maps, shear wave velocity logs, intensity data from the 1906 and 1989 earthquakes, and weak and strong motion records. The geological deposits of the San Francisco Bay area have many similarities with those encountered in the Wellington region, including the Kapiti Coast.

Borcherdt (1991) presents correlations among the near-surface geological materials present in the San Francisco Bay area; near-surface shear-wave velocity measured for the upper 30 m; amplification of ground motion, expressed as a ratio of average Fourier spectra for the period band 0.4-2 seconds, measured both during low-strain (non-damaging) shaking and the damaging Loma Prieta earthquake; and felt intensities for the great 1906 San Francisco earthquake. These correlations are summarized in Table 2, and Figures 5 & 6. Figures 5 & 6 show that mean amplification in terms of measured ground motions or felt earthquake intensity increases with decreasing near-surface shear wave velocity of the local geological material. Also shown on Figure 5 are characteristic shear wave velocities for typical near-surface geological materials present in the Wellington region, and the correlation of these materials with the mapped Ground Shaking Hazard Zones.

The ground motion results summarized in this report and those presented in Borcherdt (1991) are highly compatible. Both studies show an increase in ground motion with decreasing firmness of the near-surface deposit.

The Ground Shaking Hazard Map for the Kapiti Coast (Fig. 1) could also be called an "amplification capability map", using the terminology of Borcherdt (1991) and Borcherdt et al. (1991). It is a map that identifies zones according to their capability to amplify ground motion. By identifying zones of differing ground shaking hazard, potential exists to reduce the risk posed by this hazard. For example, during the 1989 Loma Prieta earthquake the areas located outside the immediate epicentral region that experienced intense damage were underlain by soft, low velocity sediments, similar to materials that have been mapped elsewhere in the Wellington region as Zone 5. In the great 1906 San Francisco earthquake, sites underlain by these materials averaged 2-3 units greater intensity shaking compared to nearby sites underlain by strong rock.

Table 2. Grouping of geological materials in the San Francisco Bay area according to amplification capability, based on measured ground motion amplification, intensity increment, physical properties, and geological characteristics. The relationship between this grouping and the Ground Shaking Hazard Zones in the Wellington region is shown. After Table 2 of Borcherdt (1991).

Wellington region Ground Shaking Hazard Zones	Amplification Capability (Geologic Descriptions)		Amplification			Intensity Incr.			Av.S.vel. (m/s)		
			mean	no.	s.d.	mean	no.	s.d.	mean	no.	s.d.
Zone 5		*rel.dens.*									
	I HIGH-VERY HIGH										
	Artificial fill/ estuarine Bay Mud	vsoft-soft	*5.70*	*33*	*3.31*	*2.43*	*33*	*0.58*	*130*	*4*	*15*
Zones 4-2	*II* INTERMEDIATE-HIGH										
	Alluvium . Merced Fm.		*2.50*	*30*	*1.10*	*1.34*	*30*	*0.58*	*310*	*32*	*77*
	Holocene		2.60	21	1.17	1.24	21	0.60	290	21	70
	Pleistocene		2.10	9	0.82	1.08	9	0.46	354	11	74
	Colma Fm.	d.-vdense							400	2	85
	Merced Fm. (med.-vfine)	d.-vdense							317	4	43
Zone 1		*fr.space.*									
	III LOW-INTERMEDIATE										
	Soft-Firm Rock		*1.50*	*17*	*0.56*	*0.68*	*17*	*0.45*	*445*	*10*	*71*
	Conglomerate, Sandstone										
	Santa Clara Fm.	none,most	1.70	6	0.64	0.82	6	0.49	442	3	55
	Sedimentary Rocks (firm-soft)	mod-vwide	1.40	9	0.45	0.64	9	0.34			
	sandst,siltst,shale,silty mudst								380	3	71
	Misc. Rocks (firm-soft)										
	Franciscan gouge,melange	vclose-mod							482	2	74
	serpentinite	vclose	1.11	2	0.64	0.29	2	0.72	510	2	0
	IV LOW-VERY LOW										
	Firm-Hard Rock		*0.87*	*19*	*0.34*	*0.03*	*19*	*0.44*	*670*	*14*	*156*
	Franciscan sandst,shale,chert	close-mod	0.96	14	0.36	0.14	14	0.45	686	6	114
	sandst, shale, mudst	vclose-mod							666	4	101
	granite (deeply weathered)	close-wide							533	3	168
	granite ,greenst	close-mod	0.63	5	0.11	-0.29	5	0.21	1000	1	0

