Client Report 33591D

CONFIDENTIAL

HAWKE'S BAY REGION EARTHQUAKE HAZARD ANALYSIS PROGRAMME

Stage 2
A Numerical Assessment of the Earthquake Hazard in the Hawke's Bay Region

prepared for
Hawke's Bay Regional Council

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Stage 2: A Numerical Assessment of the Earthquake Hazard in the Hawke's Bay Region

By

Kelvin Berryman[†]
Graeme McVerry[†]
Pilar Villamor[*]

[†]*Institute of Geological and Nuclear Sciences, Lower Hutt*
[*] *Department of Geodynamics, Madrid University, Spain*

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Earthquake and Ground Movement Hazards Group
Gracefield Road, PO Box 30-368, Lower Hutt, New Zealand, Telephone: +64-4-570 1444, Facsimile +64-4-566 6168

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SUMMARY

An earthquake ground shaking hazard study of the Hawke's Bay region has been performed using a US Geological Survey-sourced computer package. As input to the computer program we used: (i) a catalogue of 1007 shallow earthquakes, of magnitude M ≥4 from the period 1840 to 1993 (interpreted to be within the upper plate); (ii) 728 deep earthquakes (interpreted to be within the lower plate); (iii) data from forty active fault sources; and (iv) the earthquake parameters for the subduction zone beneath the Hawke's Bay coast. This study forms a part of the Earthquake Hazard Analysis Programme conducted by the Institute of Geological and Nuclear Sciences Limited (IGNS) for the Hawke's Bay Regional Council (HBRC).

The hazard estimation provides a regional revision of nationally-based earthquake hazard calculations of Smith and Berryman (1986; 1992). Throughout this study predicted values of Modified Mercalli Intensity (MM), and Peak Ground Acceleration (PGA) are for average ground conditions, such as the firm alluvium that underlies many of the towns of southern Hawke's Bay, and the firmest parts of Napier and Hastings. A few parts of the region are on very firm sites that are likely to experience a lesser intensity of shaking than predicted in this study, but many places are underlain by soft ground that will amplify the intensity of earthquake shaking. In a later stage of the Earthquake Hazard Project the results of this study will be further improved by incorporation of amplification factors based on mapping of ground conditions throughout the region to produce final estimates of the earthquake hazard.

Earthquake hazard results have been computed mainly for ground motions with 10% probability of exceedance in 15 years, 50 years and 500 years, corresponding to 142, 475, and about 5000 year return period events. The 142 year event is likened to the Operating Basis Event (OBE) – one that can be expected with reasonably high probability, the 475 year event is likened to a Design Level Event (DLE) and corresponds to the New Zealand Loadings Standard provisions (NZS4203:1992) for many structures, and the 5000 year event is likened to the Maximum Design Event (MDE). The MDE has a low probability of occurrence, but it is important that critical facilities and structures such as schools, hospitals, fire stations, and core lifeline services perform well even in this extreme event.

The results of this study indicate that for the OBE the Hawke's Bay region may experience MM Intensity of about 8.5-9.0, and PGA of 0.26-0.40 g. MM Intensity 8-9 damage to modern structures should be minimal, but serious damage could occur to older unreinforced masonry, poorly reinforced structures, and to well constructed buildings where permanent ground deformation occurs as a result of liquefaction of settlement (see Appendix 1 for description of

damage likely at various MM Intensity). Because of the high probability of occurrence of this level of shaking (10% chance of exceedance in any period of 15 years), all significant structures should be upgraded to maintain life safety and operability at this level of hazard. .

The variation in strong ground shaking across the region for a 475 year return period is estimated to be MM Intensity 9.1-9.7, and 0.4-0.6 g PGA. These hazard estimates represent a revision of ground motion estimates corresponding to code requirements for risk factor R=1 structures. This estimate of hazard has a 10% chance of exceedance in any period of 50 years. The variation in strong ground shaking across the region in the 5000 year return period is estimated to be MM Intensity 10-11, and 0.7-1.05g PGA. These hazard estimates represent the likely level of shaking during the maximum earthquake event. This level of shaking has a 10% chance of exceedance in any period of 500 years.

Because the hazard at each return period varies throughout the region, there is a variation in susceptibility to earthquake damage, but this depends also on the style, age, and maintenance of buildings or facilities, and on variations in ground conditions.

In the absence of quantitative measures of uncertainty for some of the model input parameters, the sensitivity of the hazard results to reasonable variation in these parameters was evaluated to test the robustness of the hazard model. Variation in rates of activity of the active faults and folds within and surrounding the region; different estimates of how earthquake shaking diminishes (attenuates) with distance from an earthquake hypocentre or fault source; and different combinations of data from the historical earthquake catalogue, and from the geological record, have all been investigated.

Hazard estimates are generally insensitive to reasonable variation in input parameters at the 150 year return period, but are increasingly sensitive at longer return periods. Variation in aspects of earthquake attenuation, particularly in relation to the standard deviation of the regression of the attenuation relationship, and maximum magnitudes of some fault sources are the main factors most likely to produce variation in hazard estimates. The variation may be more than one MM Intensity unit, and up to 0.3 g at 5000 year return periods.

This report presents a quantified assessment of one part, the hazard, of the earthquake risk equation:

$$\text{Risk} = \text{Hazard} \times \text{Vulnerability}$$

Studies are now required to assess the vulnerability within the Hawke's Bay region, and then the risk can be calculated. Effective strategies and policies for risk avoidance or reduction can only occur after complete evaluation of the risk equation.

