Earthquake Hazards in the Auckland Region

A report prepared for the Auckland Regional Council

A G Hull, G D Mansergh, T D Townsend and V Stagpoole
Institute of Geological and Nuclear Sciences Limited
Lower Hutt, New Zealand

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Summary

The Auckland region lies in one of the lowest earthquake activity regions of New Zealand. Over the last 150 years only the 1891 Waikato Heads earthquake of magnitude 5.7-5.9 is known to have caused significant earthquake damage in the Auckland region. This earthquake produced the strongest shaking (MM6–7) experienced since European colonisation of the Auckland region. Historical records of seismicity have been used to estimate the average return period for moderate to strong shaking in the Auckland region. On average we expect shaking of intensity MM6 or greater to occur about every 90 years, MM7 or greater about every 650 years and MM8 or greater about every 5,400 years. This can also be expressed as a 100 year return period intensity of MM6, 500 year return period intensity of MM7 and 1000 year return period intensity of MM7.2.

There are many geological faults within the Auckland region that have been active over about the last 2 million years. Based on existing information we believe that the greatest potential for future fault activity and consequent large earthquakes exists along faults in the southern and eastern parts of the region. In particular, the Wairoa North fault that bounds the western margin of the Hunua Ranges is judged to show the highest rate of movement in the recent geological past, and hence the greatest potential for future activity. No data are presently available to determine past earthquake recurrence and magnitude along the Wairoa North fault. Similarly, the Drury, Beachlands and eastern Waikato faults may also have some potential for future fault activity, but no data are available to determine their potential for future fault movement and large earthquake generation.

There is no evidence for activity of offshore faults during the last 100,000 years on either the west or eastern coasts of the Auckland region. There is, however, clear evidence that the Kerepehi fault extends offshore of the central Hauraki Plains into the Firth of Thames. This fault has proven Holocene activity onland, and is likely to be active offshore as well. Although this fault lies outside of the Auckland region, future movements will generate earthquakes of about M 7, and result in moderate to strong earthquake shaking (MM7-9) throughout the Auckland region.

Surficial geological materials in the Auckland region can be divided into five major classes of expected response to earthquake shaking. The worst response is likely to come from the soft to firm sand, silt and estuarine mud in coastal areas such as Orewa, Helensville and near Takanini. The response of these materials to moderate earthquake shaking is that they are likely to amplify it, such that felt intensities in a single earthquake could be up to two MM units higher on the soft materials compared to those on adjacent rock sites. The probability of liquefaction of loose water-saturated sand and silt layers within these deposits is moderate to high when earthquake shaking intensities reach MM7 or greater.

The principal earthquake hazard in the Auckland region is that caused by moderate to strong ground shaking from local faults. At present there are no data on the past and potential activity of these faults, and we recommend that these data be obtained by further study of the Wairoa North fault initially, and other related faults if the Wairoa North fault proves to be a significant hazard. Successful completion of these further studies will provide the data necessary to constrain a reliable model for longer term earthquake

hazard in the Auckland region, determine the level of planning response required for areas identified as capable of significant modification of earthquake shaking, and indicate the level of hazard posed to major water supply infrastructure located close to this fault.

1 Introduction

Under the Resource Management Act, responsibilities for natural hazard mitigation and avoidance are clearly defined and distributed among Central, Regional and Territorial Government. Key functions of Regional Councils are the collection and distribution of information on hazards and developing policies and objectives related to natural hazard mitigation.

In the ARC draft Regional Policy Statement, earthquakes related to tectonic and volcanic activity are recognised as important natural hazards affecting the Auckland region. Earthquakes are an important natural hazard because of their potential to cause loss of life and major damage to property. The ARC has already implemented a programme to monitor volcanic-related earthquakes with an appropriate seismic monitoring programme.

Tectonic earthquakes are those caused by ongoing geologic processes that are related to New Zealand's position along the boundary between two of the tectonic plates of the earth. The level of earthquake activity in the Auckland region is less than in most other parts of New Zealand, and has consequently had only limited attention from researchers. There remains a need, however, to understand better the effects of possible future earthquakes occurring within and at a distance from the region.

Because earthquake hazards generally affect wide regions, the Auckland Regional Council is well placed to address resource management issues and concerns pertaining to the impacts of future earthquakes in the Auckland region. This scoping study aims to collate and integrate existing information related to the location and occurrence of earthquake hazards in the Auckland region. This report and accompanying maps are provided to assist Auckland Regional Council in preparing a plan to:

- identify relevant information required to prepare appropriate emergency response plans;
- initiate an earthquake hazards information register;
- develop policies and objectives that mitigate and avoid the effects of earthquakes in the Auckland region.

Our study was established with the following objectives:

- To present existing information on the occurrence and effects of historical earthquakes in the Auckland region.
- To present existing information on the location and past movements along recently active faults within the boundaries of the Auckland region, and those that might have an impact but are located outside of the ARC boundaries.
- To collate existing information on the activity of faults that are of importance to earthquake hazard assessment from regions offshore of the Auckland region.

- To identify areas that warrant further study because of their suspected susceptibility to amplify earthquake ground shaking.

- To recommend possible future actions for Auckland Regional Council to define better the earthquake hazard in the Auckland region so that earthquake hazard avoidance and mitigation policies and objectives can be formulated.

In accordance with these objectives we have undertaken the following work:

(1) Prepared preliminary maps of the Auckland region at a scale of 1: 250 000 that identify zones believed to contain geologic materials capable of amplifying strong earthquake ground motion.

(2) Collected data from Institute records and other unpublished information on the location of potentially active faults and historical earthquakes in the Auckland region.

(3) Prepared maps at a scale of 1: 250 000 that show the location of these faults and earthquakes. Detailed fault location information is provided at the scale of 1: 50 000, where available.

(4) Prepared the technical report below to accompany the maps that specifies the purpose of the study, definition of terminology and the assumptions and limitations of the data and interpretations presented. An assessment of the probability of certain levels of shaking (felt intensity) is included for the region and its major population centres. Our report recommends further studies that could improve the quantification and understanding of faulting and historical earthquake effects in the Auckland region. We also recommend further studies to improve the quantification and understanding of earthquake shaking and ground response in the most hazardous zones in the Auckland region.

The data collection and analysis was completed by Dr Alan Hull for earthquake location and return periods of ground shaking, Mr Graham Mansergh, Graham Mansergh and Associates, for fault location and activity assessment, Ms Tracey Townsend for earthquake shaking amplification and Mr Vaughan Stagpoole for analysis of offshore geology. The report was reviewed by Dr John Begg and Dr Mauri McSaveney from the Institute.

2 Geology of the Auckland Region

In the following sections we provide a brief outline of the distribution of major rock types and geological history of the Auckland region. This information provides the setting for the geological and historical records of earth movements.

2.1 Geological Setting and History of the Auckland Region

Previous work on the geology of Auckland dates back to Hochstetter's 1864 published report and coloured geological map. In the 130 years since this publication, many others have investigated the geology within the Auckland region; e.g. Cox (1881), McKay (1888), Park (1886), Searle (1964a) and Lillie (1959). As outcrops and landscape features disappeared through urban landscape modifications, the need to retain, for future use, the rapidly accumulating data from drill holes and excavations in the city and suburbs led to the publication of the nine Industrial Series geological maps (Kermode 1966; 1968; 1969; 1975; 1978; 1982; 1986b, c; Kermode and Searle 1966). Ballance (1964a; 1974; 1976b) and Hayward (1976) worked in detail on the Miocene rocks, and many other workers have contributed to the understanding of the geology of Auckland.

The Auckland region has been affected by two periods of major tectonic activity. The most recent phase of activity being regional block-faulting, inferred to have occurred during late Miocene–Pliocene time, from 7–2 million years ago. The most conspicuous geological feature of Auckland is its field of young, largely uneroded, basaltic volcanoes, the most recent of which (Rangitoto) erupted only about 600 years ago. The larger part of Auckland City is built on older, Miocene, Pliocene, and Quaternary sedimentary rocks. A description of the deposits found within the Auckland Region, their mode of deposition, and their geological history, is summarised from Kermode (1992):

- The oldest known rocks in the Auckland area are indurated, marine sedimentary strata constituting the "greywacke basement" of Late Permian to Late Jurassic age (200-140 million years BP).

- These marine sedimentary rocks were elevated during the Cretaceous (130–65 million years BP) to form a landmass that was subjected to prolonged erosion, and developed a generally subdued topography. During the Late Eocene and Early Oligocene (40–35 million years BP), a major rise in relative sea level occurred. The swamplands marginal to the advancing seas were inundated, and basal coal measures of the Te Kuiti Group were deposited. The marine transgression culminated during the Late Oligocene and Early Miocene (25–15 million years BP) with the deposition of a thick sequence of calcareous marine sedimentary rocks.

- An important period of deformation during the Late Oligocene to Early Miocene (25–15 million years BP) raised the Mesozoic basement of eastern Northland and Auckland, as the more central Waitemata Basin developed and rapidly deepened. A chain of underwater volcanoes formed along the western margin of the basin during the Late Miocene (12–5 million years BP), and later a chain of mainly terrestrial volcanic mountains developed on the eastern margin.

- An episode of major regional uplift brought to an end the marine sedimentation during the Miocene Period, and produced a significant break in the stratigraphic record. Above this break, coastal and shallow marine Pliocene sediments of Kaawa Formation (5–1.63 million years BP) accumulated in inlets around many small islands. Fluctuating sea levels during the Pleistocene (1.8 million years to 10,000 years BP) brought many changes to the ephemeral islands and channels of the Auckland region.

- The Auckland Volcanic Field consists of young volcanic rocks 400 km from the plate boundary during a period of little or no land movements over the last 1–2 million years. All the known vents have erupted through East Coast Bays Formation or Tauranga Group sediments.

2.2 Geological Units

For the purposes of this study, the various rock types of the Auckland region have been grouped into five major geological units, based on age and inferred strength (Table 2.1). These units form the basis for our preliminary ground shaking hazard map (in pocket), and are, in order of increasing age and strength:

- A) Very soft to stiff deposits, usually less than 10,000 years old; sand, silt, mud, shell, and peat deposits mainly on coastal areas, having been (and still being) deposited in estuaries, swamps, low-lying alluvial plains and lakes. Also included is artificial fill.

- B) Loose to dense alluvium and sand, fossiliferous and pumiceous deposits, silt, mud, lignite, and clay; less than 3 million years old. Primarily deposited by marine processes during the last 3 million years.

- B1) "Floating Volcanoes"; thin (<30m thick) volcanic deposits overlying stiff Pleistocene, sediments. Quaternary (1.6–0 million years) in age.

- C) Very weak to moderately strong sandstone, siltstone, mudstone, limestone and conglomerate. Deposits derived from volcanic sources, 0 to 65 million years ago, are also included in this Tertiary–aged class of sediments. Basal coal measures are overlain by non-calcareous deposits, that are in turn overlain by calcareous, fossiliferous sediments including limestone deposited in shallow marine to estuarine and fluviatile environments.

- D) Moderately strong to very strong basement and old sedimentary rocks, Mesozoic in age (235 to 65 million years). This group contains greywacke, argillite, conglomerate, fossiliferous and tuff beds, deposited by marine processes.

Important geological maps illustrating the distribution and character of rock types in the Auckland region include: Schofield (1976; 1979; 1989), Skinner (1976), Waterhouse (1978), Hayward (1983), and Kermode (1992). A compilation of the geology of the southern Manukau Harbour area is currently being prepared by the Institute.

In general terms, the distribution of geological units within the Auckland region can be characterised by a zone of volcanic debris in the west, greywacke terrain in the east, and marine sedimentation in the centre of the region overlaid, in part, with basaltic volcanoes.

3 Historical Seismicity

Auckland is located in the least seismically active region of New Zealand. Auckland City is about 300 km from a major seismically active zone of descending tectonic plate that lies offshore and beneath the east coast of the North Island, and which is capable of producing the largest (M≥ 8) damaging earthquakes in New Zealand. There has been little historical (~ last 150 years) earthquake activity in Auckland (Figure 2). The purpose of this section is to outline existing information on those earthquakes that have been recorded in or adjacent to the Auckland region, and to give details of location and effects of the significant earthquakes.

3.1 Data Sources and Limitations

The Institute maintains the National Earthquake Information Database which includes locations of nearly 100,000 earthquakes. The historic section of the database records important pre-instrumental shocks from about 1840, when European colonisation of New Zealand began, but of the early historic earthquakes, only those which occurred before 1855 have been studied in detail. For the period 1855-1940, a definitive list of earthquakes has not been prepared, and the database is known to be inhomogeneous and incomplete over that period. Generally, only larger magnitude[1] events have been recorded. Significant smaller events away from centres of population await identification with further research. It is, however, likely that all shallow earthquakes of magnitude 7 and greater have been recognised.

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

The distribution of the seismographs of the National Network had developed sufficiently by the early 1940's to give reasonable coverage for shallow earthquakes of magnitude 4.3 and greater between the latitudes 38° (south of Auckland) and 42°S, providing all stations were operating. All magnitude 6 and greater events have been located reliably since 1940.

