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Earthquake hazards in Hawke's Bay: initial assessment

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by

J. G. Begg, A. G. Hull, G. L. Downes

Prepared for

HAWKE'S BAY REGIONAL COUNCIL

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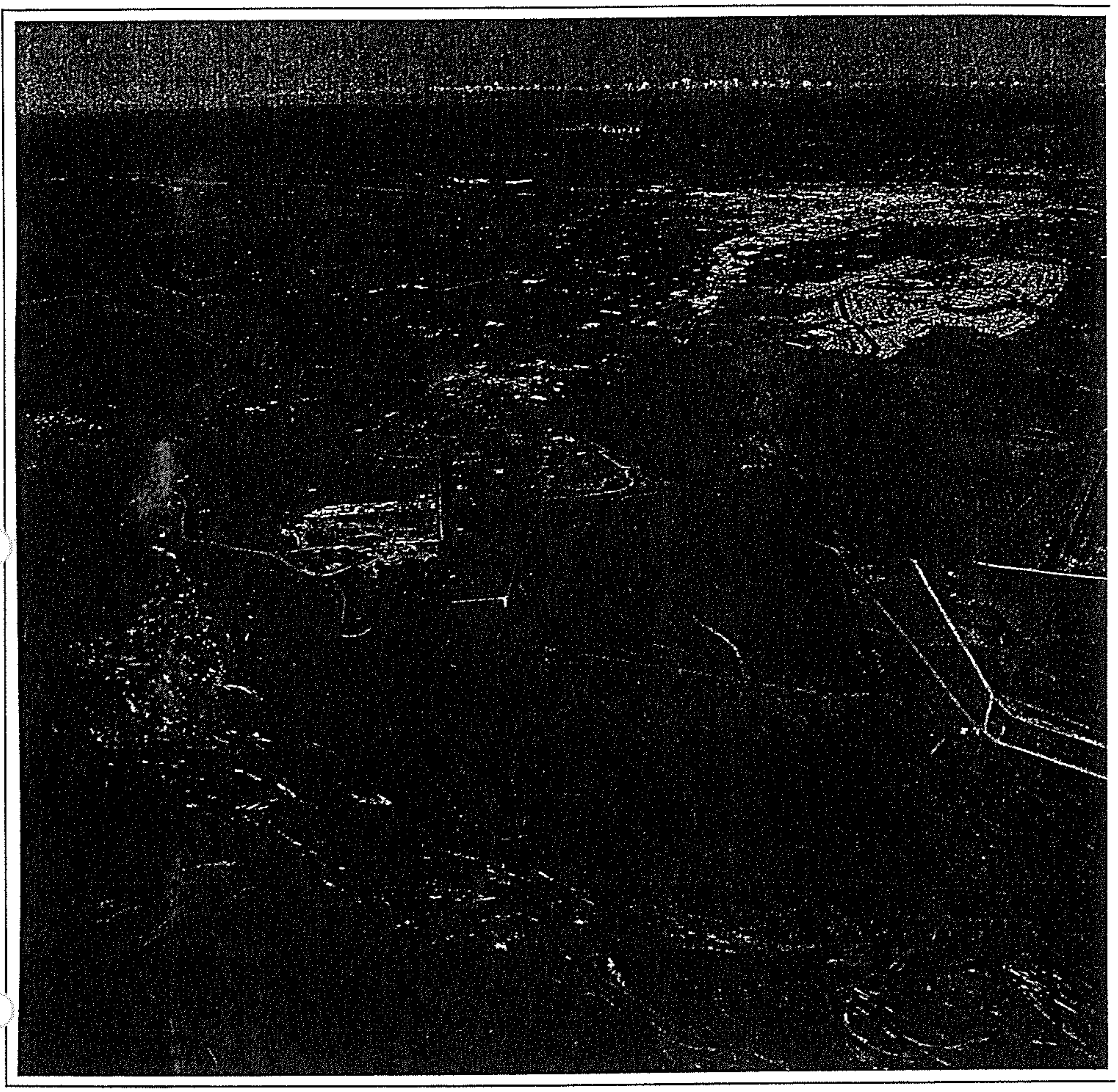

Frontispiece: Oblique aerial photograph of the Heretaunga Plains, looking east down the Ngaruroro River from above Fernhill, to Cape Kidnappers. Flaxmere and Hastings are on the right.

Photo: Lloyd Homer

Earthquake Hazards in Hawke's Bay: Initial Assessment

Summary

Studies of historical moderate to large earthquakes, and past large earthquakes inferred to have occurred along active faults and folds indicate that the Hawke's Bay Region is one of the most earthquake-prone regions of New Zealand. Historically, strong earthquake shaking in excess of Modified Mercalli Intensity VII has been felt in Hawke's Bay on at least 19 occasions. There are a minimum of 22 known active faults and folds within the onshore and offshore regions of Hawke's Bay that are capable of producing very strong earthquake shaking in the future. Five of these are capable of producing levels of earthquake shaking similar to those experienced in 1931 in the Heretaunga Plains.

The short historical record and very limited data on past movements along both these faults, and other faults that pose significant earthquake hazards to Hawke's Bay, do not permit an accurate quantification of the probability of future large or great earthquakes and the associated strong shaking and damage.

We therefore recommend a four-stage programme of further study of earthquake hazards in Hawke's Bay. These studies focus on quantifying the geological, seismological and geotechnical properties of the earthquake sources and the effects of shaking on the water-saturated and weak ground of the Heretaunga Plains. The programme of extra studies would result in a series of reports and maps that quantify more accurately the earthquake hazards in Hawke's Bay.

The benefits of these studies would be: 1) to provide a comprehensive information base on which to develop appropriate emergency response plans for Civil Defence, 2) to provide quality data for inclusion in regional and district land information systems, 3) to provide a foundation for the development of suitable hazard avoidance and mitigation measures; to encourage informed public debate about the nature of earthquake hazards and appropriate community response to the hazard, and the reduction of vulnerability to earthquake hazards.

Fault	Maximum probable earthquake Magnitude	Calculated Felt Intensity (MM)			Estimated recurrence interval (years)	Time of last movement (yrs B.P.)
		Waipukurau-Waipawa	Napier-Hastings	Wairoa		
Napier-Hawke Bay fault	7.8	10	10	10	>1800	AD1931
Waipukurau-Poukawa shear zone	7.8	10	10	10	500-800	AD1931
Kidnappers anticline	7.5	8	9-10	9	c. 1000	1-2 post-2200
Lachlan anticline	7.8	8	8	9	500-1500	c.300
Subduction zone	8.0+	9-10	9-10	9-10	?	?AD1931

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1.0 Introduction

Earthquakes are an integral part of the natural environment in New Zealand as a result of New Zealand's location at the collision zone between the Australian and Pacific plates - two of the great crustal plates of the earth. Earthquakes cannot be controlled, but with an understanding of the frequency and rate of occurrence of earthquakes in a region, and how the shaking generated by these earthquakes is modified by near-surface geological ground conditions, earthquake hazards can be assessed. Effective measures may then be introduced to mitigate the effects of these earthquake-related hazards on the community. Some mitigation measures against the effects of earthquakes are already in place in New Zealand, most notably a comprehensive building code that requires a high level of earthquake resistant design.

Under the Resource Management Act (1991), responsibilities for natural hazard identification and mitigation are defined and distributed among Central, Regional and Local Government. Key functions of Regional Councils are the collection and distribution of information on natural hazards. Earthquake hazards are one of the major natural hazards, and are present to varying degrees in all parts of the country. Because earthquake hazards generally affect wide regions, the Hawke's Bay Regional Council is well placed to address management issues and concerns pertaining to the impact of earthquakes in the region. As a result of agreement reached between the Hawke's Bay Regional Council and the Institute of Geological & Nuclear Sciences Limited (Memorandum of Understanding - 31 May, 1993), this study was undertaken by the Institute with the following objectives:

- To assemble existing information on the location of historical earthquakes in the Hawke's Bay Region.
- To assemble existing information on the locations of past movements along known active faults within the boundaries of the Hawke's Bay Region.
- To collate any existing information on the activity of faults from offshore regions important to earthquake hazards assessment in the Hawke's Bay Region.
- To identify general regions that are underlain by materials capable of amplifying earthquake ground shaking.
- To recommend possible future actions for Hawke's Bay Regional Council to quantify the earthquake hazards in the Hawke's Bay Region so that earthquake hazards mitigation policies and objectives can be formulated.

In accordance with the objectives stated above we have completed the following work:

(a) Data pertaining to the locations of active faults and historical earthquakes in the Hawke's Bay Region have been collected from the Institute's records, both published and unpublished, and other publications.

(b) Maps at 1:250 000 scale showing the locations of these faults have been prepared. Detailed fault location information, where available, is provided at the scale of 1:50 000.

(c) A 1:500 000 scale map identifying regions underlain by geologic materials capable of amplifying earthquake shaking has been prepared.

(d) The report below accompanies the active fault maps and the ground shaking hazard map. Our report specifies the purpose of the study, and defines our terminology, assumptions, and limitations of the data and interpretations presented. We make recommendations for further studies that will improve the quantification and understanding of earthquake hazards in Hawke's Bay Region, including fault rupture and ground shaking hazards.

In the report below we describe firstly the geological setting of Hawke's Bay, then present what is known about the location and past activity of active faults within the region. We describe some of the past and future expected effects from moderate to large earthquakes in the Hawke's Bay Region, discuss some of the important planning issues related to earthquake hazards, and conclude with recommendations for a range of further earthquake hazards studies.

Responsibility for the various sections of this report are as follows: J. Begg compiled the geological and fault trace data, G. Downes completed the section on historical seismicity, C. Uruski and J. Begg compiled the offshore information and the corresponding section of the report was written by J. Begg, and the section on earthquake hazards assessment was completed by J. Begg and A. Hull.

2.0 Geology of Hawke's Bay

2.1 Tectonic setting of Hawke's Bay

New Zealand lies along a boundary zone between two of the tectonic plates that make up the earth's crust (eg Walcott 1978a). The north-western side of the country is part of the Australian plate, while the south-eastern side is part of the Pacific plate (Figure 2.1). Strain and crustal deformation is concentrated along the boundary zones between these plates.

The plate boundary zone runs through and east of the North Island and involves oblique subduction. That is, in the Hawke's Bay area, the Australian plate is moving towards the Pacific plate at c. 50 mm/yr (eg De Mets et al. 1990; Figure 2.1), and over-rides it (Figure 2.2). Convergence between the two plates in central Hawke's Bay is at an oblique angle, about 50°, to the coast and the trend of the Hikurangi trough offshore (eg Kamp 1992). The Pacific plate starts sliding beneath the Australian plate at the Hikurangi trough about 160 km east of Napier, and becomes progressively deeper below the surface to the west. The down-going Pacific plate dips gently (about 6°) immediately west of the trough (Reyners 1980; Bannister 1986), but the dip steepens beneath central Hawke's Bay to about 25° (Adams and Ware 1977). The zone between the trough and the axial ranges of the North Island is a zone of intense deformation and is known variously as the East Coast Fold Belt (Katz 1974), the Axial Tectonic Belt (Walcott 1978) and the East Coast Deformed Belt (Spörli 1980; used within this report). Folding and faulting within the belt is largely caused by oblique compressional stress generated by the subduction process.

The East Coast Deformed Belt is characterised by a set of strike-slip faults in the west, (including the Ruahine and Mohaka faults; Figure 2.1) and a reverse fault zone, (including thrust faults) dipping away from the Hikurangi trough in east (Spörli 1980; Figure 2.2).

Figure 2.3 illustrates fault nomenclature and the effects of different fault types on surface and near-surface features. Throughout this report, geological time is indicated in years before present, where the conventional meaning of the term "Present" refers to the datum year, 1950.

2.2 Geological history of Hawke's Bay

No discussion of the older geological history (up to the early Pliocene, c. 5 million years ago) of the Hawke's Bay Region is given here because the present active deformation pattern developed only about 2 million years ago. Prior to the late Pliocene (c. 5 - 2 million yrs), most of the region formed part of an offshore oceanic basin. Shortening was ongoing within the basin, and at its margins, particularly after the end of the Miocene (c. 5 million yrs). During this period sediments derived from emerging ranges to the west were deposited within the basin. Deformation between the end of the Miocene and the end of the Pliocene (c. 2 million yrs) was characterised by rapid uplift and folding and faulting. By the end of the Pliocene, the region was largely above the sea, and faulting and folding continued. The present day physiography of coastal Hawke's Bay has evolved during the last c. 1.5 million years.

The Heretaunga Plains is a tectonic depression that has developed between growing folds within the East Coast Deformed Belt during the last 1.5 million years (Ravens 1990; 1991).

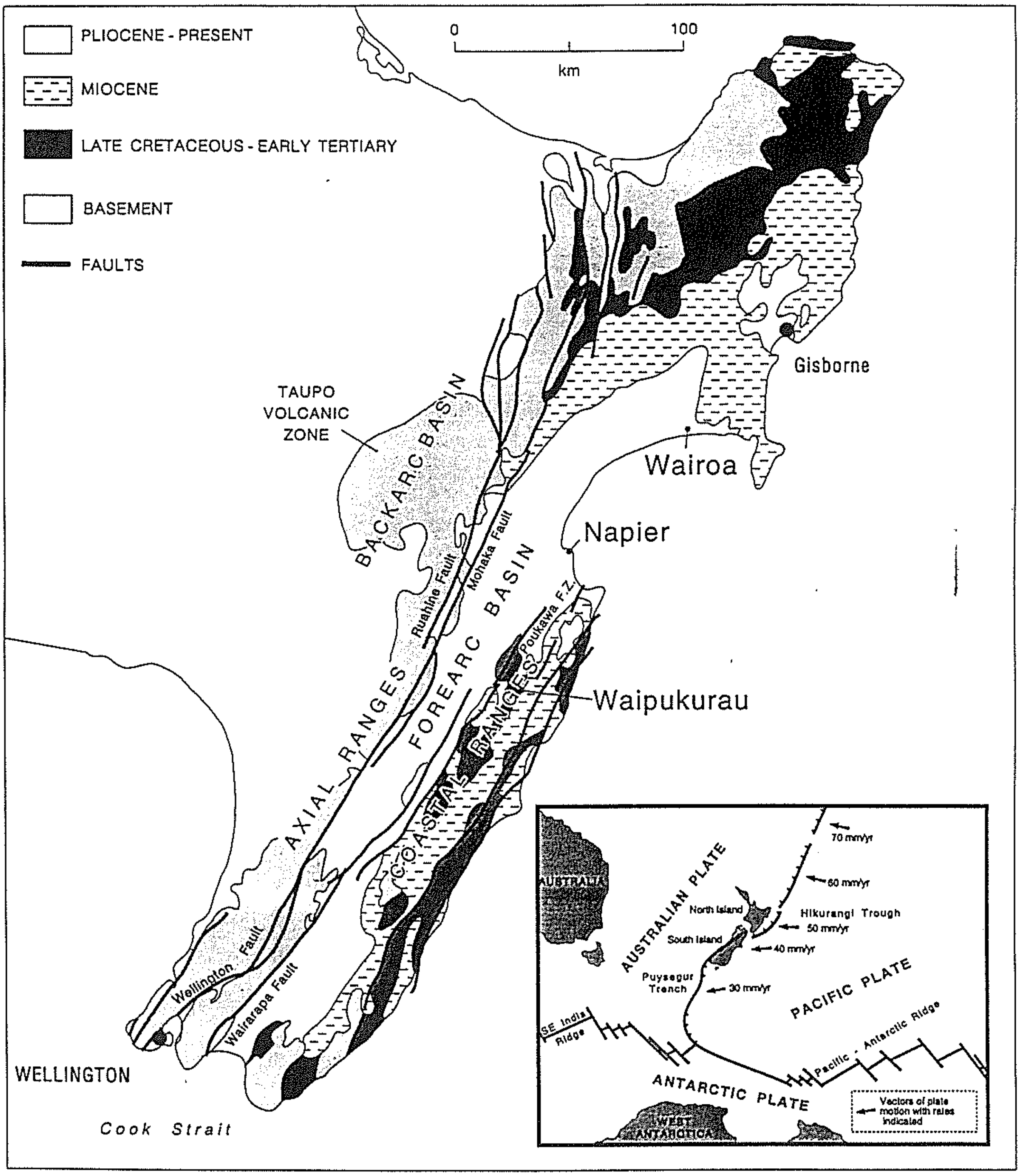


Figure 2.1: Map illustrating the major structural elements of the geology of eastern North Island. Inset is a map showing the position of plate boundaries, and azimuth and rates of convergence (mm/year) of the Australian and Pacific plates in the New Zealand region.