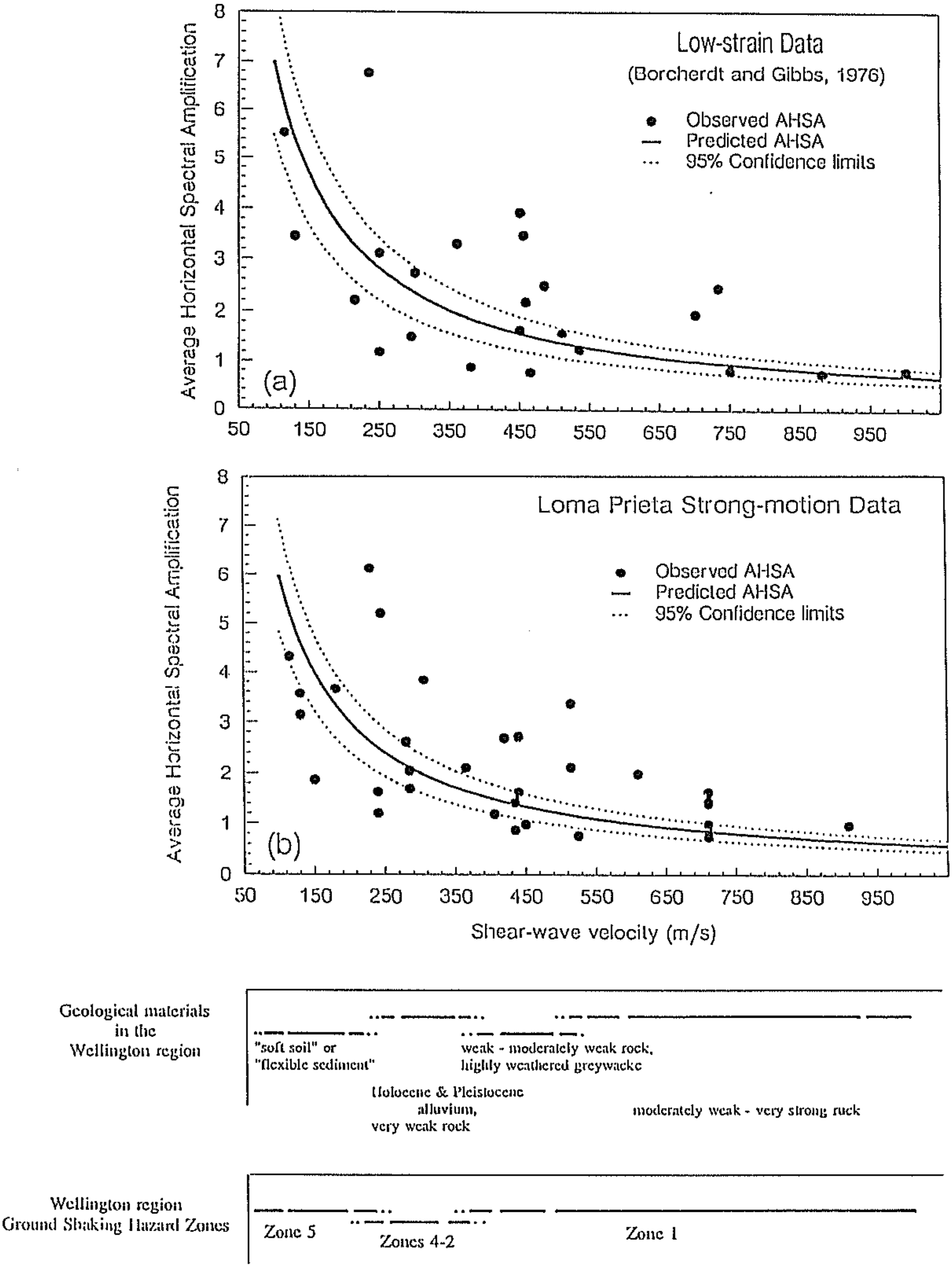

Figure 5. Average horizontal spectral amplification (AHSA) of ground shaking, plotted against near-surface shear wave velocity, measured in the San Francisco Bay area during both (a) low-strain shaking and (b) the Loma Prieta earthquake. Also shown are typical measured, and estimated, near-surface shear wave velocities for the geological materials in the Wellington region, and corresponding Ground Shaking Hazard Zones. After Figure 5 of Borcherdt (1991).