The New Zealand National Network of seismographs has been progressively upgraded. A network of over 70 digital stations, including several special purpose local networks, now cover the country. All shallow earthquakes of M≥ 3.5, and deep earthquakes of M≥ 3.8 on or near the New Zealand mainland can now be well located. Earthquakes of much lower magnitudes are also routinely analysed.

[1]The magnitude is a measure of the energy released by an earthquake at its source and it is calculated from seismographic records. M, M_L, M_S and M_W are commonly used when describing earthquake magnitudes - M_L resulting from analysis of New Zealand seismograms, M_S from analysis of the surface waves appearing on distant, or overseas, seismograms, and M_W, the moment magnitude, obtained from the length of fault rupture and the amount of slip associated with the earthquake event. For pre-instrumental earthquakes, the magnitude, M, has been estimated by comparison with later instrumentally recorded events.

3.2 Significant Earthquakes Affecting Auckland since European Settlement.

Over the period of good recordings (1964-present) the greater Auckland area has experienced low levels of seismicity relative to other areas of the country. Table 1 records shallow earthquakes of magnitude >3 that have occurred since 1830. Figure 2 shows in detail the location of all earthquakes of magnitude 2.5 and greater (depth<40 km) from the catalogue, and all historic earthquakes known to have occurred within the Auckland region since European settlement. It should be noted that while earthquakes of magnitude 2.5 and greater have been plotted, earthquakes of magnitudes less than 4.0 would neither be felt widely nor cause damage, unless the epicentre was very shallow (~ 5 km). However, damage from such a shallow, small magnitude event would be minor and very weak.

Two larger magnitude earthquakes, the 1891 Waikato Heads earthquake (M=5.7–5.9) and an earthquake in 1834 or 1835, reportedly near Auckland (Figure 2) are discussed in the next section. Several earthquakes of magnitude M_L=4.0–4.9 are also indicated, four occurring in the 1950's. These were reported as not felt and their epicentres were determined from a widely spaced network of less than fifteen seismographs covering New Zealand, so their locations are probably inaccurate. However, the earthquakes in 1927, 1963 and 1983 with M_L>4.0 (Figure 2) were felt locally, generally with low shaking intensities[2], the maximum being Modified Mercalli Intensity (MM) 6 at Morrinsville in 1927. None were reported felt in Auckland. The 1927 and 1963 events were the largest of swarms of earthquakes.

Large earthquakes, both shallow and deep, occurring at large distances from Auckland have often been felt in Auckland, but rarely with intensities exceeding MM 4. These earthquakes are not considered a significant hazard and are not discussed further.

Table 2 lists all earthquakes known to have been felt in the greater Auckland area with an intensity ≥ MM 5 or for which an intensity ≥ MM 5 can be inferred from an isoseismal map, or from observations from other nearby locations. Detailed discussion of the two larger magnitude earthquakes is given below. Sources of information include Eiby (1968), unpublished data and an isoseismal map held within the Institute of Geological and Nuclear Sciences.

[2]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 (ie. up to MM10) 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. The Modified Mercalli scale for New Zealand has recently been revised and is given in Appendix 1.

TABLE 1: Felt earthquakes (M_L>3.0) less than 40 km deep recorded by the National Seismograph Network in the Auckland region between 1 January 1830 and 1 July 1994.

Year	Date	Time	Latitude (°S)	Longitude (°E)	Depth (km)	Mag. (M_L)
1891	Jun 23		37.4	174.7	C	5.9
1950	Nov 06	2103	37.29	174.95	12R	4.8*
1952	May 02	1203	37.05	174.66	12R	4.3*
1953	Jun 13	1856	35.71	175.23	12R	3.4
	Jun 17	0822	35.71	175.23	12R	3.6
	Jun 17	1447	35.71	175.23	12R	3.1
	Jun 20	0414	35.85	175.25	12R	3.2
1956	Jan 08	1639	37.25	175.25	0?	4.3*
1957	Jan 21	0114	36	175.25	N	3
	Jan 24	1718	36	175	N	3.5
	Jun 02	1208	35.7	175	S	3.5
	Jun 03	1212	35.7	175	S	3.5
	Jun 08	2212	35.9	175.1	C	3
	Jun 09	0431	35.9	175.1	C	3.7
1963	Apr 08	1534	37.39	174.70	12R	3.1
	Apr 10	0518	37.29	174.91	12R	3.2
	Apr 12	1301	37.13	175.30	12R	3.4
1966	Jan 19	2111	36.92	175.36	12R	3.9
	May 10	1202	36.10	174.18	12R	3.4
	Jul 05	2232	37.41	174.99	12R	3.5
	Oct 18	1532	36.11	175.52	12R	3.3
1969	Apr 14	0744	37.07	175.16	12R	3.3
1975	Feb 11	1645	35.93	174.76	12R	4.4
	Aug 16	2356	35.99	174.36	12R	3.1
1978	May 15	2033	36.07	174.34	9	3.9
	May 20	1149	35.84	174.70	12R	3.3
1983	Jun 01	1343	36.91	175.23	7	4.1
1988	Mar 21	1530	36.95	175.13	5R	3.0
1993	Oct 29	1742	37.05	175.10	33R	3.8
	Dec 23	0403	36.00	174.25	30	3.3
	Dec 23	1406	36.07	174.24	12R	3.0

Notes:
(1) Time is Universal Time
(2) Depth: S =shallow, upper crustal; R=depth restricted to arbritray value; C = undifferentiated crustal
(3) M_L is local Richter magnitude
* earthquake event is not recorded as felt

Table 2: Historical earthquakes producing observed or inferred felt intensities of MM≥ 5 at locations in the greater Auckland area.

Date[1]	Lat	Long	Depth[2] (km)	Magnitude[3]	Epicentral distance from Auckland City (km)	Observed MM Intensity	Location	Comment
1834/35	37	175	C	5.5–6.5	25	≥7	Auckland	see discussion
1891 June 23	37.4	174.7	C	5.7–5.9	60	6 6 6 5	Onehunga Otahuhu Papakura Lucas Creek	MM 6 over most of greater Auckland; see discussion
1974 Feb 28	36.6	177.0	33R	5.9	>200	5 5	Auckland City Manurewa	Isolated reports

Notes:
(1) Time is Universal Time
(2) Depth: S =shallow, upper crustal; R=depth restricted to arbitray value; C = undifferentiated crustal
(3) See footnote 2

1834/35 (Exact Date Unknown)

The only evidence for this earthquake is a report by Vennell (1891) describing briefly a large, shallow earthquake followed by aftershocks which was reported to him to have occurred near Auckland about 1834 or 1835. Eiby (1955; 1968) considers the report, 60 years after the event, doubtful and could not confirm the occurrence with his research into contemporary newspapers. Few records are available, as only a small number of missionaries and whalers were living in New Zealand at this time, and Auckland was not established as a town until 1840. However, the description indicates an earthquake of no less than M 5.5 and possibly M 6.5, with an intensity of at least MM 7, but the location is very uncertain and may be grossly in error. Further historical research is required to confirm the location and intensity of this apparent earthquake.

1891 June 23

This earthquake, assigned a magnitude of M 5.7 – 5.9, caused much excitement in Auckland and environs, as few earthquakes had been felt there, and certainly none with an intensity which caused other than minor damage. Based on contemporary newspaper reports, lighthouse reports and Hogben's (1891) paper, the epicentre appears to have been close to the Waikato River mouth. In the greater Auckland area, several chimneys were slightly damaged, and several shop display windows and crockery were broken (MM 6).

The maximum intensity was MM 6–7 near the Waikato River mouth (Figure 3). One small aftershock was reported. The earthquake is estimated to have been of shallow to moderate depth (≤ 30 km).

4 Faults of the Auckland Region

The incompleteness and limited time ranges of the written and instrumental records of earthquakes reduce their usefulness for long term seismic hazard assessment in New Zealand, particularly as the recurrence of large earthquakes in different regions may range from several hundreds of years to tens of thousands of years. We look, therefore, to the geological record to increase our knowledge of the longer-term history of past major New Zealand earthquakes.

Surface fault traces are one manifestation of the brittle failure of crustal rocks in association with earthquakes. In New Zealand, generally only moderate to large earthquakes (M≥~6.5) with focal depths ≤ 30 km are associated with surface rupture. Fault traces preserve an incomplete record of the location and magnitude of the largest shallow earthquakes that have occurred in the recent geological past.

In the following sections we examine the geological evidence for the occurrence of large (M≥~6.5) earthquakes to determine whether there are potential earthquake sources in the Auckland region that could produce shaking intensities greater than those experienced during historical times.

4.1 Introduction

This section of the report has been compiled as a desk study of published geological journals, and books, and unpublished data held as theses in the Geology Departments of Auckland University and the University of Waikato. Technical reports prepared mainly for the Auckland Regional Council, Waikato Regional Council and Ministry of Works have also been examined. A brief stereo-photo overview was made of the Maraetai – Hunua hills using the ARC photo set, SN5783 at a scale of approximately 1:25,000. The area east of Papakura was also examined using aerial photographs at a scale of 1:16,000.

4.1.1 Tectonic Setting

Auckland lies to the west of the southernmost active volcanic mountain chain of the Tonga – Kermadec – New Zealand arc-trench system (Hochstein and Ballance 1993). Hochstein and Ballance suggest that the rocks in the region have been greatly stretched for at least the last 13 million years, and that the direction of stress has rotated some 40° clockwise over that period to a present day orientation of 335°.

Cenozoic (65 million years BP–present) faulting in the greater Auckland region is dominated by a system of rectilinear faults which is well developed south and east of Auckland City, and by the Hauraki Rift which extends, as a partially terrestrial – partly offshore feature, from beneath the Mamaku Ignimbrite Plateau to near Whangarei. Both fault systems appear to follow pre-existing geological structures (Sporli 1989, Hochstein and Ballance 1993).

The area to the south and west of Auckland City affected by faulting can be divided into three prominent sub-parallel geographic elements separated by the Drury and Firth of Thames faults (Figure 1). The western element, the Manukau Lowlands, is bounded to the south by the Waikato fault and terminates close to the north shore of the Manukau Harbour. The Hunua-Maraetai hills lie to the east of the Drury fault and are bounded to the south by the Pokeno fault. The northern extent of the Hunua-Maraetai hills element is unknown. The eastern most element, the Hauraki Rift, is bounded by the Hauraki and Firth of Thames faults and extends from beneath the Mamaku Ignimbrite to Whangarei Heads. Further faults exist within each geographic element.

Within the Manukau Lowlands north-trending faults generally offset east-trending faults, whereas the NE trending faults within the Hunua-Maraetai Hills generally offset the NNW trending faults. Similar structural relationships have not been recognised within the Hauraki Rift.

High (1975) stated that in the past Auckland was regarded as seismically quiet (e.g. Cotton 1951; Gage 1953; Brothers 1954) but then cited several papers describing the presence of both tilted Pleistocene surfaces and a fault disrupting a Pleistocene tephra at Beachlands. Several lines of evidence indicate that the level of Quaternary tectonic activity is greater than formerly recognised. Barter (1976) described warped tephra beds from Awhitu Peninsula. Berryman (1984) cited the Northland and Auckland region as relatively stable, but stated that there is evidence of small but significant uplift of coastal terraces. Hochstein (1986) plotted several active faults within the Hauraki Rift extending from the Taupo Volcanic Zone to Whangarei, and Cassidy et al. (1986) stated that of the 81 seismic events of magnitude >4.0 recorded in the Auckland region between 1960 and 1983, the majority were clustered beneath the Hunua hills and the Coromandel Range. He interpreted the seismicity as reflecting ongoing regional block faulting in those areas.

Evidence of upper Pliocene or Pleistocene faulting north of the Manukau Harbour is sparse. Turner and Bartrum (1929) and Searle (1944) both describe tilted Pleistocene silt beneath a 12 m terrace at New Lynn, and Clark (1948) reported tilting of 30 m and 60 m – 66 m terraces near Huapai and Whenuapai, and suggested the tilting followed Pleistocene movement on a fault he named the Rewhiti –Huapai fault. This fault was not shown on subsequent geological maps prepared by Schofield (1967; 1989).

All faults recognised and referred to in this text as showing evidence of Quaternary movement have been plotted at a scale of 1:250,000 on Map Sheet 262-3. Those within the Hunua-Maraetai hills for which definite traces can be determined or fault planes seen are plotted on Map Sheets R11, R12, S11, and S12 at 1:50,000 scale.

4.2 Boundary Faults

4.2.1 Waikato fault

The Waikato fault can be followed on land NE from Port Waikato for about 25 km, and possibly a further 6 km. Hochstein and Nunns (1976) described the fault, using gravity measurements, as a simple NE trending normal fault which dips to the north at 75°± 15°. They determined a throw on the greywacke basement rocks of 2.7 km at Port Waikato decreasing to 0.7 km some 25 km along strike near Tuakau. They showed an offset of the fault near Tuakau which Waterhouse (1978) suggested could be attributed to sinistral movement on the Mangapapa fault. They also suggested that the Pokeno fault, which shows a reversed sense of throw, may be an eastward extension of the Waikato fault and that the two should be regarded as a scissor fault. Petch et al. (1991) noted lineations on aerial photographs on the alignment of the Waikato fault south of Tuakau and mapped a second parallel structure as well as a lineation aligned north from Tuakau to the St Stephens fault (Map Sheet 262-3). Using Hochstein and Nunns (1976) gravity section and data from a coal exploration borehole, Petch et al. (1991) determined that basement on the north side of the Waikato fault was at approximately 1400 m below sea level and thus the scissor model is unlikely.