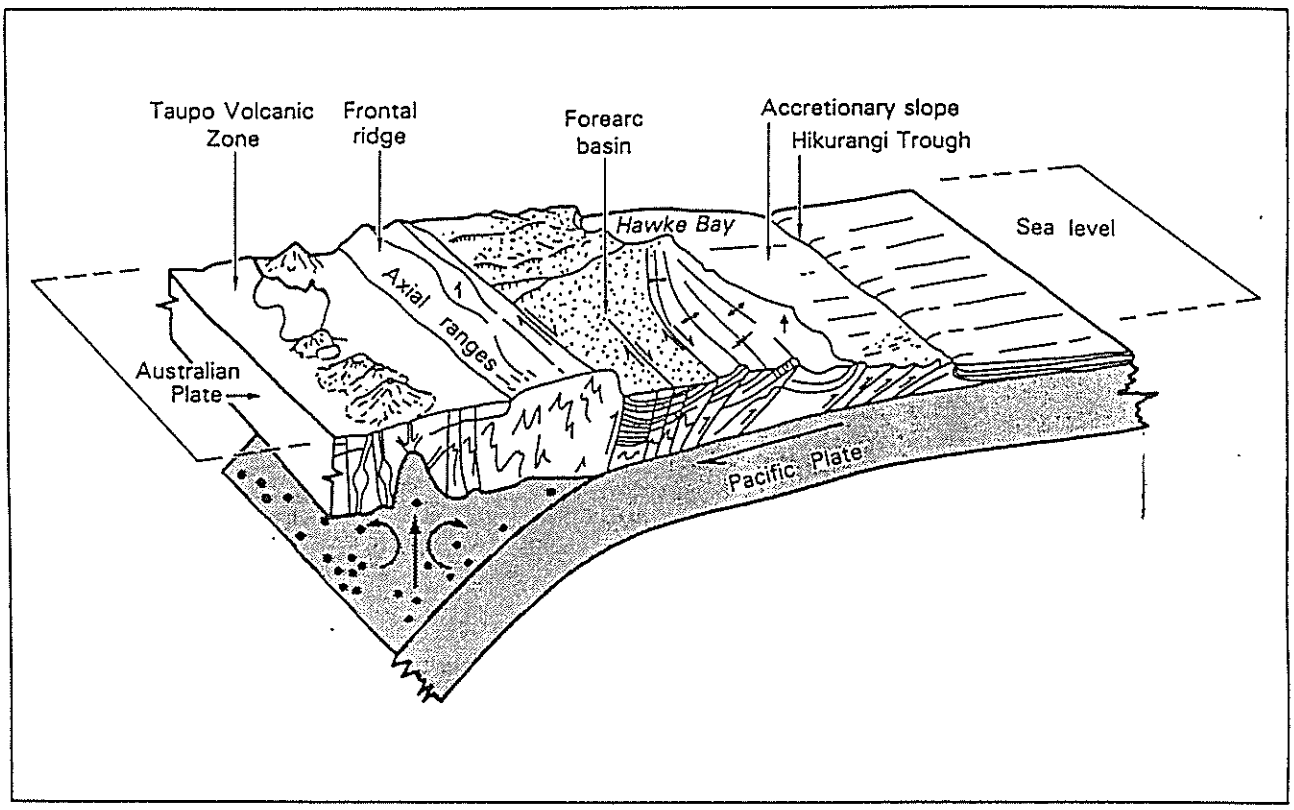


Figure 2.2: An idealised model of the structural elements of the plate margin in the Hawke's Bay area. The Taupo Volcanic Zone represents the backarc basin (see Figure 2.1), the Ruahine Range the frontal ridge, the Takapau/Napier/Eskdale topographic low, the forearc basin, and everything east to the Hikurangi trough, the accretionary slope (after Lewis et al. 1988).

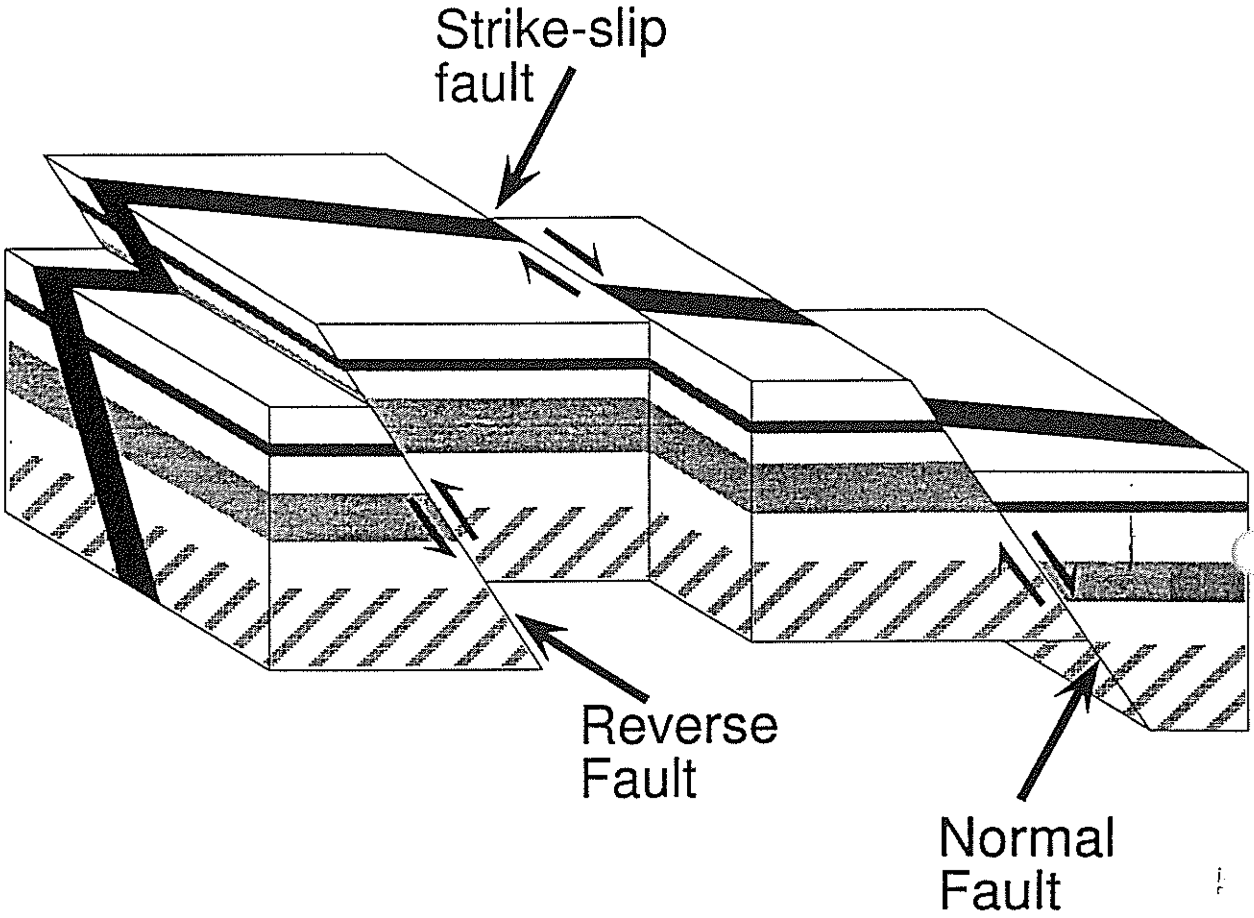


Figure 2.3: Classification of fault types. This diagram illustrates the three main types of faults, and the effect they have upon the earth's surface, and geological strata. Normal faults are principally found in extensional geological environments, reverse faults in compressional environments, and strike-slip faults in shearing conditions. Thrust faults are shallow-dipping reverse faults. The illustrated strike-slip fault is a sinistral (or left lateral) fault; that is, the relative slip directions form an anticlockwise couple. The relative slip directions characteristic of the western part of the Hawke's Bay Region form a clockwise couple and are therefore dextral in nature. Strike-slip faults are characteristic of the frontal ridge and, to some degree, the forearc basin; reverse faults are typical of the forearc basin; normal, reverse and thrust faults commonly occur on the accretionary slope.

Within the basin, up to 1 km of Pleistocene (post c. 2 million yrs) gravel, sand and silt overlie the limestone and sandstone that form the local bedrock.

Formation of the gravel-filled basin comprising the Ruataniwha Plains has been in response to the activity of a series of west-dipping, NE-trending reverse faults in the area during the last 1.5 million years. Reverse faulting elevated the hills east of the plains, resulting in sediment deposition in the relatively low land of the Ruataniwha Plains.

Since the end of the cold period of the Last Glaciation (c. 18 000 yrs ago), climatic warming and melting of polar icecaps has caused a sea level rise of about 120 m. Sea level reached its present position c. 6 000 yrs ago, and has remained more or less stable to the present day. The Heretaunga Plains were once more extensive, but were largely inundated by this rise in sea level. Areas inundated are now underlain by intertidal marine silts. Subsequently, the continuing supply of sediment from the mountain ranges to the west, and regular changes in the course of the Tukituki, Ngaruroro and Tutaekuri rivers, with resulting gravel deposition, have built up the plain above sea level and shifted the coastline eastwards.

After the most recent large eruption of Taupo c. 1 800 yrs ago, large quantities of river-deposited Taupo Pumice built up rapidly on the Heretaunga Plains. The pumice has been eroded in some places by alluvial processes, but up to 10 m thickness of pumice gravel and sand are found in many parts of the plains. Aggradation of the rivers has continued since the pumice deposition, so that 5-10 m of alluvial sediment overlie the pumice in parts of the Heretaunga Plains.

2.3 Geological units

For the purposes of this study, the various rock types of the Hawke's Bay Region have been grouped into four major geological units, based on age and inferred strength (Table 2.1). These units form the basis for Map 15, and are, in order of increasing age and strength:

- A) Very soft to stiff deposits, usually less than about 6 000 years old; fine sand, silt, mud, peat, pumice and clay with some interbedded gravel; generally water saturated. These sediments were (and are being) deposited in estuaries, swamps, low-lying alluvial plains and lakes.

- B) Loose to dense gravel and sand; gravel with very weak to very strong cobbles; less than 3 million years old. Primarily deposited by rivers during the last 2 million years.

- C) Very weak to moderately strong sandstone, siltstone, mudstone, limestone and minor conglomerate; 3-75 million years old. Most of the hill country to the east of the axial ranges is underlain by this unit.

- D) Moderately strong to very strong basement and old sedimentary rocks that are greater than 110 million years old; this unit includes a variety of rock types, including "greywacke" sandstone, conglomerate, siltstone, mudstone and minor volcanics and chert (the latter two usually in the form of blocks of varying sizes). Near the western boundary of the region, there are a few places where weak to strong volcanic rocks of the Taupo Volcanic Zone occur. These consist largely of ignimbrites, and are less than one million years old. They have been included within Unit D because they are often significantly lithified.

Table 2.1 provides guidelines for rock and soil strength.

ROCK STRENGTH	
Term	**Diagnostic features**
Extremely strong	Can be chipped with a geological hammer
Very strong	Requires many blows of geological hammer to break
Strong	Requires more than one blow of geological hammer to break
Moderately strong	Cannot be scraped or peeled with pocket knife. Can be broken with a single firm blow from geological hammer
Weak	Can be peeled with difficulty by pocket knife. Shallow indentations made by firm blow with point of geological hammer
Very weak	Crumbles under firm blows with point of geological hammer. Can be peeled by pocket knife.
Extremely weak	Indented by thumb nail, or other lesser strength terms applicable (classify as a soil)

SOIL STRENGTH			
Cohesive		**Non-cohesive**	
Term	**Diagnostic features**	**Term**	**Std Penetration (no. of blows/300 mm)**
Hard	Difficult to indent with thumbnail	Very dense	>50
Very stiff	Indented by thumbnail	Dense	30 - 50
Stiff	Indented by firm pressure	Medium dense	10 - 30
Firm	Indented only by strong finger pressure	Loose	4 - 10
Soft	Easily indented by fingers	Very loose	0 - 4
Very soft	Exudes between fingers when squeezed		

Table 2.1: A guide to the rock and soil strength terms used in definitions of geological units for Map 15.

Important published geological maps illustrating the distribution and character of rock types in the Hawke's Bay Region include Lillie 1953; Grindley 1960; Kingma 1962; Kingma 1964, 1971; Kelsey et al. 1993; and Cutten (in prep).

In general terms, the distribution of these geological units within Hawke's Bay can be characterised by a western belt of greywacke axial ranges, bounded to the east by two belts of younger largely marine sediments that are separated by a low-lying belt of weaker shallow marine sediments and non-marine deposits (see Map 15).

3.0 Historical seismicity

3.1 Introduction

The Hawke's Bay Region lies within the main seismic region of New Zealand. It is located within a region with the highest rates of historical earthquake occurrence for about the last 150 years. The high level of seismicity is a result of the location of the Hawke's Bay Region within the boundary zone of the Pacific and Australian tectonic plates. Relative motions of these plates result in the Pacific plate sinking beneath the Australian plate to the east of the North Island and northern South Island. Earthquakes are generated as accumulated strain is released largely at the boundary between the two plates, within the overlying Australian plate, and within the sinking Pacific plate.

The purpose of this section is to examine the historical record of past earthquakes, both large and small, as a means to understanding the location and nature of past earthquakes. This examination provides an indication of the likely rates of occurrence and locations of earthquakes in the immediate future. Similarly, the nature and distribution of damage from the larger historical earthquakes provides important indications of possible damage from future earthquakes.

3.2 Data sources and limitations

The Institute of Geological & Nuclear Sciences maintains the National Earthquake Information Database which includes the locations of nearly 100 000 earthquakes. The historic section of the database records important pre-instrumental shocks from about 1840, when organised colonisation of New Zealand began, but only those earthquakes which occurred before 1855 have been studied in detail (Eiby 1968b; 1973). For the period 1855-1940, a definitive list of earthquakes has never been prepared and the database is known to be inhomogeneous and incomplete, generally only the larger magnitude events having been recorded. The occurrence of significant smaller magnitude events in more remote areas away from the main centres of population await identification with further research. It is, however, considered unlikely that shallow earthquakes of magnitude 7 and greater have failed to be recognised.

The location accuracy of the early earthquakes is non-uniform, as few have been studied extensively, and many have been located only to the nearest degree or half degree of latitude and longitude. Consequently there may be up to a 50 km error in given locations.

By the early 1940's the distribution of the seismographs of the National Network had developed sufficiently for a reasonable coverage of shallow earthquakes of magnitude 4 and greater between the latitudes 38 and 42 degrees S, provided all stations were operating. All magnitude 6 and greater events were reliably reported in the period.

The New Zealand National Network of seismographs has been progressively upgraded since then such that, in 1993, a network of over seventy digital stations, including several special purpose local networks, cover the country, with the result that all shallow earthquakes M $\geq$= 3.5 and deep earthquakes M $\geq$= 3.8 can now be well located on or near the New Zealand mainland. Many earthquakes of much lower magnitudes are also routinely analysed.

The magnitude and Modified Mercalli Intensity are frequently used parameters in the following sections. The magnitude is a measure of the energy released by an earthquake at its source and it is calculated from seismographic records. Both M and M_s are referred to in Table 3.1 and elsewhere, M resulting from analysis of New Zealand seismograms and M_s from analysis of the surface waves appearing on distant, or overseas, seismograms. For pre-instrumental earthquakes, the magnitude has been estimated by comparison with later instrumentally recorded events. The Modified Mercalli Intensity scale (MM scale) categorises non-instrumental observations of the effects of an earthquake on people, fittings (furniture, crockery, etc), structures and the environment. Although there are twelve levels in the scale, only the first ten (i.e. up to MM 10) have been reliably observed in New Zealand. The distribution of the observed intensities from an earthquake is shown on an isoseismal map, each isoseismal line enclosing areas experiencing approximately equal intensity of shaking. The progression from the most strongly shaken region to the least is easily recognised. Prior to the common use of the Modified Mercalli scale in the 1940's the Rossi-Forel (R-F) scale was used to record intensities for New Zealand earthquakes. There is not a one-to-one correspondence between the scales and some approximations are required to convert from R-F to MM intensities. The Modified Mercalli scale for New Zealand (Eiby 1966) has recently been revised and is given in Appendix 1.

Dates and origin times are quoted in Universal Time, which for most of the period of interest is New Zealand Time less 12 hours.

3.3 Significant earthquakes affecting Hawke's Bay since 1840

In recent times the Hawke's Bay Region has experienced moderately high levels of seismicity relative to most other areas of the country (Figure 3.1). Within historic times, large shallow earthquakes known to have occurred within the region include the 1863 Waipawa/Waipukurau earthquake ($M \geq 7.0$), the 1931 Hawke's Bay earthquake ($M_s = 7.8$) and aftershock ($M_s = 7.3$), and the 1932 Wairoa earthquake ($M_s = 6.9$). Large deeper events have occurred, notably the 1921 Hawke's Bay earthquake at a depth of c. 80 km and M = 7.0. Extensive areas of Hawke's Bay have also experienced felt intensities of up to MM 7 from large earthquakes, both shallow and deep, occurring outside the region, eg. the 1904 Cape Turnagain earthquake ($M_s = 6.7$) and the 1914 Bay of Plenty earthquake (depth 300 km, $M \geq 7.0$). Many moderate magnitude events have occurred within the region. Table 3.1 lists all earthquakes of $M \geq 5.0$ which are known to have caused intensities ≥ MM 5 at Wairoa, Napier, Hastings, Waipawa or Waipukurau. When there is no felt report for these particular locations but an intensity ≥ MM 5 can be inferred from an isoseismal map or from observations at other nearby locations a comment is given outlining this information. Small earthquakes of $M \leq 5.0$ can result in isolated intensities of MM 5 among predominantly MM 4 areas, but these are not listed in Table 3.1 because they do not constitute a significant hazard. The locations of all the earthquakes listed in Table 3.1 are shown in Figure 3.2.