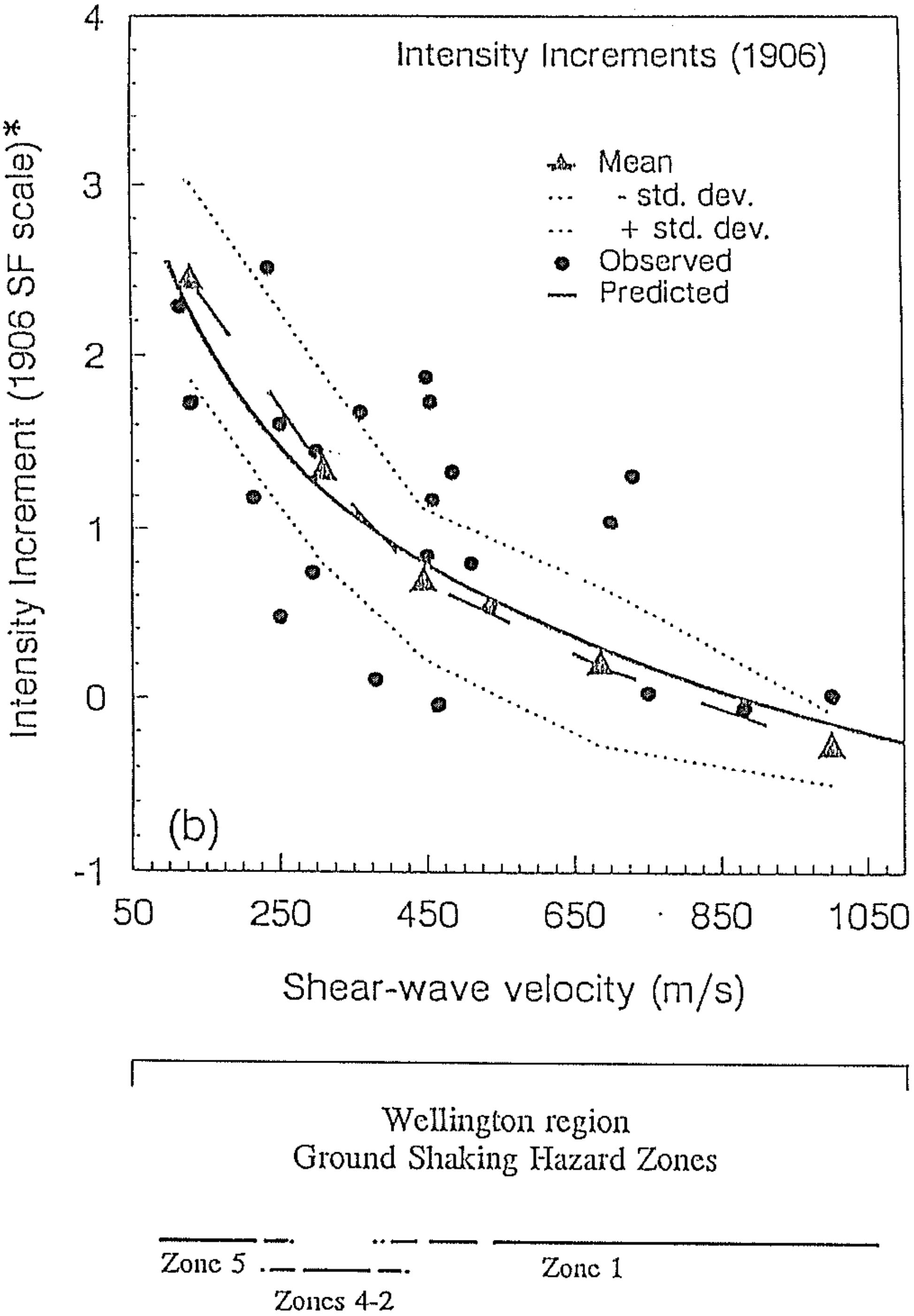

Figure 6. 1906 San Francisco earthquake intensity increments for individual sites in San Francisco, plotted against the near-surface shear wave velocity of the site. Also shown are representative correlations between near-surface shear wave velocity and the Ground Shaking Hazard Zones mapped in the Wellington region. This plot, as well as Figure 5, shows that average ground motion amplification increases with decreasing near-surface shear wave velocity. * Note, an increment on the 1906 San Francisco intensity scale is approximately equal to an increment on the MM intensity scale, at the levels of shaking experienced in San Francisco during the great 1906 earthquake. After Figure 6 of Borcherdt (1991).

4. ASSUMPTIONS, LIMITATIONS, AND RECOMMENDATIONS

Important assumptions that limit the certainty with which the Ground Shaking Hazard Zones can either be mapped or quantified are discussed below. Recommendations for further work are also presented.

a) 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.

Along most of the Kapiti Coast the Postglacial cliff marks the boundary between Zone 2, and Zone 3-4 (Fig. 1). However, near Waikanae, and north of Otaki, sand derived from the Postglacial wedge has been blown up and over the Postglacial cliff and formed dunes on top of the Pleistocene wedge. The tallest dunes rise 20 m above the surrounding surface of the Pleistocene wedge. In places, peat has formed between the dunes. Even though these geologically young deposits lie east of the Postglacial cliff, they are mapped as Zone 3-4. The position of the cliff in these cases is marked by a dotted line on figure 1. Where these deposits are thin however, in the order of less than 5-10 m thick, their shaking response may be more typical of Zone 2.

The Waikanae and Otaki Rivers flow west across the Postglacial wedge. Coarse-grained channel deposits (gravel and sandy gravel) and finer-grained overbank flood deposits (sand and silt) proximal to these rivers commonly form lenses within, or a thin veneer (less than 5 m thick) of alluvial sediment on top of the Postglacial wedge. The Postglacial wedge is primarily composed of beach and dune sand, and interdune peat, and the presence of thin alluvial deposits is not expected to alter the Zone 3-4 designation given the Postglacial wedge. However, it is possible that in places the coarse-grained alluvial deposits are thick, in the order of the thickness of the Postglacial wedge. In these cases, the response to earthquake shaking may be more characteristic of Zone 2.