A number of workers (Cousins 1993; Dowrick 1992; Prebble 1991; Gulliver & Matuschka 1990) infer that the Waikato fault is active. Three lines of evidence are used. The 1891 Port Waikato Earthquake (M_L 5.7) and the 1950 Earthquake (M_L 4.8 but not reported as felt locally) are both cited by Gulliver & Matuschka (1990) as indicating activity of the Waikato fault. It should be noted, however, that these earthquakes are poorly located, and attributing them to movement along a specific fault is beyond the resolution of available data.

Christie (1979) recognised structures in upper Quaternary sand in the Waiuku State Forest to which he ascribed a possible seismic origin. Barter (1976) mapped the Pehiakura Ash (0.74±0.07) Ma, exposed along the Awhitu Peninsula, as downwarped towards the Waikato fault and estimated that there had been some 200 m of displacement on the Waikato fault since its deposition. Barter (1976) described the Pehiakura Ash Bed as an airfall deposit and the oldest and thickest of several rhyolitic tephras found within the dominantly aeolian Awhitu Formation. He suggested it could be a distant part of the Ongatiti Ignimbrite. It is seen as interbedded with the developing dunes of the Awhitu Formation and hence may have been deposited on a surface with some initial relief.

4.2.2 Drury fault

(Map Sheets R11, R12) The Drury fault was mapped by Laws (1924, 1931) as the Papakura – Drury fault. Nixon (1977), using gravity, magnetic and seismic profiling, determined the Drury fault as a normal fault, trending NNW over a distance of 16 km and dipping between 65° and 90° to the west. Nixon determined a throw of 600 m on the basement rocks beneath the Clevedon depression, a throw which increased to 1.8 km at Ramarama. A subtle trace of the Drury fault can be followed on the 1:16,000 scale aerial photographs (Run nos 1927/11-12 & 1928/13-14) part way across the Clevedon depression through deposits mapped by Kermode (1992) as the upper-Pliocene Puketoka Formation. It is considered in this report however that the deposits are considerably younger than Pliocene. Anderson (1977) found no evidence of an extension of the Drury fault north of the transecting Papakura Valley fault, although Yang (1989) recognised a basement structure that he called the Whitford fault, which he said could be a continuation of a basement Drury fault. His interpretation placed the Whitford fault some 4 km to the east on the north side of the Papakura Valley fault, but swinging back on strike with the Drury fault some 3 km further north. To the south, the Drury fault is generally mapped as terminating at its junction with the Waikato and Pokeno faults, although Fellows (1987) suggested it may continue to the south as the Kimihia fault (Not shown on map).

A number of basaltic eruptions have occurred along the Drury fault. Rafferty (1977) stated that all the basalts extruded along the fault have been displaced by subsequent movement along the fault except the Red Hill basalt. Rosenberg (1991) suggested that there has been up to 100 m of vertical movement of the Maketu Tuff ring on the Drury fault since its eruption, but did not elaborate. Briggs et al. (1994) gives KAr ages for the basalts found along the fault as ranging between 0.59 and 1.35 million years with one date of 2.09±0.37 million years from the Drury Hills cone. The age given for Red Hill is 1.10±0.04 million years. Nixon (1977) quoted Rafferty (pers. comm.) as saying that downfaulted basalt is, in places, buried by an average of 14 m of Quaternary material.

4.2.3 Firth of Thames and Hauraki faults

The Hauraki Rift is described as comprising fault-angle depressions each dipping to the east (Hochstein and Ballance 1993, Hochstein et al. 1986). They argue for little vertical displacement on the Firth of Thames fault, but up to 1 km of displacement on the Hauraki fault. Both faults are described as part of an active rift zone. Schofield (1967) described a soft pyritized zone some 12 m wide near Torehape, but most authors (Hochstein and Nixon 1979; Naish 1990) consider the Firth of Thames fault as a hinge fault, and that there has been negligible vertical movement on it in late Quaternary time.

The Hauraki fault has displaced the 800,000 year old Waiteriki Ignimbrite by about 400 m vertically but no movement has been recognised on it for 140,000 years (Beanland and Berryman 1986).

4.2.4 Pokeno fault

The Pokeno fault lies to the east of the Drury fault, almost on the same strike as the Waikato fault, but is downthrown to the south. The trace is concealed over its entire length. Observed Bouguer gravity anomalies determined by Hochstein and Nunns (1976) on the Waikato and Pokeno faults, some 5 km west and east of the Drury fault respectively, indicate throws in the order of 500 m at both sites, but in opposite directions.

Fellows (1987) suggested that the Pokeno fault was active in Pleistocene times ,giving rise to a fault-angle depression (Hegan, Pers. comm.) which is now filled with Pleistocene Tauranga Group sediment.

4.3 Manukau Lowlands

High (1975; 1977) inferred five faults from drill-hole data, the Wiri, Karaka, Waiau, Glenbrook and Pukekohe faults, which bound east – west trending horsts and grabens beneath the Manukau Lowlands. No surface trace was recognised for any of the faults. Berry (1986) refined High's work introducing a number of north-trending faults to offset High's structures. He found an exposure of the Karaka fault at Wattle Downs showing upper-Pliocene sandstone faulted against mid-Pliocene sandstone. Barter (1976) recognised Pleistocene faulting and warping on the Awhitu Peninsula and mapped the Pukekohe fault as having dislocated Pleistocene sediments.

4.3.1 Wiri, Karaka, Waiau and Glenbrook faults

High (1977) described the four faults as being continuously active up into mid-Nukumaruan times (1.0 to 2.2 million years), with the horsts representing stable blocks and the grabens subsiding between them. However, he says any post-Pliocene movement on the Karaka fault was confined to the western end beneath the Manukau Harbour, but presents no data to support this hypothesis. The north-trending offsetting faults are assumed to have been active at the same time or later than the east-trending faults.

4.3.2 Awhitu Peninsula

Three unnamed faults have been recognised by Barter (1976) on the Awhitu Peninsula. Each is seen to displace Pehiakura Ash (0.74 ± 0.07 million years). The northern fault shows downthrow to the north of 10 m, and the middle fault a total of 25 m across the two branches. The southern fault is downthrown 24 m to the south. Barter suggested that the middle and southern faults may represent extensions of the Waiau and Glenbrook faults mapped by High (1977), thus adding support to High's view that these inferred faults were active in Pleistocene time.

Hollis (1986) replotted the positions of the faults recognised by Barter on the Awhitu peninsula by moving the middle fault 2.5 km north, and mapping the southern fault at the position of Barter's middle fault. Both fault patterns are shown on the fault map (in back pocket) but because of the doubt on its location, they are not shown on the 1:50,000 scale maps accompanying this report.

Christie (1979) described small-scale folding and faulting in sand of the Hood Formation, thought to have been deposited between 105,000 and 125,000 years before present.

4.3.3 Pukekohe fault

This fault has also been mapped as the Waiau fault (Briggs et al. 1994), or the Puni fault (Petch et al. 1991). Barter (1976) plotted the Pukekohe fault and described it as offsetting Pleistocene sediments, but he presented no supporting evidence. Briggs et al. (1994) show it as displacing basalts dated as greater than 0.56 million years and less than 1.16 million years. Hadfield (1987) stated that the Pukekohe fault has obviously been active recently as it has a very clear surface trace. He stated (pers. comm.) that the trace can be observed on aerial photographs on both the alluvial and volcanic deposits, but that it fades out in the volcanic deposits. No aerial photo study was made of the Pukekohe fault for this report.

4.3.4 St Stephens fault

Schofield (1958) tentatively mapped a scarp trending NE on the same alignment as the Pukekohe fault but with apparent downthrow to the north. Omerod (1989), using geophysical data, described the St Stephens fault as having a shallow dip to the north and a throw of 1.5 km. The scarp appears to displace basalts subsequently dated by Briggs et al.(1994) at 0.65 ± 0.03 million years.

4.3.5 Aka Aka fault

Petch et al. (1991) mapped an unnamed trace, here called the Aka Aka fault, cutting a volcanic vent dated at 0.66 million years (Briggs et al. 1994). Hadfield (pers. comm.) believes the trace can be followed through into Holocene sedimentary deposits. No aerial photo study was made of the Aka Aka fault for this report.

4.4 The Hunua–Maraetai Hills

Block faulting has long been recognised in the Hunua – Maraetai hills (Laws 1924 1931; Firth 1928; Schofield 1967, 1979) with Firth recognising a fault displacing Pleistocene deposits at Beachlands. More recently, various authors (Prebble 1991; Mansergh 1992; Cocks 1993) have suggested that Pleistocene movement also may have occurred on NNW trending faults, but there has been no evidence found for Pleistocene movement on any of the NE trending faults despite the tendency for the NE faults to be offset by the NNW trending faults.

4.4.1 Wairoa North fault

(Map Sheets S11, S12) The Wairoa North fault can be followed for 24 km. It trends NNW, downfaulting Mesozoic basement rocks to the west. Tertiary rocks are downfaulted against greywacke in places along the middle segment, indicating an approximate throw of 100 m, but elsewhere greywacke or Quaternary alluvium lie to the west of the fault. The fault comprises three segments, each progressively offset to the east in a southward direction. Basalt dated at 1.30 ± 0.05 million years has been mapped by Schofield (1976) on the downthrown side of the middle segment of the fault.

Cocks (1993) studied the middle segment only, where he found two exposures of the fault plane, one showing Tertiary rock in contact with a 100 m wide shear zone in the greywacke and the second exposing an upstanding ridge of gouge in a rapidly eroding stream bed. Cocks (1993) recorded a dip of 65°E on the fault, whereas Schofield (1976) observed the fault to dip 70°W. SEM grain morphology carried out by Cocks (1993) indicated two or more phases of movement at both sites.

Cocks suggested the Wairoa North fault has been active within the last 1.0 million years, probably active within the last 0.5 million years, and possibly active more recently. Possible fault sag ponds and an offset ridge and stream observed on aerial photographs along all three segments during the preparation of this report support the concept of late Pleistocene activity.

4.4.2 Waikopua fault

(Map Sheet R11, S11) The Waikopua fault trends at 330° and dips to the west. Anderson (1977) determined a post-Miocene throw of basement rocks of 250 m. It extends over 6 km from the Papakura-Clevedon corridor towards the west branch of Waikopua Creek bringing Waitemata Group rocks in contact with Waipapa Group basement over most of its length. Recent drilling for Manukau City Council reveals that the fault continues at its northern end for a short distance through Waitemata Group rocks but with a diminished throw before it disappears beneath sediments mapped as Pliocene-Pleistocene.

There is no direct evidence available to date movement on the Waikopua fault. Firth (1928) observed faceted spurs along the fault scarp. The morphology of the fault scarp appears younger than that of the Drury fault, suggesting movement in mid to upper Pleistocene time.

4.4.3 Kiripaka fault

(Map Sheets R11, S11) The Kiripaka fault comprises five segments striking between 280° and 340° and downthrown to the SW offsetting basement by up to 40 m. To the NW, Waipapa Group is faulted against itself, but to the SE Waitemata Group rocks are faulted against the Waipapa Group.

Firth (1928) noted the presence of both faceted spurs and hanging valleys along the scarp of the Kiripaka fault. The scarp itself displays a youthful morphology which is interpreted as signifying that the Kiripaka fault has probably moved more recently than any other fault within the Hunua – Maraetai hills.

4.4.4 Beachlands fault

(Map Sheet R11) This fault has been described by Glading (1987) and Firth (1928) as striking at 320°, putting it on strike with the Kiripaka fault. Prebble (1991) mapped the Beachlands and Kiripaka fault as a continuous feature. The fault is seen as displacing the Waitemata Group and also the overlying Quaternary beds (Fig. 4).

The Beachlands fault offsets an erosion surface cut into the Waitemata rocks dated at 105,000 YBP (High 1975) and two discrete ash beds in the overlying Quaternary terrace. Glading (1987) stated that the upper ash bed pre-dated the 50,000 year ash recognised elsewhere in Auckland, but could not assign a precise age to the offset ash.

4.4.5 Mangemangeroa fault

(Map Sheet R11) Tilsley (1993) identified a 0.3– 0.4 m offset trending at 102° in a Quaternary tuff bed exposed at a shallow depth in slip prone country in a temporary roadcut on the east side of the Mangemangeroa Creek. The discontinuity dips steeply to the north. There is no evidence of relaxation along the feature as would be expected if it were the slip circle of a slump and this, together with its attitude, suggests it is a fault rather than a slip plane (Prebble, pers. comm). No surface trace was seen.

4.5 Hauraki Rift

The Hauraki rift comprises a set of fault-angle depressions bounded by active faults showing right-lateral shear (Hochstein, et al. 1986). The Kerepehi fault is the only active structure recognised on land, but several NNE structures have been recognised offshore between Thames and Whangarei, and one doubtful WNW structure lies SE of Tiritiri Matangi Island.