Detailed descriptions and discussions of the larger magnitude earthquakes which caused damage within Hawke's Bay to the extent of MM 8 or greater or which caused damage over a wide area to MM 7 with accompanying areas of liquefaction and/or minor disruption of services, is given below. Isoseismic maps are shown in Figure 3.3. Sources of information include, unless otherwise indicated, unpublished isoseismal maps (Eiby, Reyners and Downes), published papers by Eiby (1980, 1989), other unpublished data (Downes) and reports held with the Institute of Geological & Nuclear Sciences' files.

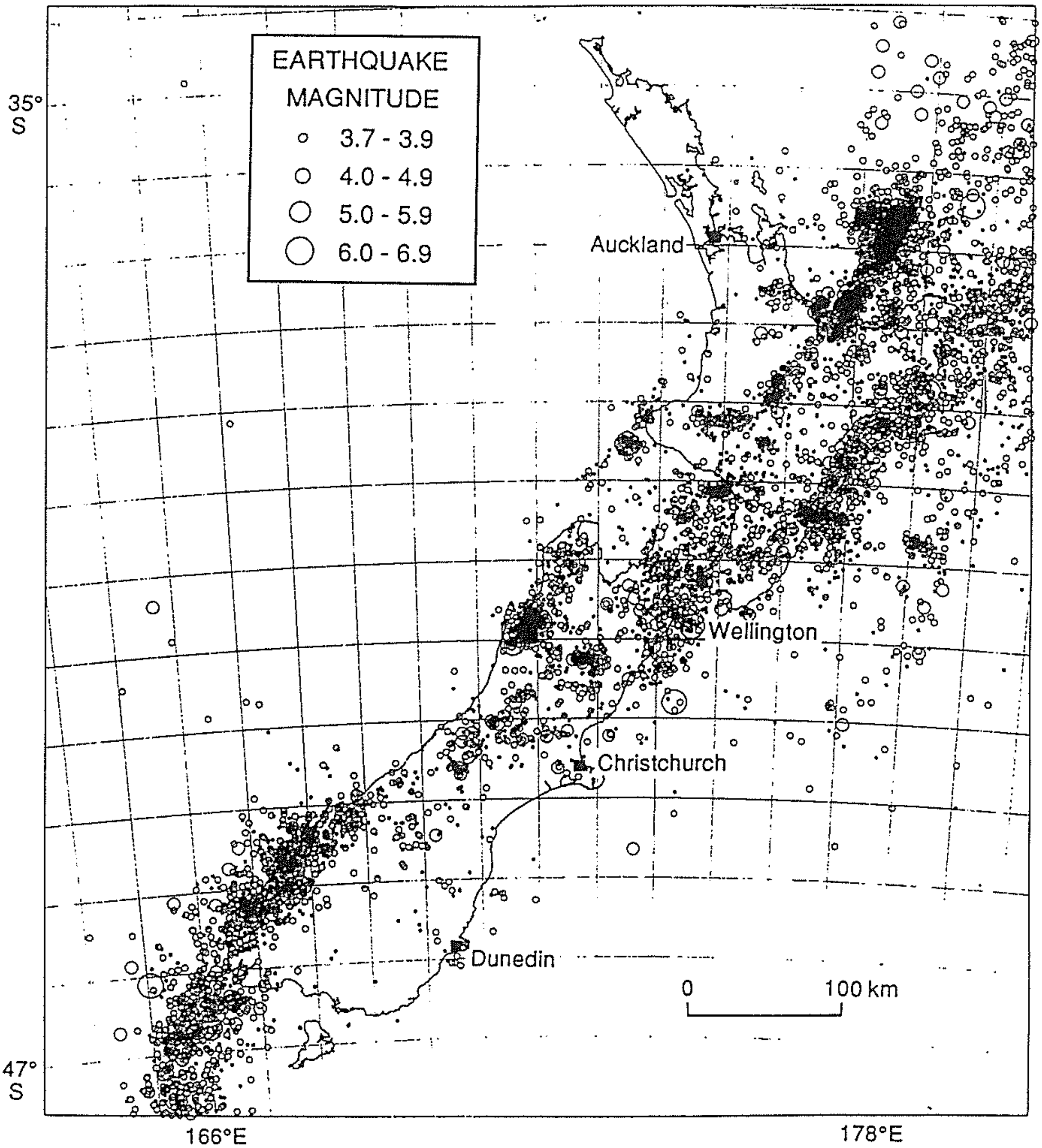


Figure 3.1: Location of all earthquakes M ≥ 3.7, and depth ≤ 45 km in the New Zealand area between 1964 and 1992. Note the large number of earthquakes along the Hawke's Bay coast, showing that Hawke's Bay is one of the most seismically active regions of New Zealand.

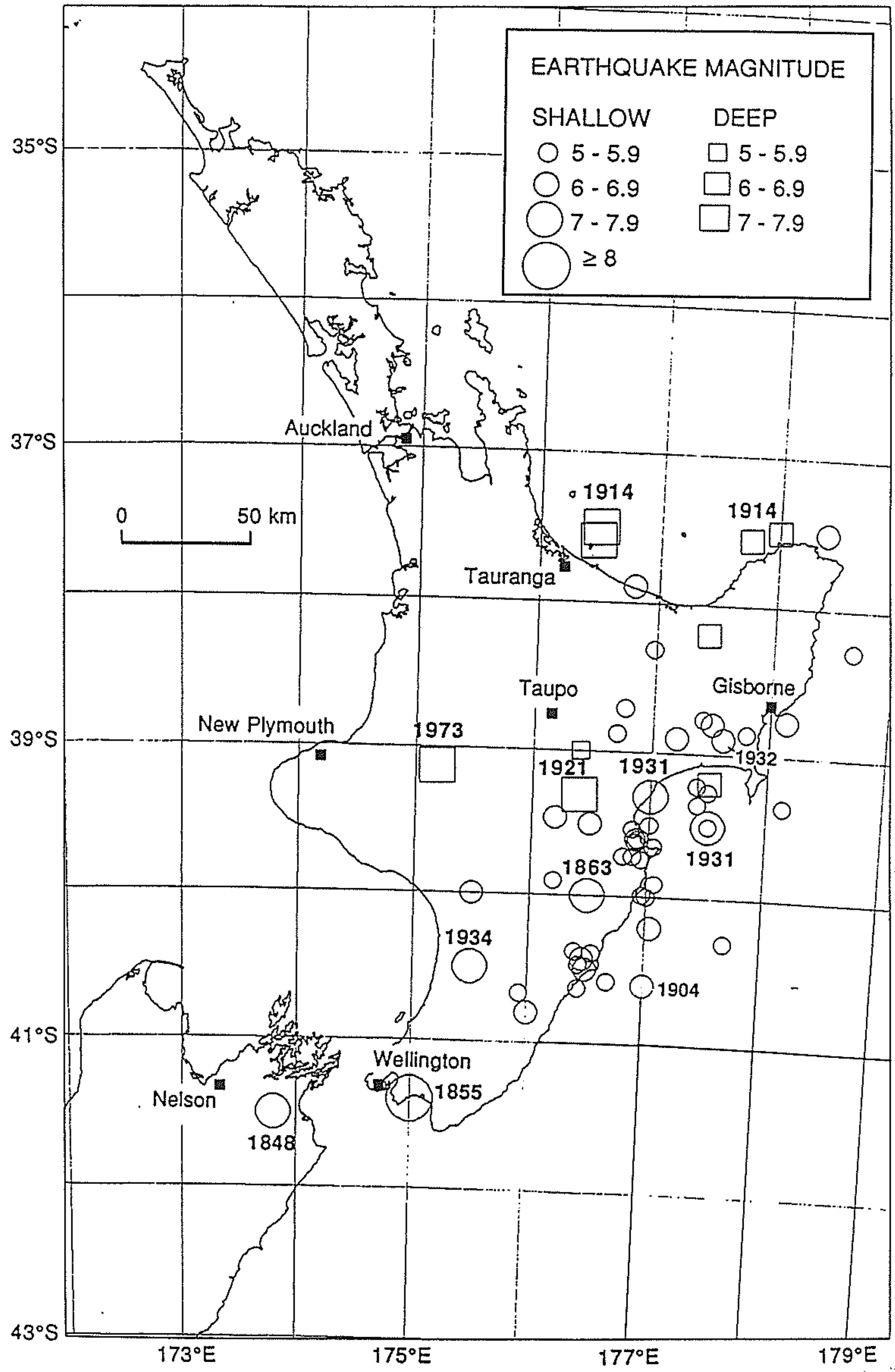
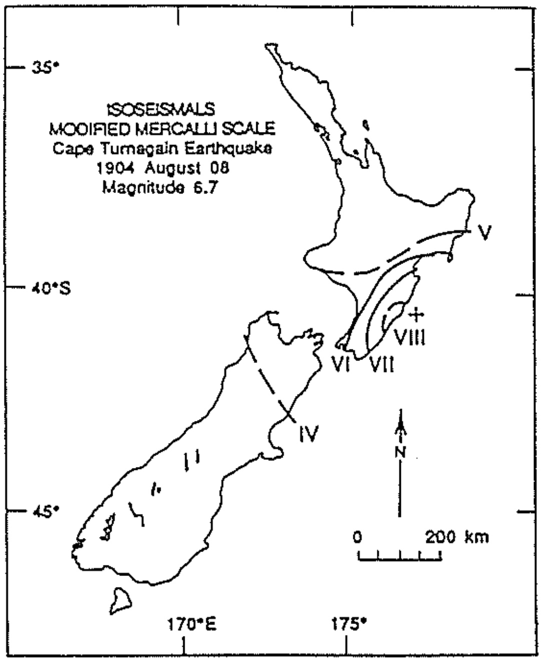
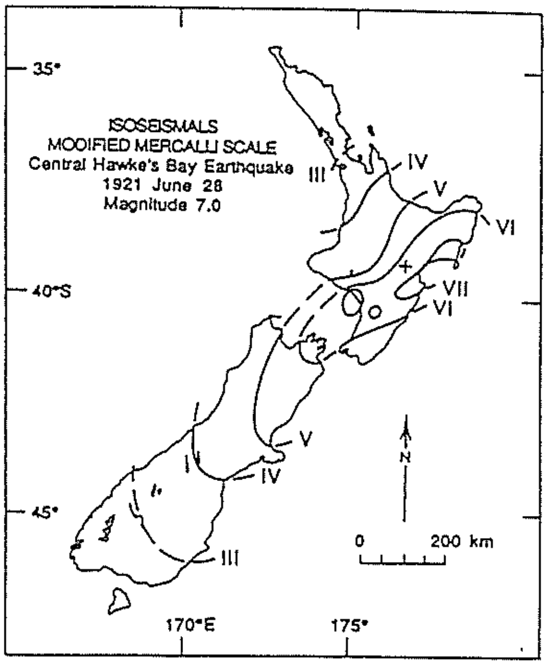
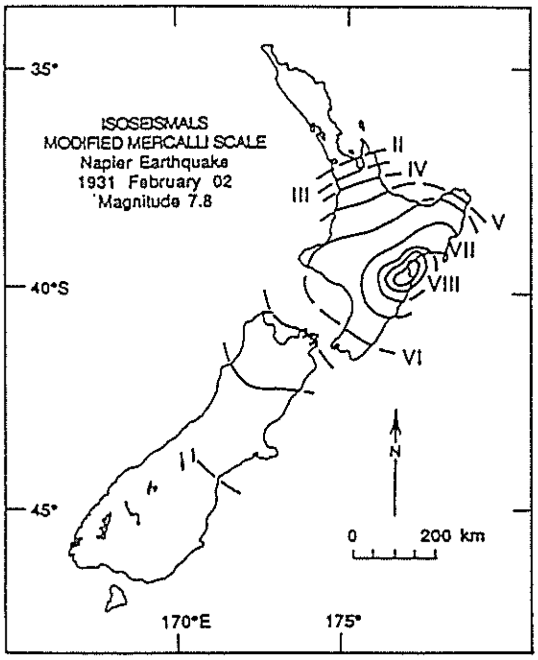
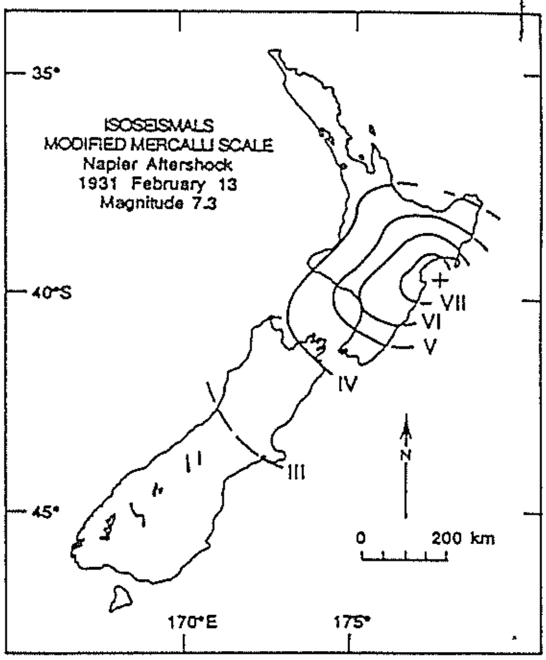


Figure 3.2: Locations of earthquakes described in Table 3.1.









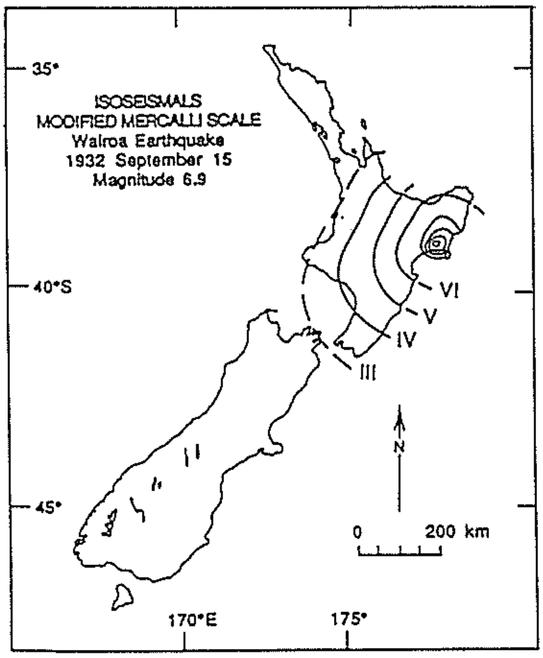


Figure 3.3: Isoseismal maps for large earthquakes felt in Hawke's Bay and described in Section 3.3.

1863 February 23: Southern Hawke's Bay

This relatively unknown and little documented earthquake has an estimated magnitude of about M = 7.0. It is the second largest shallow event after the M_s = 7.8 Hawke's Bay earthquake known to have occurred in the Hawke's Bay Region since European settlement in about 1843. The epicentre has been located near Waipawa, but note that the estimated magnitude and epicentre location are based on minimal information, as the newspaper reports held on this earthquake are not comprehensive, and few other reports are readily available. The lack of reports is related to the small and widely dispersed population at that time. Further research may suggest a more accurate location.

McKay (1902) states that: (1) it was common knowledge that there was surface faulting in 1863; (2) at the time of the earthquake the Waipawa River abandoned its bed and assumed a new course several kilometres to the east; and (3) there were "considerable number of vertical displacements in various parts of Hawke's Bay". No specific locations for the surface faulting were given by McKay, but the Hawke's Bay Herald (August 1903), in recalling past earthquake events states that a cleft was formed between Pakipaki and Te Aute, with part of the land raised about 1.5 m. A less reliable source suggests a rift further south between Waipukurau and Takapau. It is possible also that the suggested change of course of the Waipawa River has been confused with the effects of a devastating flood which occurred several years after the 1863 earthquake, and which is known to have altered the river's course onto Te Aute College lands. Subsequently the river was diverted away from Te Aute College property with the building of embankments near Waipawa.

The shaking intensity in southern Hawke's Bay, including Waipawa, Waipukurau, and towards the east coast and Porangahau appears to have been at least MM 8, probably MM 9. The intensity at Napier was MM 7-8. Liquefaction was reported from the Waipawa/Waipukurau area. No data are available for the remainder of Hawke's Bay, but the earthquake was widely felt in both the North and South islands from Auckland to Christchurch, indicating an event of similar size to the 1931 Hawke's Bay earthquake. Although aftershocks were reported to have occurred continuously in the following three weeks, there is no information on the damage caused, if any.