Recommendation:
We recommend that detailed geological mapping, supplemented by penetrometer probing and seismograph instrumentation, be undertaken to resolve these questions, particularly in areas of ongoing or projected population growth.

b) High amplifications ($FSR \geq 20$) have been recorded at Paraparaumu Beach (Taber & Richardson 1992) but the areal and subsurface distribution of the materials causing these amplifications is not well defined. This area has been mapped as Zone 3-4 because the presumed non-cohesive nature of the near-surface sediment at this site implies that high amplifications will not persist at high levels of shaking. If the sediment properties are not as presumed, then high amplifications could occur at high levels of shaking, and the area would be better mapped as a more hazardous zone, Zone 5.

Recommendation:

Detailed geological mapping, supplemented by penetrometer probing, and seismograph instrumentation should be undertaken to define the areal extent of these high amplifications, and the distribution and physical properties of the geological materials causing them. This work would result in a more accurate ground shaking hazard zonation. This is most critical in areas of present or projected urban growth.

c) Near-surface shear wave velocities, including velocity profiles, for the geological materials in the Kapiti Coast area are not well known. Shear wave velocity, not strength, is the parameter that best correlates with site amplification. Velocity profile provides information regarding possible site resonance.

Recommendation:

Seismic cone penetrometer probing is ideally suited for measuring shear wave velocities for near-surface "flexible sediment". Geophysical techniques, and down-hole measurements would be required to determine the shear wave velocities of the more compact, or stiff, materials in the Kapiti Coast area.

d) Amplification of ground motion due to topographic effects has not been addressed in this study. Though probably localized, these effects can nevertheless be pronounced. Spectral ratios of up to 8 have resulted from topographic amplifications at rock sites (Tucker et al. 1984). In the Porirua area, Taber & Smith (1991) suggest that the high amplifications at a firm site in Whitby were also, in part, the result of topographic effects.