4.5.1 Kerepehi fault

Geophysical studies summarised by Hochstein & Nixon (1979) and Hochstein et al. (1986) reveal that the Kerepehi fault is a NNW-striking normal fault that displaces the greywacke sandstone basement rocks by about 2.5–3 km. A surface scarp up to 8 m high indicates surface displacements during the last c. 18,000 years.

Our unpublished paleoseismic studies of the Kerepehi fault indicate that the fault has at least three seismically active segments: the Elstow segment to the NW of Elstow; the

Waitoa segment between Waitoa and Te Poi; and the Te Poi segment from NW of Waharoa to Te Poi.

Two trenches excavated across the south-east end of the Waitoa segment reveal that surface rupture along the Waitoa segment last occurred between ~1,800–4,800 years ago. At least 1.8 m of surface rupture occurred in association with this earthquake event, and in places it may have been as large as 3–4 m. Based upon the size of single earthquake events identified in subsurface trenches, an average recurrence interval for earthquake events is between 4,500 and 9,000 years. Without further study, we are unable to refine this recurrence interval further. The most recent surface rupture appears to have occurred on the Te Poi segment between 450 and 900 years ago.

On the Elstow segment of the fault, deLange and Lowe (1990) have inferred small displacements of 0.2–0.7 m at ~1,400, ~5,600, ~6,800 and ~ 9000 years ago, based upon displaced volcanic ash layers in the Kopouatai bog, about 20 km NW of Te Aroha. The size of these displacements is much smaller (~1 m) and the recurrence interval much shorter (1,200–4,200 years)than we have observed from the other two segments of the fault. This may be due to either a different character of faulting on the Elstow segment of the fault and/or differences in the records preserved in peat swamps compared to large surface fault scarps.

The fault recurrence and slip-per-event data from our trenching studies of the Waitoa segment can be used to estimate an average vertical separation rate of ~0.5 m/1000 yrs, recurrence interval of 4,500–9,000 years and MCE of M_W=6.9 for the Waitoa segment of the Kerepehi fault. This moment magnitude has been calculated assuming a surface rupture length of about 25 km, an average fault slip of 2.5 m, a focal depth of 10 km and a fault dip of 60°.

It is important to note that there are at least three geomorphologically and seismologically distinct segments along the Kerepehi fault. Thus although the recurrence interval for a single segment may be relatively long, it must be taken into account that there are at least three separate earthquake sources of moderate to large earthquakes along the Kerepehi fault.

5 Offshore Geology and Faulting

Earthquakes with intensities high enough to cause significant damage in the Auckland region can also be generated by faults located offshore. In this section we examine existing offshore geological data to determine whether there are any geological structures with sufficient activity to pose a threat to the Auckland region.

5.1 Introduction

The geology of offshore regions of Auckland and Northland have not been studied beyond the level of general reconnaissance. Moderate to poor quality seismic reflection and refraction profiles were collected in the late 1960s and early 1970s for petroleum exploration. Line spacings of 20-50 km provide a low density of data from which interpretation of the location and continuity of major geological structures can be made. Interpretation of these geophysical data has been presented by Thrasher (1986, 1988), Hochstein et al. (1986). Additional gravity and magnetic data were reported and interpreted by Hochstein et al. (1986) from the Hauraki Gulf and the Firth of Thames.

Throughout all offshore regions of Auckland and Northland, geophysical data suitable for determining the activity of faults is generally absent or of doubtful quality. There is poor offshore stratigraphic control for determining the age of any displaced sediments. In many regions, basement rock crops out on the seafloor, so that although some faults have seafloor expression, there is no evidence to determine the age of faulting, and potential for future movement. Furthermore, because of the poor petroleum prospectivity it is unlikely that any additional oil exploration data will be collected in the near future (Thrasher 1986). Geophysical data west of Auckland are of variable quality, ranging from single-channel analogue records to sixty-fold multi-channel data. Most surveys used large airgun arrays for the seismic source; typically 2000–4000 cubic inch guns at 2000–4000 psi. The large bubble pulse from these airguns combined with de-convolution and filtering techniques used in data processing tend to reduce the frequency content of sea-bed reflections to no higher than 20 Hz. We estimate that at best, scarps in the sea bed of no less than 5m can be resolved.

5.2 Faults in Offshore Regions of the East Coast

Thrasher (1986) identifies a number of faults that have seafloor expression, particularly near the continental shelf break. Faults have both northerly and north-westerly trends, although Thrasher (pers comm.) believes the north-westerly trend is late Miocene in age and offset by the northerly trending faults. Using the same oil company seismic data and additional gravity, magnetic and high frequency seismic reflection data, Hochstein et al. (1986) recognised many of the same geological structures as Thrasher (1986). They proposed that many of the faults recognised from the onland Hauraki Depression continue north-west into the Hauraki Gulf to near Whangarei. They did not distinguish those faults with seafloor expression, but considered that because of the relative youth of the Hauraki Rift (Pliocene) and the presence of a late Pleistocene active trace on the Kerepehi fault, all of the faults in the Hauraki Gulf are still active.

The only fault known to have clear seafloor expression and to clearly displace deposits of probable Holocene age is the north-westward extension of the Kerepehi fault within the Firth of Thames (Greig 1982; University of Waikato unpublished data).

The onland parts of the Kerepehi fault are clearly broken into geomorphologically and seismologically distinct segments. If we assume that the onland fault characteristics continue offshore, then past and future fault displacements could be expected to be associated with earthquakes of about M_W=7, involving displacement of the seafloor of about 4 m along a scarp of about 30 km length. We cannot determine from paleoseismic data what area of land was displaced during each earthquake. A conservative estimate would require all of the Hauraki depression to the east of the Kerepehi fault, about 15 km, to subside by 4 m.

5.3 Faults in Offshore Regions of the West Coast

For this part of our study we have examined evidence for all the faults in the area offshore of the North Island between 37°–38°S. We have used petroleum industry seismic refraction data, of which there is about 4500 line kilometres in the area.

All Pleistocene-age faults are of normal sense of throw with very little or no strike-slip component. No faults clearly offset the seabed, and none have had significant (≥100 m) offset in the about last 2 million years. The greatest Pleistocene offset observed is on a fault that curves in towards the Waikato River mouth (the offset is 0.03 sec, or about 25 m). This fault extends to within 100 m of the sea bed, but appears not to be a major tectonic fault. The only major tectonic faults that have been active in the Pleistocene are the two south-eastern-most faults on the map, and both have probably been inactive for the last 1.2 million years.

6 Earthquake Hazard Assessment

In previous sections of this report, we summarise available data on historical earthquakes and their effects in the Auckland region and examine evidence from onshore and offshore geology for the past occurrence of potentially damaging earthquakes. In this section we examine the principal effects and hazards from the occurrence of earthquakes, determine average return times for moderate to strong ground shaking in Auckland City, and present our preliminary assessment of the variation in ground-shaking response throughout the Auckland region.

6.1 Earthquake Effects

6.1.1 Ground Shaking

The predominant hazard from earthquakes is that resulting from strong ground shaking, ie. the dissipation of earthquake energy by the radiation of earthquake waves. The larger the magnitude of the earthquake, the greater the amount of energy released. As the waves travel away from their source, they gradually lose energy, thus locations further from the source feel a lower level of shaking than locations near the epicentre. In addition to the main factor of distance from earthquake source, some ground conditions amplify earthquake waves. Thus different levels of shaking may be felt from the same earthquake within even quite a small area. In general, rock sites record the lowest levels of shaking during an earthquake. It is usually the combined effect of shaking and associated, secondary ground damage that causes the main damage to man-made structures during earthquakes.

6.1.2 Amplification of Ground Shaking

Amplification of seismic shaking in soft soils can occur, but it is not general at all levels of shaking. It generally occurs for the following:

- all frequencies of vibration if the amplitudes are small (intensities up to MM8);
- longer periods of vibration, approximately 0.6 seconds and longer, for intensities up to MM10.

Conversely, peak ground accelerations and short period vibrations appear to be attenuated on soft soils when they exceed about 0.4 g, i.e. intensities greater than about MM8. Thus the relative damage levels on soft soils, such as those that underlie parts of the Auckland region, depends on the strength of shaking and on the natural period of the structure being examined. This effect is discussed in greater detail in Section 6.3.

6.1.3 Surface Fault Rupture

In a large, shallow crustal earthquake on a fault that reaches the ground surface, the fault rupture will break the ground surface to form a scarp as seen, for example, during the Edgecumbe earthquake in 1987. This breaking of the ground surface represents a localised hazard, but one which can often be anticipated because faults tend to re-rupture along pre-existing traces. 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, although displacements less than 5 m are much more common. At present in the Auckland region there are no known active surface faults, so this potential hazard is not considered further. However, if future work establishes that active faults are present, then it will be necessary to determine what, if any, hazards are posed by surface rupture to engineered structures.

6.1.4 Tsunami and Seiching

Tsunami, large ocean waves, are long-wavelength, long-period sea waves generated by an abrupt movement of large volumes of water. Tsunami are generally caused by fault rupture or sediment slumping on the sea floor. They are generated from both local and distance earthquake sources, have wave periods that vary from 5 minutes to one hour, and travel at speeds of 600–800 km per hour. Tsunami reaching New Zealand have been generated on the opposite side of the Pacific Ocean: the most extensively recorded New Zealand tsunami occurred following the 1868 northern Chile earthquake (de Lange & Healy 1986). The coast of New Zealand is considered susceptible to tsunamis generated from local sources despite the lack of major tsunami in historical times. The areas most at risk are low lying coastal settlements, particularly those around river mouths.

In 32 documented cases of tsunami affecting the coast of New Zealand, 13 reports are known within the Auckland region. ARC has commissioned a separate report on past tsunami effects in the Auckland region, and further discussion and recommendations are identified in that report.

Earthquake shaking commonly induces seiching, periodic standing waves travelling back and forth, in bodies of standing water and even in rivers. These waves are analogous to the sloshing of water that occurs when one suddenly sits down in a bath. 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. The waves generated were up to 0.5 m high. Swimming pools are commonly affected by seiching and in some cases have been emptied. Dams are vulnerable because of seiching in the reservoir behind them may result in the dam being overtopped in some situations. With the large number of man-made lakes in the region, earthquake-induced seiching may pose a major hazard to the lake-impounding structures (dams) and consequent flooding downstream.

6.1.5 Liquefaction and Settlement

Liquefaction occurs when saturated sand or silt is shaken violently enough to rearrange the individual grains, usually resulting in water expulsion and compaction. Sandy and silty layers only several metres below the ground may liquefy, provided there is sufficient confining pressure, and may cause sand/water fountaining at the ground surface. Liquefaction is commonly responsible for lateral spreading along riverbanks (e.g. near the Highway Bridge at Whakatane during the 1987 Edgecumbe earthquake), and the loss of bearing strength under foundations and roadways. Buildings can topple, tilt or partially collapse when liquefaction occurs beneath their foundations. Unconsolidated, water-saturated sandy material is a prerequisite for liquefaction, so that areas prone to this hazard tend to coincide with those prone to amplification of earthquake shaking and settlement.

Liquefaction is known to occur when the earthquake shaking intensity reaches MM7 or greater. Only the most liquefaction-prone sediments will liquefy at MM7, but it is commonly observed in regions subjected to intensities of MM8 and higher. At intensities of MM8 to MM10 damage related to liquefaction often occurs and can cause substantial damage to buildings if they are located above a major liquefaction zone.

In the Auckland region, liquefaction could prove to be a significant hazard only in areas underlain by very weak, watersaturated sediments such as those shown in region A in the accompanying map. This region includes the waterfront and parts of downtown Auckland City and estuarine sediments believed to underlie the International Airport. At present we believe that the return time for earthquake shaking capable of causing liquefaction damage in the worst areas is more than 500 years (Section 6.2). Based on this relatively long average return period, we believe that only important lifeline facilities located on proven liquefiable ground warrant further examination for the potentially damaging effects of this hazard.

6.1.6 Rockfall and Landsliding

Widespread rockfall and landsliding are characteristic of most moderate to large earthquakes in regions of moderate to high topographic relief. The extent and severity of this hazard often depends on the water content of the soils at the time of the earthquake, usually related to the amount of rain that has fallen in the preceding few days or weeks. Many large-scale failures occur on pre-existing landslides, new slides are generally shallow-seated failures and are particularly common in the thin soils of the hill country. There are a number of pre-existing landslides and slumps in the Orewa area, within the Waitemata Group sediments. These failures have typically occurred on thin, continuous clay seams, found commonly on bedding planes and other discontinuities (Mansergh 1990). Rockfalls usually occur along river valleys and artificially steepened hillsides such as along roads and railways. As a general guide, rockfall and landsliding is expected within about 50 km of a shallow (i.e.. less than 15 km deep) earthquake of magnitude 6 and within 100 km if the magnitude is about 7 (under average wet conditions).