1904 August 08: off Cape Turnagain

This earthquake of magnitude M_s = 6.7 was centred off Cape Turnagain with a maximum intensity of MM 8 from Porangahau to Castlepoint. Fallen and cracked chimneys, minor structural damage, landslips and some cracking of roads (MM 7) occurred over the whole of southern Hawke's Bay from just north of Napier to Masterton. Liquefaction was reported within the wider Napier area, at Taradale, Maraenui and near the Tutaekuri River and further south near Waipawa, Otane and Porangahau. Subsidence of the railway line occurred near Kopua, and near Te Aute. It is also possible that the earthquake caused a small tsunami. The earthquake was felt over a wide area of both North and South islands from Auckland to Dunedin.

1921 June 28: Central Hawke's Bay

This earthquake of magnitude 7.0, has an epicentre about 60 km northwest of Napier. The depth, estimated by Bullen (1937) at 80 km, precluded any serious damage. Damage in Hawke's Bay was confined to the collapse of several chimneys in Napier, Hastings and Waipawa, suggesting a felt intensity of MM 7 in these towns. In Wairoa an intensity of MM 6-7 seems appropriate.

1931 February 02: Hawke's Bay

The 1931 Hawke's Bay earthquake caused the greatest loss of life and the most extensive damage ever recorded in New Zealand (Callaghan et al. 1933). The effects of the earthquake were greatest in the towns of Napier and Hastings (both MM 10), but other towns in the Hawke's Bay Region also suffered major damage - Te Aute, Mohaka, MM 10; Waipawa, Waipukurau, MM 9; Patoka, MM 8; Wairoa, MM 7 (Figure 3.4). Current research work is aimed at providing a more reliable felt intensity map for the 1931 Napier earthquake. The official death toll was 256, 161 occurring in Napier, 93 in Hastings and 2 in Wairoa; no deaths were reported in the Waipawa/Waipukurau/Takapau area. The earthquake was followed by fires in the central business areas of both Napier and Hastings. The fires, fanned by the changeable breezes, raged uncontrollably as the water pressure needed for firefighting dwindled because of the many broken water mains.

The earthquake epicentre has been located 30 km to the NNE of Napier, and the magnitude has been determined at $M_s = 7.8$ (Dowrick & Smith 1990). It was felt throughout most of New Zealand except for the areas in the far north and south. It was accompanied by well-documented faulting and uplift with extensive fissuring, slumping and landslips occurring over much of Hawke's Bay (Henderson 1933; Hull 1990). These effects resulted in widespread disruption to services, including road and rail traffic. There was permanent change in local drainage patterns as seen by the shift in the mouth of the Tutaekuri River. Subsidence of alluvial ground was widespread, and liquefaction (sand boils) apparently occurred over a wide area, including at Wairoa, Mohaka, Tongoio, Petane, Napier, Taradale and Hastings (Fairless 1984). Aftershocks - some causing minor damage - followed the mainshock, their locations being spread widely in the Hawke's Bay Region. The largest aftershock on February 13 ($M_s = 7.3$) was located 50 km to the east of the mainshock, and resulted in intensities of MM 7 over the greater part of the Hawke's Bay Region. It was reported to have been felt more intensely in the inland areas where it is possible that the intensity may have reached MM 8.

1932 September 15: Wairoa

The Wairoa earthquake of magnitude $M_s = 6.9$ (Dowrick & Smith 1990) followed nineteen months after the 1931 Napier earthquake. Description of the effects of this earthquake is provided by Henderson et al. (1937). In Wairoa and Gisborne many buildings were badly damaged, and the Wairoa bridge, damaged beyond repair in the 1931 earthquake, collapsed completely. The damage to the new bridge under construction was extensive, and repairs were delayed for some months while consideration was given to more serious concerns regarding the water supply to Wairoa. The earthquake caused extensive fissuring, slumping and landslides, some large, especially around Wairoa and in the country to the northeast of Wairoa. The intensity in Wairoa is estimated to have been MM 9-10, and in Napier MM 6-7. The earthquake was felt strongly over a large part of Hawke's Bay. No primary surface rupture was identified, but Haines & Darby (1987) have indicated the possibility that the

Wairoa earthquake occurred on the northeastward extension of the Napier-Hawke Bay fault earthquake rupture of 1931. The possibility of some regional deformation cannot be excluded.

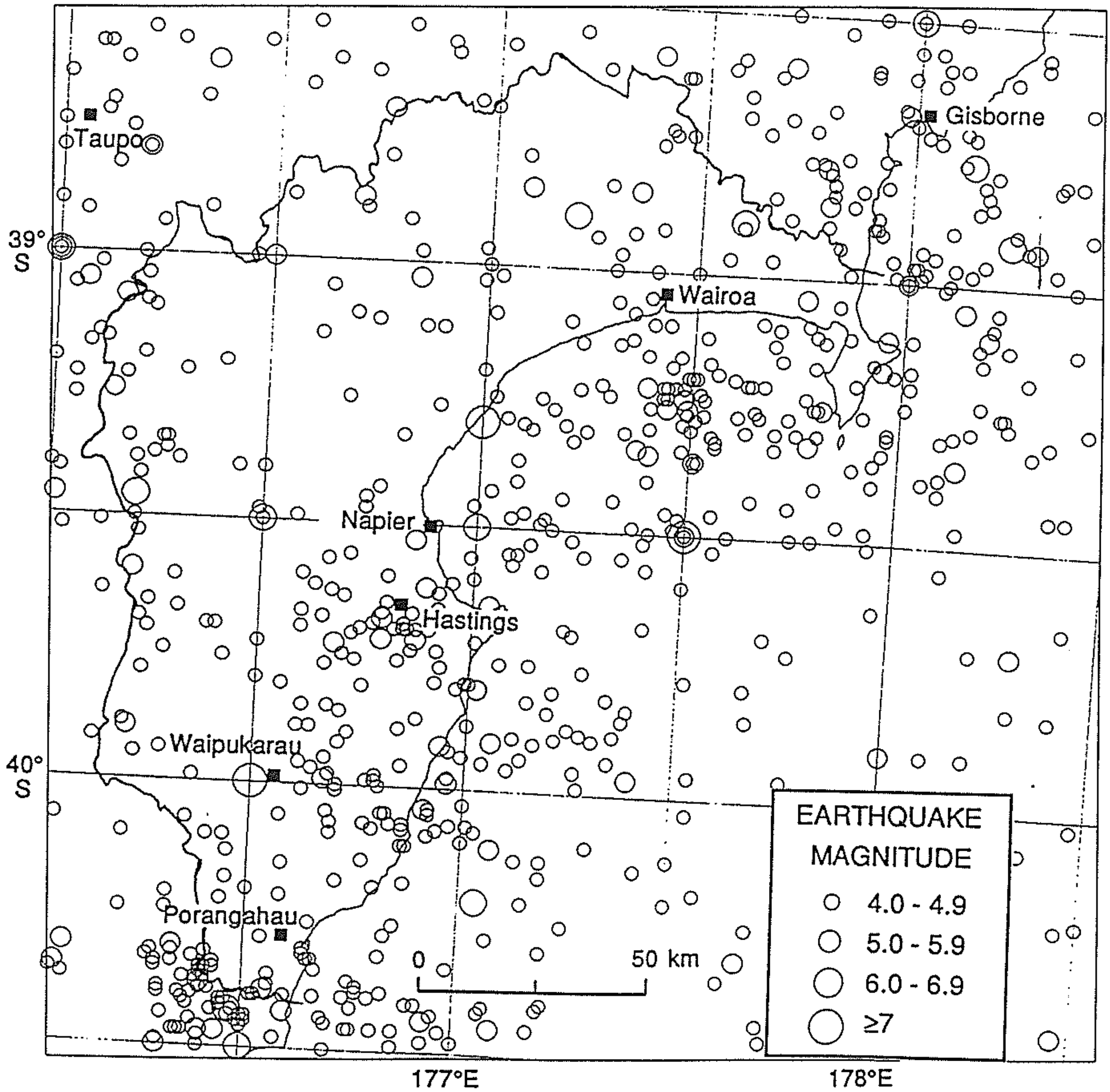


Figure 3.4: Plot of all earthquakes in the Hawke's Bay Region from the earthquake catalogue with M $\geq$ 4.0 and depth $\leq$ 45 km.

Table 3.1: **Significant historic earthquakes producing observed or inferred felt intensities of MM≥V at any of the locations: Wairoa, Napier, Hastings, Waipawa, Waipukurau**

Date[1]	Lat. (°S)	Long. (°E)	Depth[2] (km)	Mag.[3]	Epicentral distance from Napier	Observed MM Intensity	Location	Inferred MM intensities observed at other locations in Hawkes Bay[4]	Common name
1848 Oct 15	41.5	173.8	S	7.1	>200			MM6-MM4 from S. to N. Hawke's Bay	Marlborough
1855 Jan 23	41.4	175.0	S	8.0-8.2	>200	6-7	Napier	MM7-MM5 from S. to N. Hawke's Bay.	Wairarapa
1863 Feb 22	40.0	176.5	C	7.5	70	8-9	Waipawa	see full discussion	S Hawkes Bay
						7-8	Napier		
1891 Aug 16	39.6	176.9	C	5.8	20	6	Hastings		
						5	Napier		
1892 Oct 11	40.5	176.5	C	6-6.3	120	7	Porangahau	MM5-MM6 over S. Hawke's Bay	
1898 Dec 04	38.8	177.5	C	6-6.2	90	7	Wairoa	MM7 over area north of Wairoa.	
1903 Aug 01	39.6	176.9	<45	6.0	20	7	Hastings		
						5-6	Napier		
1904 Aug 08	40.6	177.0	30	6.7M_s	120	8	Porangahau	see full discussion	Cape Turnagain
						7	Napier		
						7	Waipawa		
						7	Waipukurau		
						5-6	Wairoa		
1911 Oct 05	39.6	176.9	30	5.3M_s	20	6-7	Napier		
						7	Hastings		
						4-5	Waipawa		
1914 Oct 06	37.5	178.4	<20	6.7M_s	250	5	Wairoa	MM5 over large part of Hawke's Bay	
1914 Oct 28	37.5	178.4	<20	6.5M_s	250	5	Napier	MM5 over large part of Hawke's Bay	
1914 Nov 22	37.5	176.5	300	≥7.0	225	7	Napier	MM6-MM7 over large part of Hawke's Bay	
						6	Hastings		
						6	Wairoa		
1917 Aug 05	40.8	176	<45	6.6M_s	170	5	Wairoa		
						5	Napier		
						5	Waipawa		
						5	Waipukurau		

Table 3.1: Significant historic earthquakes producing observed or inferred felt intensities of MM≥V at any of the locations: Wairoa, Napier, Hastings, Waipawa, Waipukurau (cont'd)

Date[1]	Lat. (°S)	Long. (°E)	Depth[2] (km)	Mag.[3]	Epicentral distance from Napier	Observed MM Intensity	Location	Inferred MM intensities observed at other locations in Hawkes Bay[4]	Common name
1921 Jun 28	39.3	176.4	80	7.0	60	7	Napier	MM6-MM7 over large part of Hawke's Bay	
						7	Waipawa		
						6-7	Wairoa		
						5-6	Waipukurau		
1929 May 07	40	175.5	C	6.0	140	5-6	Waipawa	MM3-MM4 over rest of Hawke's Bay	Manawatu
						6-7	Waipukurau		
1930 Feb 12	40.5	176.5	<45	6.2	120	7-8	Porangahau		
						6	Napier		
						6	Hastings		
						6	Waipawa		
						6	Waipukurau		
1931 Feb 02	39.3	177	30	7.8M_s	30	10	Napier	see full discussion	Napier
						10	Hastings		
						9	Waipawa		
						9	Waipukurau		
						7	Wairoa		
1931 Feb 08	39.2	177.5	<60	6.3M_s	50	6-7	Napier		Napier Aftershock
1931 Feb 13	39.5	177.5	30	7.3M_s	40	7	Napier	see full discussion	Napier Aftershock
						7	Hastings		
						7	Waipawa		
						6-7	Waipukurau		
						7	Wairoa		
1931 Sep 21	37.5	178	80	6.1M_s	250	5-6	Wairoa	MM5 over large part of N. Hawke's Bay	
						4-5	Napier		
1932 May 05	39.5	177.5	C	5.9M_s	40	6-7	Taradale	MM5-MM6 over large part of Hawke's Bay	
						6	Napier		
						5-6	Wairoa		
						5-6	Hastings		

Table 3.1: Significant historic earthquakes producing observed or inferred felt intensities of MM≥V at any of the locations: Wairoa, Napier, Hastings, Waipawa, Waipukurau (cont'd)

Date[1]	Lat. (°S)	Long. (°E)	Depth[2] (km)	Mag.[3]	Epicentral distance from Napier	Observed MM Intensity	Location	Inferred MM intensities observed at other locations in Hawkes Bay[4]	Common name
1932 Sep 15	38.9	177.5	30	$6.9M_s$	80	10	Wairoa	see full discussion	Wairoa
						6-7	Napier		
						5-6	Hastings		
						5-6	Waipawa		
						5	Waipukurau		
1934 Mar 05	40.5	175.5	45?	$7.6M_s$	170	5-6	Napier	MM5-MM7 over S. Hawke's Bay	Pahiatua
						5-6	Waipawa		
1934 Mar 10	40.5	176.5	C	6.0	120	7	Porangahau		
1934 Mar 15	38.9	177.2	40	$6.4M_s$	70	6	Wairoa	MM5-MM6 over large part of N. Hawke's Bay	
1938 Dec 15	40.3	176.4	<45	$5.6M_s$	110	7	Waipawa		
						5-6	Hastings		
						5	Wairoa		
1940 Feb 26	39.5	176.5	C	6	40	6	Hastings		
						4-5	Napier		
1943 Apr 07	39.4	178.1	12	5.1	100	5	Wairoa		
1945 Jan 02	39.9	177.1	12	5.5	50	5	Wairoa		
						5	Hastings		
						5	Waipawa		
1947 Mar 27	38.9	177.8	12	5.3	100	5	Wairoa		
1947 Apr 21	39.6	177.0	12	5.4	20	5	Hastings		
1947 May 17	38.3	178.7	12	5.6	200	5	Wairoa		
1947 Aug 27	39.6	179.4	12	6.2	200	5	Wairoa		
						5	Havelock N.		
1950 Feb 28	38.9	176.7	33	5.7	80	5	Wairoa	MM5 distributed widely in Wairoa district.	
1951 Feb 10	40.2	177.0	33	6.1	80	5	Napier	MM6 from Hastings to Porangahau, MM5 elsewhere in Hawke's Bay	
						5	Wairoa		
						5	Waipawa		
						6	Porangahau		
1951 Apr 23	37.6	177.8	125	6.2	220	5	Wairoa	MM5 over N. Hawke's Bay	

Table 3.1: Significant historic earthquakes producing observed or inferred felt intensities of MM≥V at any of the locations: Wairoa, Napier, Hastings, Waipawa, Waipukurau (cont'd)

Date[1]	Lat. (°S)	Long. (°E)	Depth[2] (km)	Mag.[3]	Epicentral distance from Napier	Observed MM Intensity	Location	Inferred MM intensities observed at other locations in Hawkes Bay[4]	Common name
1951 Jun 24	39.5	176.2	33	6.3	70	6	Wairoa	Isolated report. Elsewhere MM4	
1952 Aug 28	40.0	177.0	12	5.8	50	6	Havelock N.	MM5 widespread in S. Hawke's Bay	
						5	Napier		
						5	Waipawa		
1953 Sep 29	37.6	176.5	273	7.2	220	6	Wairoa	MM6 widespread in Hawke's Bay	
						6	Napier		
						6	Hastings		
						6	Waipawa		
1953 Oct 28	40.3	177.7	12	5.1	110	5	Waipawa		
1958 Jan 31	40.0	176.5	33	6.1	80	7	Ashley Clinton	MM6 widespread in SW Hawke's Bay	Ashley Clinton
						6	Waipawa		
						5	Waipukurau		
						4-5	Napier		
						4-5	Hastings		
1963 Apr 12	38.7	176.8	12	5.5	90	6	Tarawera	MM6 widespread in NW Hawke's Bay	
1966 Mar 04	38.8	178.1	33	6.0	130	5	Wairoa	MM4 central Hawke's Bay	Gisborne
1968 May 26	39.5	176.9	33	5.0	12	5	Napier	MM 5 widespread in central Hawke's Bay	
						5	Waipukurau		
1971 Apr 28	40.6	176.7	33	5.2	120	5	Waipukurau		
1971 Oct 31	39.0	176.4	141	5.9	80	5	Wairoa	MM5 over most of Hawke's Bay	
						5	Waipawa		
1972 Dec 21	40.4	176.5	12	5.1	110	5	Waipawa	MM5 widespread in S. Hawke's Bay	
						5	Waipukurau		
1973 Jan 05	39.1	175.2	173	7.0	170	5	Napier	MM5 over most of Hawke's Bay	
						5	Waipawa		
1973 Feb 21	39.7	176.8	12	5.4	30	5	Napier	MM5 widespread in S. Hawke's Bay	
						5	Hastings		
						5	Waipukurau		
1976 Mar 20	39.3	177.5	12	5.4	50	7	Wairoa	—	