The effects of topography on ground motion are outlined in Finn (1991), and depend on the shape of the topography and how the dimensions of the topography relate to the wavelengths of earthquake motion. Over a frequency range of engineering interest, 0.2 Hz to 25 Hz, the range in wavelengths is from 40 m to 5 km, assuming a shear wave velocity in rock of 1 km/s. Topographic features with characteristic lateral dimensions in this range, 40 m to 5 km, have the potential to significantly effect earthquake ground motions, depending also on the shape of the topography.

Recommendation:

We recommend undertaking a detailed assessment of previous case histories, instrumentation of characteristic topographic shapes, physical modelling, and/or sophisticated mathematical modelling, such as that described in Benites & Haines (1991), in order to develop a systematic approach for the identification of "higher risk" topographic shapes and orientations in the Kapiti Coast area.

e) Figure 6 illustrates the important information regarding site response that can come from the analysis of historical earthquake intensity data. The strongest shaking Kapiti Coast has experienced this century resulted from the 1942 south Wairarapa earthquakes, yet the intensity data from these earthquakes remains relatively unstudied.

Recommendation:

A detailed investigation should be undertaken to document possible geographic variations in ground response (intensity), and building damage in Kapiti Coast resulting from the 1942 earthquakes.

f) Near-surface geology (site condition) is a primary factor influencing the relative level of earthquake shaking at a site. Earthquake source and path effects, including size of and distance from an earthquake, complexity of rupture, direction of rupture propagation, and possible crustal reflections, can also play an important role; however, most of these factors are unique for every earthquake impacting on a site, and are thus difficult to characterize on a regional scale.

The subsurface distribution of sediment, including the shape, depth and type of sediment fill, can influence both the direction and frequency content of shaking at a site. It is not uncommon for sites within a sedimentary basin to show a marked directionality of response during earthquakes. Also, total sediment thickness, not just the physical properties of the near-surface sediments, can strongly influence the frequency band over which shaking is amplified. Deeper sediment sites tend to show broader band amplifications and stronger long period response. If the sediment of the coastal plain, or a region of the plain, consistently responds strongly in certain directions, then this information can be incorporated into the design and siting of safer man-made structures.

Recommendation:

Additional seismograph instrumentation, further analysis of existing earthquake records, and mathematical modelling should be combined to develop methods of predicting the direction of strongest response at various frequencies during different types of earthquakes.

g) 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 be most pronounced in the southern portion of the study area, and 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.

h) This report provides useful information for the mitigation of the ground shaking hazard in the Kapiti Coast area, but should not be used to replace site specific studies.

5. CONCLUSIONS AND IMPLICATIONS

The zonation presented in this report accounts for geographic variations in strong earthquake ground shaking resulting from near-surface geological ground conditions. This zonation, coupled with land-use policy, is an important step towards reducing earthquake related damage and life-loss in the Kapiti Coast area.

In the Kapiti Coast study area, three Ground Shaking Hazard Zones have been identified: Zones 1, 2, and 3-4 (Fig. 1). Zone 3-4 is 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 1. In general, the level of shaking in Zone 3-4 is expected to be 1 to 2 MM intensity increments greater than in Zone 1.

Zone 3-4 areas are typically underlain by loose beach and dune sand, river and fan alluvium, and peat. These sediments comprise the Postglacial wedge. Zone 2 areas are characteristically underlain by compact gravel and sand, interbedded with weaker silt and peat. These materials comprise the Pleistocene wedge. Zone 1 areas are underlain by bedrock.

In the Kapiti Coast study area there does not appear to be extensive areas underlain by thick deposits of "soft soil" or "flexible sediment". These materials, characteristic of the low-relief, coastal areas of Wellington, Lower Hutt, and Porirua, are expected to most strongly amplify earthquake ground motions. Areas underlain by such materials are thus subject to the greatest earthquake ground shaking hazard in the Wellington region. The absence of these sorts of materials in the Kapiti Coast study area implies that earthquake microzone effects in the Kapiti Coast area will be less pronounced than in, for example, Wellington or Porirua.

6. ACKNOWLEDGMENTS

Review of this report by Alan Hull, and Nick Perrin (DSIR Geology & Geophysics) are acknowledged.

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APPENDIX

MODIFIED MERCALLI INTENSITY SCALE

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.

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.