6.1.7 Tilting and Changes of Level of the Land Surface

During a moderate to large earthquake, the ground in the epicentral region, and even up to tens of kilometres away, may be uplifted, dropped, or tilted. An example of extensive land movement is provided by the 1987 Edgecumbe earthquake (M=6.3), during which a large part of the Rangitaiki Plain was permanently lowered by up to 2 m with respect to mean sea level. Permanent uplift of 1–2 m during the 1855 earthquake had significant impact on the development of the Wellington area.

The absence of major faults and recent folds suggests that this is not significant hazard for the Auckland region.

6.2 Return Time for Strong Ground Shaking

An analysis of the frequency of occurrence and magnitude 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 earthquake source (attenuation) can be used to estimate the return period for various levels of earthquake shaking. Smith and Berryman (1986) carried out this type of analysis, and estimated the mean return period 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. In the Auckland region they assumed that seismicity was distributed uniformly around the Northland/Auckland region and that 7.5 was the likely maximum earthquake magnitude in that region. For Auckland, they estimated average return periods for MM ≥ 6 at 62 years, MM ≥ 7 at 260 years, MM ≥ 8 at 1400 years (Table 3).

Smith and Berryman (1992) used an updated seismicity model, but with the same maximum magnitude assumptions, and a further seven years of earthquake records to revise their 1986 results. Their revision resulted in an increase in the estimated mean return periods for MM intensity for most parts of New Zealand. Auckland City now has an estimated mean return period of 65 years for MM ≥ 6, 280 years for MM ≥ 7, and 1700 years for MM ≥ 8 (Table 3).

Dowrick (1991a) used a similar model of uniformly distributed seismicity around the Auckland region and a modified attenuation expression to calculate average return periods for earthquake shaking intensities in Auckland City. However, he calculated his seismicity model assuming that the maximum magnitude for the Auckland/Northland region was M 7.0, and showed how this same reduction of 0.5 in the maximum magnitude in the Smith & Berryman (1986) model increased their calculated average return periods by an average of 65% for MM 7 and MM 8. Dowrick's model yielded an average return period of 105 years for MM ≥ 6, 880 years for MM ≥ 7, 8500 years for MM ≥ 8 (Table 2).

Table 3: Average return period for felt intensities for earthquake shaking in Auckland calculated from four different earthquake hazard models.

Intensity (MM)	Average Return Period (yrs)			
	S & B [1](1986)	S & B [1](1992)	Dowrick (1991a)	This Study
≥ 6	62	65	105	91
≥ 7	260	280	880	640
≥ 8	1400	1700	8500	5400

Notes: (1) S & B = Smith and Berryman

For this study we have selected a combination of models to derive the average return periods for various intensities of shaking, and the estimated intensities for 100-, 500- and 1000-year return periods. We have chosen to use the seismicity parameters and maximum magnitude of Smith & Berryman (1992) and the MM Intensity attenuation function of Dowrick (1991b; 1992). The resulting estimates are shown in Table 2. Based on this model the 100-year MM intensity for Auckland is MM 6, 500-year MM 7 and 1000-year MM 7.2.

We believe that this model produces suitably conservative estimates of average return periods of MM intensity for the Auckland region.

The return periods for the highest levels of shaking intensity — MM 9 and MM 10 — cannot be estimated reliably from the historical record for Auckland because levels of shaking of MM 6 and greater have never been reported in the greater Auckland area since its settlement. In the absence of proven active faulting near Auckland City, we believe that the only possible source for MM 9 shaking is from a moderate earthquake centred at a shallow depth immediately under Auckland, and on a site with worse than "average" ground conditions. For example, a magnitude 5–6 earthquake beneath Auckland City is estimated to produce shaking of MM 7–8 over much of the Auckland Urban area, and perhaps MM 9 at sites underlain by weak, water saturated materials. Accepting the limitations above, extrapolation of our model estimates the average return period for MM 9 in Auckland City to be about 50,000 years, with a very large uncertainty.

6.3 Characterisation of Ground Shaking

Ground shaking is the most widespread earthquake hazard. Geological units defined in relevant map legends (Kermode, 1992; Schofield, 1967; 1976; 1979; 1989; Skinner, 1976; Waterhouse, 1978) form the basis for the 1:250,000 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. An assumption is made in preparing the accompanying map that broadly similar rock types produce broadly similar ground shaking responses. This assumption has proved valid in other areas.

This map is a preliminary ground shaking response map which separates areas characterised by one of five types, classes A to D. Each class responds in a different way to the same earthquake motion.

Areas mapped as Class A are likely to respond worst to ground shaking. These areas include Orewa, Helensville and the Ardmore/Clevedon corridor, all being composed of soft to stiff sediments usually less than 10,000 years old. Included are sands, silts, mud, shell, and peat deposits mainly on coastal areas. Man-made landfills in the downtown harbour area and at the Auckland International Airport are included within this class.

A moderate ground shaking response can be expected from classes B and B1. Class B covers much of south-west Auckland, and is composed of loose to dense alluvium and sand; fossiliferous and pumiceous deposits, silt, mud, lignite, and clay. These deposits are less than 3 million years in age. Class B1 has been created to cover the occurrence of "floating volcanoes" within the region. Located predominantly in south and central Auckland, these volcanic deposits overlie Pleistocene sediment which is termed stiff (class B). It is believed that no significant modification to the level of ground shaking should occur due to the in situ tephra cover or weathering.

Classes C, and particularly D, are least likely to behave unfavourably to ground shaking. Class C covers most of the region north of Auckland City and contains very weak to moderately strong sandstone, siltstone, mudstone, limestone and conglomerate. Deposits derived from volcanic sources are also included in this Tertiary aged class of sediments.

Class D consists of moderately strong to very strong basement and old sedimentary rocks. Due to their stability these deposits are resistant to shaking caused by earthquake motion. Deposits of class D are found in the south-east of the region and outcrop on many of the islands within the Hauraki Gulf.

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

The scale at which the ground shaking hazard map was produced has led to generalisations being made. Isolated blocks of all classes of ground shaking intensity could not be presented at a scale of 1:250,000. When this was the case, areas were not delineated. In the Cornwallis area small zones of both class A and class B were left undefined due to their small size. On Waiheke, most bays have a small amount of class A present that is not always possible to map. In this case it was included in the surrounding class C. Also on Whangaparaoa and at Helensville this generalisation has occurred.

The ground shaking response classes used in the map are gradational, so that differences between some areas classified class D and some areas classified class C are probably small. Responses of areas classified class C may also overlap with areas within classes B and D. Class A may also overlap with class 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 class A. The most obvious of these areas are the airport, Ardmore/Clevedon corridor, land underlain by fill in the harbour area, Omaha, Orewa, Helensville area, Warkworth area, and the eastern side of Great Barrier Island. Some attempt should, however, be made to evaluate the response of each of the classes to a range of earthquake scenarios.

7 Conclusions

(1) The Auckland region lies in one of the lowest earthquake activity regions of New Zealand. Over the last 150 years only the 1891 Waikato Heads earthquake of magnitude 5.7-5.9 is known to have caused significant earthquake damage in the Auckland region. This earthquake is known to have produced the strongest shaking experienced since European colonisation of the Auckland region: MM 6-7 in the western part of the region and MM6 in Auckland City. Another similar earthquake may have occurred near Auckland City in 1834/35, but further historical research is required to confirm its occurrence and any damaging effects.

(2) Historical records of seismicity and existing models of earthquake energy decrease with distance from the earthquake source, have been used to estimate the average return period for moderate to strong shaking in the Auckland region. On average we expect shaking of intensity MM6 or greater to occur about every 90 years, MM7 or greater about every 650 years and MM8 or greater about every 5,400 years. This can also be expressed as a 100 year return period intensity of MM6, 500 year return period intensity of MM7 and 1000 year return period intensity of MM7.2.

(3) There are many geological faults within the Auckland region that have been active over about the last 2 million years. Based on existing information that is often incomplete and equivocal, we believe that the greatest potential for future fault activity and consequent large earthquakes exists along faults in the southern and eastern parts of the region. In particular, the Wairoa North fault that bounds the western margin of the Hunua Ranges is judged to show the highest rate of movement in the recent geological past, and hence the greatest potential for future activity. No data are presently available to determine past earthquake recurrence and magnitude along the Wairoa North fault. Similarly, the Drury, Beachlands and eastern Waikato faults may also have some potential for future fault activity, but no data are available to determine their potential for future fault movement and large earthquake generation.

We believe that this lack of information on the past activity of these significant potential earthquake sources within 50 km of Auckland is a major deficiency in knowledge of the earthquake hazard. Until reliable data on their past activity and potential for future activity are available, it is not possible to provide an accurate estimate of the earthquake hazard for the central and southern parts of the region. Furthermore, future movement of these faults poses a significant potential threat to water storage facilities in the southwestern part of the region. Existing studies of the recurrence and magnitude of past earthquakes along the Kerepehi fault are inconclusive, with studies of the northern segment nearest to the Auckland region indicating smaller and more frequent events than segments further south. Further field studies are recommended to determine more accurately the frequency and magnitude of earthquakes from this source.

(4) There is no evidence for activity of offshore faults during the last 100,000 years on either the west or eastern coasts of the Auckland region. There is, however, clear evidence that the Kerepehi fault extends offshore of the central Hauraki Plains into the Firth of Thames. This fault has proven Holocene activity onland, and is likely to be active offshore as well. Although this fault lies outside of the Auckland region future movements will

generate earthquakes of about M 7, and result in moderate to strong earthquake shaking (MM7-9) throughout the Auckland region.

(5) Surficial geological materials in the Auckland region can be divided into five major classes of expected response to earthquake shaking. The worst response is likely to come from the soft to firm sand, silt and estuarine mud in coastal areas such as Orewa, Helensville and near Takanini. The response of these materials to moderate earthquake shaking is that they are likely to amplify it, such that felt intensities in a single earthquake could be up to two MM units higher on the soft materials compared to those on adjacent rock sites. The probability of liquefaction of loose water-saturated sand and silt layers within these deposits is moderate to high when earthquake shaking intensities reach MM7 or greater. A moderate amplification is probable on sites underlain by the older Pleistocene-age sand, silt, mud and lignite deposits comprising much of the southwestern part of the region. These materials may amplify earthquake shaking by up to one MM intensity unit higher than adjacent rock sites.

8 Recommendations

In this section we outline our recommendations for further work, describe what level of work we believe is required and present the likely benefits of undertaking this additional work. We offer these recommendations for discussion, and if appropriate they can be developed more fully into a focussed programme of work.

8.1 Further Studies

8.2.1 Active Faults

Our studies reveal that there are a number of faults in the region for which there are no data to determine reliably their past history of activity. The lack of these data makes it difficult to develop a reliable earthquake hazard model for the Auckland region. This is particularly important for a region such as Auckland where the historical record indicates a very low level of activity. If there were no major faults with activity over the last 2 million years or more, then it might be reasonable to accept that the historical record was a representative sample of the likely earthquake activity for the next several millennia. However, if the faults to the south and east of Auckland City are indeed capable of generating earthquakes as large as M 7, then this makes a significant difference to the overall hazard for the Auckland region. It is thus important that the past activity of these faults is more precisely determined to constrain better the longer term earthquake hazard model for the Auckland region.

The probability of tectonic activity in the greater Auckland area increases to the east and south of the city. Historical seismic activity (within the last 150 years) is greatest in the Hauraki rift, beneath the Hunua-Maraetai Hills and near the inferred position of the Waikato fault. We believe, therefore, that further investigations should be concentrated within these areas because they have the greatest potential for future activity. Three faults offer potential for further study: the Wairoa North fault, Beachlands fault and Drury fault. Although the Kiripaka fault appears to be potentially active, we believe it is unlikely that any definitive data could be found along its trace without major effort.

Wairoa North fault: We believe this fault to show the greatest potential for successful future study. It has a clear trace bounding the western margin of the Hunua Ranges, appears to fault rocks of Pleistocene age, and appears to be largely unmodified by human activity. Furthermore, it is close to major water supply facilities that will be subjected to very strong (MM9–MM10) shaking if this fault is capable of generating major earthquakes in the future. We believe that it is imperative that this major geological feature be understood better because of its potential hazard to local infrastructure and urban areas of south Auckland.

We recommend that as a first stage of investigation, detailed geological and geomorphological mapping be undertaken along all three segments of the Wairoa North fault. From the results of this mapping, sites can be chosen for subsurface investigations including seismic profiling and trenching that could comprise a second stage of investigation. We also recommend that terraces on the Wairoa river and its tributaries at the northern end of the fault be examined in detail as part of the first stage of study to determine any evidence for tectonic tilting or development of tectonic terraces during upper Pleistocene or Holocene time (last c 100,000 years).

Beachlands fault: We recommend that two shallow drill holes, each of about 15 m depth, be put down on either side of the Beachlands fault to recover and date the tephra horizons observed by Glading (1987). These data could be used to determine the timing and possibly the frequency of past movements along the fault.

Drury fault: We recommended that two drill holes be put down on either side of the Drury fault in sediments, mapped by Kermode (1992) as Puketoka Formation, in the Clevedon depression west of Ardmore Aerodrome to determine if evidence of vertical movements can be recognised from sediment or tephra layers thereby indicating the possible time and frequency of past movements.