Table 3.1: Significant historic earthquakes producing observed or inferred felt intensities of MM≥V at any of the locations: Wairoa, Napier, Hastings, Waipawa, Waipukurau (cont'd)

Date[1]	Lat. (°S)	Long. (°E)	Depth[2] (km)	Mag.[3]	Epicentral distance from Napier	Observed MM Intensity	Location	Inferred MM intensities observed at other locations in Hawkes Bay[4]	Common name
1976 Mar 20	39.2	177.4	12	5.4	45	5	Waipawa		
1977 Oct 30	39.6	176.9	33	5.0	20	5	Napier		
1979 Apr 22	39.3	177.4	12	5.4	40	7	Wairoa		
1979 Oct 17	38.3	177.0	33	5.1	130	5	Wairoa		
1980 Jul 03	40.4	176.9	33	5.2	100	5	Hastings		
1980 Oct 05	39.7	176.9	30	5.6	30	5-8	Napier	4 reports poss. reflecting different ground conditions	
						6	Hastings		
						6	Waipawa		
						5	Waipukurau		
1981 Nov 04	40.4	176.4	33	5.2	110	5	Waipawa		
1981 Dec 27	40.6	176.4	33	5.4	130	5	Waipawa		
1982 Feb 05	40.7	175.9	33	5.2	160	5	Hastings		
1982 Sep 02	39.7	176.9	41	5.4	30	6	Hastings	MM5 widespread in Central & S. Hawke's Bay	
						5	Waipawa		
						5	Waipukurau		
1984 Mar 08	38.2	177.4	75	6.4	150	5	Hastings	MM5 widespread in central & N. Hawke's Bay	Motu River
						5	Waipawa		
1984 Aug 17	39.6	176.6	84	5.3	40	5	Wairoa	MM5 widespread in central Hawke's Bay	
						5	Napier		
1985 Jul 19	38.8	177.4	41	5.7	90	5	Ormond	MM5 widespread in N. Hawke's Bay	
1987 Mar 02	37.89	176.80	10	6.0	180	5	Wairoa	isolated MM5 among MM3-4	Edgecumbe
						5	Hastings		
1988 Sep 06	40.41	176.81	64	5.1	100	5	Hastings		
1990 Feb 19	40.47	176.44	34	5.9	120			MM5-MM7 over large part of S. Hawke's Bay	Weber I
1990 May 13	40.43	176.47	30	6.2	110	6	Waipukurau	MM5-MM8 over large part of S. Hawke's Bay	Weber II

Notes
(1) Time is Universal Time
(2) Depth: S shallow, upper crustal; R restricted depth; C undifferentiated crustal
(3) Magnitude is Richter local magnitude or, where indicated, surface wave magnitude (M_S)
(4) Generally from an isoseismal map.

3.4 Seismicity 1964-1992

New Zealand earthquakes have been analysed since 1964 in a consistent manner, and an effort has been made to locate all events of $M \geq 4.0$ throughout the country. In recent years the New Zealand network has been significantly upgraded and all shallow events of $M \geq 3.7$ can now be well located. Since April 1987, a network of stations has been maintained within the Hawke's Bay Region, and an endeavour made to analyse all earthquakes which have been recorded by at least three stations. Close station spacing not only allows more accurate epicentre location but significantly improves depth control of shallow earthquakes, although it is often still necessary to assign standard depths of 5, 12 and 33 km to a number of recorded earthquakes. Epicentres of all known shallow earthquakes (depth < 45 km) of magnitude $M \geq 4.0$ for the period 1964-1992, and all other large events from the historical file for the Hawke's Bay Region are shown in Figure 3.2. This depth cutoff was chosen because although shaking from deep earthquakes has been felt often in Hawke's Bay, only the large, shallow earthquakes have the potential to produce very strong earthquake shaking and its associated severe damage.

4.0 Active faults of Hawke's Bay

4.1 Introduction

Fault ruptures associated with earthquakes can occur at depth in the earth's crust. Those that are shallow enough to extend upward to the ground surface form surface fault traces. Most ruptures that generate a surface trace are associated with large earthquakes, and so it is expected that surface active faults represent likely sites for future large earthquakes.

Some surface traces record single earthquake events, but many are the sites of repeated rupture through time. In this section discussion is focused on surface traces no older than 125 000 years. Such faults are regarded as active. Active fault traces that are preserved in the region (and have been recognised) are plotted on Maps 1 to 14. Some active faults, usually reverse faults, fail to propagate to the surface, but have surface expression as actively growing folds. These are regarded as seismic sources and are also plotted on Maps 1 to 14.

These have been identified onshore from aerial photographs and geological mapping, and offshore from bathymetry, earthquake locations, and interpretation of seismic reflection/refraction surveys. In the summary of existing information on the Hawke's Bay Region presented below, known active faults are described from west to east. The positions of active fault traces and folds are plotted on 1:250 000 scale maps (Maps 1 to 3). It is important to note that offshore faults and folds have been located using different techniques to those onshore. There is less certainty in the position, the near-surface nature, and activity of offshore structures, but there is more certainty in the deeper structure, and, therefore, in structural styles.

Where sufficiently accurate locations of active fault traces are known, they are plotted on 1:50 000 scale maps (Maps 4 to 14). Important characteristics of the better studied active faults and folds of the region are summarised in Table 4.1.

There is no doubt that some earthquakes inducing strong ground motions in the Hawke's Bay Region in pre-historic times have failed to leave surface traces. Examples of such seismicity could include fault ruptures on offshore faults, movement along the subduction thrust at the interface between the Pacific plate and the Australian plate, and deeper earthquakes located within the upper part of the down-going Pacific plate. The contribution of these earthquakes to the overall seismic hazard is unable to be assessed using current methods.

4.2 Major on-shore structures

Major active faults and folds of the Hawke's Bay Region are discussed below, in order from west to east.

4.2.1 Ruahine fault

The Ruahine fault is predominantly a strike-slip fault separating the stable microcontinental platform area of New Zealand from the zone of deformation known as the East Coast Deformed Belt, immediately west of the Hikurangi trough. The Ruahine and Mohaka faults are two of the major active faults of the Hawke's Bay Region, and are major strands of the

Wellington fault system. This system can be traced continuously through the North Island from Wellington to the Bay of Plenty. Between them, the Ruahine and Mohaka faults account for 2000 m of vertical uplift of the Ruahine and Ahimanawa ranges during the last c. 5 million yrs. The Ruahine fault trends northeast, and has straight, demonstrable active traces discontinuously along its length of more than 100 km.

Studies along the Ruahine fault (Beanland and Berryman 1987) indicate that several rupture events have occurred since 16-17 000 years ago. One event may have occurred during the last 1800 years. Each event is thought to be accompanied by two to five metres of right lateral, oblique-reverse slip. An average horizontal slip rate of 1-2 mm/year for the Holocene (the last c. 10 000 years) has been inferred, and a recurrence interval of between 1 000 and 5 000 years between major earthquake events is calculated.

4.2.2 Waipunga fault

The Waipunga fault has been examined only at reconnaissance level and is assumed to be related to the Ruahine/Mohaka system, and to have a similar rupture history and seismic potential as the Rangiora fault (see Section 4.2.9). The sense of movement is unknown.

4.2.3 Big Hill fault

The Big Hill fault was named and described by Erdman and Kelsey (1992). Slip in the southern part of this fault, where it trends SSE, is reverse in character. Further to the north, where the fault swings to trend NNE, a strike-slip component becomes increasingly important. Youthful scarps along the length of the fault indicate that it is active, but there are no constraints available on slip rates or earthquake generation potential. The Big Hill fault is thought to transfer strain between the Ruahine and Mohaka faults, but is regarded as a separate earthquake source.

4.2.4 Thorn Flat fault

The Thorn Flat fault is a reverse or thrust fault with an active scarp. There are no constraints on slip rates or recurrence intervals. This fault is thought to be a southern propagation of the Big Hill fault, and is active in transferral of strain between the Ruahine and Mohaka faults.

4.2.5 Mohaka fault

The Mohaka fault is a major northeast-trending, dextral-reverse strike-slip fault which, with the Ruahine fault, forms one of the principal structural features of the eastern North Island. Raub et al. (1987) conclude that events on the Mohaka fault involve c. M 7.5 earthquakes, right lateral oblique movements of about 3.5 m, and have a recurrence interval of c. 1000 years. The average right lateral slip rate of the Mohaka fault is about 3 mm/year. Radiocarbon dating of wood fragments from a trench across the fault in the Wakarara area indicates that the last surface rupture is less than 1200 years old (Raub et al. 1987).

4.2.6 Patoka fault

The Patoka Fault has not been studied in detail, but is considered here to be an element of the Ruahine/Mohaka fault system. The trace of the fault is only slightly divergent in trend to that of the Mohaka fault. It is thought to be dominantly a right lateral strike-slip fault, but no further details are available, and its earthquake generation potential is unknown.

4.2.7 Hinerua thrust

Little information is available on the Hinerua thrust. It trends N to NW, thrusts E to NE-wards, and probably transfers strain on the Mohaka fault to the Wakarara fault. There is reportedly an active scarp, but no constraints on earthquake generating potential, slip rate or recurrence interval are available.

4.2.8 Wakarara fault/thrust

The Wakarara fault is a reverse fault with a small strike-slip component. The fault disappears in the north near the axis of a monoclinal fold, and is thought to continue northwards beneath the surface, along the axis of the fold. It does not appear to have ruptured within the last c. 30 000 years B.P., as aggradational gravels of that age are undeformed across the monoclinal fold in the north (Raub et al. 1987).

4.2.9 Rangiora fault

The Rangiora fault was the subject of a study by Cutten et al. (1988). It is considered to be part of the Ruahine/Mohaka system, although it contrasts with those faults in having a short surface expression (c. 14 km), and in having late Neogene vertical displacement of no more than a few hundred metres. The active trace of the fault is 5 km long, trending 030°, and lies about 13 km east of the Mohaka fault in central Hawke's Bay. Three faulting events involving right lateral offsets of 4-6 m are recognised, one between 3300 and 1900 years ago, and two in the last 1900 years. Late Holocene average slip rates, at c. 4.5 mm/year, are considered comparable to those of the Ruahine and Mohaka faults.

4.2.10 Taniwha fault

Lillie (1953) mapped the trace of the Taniwha fault, a northeast-trending trace, c. 2 km to the west of Takapau. He reported a 7.5 m step down to the east on alluvial flats. Geophysical work in the area (eg Hollingsworth 1971; Melhuish 1990; Melhuish 1993) illustrates the reverse nature of the Taniwha fault, and a displacement of at least 400 m during the last 2.3 million years. Over most of the length of the trace, however, only minor vertical displacement is inferred to have occurred in the last 14 000 years.

4.2.11 Waikopiro fault

Lillie (1953) mapped and named this fault, but did not indicate whether active traces occur. He showed upthrow on the western side of the fault, and a dextral strike-slip component. Seismic profiles (Hollingsworth 1971; Melhuish 1990; Melhuish 1993) show a reverse fault penetrating to close to the surface, and rapid lateral thickening of surface sediments on the downthrown (eastern) side. Vertical throw during the last 2.3 million years is more than 550 m, and there is no indication of strike-slip movement. No estimates have been made on slip rate or recurrence interval. Seismic profiles indicate that the Waikopiro fault is one of a zone of major reverse faults in this area (including the Taniwha and Oruawharo faults). Movement on these faults have resulted in uplift and relative downwarping, resulting in sediment deposition and development of the Ruataniwha Plains.

4.2.12 Oruawharo fault

Lillie (1953) also mapped the Oruawharo fault which he regarded as being part of a larger system extending south into the Waewaepa Range. The Oruawharo fault brings basement rocks to the surface, and is an active reverse fault. The fault plane dips west at c. 75-85° where exposed at the surface. Displacement increments, slip rates and rupture lengths are unknown for this fault, as is the earthquake generating potential.

4.2.13 Glendevon faults

A number of active traces are found in this system. The traces lie to the west of Waipukurau, and the trend of the system swings from NNW in the south to NE in the north. They have been interpreted as flexural-slip faults (i.e. related to slip on bedding planes during folding; Van Dissen et al. 1989), and all traces are upthrown to the west, with scarp heights ranging up to c. 10 m. The entire system of active traces is 6 km long. Across the system there is a total vertical displacement of c. 500 m during an active period of c. 4 million years. This corresponds to a long-term average vertical slip rate of c. 0.15 mm/year. The most recent displacements across the fault involve 1.3 to 1.7 m vertical movement. It is likely that two such events have occurred within the last c. 20 000 years and that the recurrence interval is between 9 000 and 15 000 years. Maximum expected earthquake magnitudes of approximately M 5.7 have been calculated for the Glendevon faults (Van Dissen et al. 1989).

4.2.14 Napier-Hawke Bay fault

The Napier-Hawke Bay fault trends northeast from Bridge Pa (perhaps from almost as far as Tikokino) through Te Awa and offshore. The fault is regarded as reverse, with a strike-slip component.

Rupture on the fault is thought to have resulted in the M_s = 7.8 1931 Hawke's Bay earthquake. The line of zero change in elevation during the 1931 earthquake is currently regarded as the most accurate location of the surface projection of the fault (Henderson 1933; Haines and Darby 1987). This location is supported by the presence of a series of springs, presumably a result of disruption of an aquifer. The 1931 rupture on the Napier-Hawke Bay fault was the first for at least 1800 years (Hull and Dowrick 1991). Interpretation of the stratigraphic record from Ahuriri Lagoon (Hull 1986) indicates that subsidence has been the dominant sense of tectonic movement during the last 3500 years, in contrast to the uplift experienced in the 1931 event.

4.2.15 Waipukurau-Poukawa shear zone

Cashman et al. (1993) show a number of active reverse-dextral, strike-slip faults trending NNE-NE on the Waipukurau-Poukawa fault zone between Waipukurau and Pakipaki. The Tukituki thrust zone on the eastern side of the Kaokaoroa Range may be related to this zone.

Froggatt and Howorth (1980) demonstrated an average vertical fault slip rate of 0.2 mm/year for the last 7000 years in the Lake Poukawa area. They estimated an average recurrence time of 800-900 years, but lacked control across the whole zone. We feel that a 500-800 year recurrence interval is more realistic for the entire shear zone. The date of the last fault rupture south of Lake Poukawa is not known, but some faults of the zone in the north moved during the 1931 event.

4.2.16 Ryans Ridge fault zone

The nature of the Ryans Ridge fault zone is yet to be established. It has been variously reported as a thrust zone (Pettinga 1982), a zone of flexural slip faulting (Berryman pers. comm.), and involving some dextral strike-slip faulting (Cutten pers. comm.). Active traces exist throughout the zone, but there are no constraints on slip rates or recurrence intervals. There is no reliable information for the earthquake potential for this zone.

4.2.17 Haumoana fault zone

A NNE-SSW trending belt of normal faults extends from the coast at Haumoana to south of the Maraetotara Plateau 35 km to the south (see Map 2). A northern extension of this zone can be identified in seismic profiles from Hawke Bay. A large number of discontinuous fault traces make up a zone that varies in width from several hundred metres to c. 8 km. The faults have formed in response to regional extension to the west of the Tukituki River during the last two million years (Cashman and Kelsey 1990). The relationship of these normal faults to the major reverse faults to the east and west is unknown, as is the depth to which the faults extend. Nothing is known of the timing of individual fault ruptures, but a major scarp to the east of Havelock North shows recent repeated movement, judged by oversteepening of a 5 m scarplet near its base.

4.2.18 Buried faults and active folding

Many of the active (growing) anticlines within the Hawke's Bay Region are believed to be cored by reverse or thrust faults. Because of the plastic nature of many near-surface sediments in coastal Hawke's Bay, many deeper faults have failed to propagate to the ground surface. In such circumstances, many faults are expressed at the surface as broad warps or folds. As was shown dramatically in 1931, these folds can develop in association with large earthquakes, and for the purposes of this study, major active folds are assumed to contain faults that are potential earthquake sources. The presence of a 2300 year-old, tilted, raised beach in the Kidnappers area may also have been a result of such an earthquake. The axial traces of many of these active anticlines have been marked on the accompanying 1:250 000 sheets. Quantification of the seismogenic history of such folds is difficult.

In addition to these faults and active folds, it is likely that there are low angle thrust faults beneath the region that have no direct or indirect surface expression. These faults are likely to be potential earthquake sources, but the only method of detecting them is deep seismic profiling. Quantification of this hazard has not so far been attempted.