Pukekohe-Waikato fault area: We suggest that observations of lineations at the eastern end of the Waikato fault and in the Pukekohe and Tuakau areas, referred to earlier in this report in sections on the Pukekohe and Aka Aka faults be re-assessed to determine, if possible, their potential for past and future earthquake activity. Any recommendation for further investigations in these areas will be dependent on this reassessment.

8.1.2 Ground Shaking Hazard Zones

Our mapping has indicated several regions where the surfical geology indicates the potential for significant earthquake shaking amplification during moderate to strong earthquakes from near and distant sources. These zones are based loosely on qualitative comparison with similar materials in other parts of New Zealand, and appear to be located largely in the South Auckland area. At present the average return period for moderate to strong shaking is relatively long, so that only the areas within Class A should be considered further. These zones are based upon surficial geology only, and many parts of Class A may be less vulnerable to earthquake shaking amplification than indicated on our map. Conversely, other areas may be worse than indicated on our map. Thus we offer them as indications of possible hazard zones, rather than definitive areas with known properties and discrete boundaries.

We recommend that some quantification of Class A — the greatest hazard zone — be undertaken by examination of drill hole information on the stratigraphy and geotechnical properties. Evaluation of a small pilot study area to be selected in consultation with appropriate ARC staff is recommended. The pilot study area should be based in South Auckland where the earthquake hazard is judged to be greatest, and where quality results can be expected within available time and budget constraints. The benefits of this study will be to quantify and to determine the degree of variability in regions mapped in the worst earthquake hazard shaking amplification zone. The results of this study will be used to determine the level of planning response, if any, required for areas mapped as Class A.

8.1.3 Slope Instability

Some parts of the Auckland region have already been identified as possessing a potential slope instability hazard. In the event of a moderate to large earthquake in the region, there is potential for major slope failure, posing a hazard to life and property. Methods exist that permit classification of slopes for their potential for failure during earthquakes and other severe events.

We recommend that important areas where potential slope failures would cause major life and/or property loss be delineated, and that more detailed studies of these areas be undertaken for earthquake-induced slope failure. This work can be undertaken as a two-stage programme. A first stage will involve classifying all of the Auckland region into one of several slope stability zones based upon available information on existing slope failures, slope angle and bedrock lithology. This should be completed initially as a desk study with existing information and techniques at a scale of 1:250,000. As a second stage, only those areas mapped as most hazardous could be examined in more detail, perhaps involving limited field work where there are existing or proposed urban developments.

9 References

Anderson, H. J. 1977: A gravity survey of the north west Manukau City, Auckland. MSc. University of Auckland.

Ballance, P.F. 1964(a): The sedimentology of the Waitemata Group in the Takapuna section, Auckland. *New Zealand journal of geology and geophysics 7(3)*: 466-499.

------- 1974: An inter-arc flysch basin in northern New Zealand: Waitemata Group (Upper Oligocene to Lower Miocene). *Journal of geology 82* : 439-471.

------- 1976b: Stratigraphy and bibliography of the Waitemata Group of Auckland, New Zealand. *New Zealand journal of geology and geophysics 19 (6)* : 897-932.

Barter, T.P. 1976: The Kaihu Group (Pliocene – Quaternary) of the Awhitu Peninsula, South west Auckland. PhD, University of Auckland.

Beanland, S.; Berryman, K.R. 1986: The Kerepehi Fault, Hauraki Depression. NZGS EDS Immediate Report 86/27.

Berryman, K.R. 1984: Late Quaternary tectonics in New Zealand. pp 91-107 in Walcott, R.I. (comp) "An introduction to the recent crustal movements of New Zealand." Royal Society Misc Pub 7.

Briggs, R.M., Okada, T., Itaya, T., Shibuya, H., Smith, I.E.M. 1994: K-Ar ages, paleomagnetism, and geochemistry of the South Auckland volcanic field, North Island New Zealand. *New Zealand journal of geology and geophysics. 37(2)*:143-153.

Brothers, R. N. 1954: The relative Pleistocene chronology of the South Kaipara district, New Zealand. Transactions of the Royal Society of New Zealand. 82(3):677-694.

Cassidy, J., Locke, C. A. & Smith, I. E. M. 1986: Volcanic hazard in the Auckland region. New Zealand Geological Survey record 10.

Christie,A. B. 1979: Sedimentary structures in Quaternary ironsands at Waikato Head, New Zealand. *New Zealand journal of geology and geophysics. 22(2)*:213-226.

Clark, R.H. 1948: Evolution of drainage of area between southern shores of Kaipara Harbour and Waitemata Harbour. MSc. University of Auckland.

Cocks, G. 1993: Engineering geology and Quaternary geology and seismotectonics on the Hunua Valley fault-angle depression. MSc. University of Auckland.

Cotton, C.A. 1951: Fault valleys and shutter ridges at Wellington. *New Zealand Geographer 7(1)*: 62-68.

Cousins, W. J. 1993: Manukau City Council Infrastructural Assets – Risk Assessment. Client Report 31390111/04. IGNS Lower Hutt.

Cox, S.H. 1881: Geology of the Rodney and Marsden Counties. *New Zealand Geological Reports of geological explorations 1879-80*, 13: 13-39.

de Lange, P.J.; and Lowe, D.J. 1990: History of vertical displacement of Kerepehi Fault at Kopouatai Bog, Hauraki Lowlands, New Zealand, since c. 10,700 years ago. *New Zealand journal of geology and geophysics. 33(2)*:277-283.

Dowrick, D.J. 1991a: Revised estimates of seismic hazard in the Auckland area, and some engineering implications. *Pacific Conference on Earthquake Engineering, Auckland New Zealand.* 147-157.

------- 1991b: A revision of attenuation relationships for Modified Mercalli intensity in New Zealand earthquakes. *Bulletin of the New Zealand National Society for Earthquake Engineering 24:* 210-224.

------- 1992: Seismic hazard estimates for the Auckland area, and their design and construction implications. *Bulletin of the New Zealand National Society for Earthquake Engineering. 25(3):* 211-221

Eiby, G.A. 1955: The direction of fault movement in New Zealand. *New Zealand Journal of Science and Technology. 36(B6)*: 552-556.

------- 1968: An annotated list of New Zealand earthquakes, 1460-1965. *New Zealand Journal of Geology and Geophysics 11(3)*: 630-647.

Fellows, D. 1987: Meremere combined cycle study: A review of seismotectonic hazards. NZGS Immediate Report 87/15.

Firth, C. W. 1928: The geology of the NW portion of Manukau County. MSc. University of Auckland.

Gage, M. 1953: The study of Quaternary strand lines in New Zealand. Transactions of the Royal Society. 81(1):27-34.

Glading, A.V. 1987: Aspects of the engineering and Quaternary geology, Whitford-Brookby-Beachlands, Auckland. MSc. University of Auckland.

Greig, 1982: University of Waikato unpublished data.

Gulliver, C.P.; Matuschka, T. 1990: Auckland Regional Council, bulk water supply dams. Seismic hazard study. Engineering Geology Ltd, Auckland.

Hadfield, J. 1987: A progress report on the geological setting and pre-Quaternary geology of the Pukekohe-Tuakau area. Waikato Regional Council Interim report.

Hayward, B.W. 1983: Sheet Q11 - Waitakere. Geological Map of New Zealand 1:50 000. Map (1 sheet) and notes (28p.) Wellington, New Zealand. Department of Scientific and Industrial Research.

High, R. 1975: Aspects of the upper Oligocene – Quaternary diastrophism in the Auckland Region. MWD Laboratory Report. Auckland.

High, R. 1977: Auckland Thermal No 1 Power Station, Waiau Pa. Underground Water right application. Auckland Engineering Laboratory. AEL No 77/46.

Hochstein, M.P.; Nunns, A.G. 1976: Gravity measurements across the Waikato Fault, North Island, New Zealand. *New Zealand journal of geology and geophysics. 19(3):*347-358.

Hochstein, M.P.; Tearney, K.; Rawson, S.; Davey, F.J.; Davidge, S.; Henrys, S.; Backshall, D. 1986: Structure of the Hauraki Rift. (New Zealand) in Walcott, R.I. comp) "An introduction to the recent crustal movements of New Zealand." Royal Society Misc Pub 7. Royal Society of New Zealand. Bulletin 24, pp 333-55.

Hochstein, M.P.; Nixon, I.M. 1979: Geophysical study of the Hauraki Depression, North Island, New Zealand. *New Zealand journal of geology and geophysics. 22(1):*1-19.

Hochstein, M.P.; Ballance, P.F. 1993: Hauraki Rift. A young active, intra-continental rift in a back-arc setting. Chapter 17. South Pacific Sedimentary Basins of the World 2. ELSIVIER.

Hogben, G. 1892: Notes on the earthquake of the 24th June, 1891. Transactions and Proceedings of the New Zealand Institute 24: 574-577.

Hollis, C.J. 1986: The subsurface Kaawa Formation at Mauku, South Auckland MSc, University of Auckland.

Kermode, L.O. 1966: Sheet N42/2 - Devonport. Geological Map of New Zealand (industrial series) 1:25 000. Wellington, New Zealand. Department of Scientific and Industrial Research.

------- 1968: Sheet N42/8 - Mangere. Geological Map of New Zealand (industrial series) 1:25 000. Wellington, New Zealand. Department of Scientific and Industrial Research.

------- 1969: Sheet N42/4 - Henderson. Geological Map of New Zealand (industrial series) 1:25 000. Wellington, New Zealand. Department of Scientific and Industrial Research.

------- 1975: Sheet N42/6 - Howick. Geological Map of New Zealand (industrial series) 1:25 000. Wellington, New Zealand. Department of Scientific and Industrial Research.

------- 1978: Sheet N42/3 - Motuihe. Geological Map of New Zealand (industrial series) 1:25 000. Wellington, New Zealand. Department of Scientific and Industrial Research.

------- 1982: Sheet N42/7 - Cornwallis. Geological Map of New Zealand (industrial series) 1:25 000. Wellington, New Zealand. Department of Scientific and Industrial Research.

------- 1986b: Sheet N42/9 - Whitford. Geological Map of New Zealand (industrial series) 1:25 000. Wellington, New Zealand. Department of Scientific and Industrial Research.

------- 1986c: Sheet N42/1 - Hobsonville. Geological Map of New Zealand (industrial series) 1:25 000. Wellington, New Zealand. Department of Scientific and Industrial Research.

------- 1992: Geology of the Auckland urban area. 1:50,000. IGNS geological map 2.

Kermode, L.O.: Searle, E.J. 1966: Sheet N42/5 - Eden. Geological Map of New Zealand (industrial series) 1:25 000. Wellington, New Zealand. Department of Scientific and Industrial Research.

Laws, C.R. 1924: The geology of the Papakura-Hunua district. MSc. University of Auckland.

Laws, C.R. 1931: The geology of the Papakura-Hunua district, Franklin County, Auckland. Transactions of the Royal Society. 62(1):37-66.

Lillie, A.R. 1959: A century of geological research in the Auckland Province. *New Zealand journal of geology and geophysics* 2(5): 920-943.

Mansergh, G.D. 1990: A reassessment of evidence for an ancient landslide at Orewa. Letters to the Editor, *New Zealand journal of geology and geophysics 33(3):* 515-522.

------- 1992: Report on investigations carried out on aspects of the geology which may impact on the Whitford Sanitary Landfill site. Graham Mansergh & Associates, Auckland.

McKay, A. 1888: On the geology of the northern district of Auckland. *New Zealand Geological Survey reports of geological explorations 1887-88,* 19: 35-37.

Naish, T.R. 1990: Late Holocene mud sedimentation and diagenesis in the Firth of Thames. bentonite in the making. MSc, University of Waikato.

Nixon, I.M.S. 1977: Geophysical study of the Drury Fault MSc, University of Auckland.

Omerod, M. P. 1989: A geophysical study of basement structures in South Auckland. MSc, University of Auckland.

Park, J. 1886: Waitemata, Eden, and Manukau Counties. *New Zealand Geological Survey reports of geological explorations 1885* (17): 147-165.

Petch, R.A.; Bell, A.R.; Depledge,D.; Hadfield,J.C.; Maggs, G.R.; Ringham, K.L. 1991: An assessment of ground and surface water resources in the Pukekohe/Tuakau area. Waikato Regional Council Technical Report 1991/12.

Prebble, W.M. 1991: Report on the field investigations carried out to search for active faults at the proposed Manukau Sanitary Landfill site. in BCHF Water right application, Vol 1.

Rafferty, W. J. 1977: The volcanic geology and petrology of south Auckland. MSc, University of Auckland.

Rosenberg, M.D. 1991: The nature and mechanism of phreatomagmatic volcanism in the South Auckland Volcanic Field. MSc Waikato University.

Schofield, J.C: 1958: Notes on volcanism and structure in Franklin County. *New Zealand journal of geology and geophysics. 1(3)*:541-559.

------- 1967: Sheet 3. Auckland. (1st ed.) Geological map of New Zealand 1:250, 000. DSIR.

------- 1976: Sheet N48, Mangatawhiri (1st ed.) Geological map of New Zealand. 1:63360 DSIR.