Earthquake source	Faulting type	Estimated Magnitude (M_s)[1]	Estimated mean return time (years)	Date of last movement (years B.P.)	Calculated intensities (MM)[2] at: Napier/ Hastings Dist(km)[3]	Napier/ Hastings MM	Wairoa Dist(km)	Wairoa MM	Waipukurau/ Waipawa Dist(km)	Waipukurau/ Waipawa MM	References
Ruahine fault	Strike-slip	7.5	1000-5000	c.500	45	8	65	8	35	8	Beanland & Berryman (1987)
Waipunga fault	Strike-slip	7.5	2000[4]	2 post-3500	50	8	65	8	90	7	Berryman (1988) Berryman et al. (1989)
Big Hill fault	Reverse-strike-slip	?	?	?	45		110		45		
Thorn Flat fault	Reverse-thrust	?	?	?	40		110		40		
Mohaka fault	Strike-slip	7.5	900	c.1100	35	8	50	8	35	8	Hull (1983) Berryman et al. (1988)
Patoka fault	Strike-slip	7.5?	?	?	30	8	70	7	50	8	Henderson (1933)
Hinuera thrust	Thrust-reverse	?	?	?	50		35		30		
Wakarara fault	Reverse-strike-slip	?	?	?30 000	40		110		30		
Rangiora fault	Strike-slip	7.5	1350	2 post-1800	40	8	45	8	90	7	Cutten et al. (1988)
Taniwha fault	Reverse	?	?	?	60		140		20		
Waikopiro fault	Reverse-?strike-slip	?	?	?	60		140		15		
Oruawharo fault	Reverse	?	?	?	60		140		15		
Glendevon fault	Flexural slip-reverse?	5.7	9 - 15 000	2 post-20 000	55	6	135	4	10	8	Van Dissen et al. (1989)

Table 4.1: Summary of existing information on active fault characteristics for the Hawke's Bay Region (continued overpage).

Earthquake source	Faulting type	Estimated Magnitude (M_s)[1]	Estimated mean return time (years)	Date of last movement (years B.P.)	Calculated intensities (MM)[2] at						References
					Napier/ Hastings		Wairoa		Waipukurau/ Waipawa		
					Dist(km)[3]	MM	Distance	MM	Distance	MM	
Napier-Hawke Bay fault	Reverse-strike-slip	7.8	>1800	AD1931	0	10	0[6]	10	15[6]	10	Henderson (1933) Hull (1986; 1990)
Waipukurau-Poukawa shear zone	Reverse-strike-slip	7.8	500-800	AD1931(north) ?(south)	0	**10**	15[6]	**10**	0	**10**	Froggart & Howorth (1980) Cashman et al. (in press)
Ryans Ridge fault zone	?Reverse	?	?	?	20		30[6]		10		
Haumoana fault zone	Normal	7.0?	1000[4]	?	10		35[6]		30		Cashman & Kelsey (1990)
Buried faults/ active folds	Various - mostly reverse?	?	?2300	?	n/a	n/a	n/a	n/a	n/a	n/a	Kidnappers raised beach
Kidnappers anticline	Reverse	7.5	~1000	2 post-2200	15	**9-10**	40	**9**	45	8	Hull (1987)
Lachlan anticline[5]	Reverse	7.8	1000	c.300	70	8	55	**9**	100	8	Berryman (1988) Berryman et al. (1989)
Subduction zone[5]	Thrust	8.0+	?	AD1931?	c.20	**9-10**	c.20	**9-10**	c.20	**9-10**	Reyners (1987)
Deep focus	Normal	7.0	?	AD1953	30-50	7-8	30-50	7-8	30-50	7-8	Reyners (1987)

Notes:
[1] M_s is surface-wave magnitude
[2] After Dowrick 1991, intensities rounded to the nearest integer.
[3] Napier/Hasting distance determined at whichever is closest to the specified fault; all distances rounded off to the nearest 5 km
[4] Indicates best estimate based on few data
[5] Indicates tsunami possible
[6] Indicates assumed hidden along strike continuation

Table 4.1 (continued): Summary of existing information on active fault characteristics for the Hawke's Bay Region.

5.0 Offshore geology and faulting

5.1 Introduction

An understanding of the offshore faulting of Hawke Bay is necessary in the evaluation of seismic hazard of the region. Many of the onshore active traces of the eastern part of the region trend into Hawke Bay, and so the presence of significant offshore seismic sources is to be expected.

Bathymetry to 200 fathoms (c. 600 m), from the New Zealand Oceanographic Institute's Mahia and Turnagain charts (Pantin 1961a and b), is marked on the Hawke's Bay 1:250 000 scale active faults and folds sheet (Map 2).

Two major submarine slumps, the Kidnappers and Paoanui slumps, have been mapped off the Hawke's Bay coast (Lewis et al. 1988). These major slump features have their headscarps at the shelf slope break at c. 100 fathoms. Approximate extents of the slumps are indicated on the 1:250 000 scale map sheet (Map 2).

5.2 Sea floor fault scarps

Recent sea floor fault scarps have been documented off the Hawke's Bay coast by Pantin (1966) and Lewis (1971). These are marked on the 1:250 000 scale sheet (Map 2). The most significant feature is the Kidnappers fault, an east-dipping reverse fault, downthrown on its western side. Lewis (1971) estimated a vertical slip rate of 0.4 mm/yr based on the relative heights of the Last Glacial (c. 20 000 years) and Last Interglacial (c. 120 000 years) wave-planed surfaces. He estimated that vertical uplift rates were about the same on the fault for the last 20 000 years as for the period 140 000 to 20 000 years.

5.3 Quaternary faulting and folding from seismic data

Because techniques for identifying major structures offshore are different from those used onshore, difficulties arise in trying to compare the two sets of fault location data. For the purposes of this study, an attempt has been made to link onshore structures with those offshore, but it should be noted that these correlations, in a complex structural environment such as the Hawke's Bay Region, are uncertain.

The most complete source of data for the geology of Hawke Bay is the Gulf HB seismic line series shot in 1972, and the CQX series shot in 1990. Both sets have been re-processed by American Exploration (1990), and are now open-file. Major relevant features identified from these lines have been plotted on the 1:250 000 scale map Hawke's Bay map sheet (Map 2). The timing of activity for the shallow features marked are poorly constrained.

The style of active structures identified in Hawke Bay is typified by reverse faulting (becoming low angle thrusts with depth) with accompanying folding. Some large normal faults have been identified, and zones or swarms of minor normal faults are shown. The reverse faults located on Map 2 penetrate shallow sediments, and active folds are characterised by folded sediments, minimal thickness of coverbeds and/or unconformities and active erosion. Gulf HB series coverage is restricted to Hawke Bay, so seismic information compiled by Lewis et al. (1988) is used to complement that data for the southern part of the 1:250 000 scale Hawke's Bay sheet. Data lines for this area are more diffuse, and locations of structures are less certain.

5.4 Major offshore structures

Major active offshore structures are discussed below.

5.4.1 Napier-Hawke Bay fault

Henderson (1933) connected 1931 fault traces at Poukawa, and deformation that occurred during that event south of the mouth of the Mohaka River, with a fault that crossed the western part of Hawke Bay. Haines and Darby (1987) modelled the 1931 Napier and 1932 Wairoa earthquake deformations and concluded that the 1931 earthquake involved movement on a major northeast-trending submarine fault in Hawke Bay, with a rupture length of about 80 km and northwest dip of about 60-70°. Dip slip was 6-8 m and right-lateral (dextral) strike-slip was likely to have been 4-8 m. The Wairoa earthquake of 1932 was probably on a northeastward extension of the same structure, and involved a rupture length of 50-70 km, a fault plane dipping c. 70° northwest, and reverse or normal displacement of c. 1 m, with c. 1 m right lateral movement.

No active faults with a westward dip in the area immediately offshore from Napier were identified in the seismic lines. Extrapolation of the fault along the line of its trend onshore comes close to the western extent of the seismic coverage, and so it is possible that the 1931 trace was missed. The only active fault seen on the seismic lines in the area is an east-dipping reverse fault which is associated with a growing anticline on its eastern side.

Two active faults of the kind modelled by Haines and Darby are mapped in the offshore Mohaka/Wairoa area (Map 2). The western fault and its associated anticline (immediately to the west) is the more likely extension of the Napier-Hawke Bay fault than the eastern one.

5.4.2 Waipukurau-Poukawa shear zone

Onland the Waipukurau-Poukawa shear zone is characterised by west-dipping reverse faults with a strike-slip component. Despite the fact that this is one of the primary onshore structures in the region, no equivalent feature has been found offshore.

5.4.3 Kidnappers anticline (ridge)/Haumoana fault zone

The Kidnappers anticline is difficult to follow offshore. An active anticline trends NE off Cape Kidnappers, continuing across Hawke Bay nearly as far as the Mahia Peninsula. It is probably not the same feature as the Kidnappers anticline, and is here called the Kidnappers ridge. It is parallel to the Lachlan ridge (anticline) which is c. 20 km to the SW.

The Kidnappers ridge is a major active structure, and is bounded on its eastern side by an active west-dipping reverse or thrust fault. The position of this fault is close to a fault recognised and named by Pantin (1966), the Kidnappers fault, but the sense of movement attributed to the Kidnappers fault is the opposite of that shown by this fault. Pantin's

Kidnappers fault is an east-dipping reverse fault.

The offshore extension of the Haumoana fault zone is marked on the 1: 250 000 scale maps as zones of closely spaced normal faults with small displacements close to the surface of the seabed. These zones are confined offshore to patches on the western side of the growing Kidnappers anticline (Map 2).

5.4.4 Lachlan ridge

The Lachlan ridge lies c. 20 km east of the Kidnappers ridge, separated from it by the northern extension of the Motukura trough. The Lachlan ridge extends southwest from just east of the Mahia Peninsula. Its surface expression is truncated east of Cape Kidnappers by the Kidnappers slump. A ridge to the south of the Kidnappers slump, the Motukura ridge, is presumably a southern analogue of the Lachlan ridge. The Lachlan ridge is another actively growing anticlinal structure that is bounded on its eastern side by a west-dipping thrust fault.

Lewis (1971) concluded from dredged bottom samples that the Lachlan ridge (Lachlan anticline) only started to grow in the early Pliocene (5 million years ago). However, the amount of movement during the late Quaternary is unknown. The absence of Quaternary sediments, and inferred scouring regime on the crest of the ridge, suggest that growth is on-going. Lewis estimated a high rate of tilting (36 μ°/thousand yrs) for the southern end of the Lachlan ridge, and identified a history of movement reversal on the western side of the ridge.

5.4.4 Hikurangi trough

The axis of the Hikurangi trough lies about 160 km to the east of the Hawke's Bay coast. The trough is not a seismogenic source in its own right, rather a geomorphological feature that is one indicator of the tectonic environment of the North Island east coast. It represents the surface expression of the subduction plate boundary, and is the line along which the Pacific plate starts dipping below the eastern edge of the Australian plate.

5.5 Net deformation on basal Pleistocene

Using seismic profiles, it is possible to evaluate the net post-2.4 million year (post-Mangapanian) and post-3.1 million year (post-Waipipian) deformation by observing seismic structures and estimating depths of sediment accumulation in that time. Most of the post-2.4 million year deformational structures are similar to the present day structures marked on the 1:250 000 scale map (Map 2). The principal structures common to the post-3.1 million, post-2.4 million year and present day maps are the downwarping structure trending NE from offshore Napier, a SW-trending basin from the Mahia isthmus, the NE-trending Kidnappers ridge, and the SE-trending Lachlan ridge. The thrust on the eastern side of the Lachlan ridge has been active since at least 3.1 million years.

6.0 Earthquake hazards assessment

Factors that must be considered and evaluated in seismic hazards assessment include surface fault rupture, ground shaking, land movements, rock fall and landsliding, settlement and liquefaction, and tsunamis and seiching. In this study, while existing information on historical seismicity and active fault traces has been compiled, equivalent data on other earthquake hazards has not. A brief explanation of earthquake hazards is given below, with reference to Hawke's Bay in general terms only.

6.1 Earthquake hazards

6.1.1 Surface fault rupture

Earthquakes occur when rupture occurs within rocks, often on a pre-existing zone of weakness termed a fault. During a large, shallow crustal earthquake the zone of rupture on the fault may reach the ground surface, and a surface trace or scarp forms. This break or rupture of the ground surface represents a localised hazard, but one which can often be anticipated because faults tend to re-rupture along pre-existing zones of weakness. In general, a fault rupture may be any length up to 100 km (or even more in rare cases), and single horizontal displacements of up to 12 m are known from New Zealand. Displacements up to 5 m are more common, however. A surface fault rupture is rarely a simple break, and most consist of zones of broken ground and warping, metres or tens of metres wide. Fault ruptures may be normal (extensional), reverse (compressional), or strike-slip (horizontal) and each type has typical features (see Figure 2.3). The principal faults in the Hawke's Bay Region are either strike-slip or reverse faults.

Surface faulting was recorded near Poukawa and Pakipaki after the 1931 earthquake. The pattern of faulting was complex with uplift to the NE and SW, and both dextral and sinistral strike-slip movements. Maximum vertical separation was 4.6 m, occurring on a NW-trending scarp c. 3 km west of Pakipaki. Maximum strike-slip motion of 1.8 m dextral occurred NE of Poukawa along an E-W-trending fault. The complexity and limited distribution of surface faulting demonstrate the difficulty of predicting ground ruptures associated with this type of earthquake, generated by a reverse fault that doesn't reach the surface.

Active fault traces occur within urban areas in Waipukurau, Waipawa and Otane. The positions of active faults within the Waipukurau urban area have been accurately mapped at a scale of 1:1200. Copies of the maps are lodged with the Central Hawke's Bay District Council. The council has created reserve areas along the fault scarps in an effort to reduce damage in the event of future fault rupture.

6.1.2 Ground shaking

Strong ground shaking, which involves the dissipation of earthquake energy from radiation of earthquake waves, is the most pervasive earthquake hazard. The larger the magnitude of the earthquake, the greater the amount of energy released. Distance from the earthquake source is a major factor in determining the strength of ground shaking. As the waves travel away from the earthquake source they lose energy, so that locations further from the source usually feel a lower level of shaking than locations near the epicentre.

A complicating factor is that some types of ground amplify earthquake waves. Differing levels of shaking may be felt within even quite a small area as a result of contrasting ground conditions. In general, rock sites record the lowest levels of shaking during low to moderate earthquake wave input, and sites underlain by soft, unconsolidated deposits record the greatest levels of shaking. This difference between hard and soft sites can be pronounced. For example, the areas in San Francisco that experienced the highest intensity shaking during the 1989 Loma Prieta earthquake were all underlain by soft material. San Francisco is about 100 km distant from the epicentre of the M 7.1 Loma Prieta earthquake. Soft soil sites in San Francisco experienced Modified Mercalli (MM) intensity VIII-IX shaking, while nearby rock sites experienced MM 6 shaking (e.g. Borcherdt 1991). In the 1989 Newcastle (Australia) earthquake, a M 5.5 earthquake located directly beneath the city, damage was concentrated in areas underlain by softer materials (Rynn & others 1992). However, in Napier in 1931, MM 10 was experienced on both the rock (on the hill) and on the soft alluvial plain. The difference from the San Francisco experience underlies the need for better understanding of such microzoning effects. Differences may in part be due to the fact that the M 7 Loma Prieta earthquake was distant to San Francisco, while the M 7.8 1931 Napier earthquake was a direct hit; topographic amplification probably occurred in Napier, but not in San Francisco.

The plasticity of unconsolidated sediment is crucial in determining its behaviour in an earthquake. Highly plastic clays will maintain their amplifying ability during intense shaking, whereas sands (which are not plastic) will dissipate energy in moderate shaking, limiting amplification. The highly plastic volcanic clays under Mexico City allowed the 1985 earthquake to be more intense in the city than at the epicentre, even though it was 400 km away.

Other factors influencing local earthquake ground shaking include the source mechanism of the earthquake (type of fault), and the nature of propagation of seismic energy in rocks between source and site. Some of these factors cannot yet be clearly defined.

It is sometimes the combined effect of shaking and associated secondary ground damage that causes the main damage to man-made structures during earthquakes. Henderson (1933) stated "Among the superficial effects of a severe earthquake none takes a more prominent place than the fissures in alluvium and recently formed ground."

The effects of ground shaking and possible variations within the Hawke's Bay Region are discussed in greater detail later (Section 6.4). Areas likely to be prone to strong ground motion amplification are coloured red and labelled A in Map 15. Such amplifications may not apply at ground shaking intensities of MM 9 and MM 10 on rock. The most susceptible areas within the region include the Heretaunga Plains (particularly the seaward part, underlain by Holocene marine sediments), the Poukawa/Otane depressions, the Porangahau flats, the Wairoa/Whakaki flats and the Pukenui Beach isthmus.