------- 1979: Part sheets N38, N39, N42, N43. Waiheke (1st ed.) Geological map of New Zealand. 1:63360. DSIR.

------- 1989: Sheets Q10 and R10, Helensville and Whangaparaoa. Geological map of New Zealand 1:50,000. DSIR.

Searle, E.J. 1944: Geology of the southern Waitakere hills region west of Auckland city. Transactions of the Royal Society of New Zealand. 74:49-70.

Searle, E.J. 1964a: City of volcanoes: a geology of Auckland. Paul's Book Arcade. 112p.

Skinner, D.N.B. 1976: Sheet N40 and part sheets N35, N36, & N39 Northern Coromandel (1st edition). "Geological Map of New Zealand 1:63 360". Map (1 sheet) and notes (28p.). N.Z. Department of Scientific and Industrial Research, Wellington.

Smith, W.D. and Berryman, K.R. 1986: Earthquake Hazard in New Zealand: Inferences from seismology and geology. *Royal Society of New Zealand Bulletin 24*: 223-243.

------ 1992: Earthquake Hazard Estimates in New Zealand: Effects of Changes in the Seismicity Model. *DSIR Geology and Geophysics Contract Report 1992/9.*

Sporli, K.B. 1989: Tectonic framework of Northland, New Zealand. in Sporli & Kear. Geology of Northland. Royal Society of New Zealand, Bulletin 26.

Thrasher, G.P. 1986: Basement structure and sediment thickness beneath the continental shelf of the Hauraki Gulf and offshore Coromandel region, New Zealand. *New Zealand journal of geology and geophysics 29:* 41-50.

------- 1988: Subsurface geology of the continental shelf, Bay of Plenty to Three Kings Islands, New Zealand. *New Zealand Geological Survey report G133.*

Tilsley, S. 1993: Engineering geology and mass movement of the Howick – Alfriston – Whitford district. MSc University of Auckland.

Turner, F.J.; Bartrum, J.A. 1929: The geology of the Takapuna – Silverdale District, Waitemata County, Auckland. Transactions of the New Zealand Institute, 59(4):864-902.

Waterhouse, B.C. 1978: Sheet N51, Onewhero, (1st ed.) Geological map of New Zealand 1:63360. DSIR.

Yang Zhongke 1989: Detection of basement fractures. MSc University of Auckland.

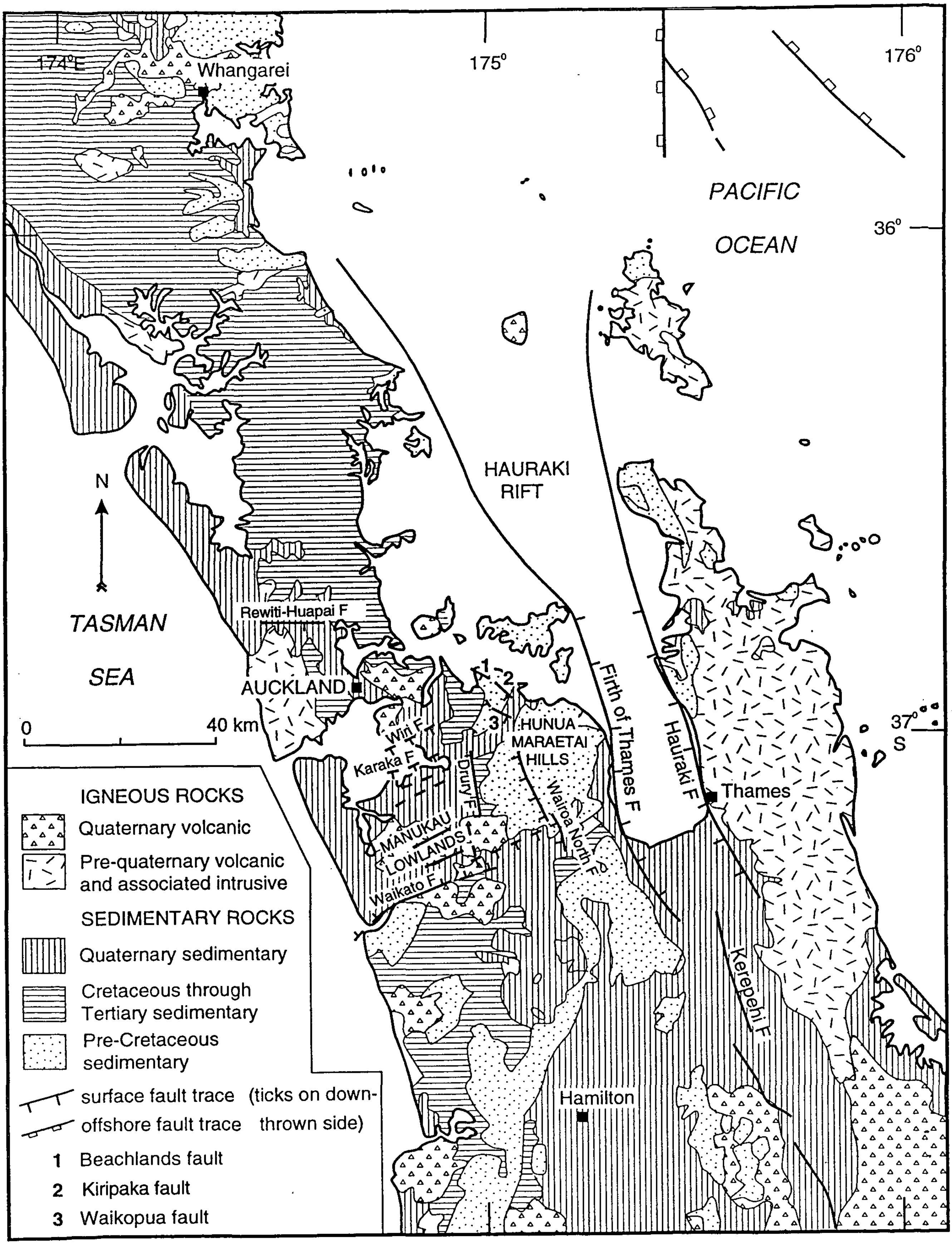

Figure 1: Generalised geology map of the Auckland region showing on and offshore faults and the generalised geographic elements of the region (Thrasher 1986).

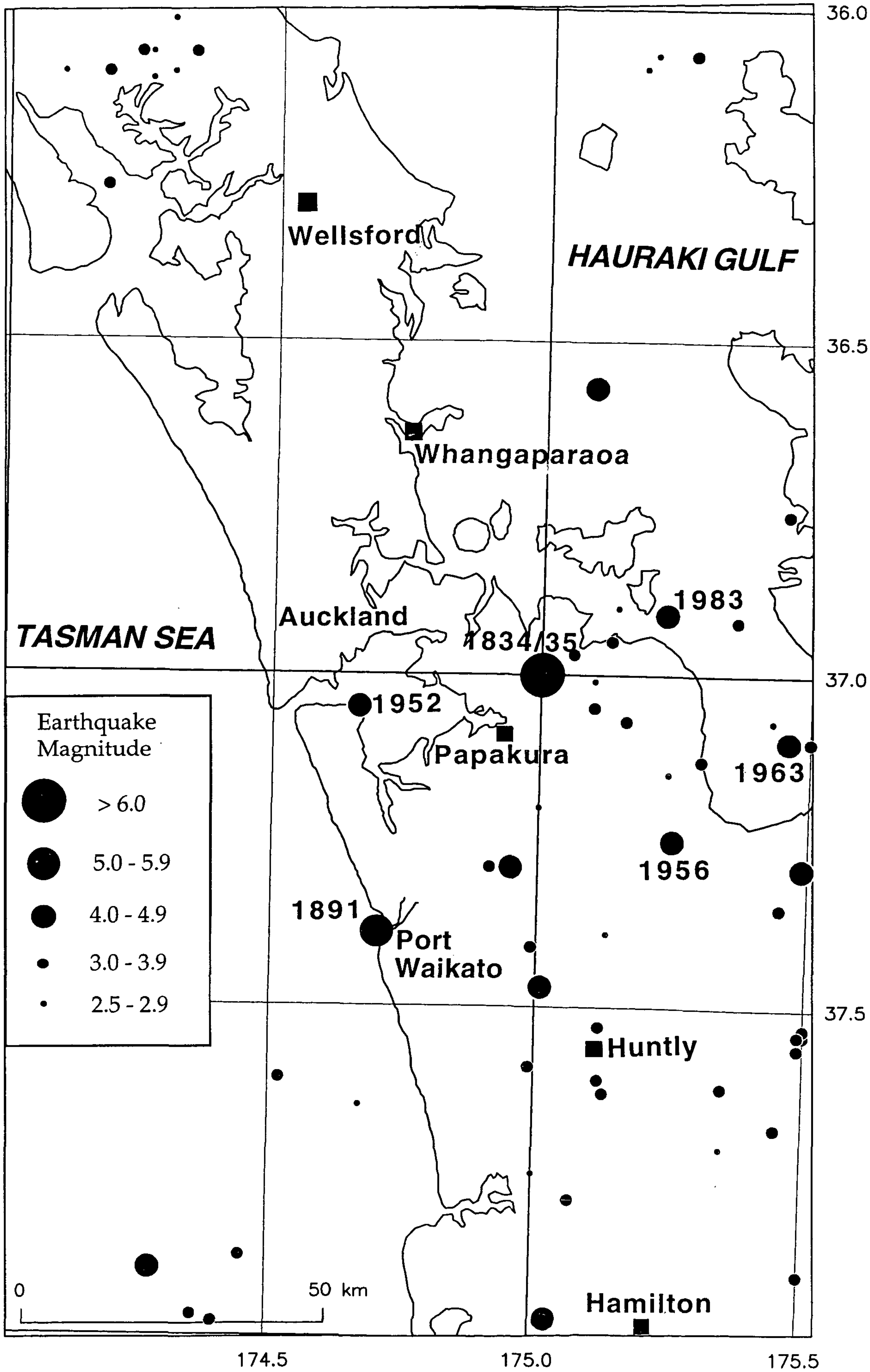

Figure 2: Location of earthquake epicentres for all known historical earthquakes in the greater Auckland region. Earthquakes M≤5 have been recorded by seismographs in the last 50 years, while larger and older earthquakes have been located by the distribution of felt reports.

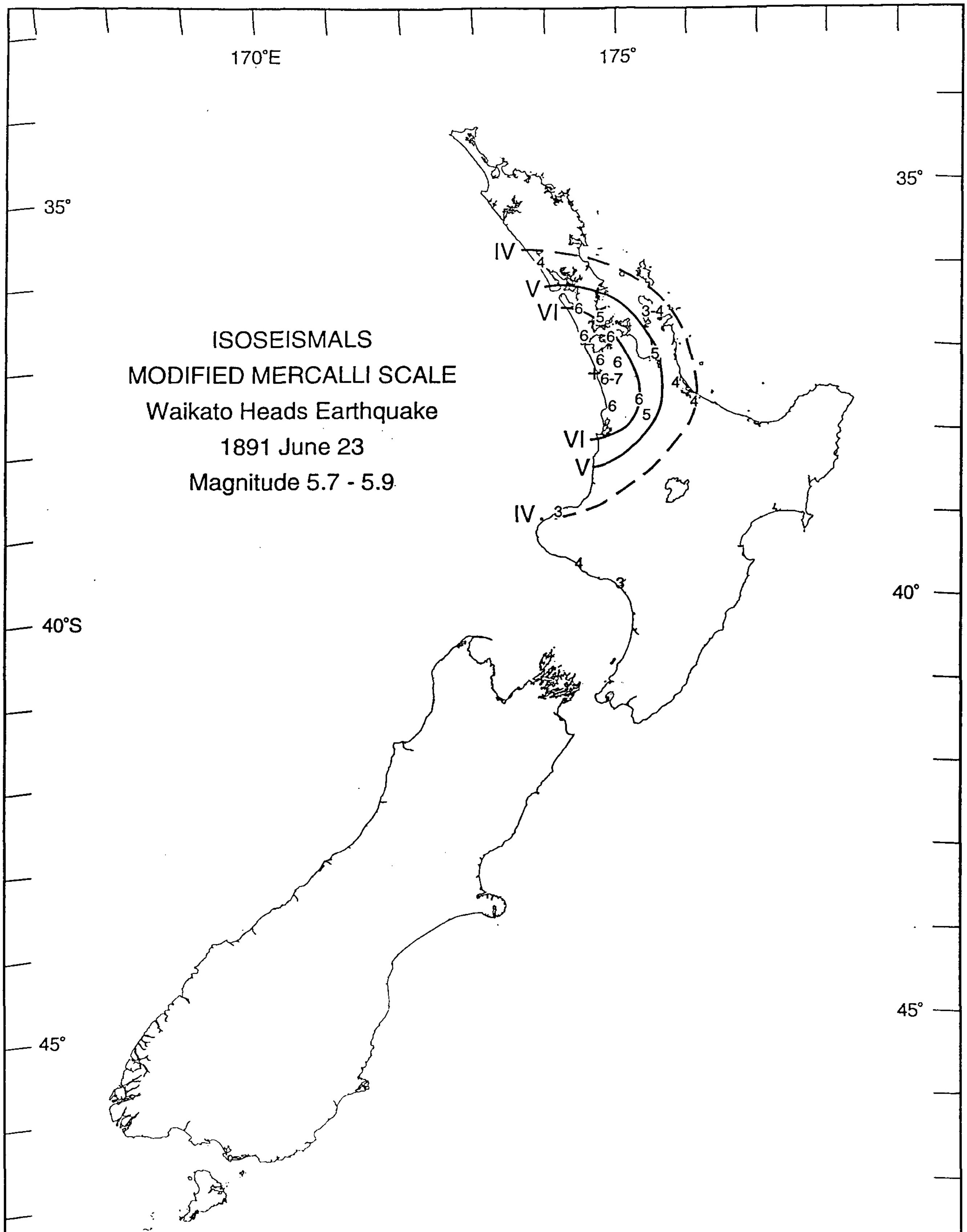

Figure 3: Distribution of felt intensities for the 1891 Waikato Heads earthquake.

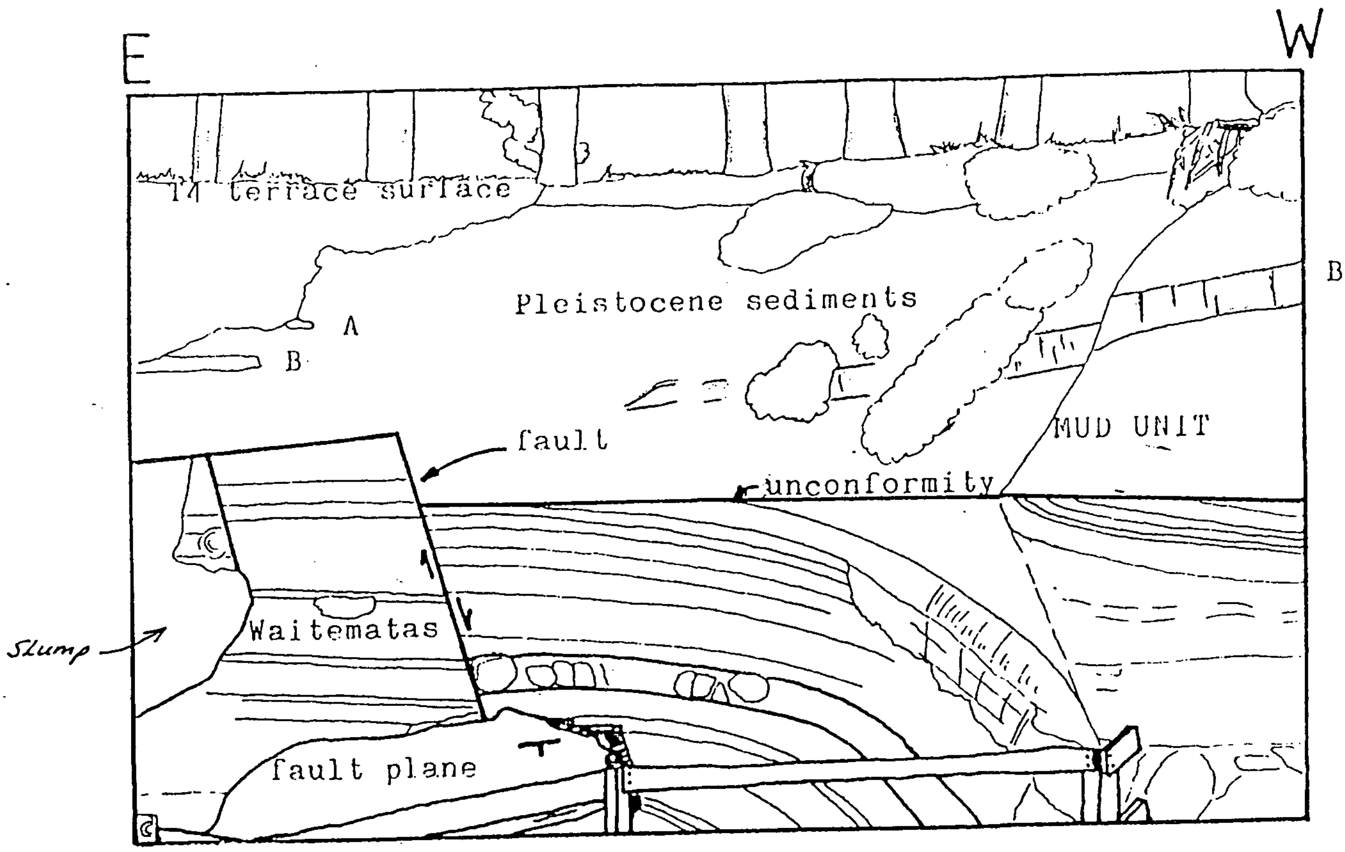

Figure 4: Sketch by Glading (1987) of the Beachlands fault exposed in the cliff face at Beachlands showing the 105,000 year BP erosion surface (unconformity) cut into the Waitemata formation, and the T4 terrace dated at > 50,000 year BP. Two rhyolite ashes are visible (labelled A and B). Ash B is offset by the fault.

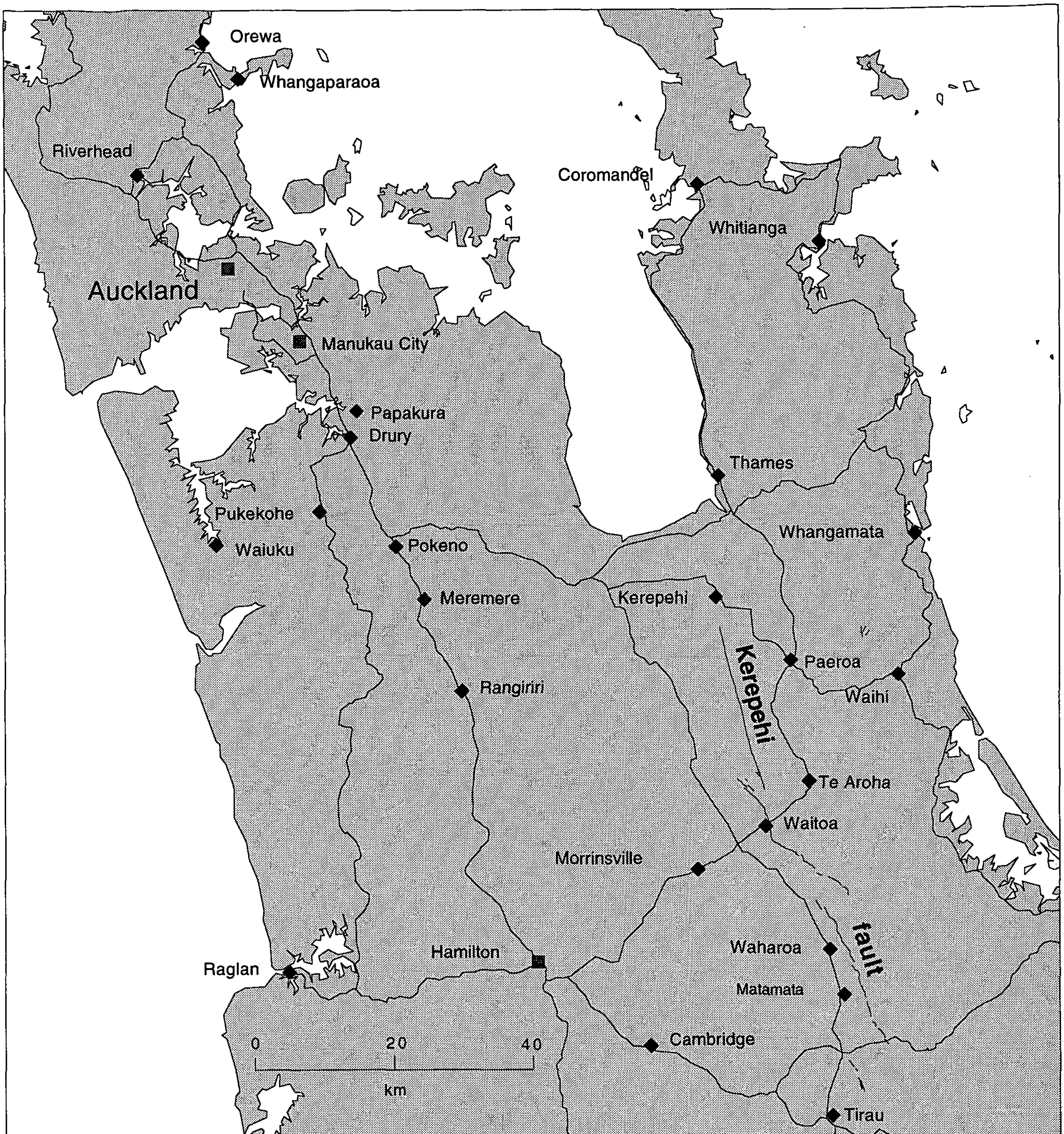

Figure 5: Map showing the location of the Kerepehi fault, North Island, New Zealand.

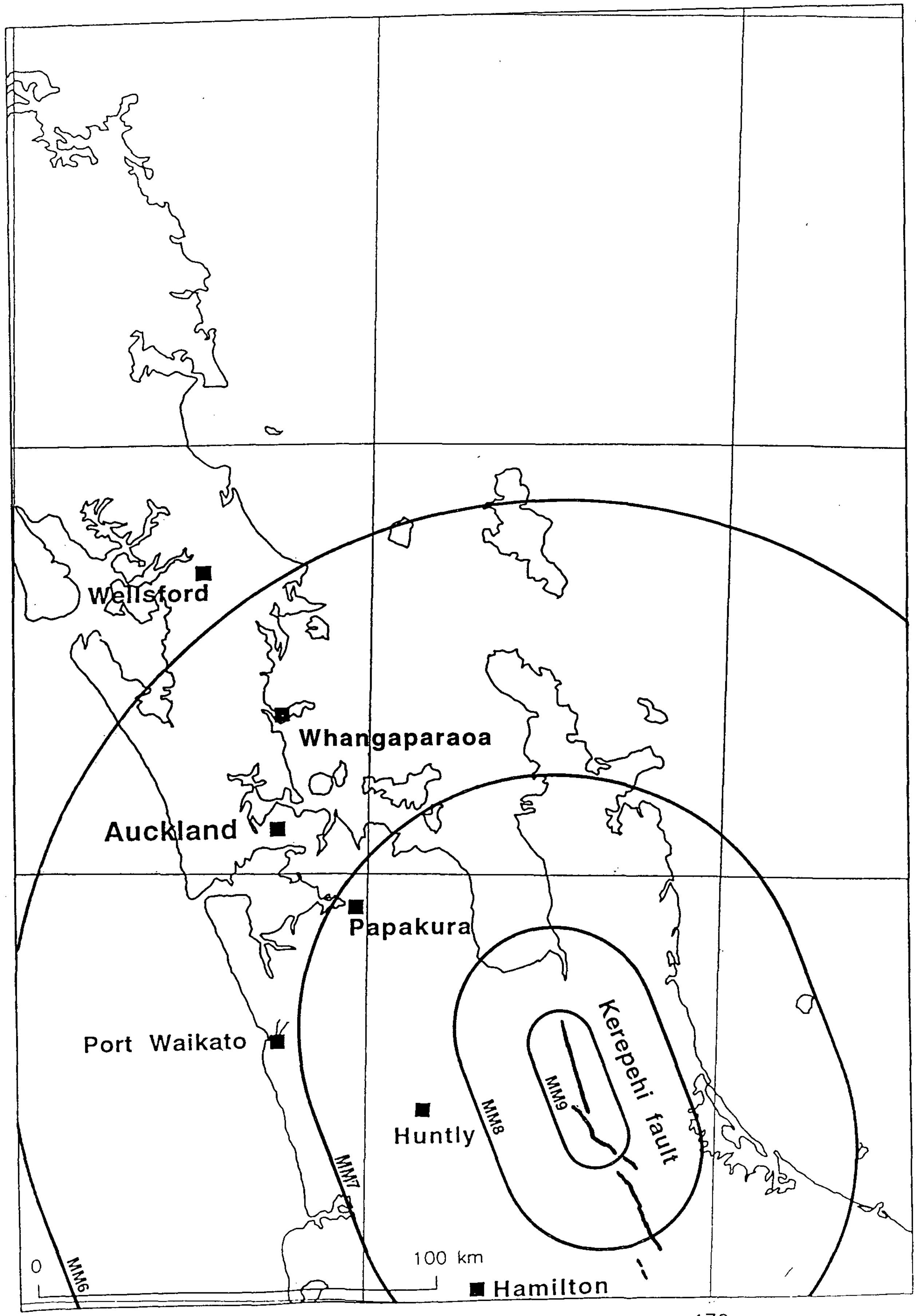

Figure 6 Distribution of felt intensities for a magnitude 7.5 earthquake on the Kerepehi fault, ~65 km south-east of Auckland.

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 1991 proposed

MM 5

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 6

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 7

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 8

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 9

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 10

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.

MM 11 & MM 12

Description not yet available.

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.