6.1.3 Land movements

After the initial ground shaking of the 1931 Napier earthquake had ceased, it was quickly realised that changes of ground level had occurred. At Ahuriri Lagoon a rapid outflow of water to the sea occurred, and the Tutaekuri River, that previously flowed into the southern part of the lagoon near Napier, changed its course to the south, bypassing the lagoon altogether. Tidal levels at Clive appeared higher, and re-levelling within the Heretaunga Plains by the Hawke's Bay Rivers Board showed that land near Hastings had subsided by about 1 m (Figure 6.1). Rapid long term subsidence of the Heretaunga Plains is demonstrated by Brown (1993 in prep), who concludes that there has been approximately 250 m subsidence in an estimated 250 000 years (an average of approximately 1 m/1000 years). In the Flaxmere drillhole, the base of the Holocene is tentatively assigned to a depth of 59.4 m. Although no depositional rates can be attached, the thickness is suggestive of ongoing rapid rates of subsidence. Similarly, deposition of several metres of sediment in many parts of the Heretaunga Plains on top of the 2 000 year old Taupo pumice is consistent with continued subsidence.

Land movements of such a scale are capable of substantially altering existing drainage and ground water systems, particularly in flat-lying areas. Significant changes in ground water were noticed immediately after the 1931 earthquake. Some previously productive wells choked after the earthquake, and in some areas the aquifers were so altered that water ceased to flow. Hot water flowed in some wells.

Surface drainage may equally be dramatically altered. Small scale drainage and even river courses (eg the Tutaekuri River in 1931) can be changed by earth movements of this magnitude. The problem of river diversion by earthquake-induced deformation is greatest where river gradients are low in flat-lying areas. Such problem areas in the Heretaunga Plains include the lower reaches of the Ngaruroro and Tutaekuri rivers, particularly in the Hastings area (see Brown 1993).

6.1.4 Rock fall and landsliding

Widespread rockfall and landsliding are characteristic of most moderate to large earthquakes in regions of moderate to high topographic relief, such as much of Hawke's Bay Region. The extent and severity of this hazard often depends on the water content at the time of the earthquake, and therefore the amount of rain that has fallen in the preceding few days or weeks. Many large-scale failures occur on pre-existing landslides. Rockfalls usually occur along river valleys, mountain slopes and artificially steepened hillsides such as road and railway cuts. The oversteepened river banks of the Mohaka River (amongst others) could potentially fail in a large earthquake, resulting in river damming, followed by the rapid release of ponded water.

As a general guide, rockfall and landsliding is expected within about 50 km of a shallow (ie less than 15 km deep) earthquake of M 6 and within 100 km if the magnitude is about M 7 (under average wet conditions).

Henderson (1933) and Marshall (1933) reported on landsliding and slope instability that was caused by the 1931 earthquake. A landslide triggered by the earthquake dammed the Te Hoe River (near Ngatapa) forming a lake c. 5 km long and up to 30 m deep. Pettinga (1987a; 1987b) documented landslides (Ponui and Waipoapoa), the former of which was activated (in part) during the 1931 earthquake. However, no movement was reported during the 1931 event on a large number of pre-existing landslides in the Hawke's Bay Region. Many of these are pre-historic features, and some are likely to have been triggered by earthquakes.

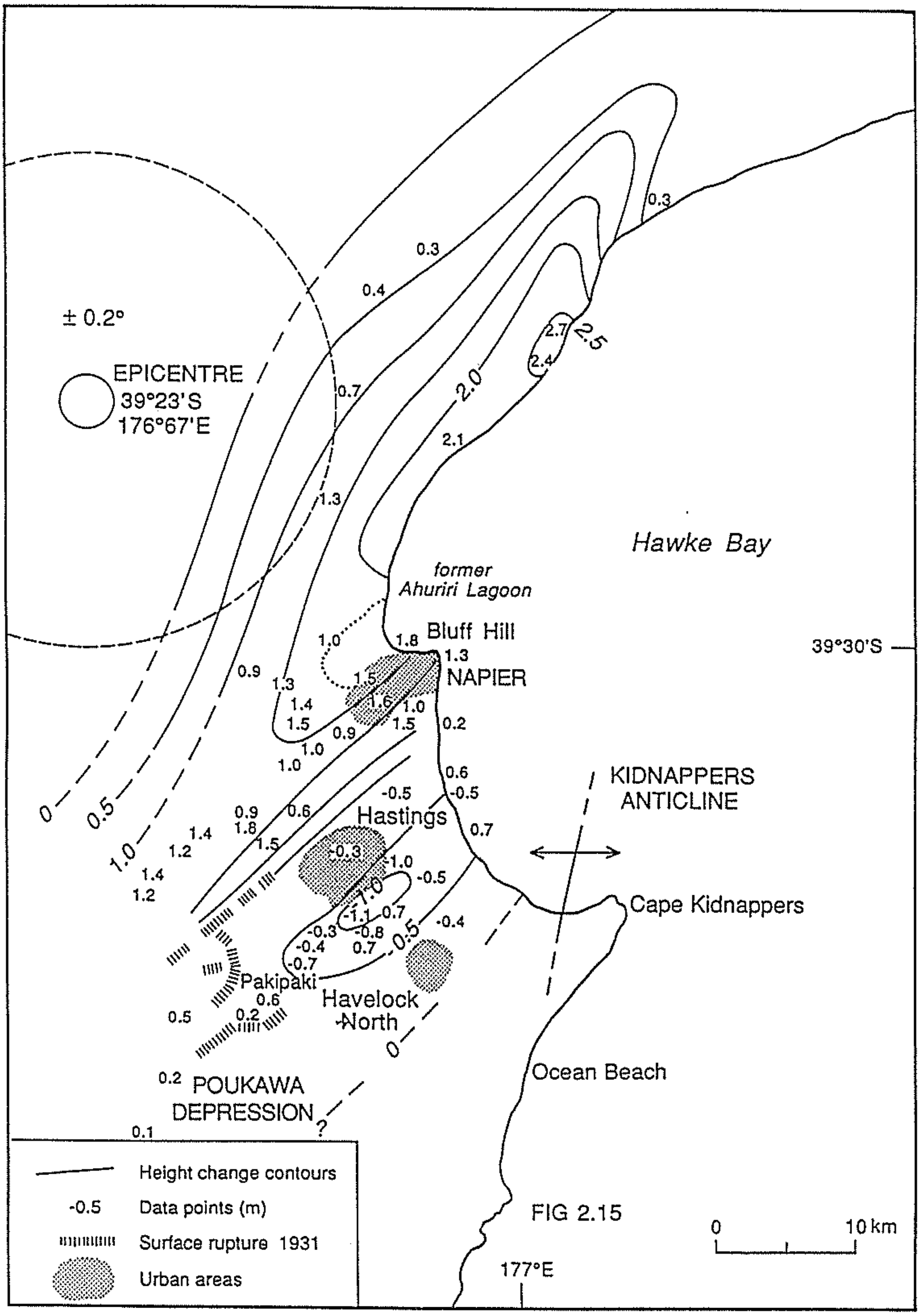


Figure 6.1: Subsidence and uplift associated with the 1931 Napier earthquake. Data points and contours are in metres change (after Hull 1990).

So far, there has been no systematic air photo mapping of landslides in the Hawke's Bay Region, other than in the Lake Waikaremoana and southeastern Hawke's Bay areas. However, major landslides that are known from local investigations are indicated on the accompanying 1:50 000 map sheets (Maps 4 to 14).

Such massive ancient landslides as those damming Waikaremoana (2,200 years ago, involving a total volume of 3.3 x 10^9 m^3; Read et al. 1992) and Waikareiti are likely to have been triggered by seismic events (eg Ongley 1932). Ongley draws parallels between the situation that existed before the Waikaremoana landslide and existing unstable conditions c. 3.5 km north of Mangataniwha on the Waiau River. Ongley (1932) and Read et al. (1992) concluded that the Waikaremoana landslide was triggered by a large, nearby seismic event, and that similar landslides could be triggered by future earthquakes.

Another major area of instability has been identified by Pettinga (1980; 1982). Major landslide features have been recognised on the eastern side of the Maraetotara Plateau, two of which are marked in fine dotted lines on the 1:50 000 Map 11. Similar features probably occur near Waimarama (Map 2). These massive landslides are probably related to a fault which has been identified offshore in bathymetric studies (e.g. Lewis et al. 1988).

The Folgers Hill landslide (Drummond 1968) which re-activated (without any obvious trigger mechanism) in 1968, could potentially fail in response to earthquake ground motion. Other pre-historic, large scale, possibly seismically-induced landslides in the region include features at Putere/Lake Rotongaio, Lake Tutira, and Bridge Pa. Slides in bentonitic sediments underlying such townships as Waipawa and Otane may be activated by strong ground shaking.

Finally, the likelihood of earthquake-induced landslides and rockfalls in oversteepened coastal areas should be considered. There is at least one record illustrating collapse of coastal cliffs (Kidnappers) during the 1931 earthquake.

6.1.5 Settlement and liquefaction

Coastal areas and river valleys are the most likely places to be affected by settlement caused by ground failure and liquefaction in underlying soft sediment. Poorly compacted, fine-grained, water saturated artificial fill is particularly prone to this type of settlement. The main problem is that settlement is rarely uniform, as for example when differential compaction occurs. Road margins and bridge approaches frequently fail by settlement and/or slumping during earthquakes.

Seismic liquefaction of sands has been studied in great detail since the dramatic slope and building failures observed in the Niigata and Alaska earthquakes of 1964. The common occurrence and potential for destruction by liquefaction is now well recognised, but its detailed mechanics are not well understood. Indicators of liquefaction include water ejection and sand boils, gross settlement and overturning of buildings, and landslides on moderate slopes. Liquefaction is commonly responsible for lateral spreading along riverbanks. Areas prone to this hazard tend to coincide with those prone to settlement and amplification of strong ground shaking (see Section 2.3).

Reports of liquefaction during the 1931 Hawke's Bay earthquake were common throughout the Heretaunga Plains, Ahuriri Lagoon, and coastal regions as far north as Gisborne. Unfortunately, few of these reports are very detailed (Henderson 1933). Areas of reclamation, such as at Napier Harbour and the Ahuriri Lagoon are likely to be severely affected by subsidence and liquefaction during future earthquakes.

Most of the large areas within the region that are likely to suffer from liquefaction and settlement during seismic events are within the red Unit A areas on Map 15.

6.1.6 Tsunami and seiching

Tsunamis, impulse generated waves, are generated from both distant and local sources. The most extensively recorded tsunamis in New Zealand have been generated from earthquakes originating off the coast of western South America (de Lange & Healy 1986). The coast of the Hawke's Bay Region is susceptible to these distant sourced tsunamis. At Napier, for example, there are records of tsunamis resulting from the 1868, 1877 and 1960 Chile earthquakes (de Lange & Healy 1986). Hawke's Bay is also considered susceptible to tsunamis generated from local sources, such as the offshore fold/fault zone, though there are no confirmed historical records of locally generated tsunamis affecting Hawke's Bay. There are, however, historical accounts of tsunamis up to 10 m high that were generated through "diapiric" processes involving the explosive extrusion of large amounts of water-saturated sediments and gas offshore from the North Island East Coast (Eiby 1982). Such tsunamis are thought to have been generated by seismic events involving predominantly low frequency shocks.

Section 5.4 identifies potential shallow seismic sources in Hawke Bay that may be capable of generating tsunamis. Tsunami hazard is this year the focus of a separate study for the Hawke's Bay Regional Council (Van Dissen et al. in prep.).

Tilting of the land resulting from an earthquake can induce seiching, periodic waves travelling back and forth, in bodies of standing water, such as lakes, or even in rivers. The 1855 Wairarapa earthquake caused seiching in Wellington Harbour with a natural period of about 20 minutes, and it continued for several hours after the earthquake. Swimming pools are commonly affected by seiching and in some cases have been emptied. Dams are potentially vulnerable because seiching in the reservoir behind them may result in the dam being overtopped. Earthquake-induced seiching of Lake Waikaremoana, and possible catastrophic failure of its landslide dam, is a possibility that should be investigated.

6.2 Earthquake magnitudes in Hawke's Bay

Because of subduction of the Pacific plate beneath the East Coast of the North Island, earthquakes in Hawke's Bay originate from strain release from three sources: (1) sudden movement along the interface between the Pacific and Australian plates; (2) internal stresses accumulated in the upper part of the Pacific plate as it bends downward beneath the North Island; and (3) stresses transferred to the overlying Australian plate from coupling at the plate interface. Large crustal earthquakes associated with faults discussed in the previous part of this section are a result of (3). Earthquakes generated on the major mapped surface active faults and folds are likely to fall within the M 7 - 7.8 range. Historical and instrumental records show, however, that a number of earthquakes felt in Hawke's Bay have been located below the plate interface. For example, a moderate earthquake with felt intensities of MM 5 and MM 6 at Hastings in 1982 (M_b = 5.6), occurred some 20 km below the plate interface (Reyners 1984). At least three earthquakes of this type of M > 6.5 have occurred since 1840, each resulting in felt intensities of MM 5-6 in central Hawke's Bay (Reyners 1987). Focal mechanisms for this type of earthquake, where available, generally indicate normal faulting in the plane of the down-going Pacific plate. The predominantly normal fault slip sense and the historical record suggests that earthquakes rupturing entirely within the upper part of the Pacific plate probably have a maximum magnitude of c. M = 7.

No large historical earthquakes have been well located along the plate interface under the North Island of New Zealand, although some slip may have occurred there in association with the 1931 Hawke's Bay and the 1932 Wairoa earthquakes (Haines and Darby 1987). The geometry of the plate interface has been deduced from seismological studies (eg Adams and Ware 1977; Reyners 1980; Bannister 1986) which show it dips westwards from the Hikurangi trough to beneath the Hawke's Bay coastline.

Lack of historical activity at the plate interface in the central North Island area and the predominance of smaller structures in the overlying Australian plate make it difficult to determine whether large earthquakes in this zone, which are common in some subduction zones elsewhere in the world, have occurred in the Hawke's Bay Region. If they do occur, then by analogy with other subduction zones, earthquake magnitudes probably exceed M 7.5, and may be up to M 8.5.

6.3 Return time of strong ground shaking

An analysis of the frequency of occurrence and magnitudes of earthquakes from the historical record over the last 150 years, and an understanding of the dissipation of energy from earthquake waves as they move away from the source, can be used to estimate the return times for various levels of earthquake shaking. For example, major population centres of the Hawke's Bay Region have experienced destructive intensities of MM 8-10 from three large earthquakes within the last 150 years. MM 8 and MM 7-8 have occurred in and near Porangahau on two occasions. Moderate regional and large, distant earthquakes, both shallow and deep, have repeatedly caused intensities of MM 5-7 over wide areas of Hawke's Bay.

Smith and Berryman (1986) carried out this type of analysis, and estimated the mean return times for various levels of Modified Mercalli (MM) intensity shaking at "average" sites throughout New Zealand. An average site is one underlain by unconsolidated coarse-grained deposits, or weak rock. Smith and Berryman (1992) used a refined seismicity model and a further seven years of earthquake records to revise their 1986 results. Their revision has resulted in an increase in the estimated mean return times for MM intensity for most parts of New Zealand. Napier/Hastings, for example, now has an estimated mean return time of 11 years for MM 6, 62 years for MM 7, 210 years for MM 8, and 640 years for MM 9 (Figure 6.1). These results agree reasonably well with observed mean return times for the last 150 years for Napier (Table 3.1), at MM 6, 10 years, MM 7, 50 years and MM 8, 75 years.

The return time for the highest levels of shaking intensity - MM 9 and MM 10 - cannot be estimated reliably from the historical record because these levels of shaking have relatively long return times and have only been recorded twice since the settlement of Hawke's Bay.

6.4 Characterisation of ground shaking in Hawke's Bay

Ground shaking is the most widespread earthquake hazard. Geological units defined in Section 2.3 form the basis for the 1:500 000 scale earthquake ground shaking map. It is important to note that the units used here are divided according to general rock and sediment strength that form a near continuum from very strong to very weak. Characteristic rock types making up each unit are summarised in Section 2.3. An assumption is made in preparing the accompanying map (Map 15) that broadly similar rock types produce broadly similar ground shaking responses. This assumption has proved valid in other areas. The only area in New Zealand that has been microzoned quantitatively is the Wellington Region. A large component of quantification is achieved using low amplitude shaking (weak ground motions generated by micro-earthquakes), and the response of the sediments at high amplitudes is based on the few existing records only.

Map 15 is a preliminary ground shaking response map which separates areas characterised by one of four types, Units A to D. In some cases, normally the result of uncertainty in sediment characteristics or because of sediment variability, areas covering a range of these units are mapped. Areas mapped as Unit A are likely to respond worst to ground shaking, while areas mapped as Unit B are likely to have a moderate response. Those areas classified as Units C, and particularly D, are least likely to behave unfavourably to ground shaking.

It is the nature of the materials above bedrock that is the dominant influence on local ground shaking. The third dimension of depth is certain in only a few areas within the region, and in producing Map 15, an assumption is made that the rock/sediment present at the surface is representative to a depth of c. 20 m.

The ground shaking response units used in the map are gradational, so that differences between some areas classified Unit D and some areas classified Unit C are probably small. Responses of areas classed Unit C may also overlap with areas classed B and D. Further study is likely to show that Unit A is subdivisible into a further unit that will respond most unfavourably to ground shaking, and another unit that amplifies ground shaking, but not on such an extreme scale. The latter unit may overlap to some extent with Unit B.

Quantification of the ground shaking characteristics of these units is clearly desirable. A logical method is to concentrate on quantification in built up areas with valuable commercial, infrastructural or horticultural investment, particularly in areas underlain by Unit A. The most obvious of these areas are the Heretaunga Plains, the Waipawa/Waipukurau depression, and the low-lying area around Wairoa. Some attempt should, however, be made to evaluate the response of each of the units.

7.0 Conclusions

Compilation of existing information leads us to the following general conclusions regarding earthquake hazards in Hawke's Bay.

1. The level of seismicity in the Hawke's Bay Region during about the last 150 years is high. Fifty-two earthquakes with observed or inferred felt intensities of MM ≥ 5 are on record for the period 1848 to the present day within the region. Large earthquakes generating maximum felt intensities of MM ≥ 7 have occurred at least nineteen times during the same period. The region is one of the most earthquake-prone areas of the country.

2. A minimum of twenty-two active faults and folds that each record one or more pre-historic large earthquakes during the last 125 000 years have been identified within the Hawke's Bay Region. These faults and folds are earthquake sources, and can be split into two types, those occurring close to populated areas and those that are distant. Distant sources are less likely to cause ground shaking intensities of MM > 8 in areas with the greatest population and capital investment such as Napier and Hastings. These sources include the Ruahine, Mohaka, Patoka, Rangiora, Taniwha, Waikopiro and Oruawharo faults. Nearby sources include the Napier-Hawke Bay, Waipukurau-Poukawa, and possibly the subduction thrust, and faults at the roots of the Kidnappers and Lachlan anticlines. For most of the nearby sources calculated ground shaking intensities of MM 9-10 in the Heretaunga Plains area can be expected. This level of shaking is equal to that experienced in the 1931 Napier earthquake in Napier and Hastings. For Waipawa and Waipukurau, the Taniwha, Oruawharo and Glendevon faults are considered additional nearby sources, the first two of which are probably capable of producing high ground shaking intensities in that area.

3. Information on the repeat times for large earthquakes is available for about half of the active faults of the region. We are unable to assess accurately the seismic hazards to the region with such limited information on the earthquake return times for many of the major active faults of the area. Quantification of repeat times for earthquakes producing ground shaking intensities of MM ≥ 8 is needed.

4. Reports of widespread liquefaction on the Heretaunga Plains, and landsliding across the region during the 1904 Cape Turnagain and 1931 Napier earthquakes indicate that earthquake hazards such as liquefaction and slope stability should also be assessed. There is a wide variety of near-surface ground conditions within the region and within the Heretaunga Plains, and therefore a wide variety of earthquake shaking responses are expected for future earthquakes. Ground shaking is likely to be amplified locally on the Heretaunga Plains. The hazards presented by the variable ground response should be quantified for both large nearby earthquake and large distant earthquake scenarios, particularly for the Heretaunga Plains.

8.0 Recommendations

The results from this study indicate that although a range of existing information is available, further studies of the earthquake hazards of the Hawke's Bay Region are needed. This need is in accordance with that recognised in the Hawke's Bay Regional Council's Strategic Plan in which the assessment of earthquake and other geological hazards has been programmed for the next four years. Our major recommendations, therefore, are focused upon determining and planning for the additional studies required to assess adequately the earthquake hazards in the Hawke's Bay Region. Additionally, we also make a number of recommendations to the Territorial Local Authorities within the Hawke's Bay Region for additional studies within their boundaries that may not be included in the more regional studies planned.

8.1 Recommendations for immediate consideration

Planning for future studies as outlined below is currently underway, and we believe these studies will provide a sound basis from which to quantify more definitively the earthquake hazards in Hawke's Bay. A number of issues, however, require immediate consideration to facilitate and direct these future studies. We make the following recommendations for immediate consideration by the Hawke's Bay Regional Council:

- That the Hawke's Bay Regional Council recognises the relatively high earthquake hazards in the Hawke's Bay Region. The hazards are indicated by the record of felt earthquakes during the last 150 years and by the existence of a large number of geological structures capable of producing damaging strong earthquake shaking throughout the Hawke's Bay Region, and particularly in the Heretaunga Plains.

- That the Hawke's Bay Regional Council recognises the potential hazards of earthquake shaking amplification and liquefaction within the Heretaunga Plains from both close and distant large earthquake sources.

- That the Hawke's Bay Regional Council adopt the maps of active faults and preliminary areas of ground shaking amplification attached to this report as a basis for future studies and initial earthquake hazards policy development.

- That the Hawke's Bay Regional Council affirms its commitment to understanding the earthquake hazards of the Hawke's Bay Region, and to developing and maintaining a database of earthquake hazards sufficient for formulating suitable policies and objectives to avoid or mitigate the effects of these hazards.

8.2 Further studies

This study has identified the nature and content of existing information on earthquake hazards in Hawke's Bay. We have also identified a number of key areas where existing information is inadequate for reliably estimating the hazards posed by future earthquakes in many parts of the Hawke's Bay Region. As a means to address this lack of data we recommend the following work programme:

Stage One - Geological and seismological studies

Complete the accurate location of active faults and folds from the onshore areas of the Hawke's Bay Region. Determine the recurrence intervals and magnitudes of past large earthquakes originating from these faults and folds. Particular attention should be focused upon those earthquake sources that are capable of producing earthquake shaking in excess of intensity MM 8 in the major urban areas of Waipukurau/Waipawa, Hastings, Napier and Wairoa. Where possible, further assessment of offshore structures should be undertaken from existing data.

Outputs

- A report indicating the dates and magnitudes of pre-historic earthquakes along the Waipukurau-Poukawa fault zone. This report would provide an estimate of the average return time for damaging earthquake shaking similar to that experienced in the Heretaunga Plains during the 1931 Hawke's Bay earthquake.
- A report assessing the nature and frequency of potential large or great earthquakes generated at the subduction zone 15-25 km beneath the Hawke's Bay Region.
- A synthesis of all existing and new data, from both geological and historical records, to provide the best possible estimate of the return times for strong earthquake shaking from earthquakes in the Hawke's Bay Region.

Benefits

- Provision of accurate data for determining the level of earthquake emergency response planning for Districts and the Region. Results would permit an assessment of the vulnerability of key lifelines such as water, sewerage, telephone and gas to the effects of earthquake faulting.
- Provision of locations of all on-land active faults and folds for input into Regional and District land information systems.
- Provision of return periods for large earthquakes involving surface rupture and average recurrence intervals for various levels of earthquake strong ground shaking as required for Stage Two studies.

Stage Two - Ground shaking hazard study

Initiate studies to determine the nature of the subsurface materials within the Hawke's Bay Region and their likely response to the, various levels of earthquake shaking determined in Stage One. Studies would focus upon urban areas of Waipukurau/Waipawa, Wairoa and the Heretaunga Plains. We will analyse subsurface information available from the Hawke's Bay Regional Council drill log database and geotechnical information available from Regional and District sources. Seismographs will be deployed to quantify the ground shaking response of different ground types identified from surface and subsurface geology. Specialised geotechnical studies, such as seismic cone penetrometry, will be undertaken at agreed sites in order to determine the flexibility and plasticity of sediments.

Outputs

- Documentation of the results of the surface and subsurface geological and geotechnical studies.
- A report quantifying the degree of expected earthquake shaking amplification, particularly for moderate level shaking from distant large earthquakes, as determined from the seismograph deployment.
- Maps and reports indicating areas susceptible to earthquake ground shaking amplification within and surrounding the major urban areas of the Hawke's Bay Region. Ground shaking will be determined for two principal scenario earthquakes: a large earthquake within 10 km of the Heretaunga Plains and a more distant (≥ 50 km) source offshore or within the Ruahine Ranges.

Benefits

- Quantification of the degree of expected earthquake shaking for two different, but probable earthquake scenarios. These results will be important for identifying any regions where special structural and design controls to accommodate the effects of strong earthquake shaking may be required.
- Essential information for detailed emergency response planning. Results are key inputs into assessment of the vulnerability of key lifelines such as water, sewerage, telephone, and gas services, and the effects of earthquake shaking on other existing man-made structures.

Stage Three - Liquefaction potential

Liquefaction of water-saturated subsurface sediment layers is an important hazard related to earthquake shaking. We believe it is important to assess the potential for this hazard within urban and industrial areas of Hawke's Bay. This assessment will be facilitated by the assembly and interpretation of available subsurface, geotechnical and earthquake shaking amplification data carried out in Stage Two.

Outputs

- Reports compiling historical and geotechnical data on the location and occurrence of earthquake-induced ground liquefaction in the Hawke's Bay Region.

- Maps showing areas susceptible to liquefaction for appropriate parts of Hawke's Bay Region.

Benefits

- Quality data on the location and extent of past and possible future liquefaction in the Hawke's Bay Region that may be incorporated into land information systems.

- Essential information for an assessment of the vulnerability of key man-made elements of the social infrastructure to the effects of liquefaction.

Stage Four - Earthquake hazards synthesis and policy development

Much of the data and its initial presentation to the Hawke's Bay Regional Council are likely to be of a technical nature unsuitable for immediate public release. Depending upon the needs of the Regional Council, much of these data will require further analysis and generalisation for public release. Coordinated with the public release of the results of the first three phases of the study, a public education campaign about the hazards and risks associated with earthquakes in Hawke's Bay should also be undertaken.

Public participation in the concluding part of the study will permit the development of robust policies that seek to avoid or mitigate the identified hazards, thus reducing the vulnerability of the community to the effects of earthquakes.

8.3 Recommendations for consideration by territorial/local authorities

Several issues have arisen from this study that may require further study that is not within the scope of the proposed earthquake hazards study for the Hawke's Bay Regional Council, but could be of interest to Territorial/Local Authorities. The completion of these studies in conjunction with the regional study offers the potential for cost saving.

Central Hawke's Bay District

We recommend that:

- Active faults in Waipawa and Otane be mapped at a scale suitable for determining a building restriction zone similar to that currently in force in Waipukurau.
- Lifeline services within or crossing active faults be assessed as to their vulnerability to fault rupture.
- New lifeline services be designed to minimise the threat to human life in the advent of a surface fault rupture.
- Emergency response procedures be reviewed to take into account the fault rupture hazard which may disrupt transport routes, energy and water supplies, and in some cases critical facilities.
- A review of public amenities (schools, hospitals etc.) and aspects of Council responsibilities be carried out to evaluate the number of structures and activities vulnerable to the fault rupture hazard.

Hastings District

We recommend that:

- Lifeline services within or crossing active faults be assessed as to their vulnerability to fault rupture.
- New lifeline services be designed to minimise the threat to human life in the advent of a surface fault rupture.
- Emergency response procedures be reviewed to take into account the fault rupture hazard which may disrupt transport routes, energy and water supplies, and in some cases critical facilities.
- A review of public amenities (schools, hospitals etc.) and aspects of Council responsibilities be carried out to evaluate the number of structures and activities vulnerable to the fault rupture hazard.

Napier City

At present none of the active faults that lie within the boundaries of Napier City have been precisely located. However, studies undertaken in Stages Two and Three would address ground shaking hazards that will be important for Napier City.

Wairoa District

A number of active faults are known in the northwestern part of the District, but the intensity of urban development probably does not warrant any studies more detailed than those to be undertaken for the regional studies. The town of Wairoa lies on alluvial materials that can be expected to amplify earthquake ground shaking. These alluvial materials may also be prone to liquefaction, and more detailed studies may be required during Stage Two and Three of the regional study.

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APPENDIX 1

MODIFIED MERCALLI INTENSITY

Construction Categories
NZ 1991 proposed

Buildings
Type I
Weak materials such as mud brick and rammed earth; poor mortar; low standards of workmanship (Masonry D in other MM scales).
Type II
Average to good workmanship and materials, some including reinforcement, but not designed to resist earthquakes (Masonry B and C in other MM scales).
Type III
Buildings designed and built to resist earthquakes to normal use standards, i.e. no special damage limiting measures taken (mid-1930's to c.1970 for concrete and to c.1980 for other materials).

Buildings and Bridges
Type IV
Since c.1970 for concrete and c.1980 for other materials, the loadings and materials codes have combined to ensure fewer collapses and less damage than in earlier structures. This arises from features such as:
(i) "capacity design" procedure
(ii) use of elements (such as improved bracing or structural walls) which reduce racking (i.e. drift)
(iii) high ductility
(iv) higher strength

Windows
Type I
Large display windows, especially shop windows.
Type II
Ordinary sash or casement windows.

Water Tanks
Type I
External, stand mounted, corrugated iron water tanks.
Type II
Domestic hot-water cylinders unrestrained except by supply and delivery pipes.

H (Historical). Important for historical events. Current application only to older houses etc.

General Comment
"Some" or "few" indicates that the threshold of a particular effect has just been reached at that intensity.

Modified Mercalli Intensity (MM)
NZ 1991proposed

MM V

People
Generally felt outside, and by almost everyone indoors. Most sleepers awakened.
A few people alarmed. Direction of motion can be estimated.

Fittings
Small unstable objects are displaced or upset.
Some glassware and crockery may be broken.
Hanging pictures knock against the wall.
Open doors may swing.
Cupboard doors secured by magnetic catches may open.
Pendulum clocks stop, start, or change rate (H).

Structures
Some Windows Type I cracked.
A few earthenware toilet fixtures cracked (H).

MM VI

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

Fittings
Objects fall from shelves.
Pictures fall from walls (H).
Some furniture moved on smooth floors.
Some unsecured free-standing fireplaces moved.
Glassware and crockery broken.
Unstable furniture overturned.
Small church and school bells ring (H).
Appliances move on bench or table tops.
Filing cabinets or "easy glide" drawers may open (or shut).

Structures
Slight damage to Buildings Type I.
Some stucco or cement plaster falls.
Suspended ceilings damaged.
Windows Type I broken.
A few cases of chimney damage.

Environment
Trees and bushes shake, or are heard to rustle.
Loose materials may be dislodged from sloping ground, e.g. existing slides, talus slopes, shingle slides.

MM VII

People

General alarm.
Difficulty experienced in standing.
Noticed by motorcar drivers who may stop.

Fittings

Large bells ring.
Furniture moves on smooth floors, may move on carpeted floors.

Structures

Unreinforced stone and brick walls cracked.
Buildings Type I cracked and damaged.
A few instances of damage to Buildings Type II.
Unbraced parapets and architectural ornaments fall.
Roofing tiles, especially ridge tiles may be dislodged.
Many unreinforced domestic chimneys broken.
Water tanks Type I burst.
A few instances of damage to brick veneers and plaster or cement-based linings.
Unrestrained water cylinders (Water Tanks Type II) may move and leak.
Some Windows Type II cracked.

Environment

Water made turbid by stirred up mud
Small slides such as falls of sand and gravel banks.
Instances of differential settlement on poor or wet or unconsolidated ground.
Some fine cracks appear in sloping ground.
A few instances of liquefaction.

MM VIII

People

Alarm may approach panic.
Steering of motorcars greatly affected.

Structures

Buildings Type II damaged, some seriously.
Buildings Type III damaged in some cases.
Monuments and elevated tanks twisted or brought down.
Some pre-1965 infill masonry panels damaged.
A few post-1980 brick veneers damaged.
Weak piles damaged.
Houses not secured to foundations may move.

Environment

Cracks appear on steep slopes and in wet ground.
Slides in roadside cuttings and unsupported excavations.
Small earthquake fountains and other manifestations of liquefaction.

MM IX

Structures

Very poor quality unreinforced masonry destroyed.
Buildings Type II heavily damaged, some collapsing.
Buildings Type III damaged, some seriously.
Damage or permanent distortion to some Buildings and Bridges Type IV.
Houses not secured to foundations shifted off.
Brick veneers fall and expose frames.

Environment

Cracking of ground conspicuous.
Landsliding general on steep slopes.
Liquefaction effects intensified, with large earthquake fountains and sand craters.

MM X

Structures

Most unreinforced masonry structures destroyed.
Many buildings Type II destroyed.
Many Building Type III (and bridges of equivalent design) seriously damaged.
Many Building and Bridges Type IV have moderate damage or permanent distortion.

Source:

Study Group of the New Zealand Society for Earthquake Engineering, 1992: A revision of the Modified Mercalli seismic intensity scale. *Bulletin of the New Zealand National Society for Earthquake Engineering 25: 345-357.*