1.0 INTRODUCTION

The Institute of Geological and Nuclear Sciences (the Institute) is pleased to present this report on the results of the Stage II Earthquake Hazard Analysis Programme: *A numerical assessment of the earthquake hazard in the Hawke's Bay region.* During the period 1994/1995 the Institute completed Stage I of the Earthquake Hazard Analysis Programme, which involved estimating the recurrence of large damaging earthquakes from geologic and seismologic data in the Hawke's Bay region. As a result of the Stage I study at least four seismic source zones which could cause future moderate to large magnitude earthquakes were identified. Events of this nature are likely to cause damage due to primary surface fault rupture and strong ground shaking, as well as secondary effects such as liquefaction, amplified strong ground shaking, and seismically induced slope failure.

The objectives of the Stage II portion of this Programme are to estimate and map the distribution of strong ground shaking for a range of time periods (Part 1), and to assess the extent and distribution of areas susceptible to seismic liquefaction in the Hawke's Bay region (Part 2). The specific objectives and scope of work completed during the Stage II study are presented below.

1.1 Stage II Study Objectives

The objectives of this study were:

- to estimate the earthquake-induced liquefaction potential for susceptible materials in the Hawke's Bay region;
- to estimate the levels of strong ground shaking in the Hawke's Bay region for various return periods that are appropriate for future planning purposes; and
- to prepare a work programme for Stage III of the Earthquake Hazard Analysis Programme.

1.2 Work Undertaken

The scope of work completed during this Stage II report included:

Part 1: *Probabilistic Seismic Hazard Assessment (this report)*

- Compiling available records of historical earthquakes within and around the Hawke's Bay Region and combining these with paleoseismic information and those of the Stage I studies to develop a seismic hazard model for the region. This model was used to estimate the distribution of strong ground shaking in the region at various return periods, or probabilities of exceedance.

- Preparing maps depicting the level of ground shaking and intensity expected at various return periods. These maps are valuable for planning purposes and consistent with return periods commonly used by the engineering community.

- Preparing an overview report to accompany the studies above that specifies the purpose of the study and the assumptions and limitations of the model, data, and interpretations presented. This overview report is submitted separately.

Part 2: *Liquefaction Hazard Assessment*

- Collecting available information regarding historical accounts of liquefaction in the Hawke's Bay Region, particularly for the 1931 earthquake.

- Preparing a series of liquefaction susceptibility maps which incorporate data from existing Quaternary geologic mapping (i.e. age and depositional environment of sediments), historical accounts of liquefaction, and geotechnical properties from existing boring logs.

- Identifying appropriate scenario earthquakes to evaluate the potential occurrence of liquefaction in the Hawke's Bay region.

- Preparing a regional scale map which depicts the liquefaction potential for the earthquake scenarios in the Hawke's Bay region.

- Preparing detailed liquefaction potential maps (1:50,000) of the Heretaunga Plains, Wairau, and Waipukerau/Waipawa which depict the occurrence of liquefaction during the scenario earthquakes.

- Preparing this report summarising the results of our studies, implications for liquefaction hazards in the Hawke's Bay region, and recommendations for the programme of work to complete Stage III of the Earthquake Hazard Analysis Programme. This report is submitted separately.

This report presents a review of earthquake data for evaluating future earthquake hazard in the Hawke's Bay Region, and uses these data to compute the level and variation of hazard throughout the region. These data are: the earthquakes that have occurred in the historical period from 1840 to the present; the occurrence and location of the much less complete record of pre-historical major earthquakes that can be inferred from specific paleoseismological studies (eg. Begg et al., 1996); and geological interpretation of topography and stratigraphy of other faults in the Hawke's Bay region.

Earlier estimates of the earthquake hazard in the region have relied solely on the historical catalogue (eg. Smith, 1978), or have been a somewhat ad-hoc mixture of the earthquake catalogue combined with inferences from the geological record (eg. Smith & Berryman, 1986; 1992). Earlier studies have been national in their scope requiring a broad-brush approach to delineation of regions within which earthquake hazard has been presumed to be uniform. In contrast, this study looks specifically at the Hawke's Bay Region, and uses a recently-developed computer analysis package that uses both the historical earthquake catalogue and the geological database in a complementary and numerically consistent fashion.

The objectives of this study are to evaluate the strength of earthquake ground shaking throughout the Hawke's Bay region for two ground motion measures, namely Modified Mercalli (MM) intensity and Peak Ground Acceleration (PGA), for three return periods. These are: 10% probability of exceedance in 15 years, 50 years and 500 years, corresponding to 142, 475, and about 5000 year return period events. These time-spans were chosen because the 142 year event is likened to the "Operating Basis Event" (OBE) – one that can be expected with reasonably high probability, the 475 year event is likened to a Design Level Event (DLE) and corresponds to the New Zealand Loadings Standard provisions (NZS4203:1992), and the 5000 year event is likened to the Maximum Design Event (MDE). The maximum earthquake event has a low probability of occurrence, but it is important that critical facilities and structures such as schools, hospitals, fire stations, and core lifeline services perform well even in this extreme event.

The emphasis in this study has been on the estimated earthquake shaking in the cities and towns of the region, thus the principal output is a series of tables indicating expected ground motion in twelve urban centres across the region. An indication of the regional variation in ground motions is illustrated by ground motion maps of the region. The hazard has been computed for average ground conditions characterised by gravel terraces or firm alluvium. Modification of expected ground motions dependent on ground condition will be assessed in a future stage of the Hawke's Bay Earthquake Hazard Analysis Programme.

2.0 GEOLOGICAL AND TECTONIC SETTING OF HAWKE'S BAY

New Zealand lies along a boundary zone between two of the tectonic plates that make up the earth's crust. The western part of the country is on the Indian-Australian plate, while the eastern part is on the Pacific plate (Figure 1). Strain and crustal deformation is concentrated along the boundary zones between these plates.

The plate boundary zone runs through and east of the North Island and involves oblique subduction. That is, in the Hawke's Bay area, the Pacific plate is in relative movement beneath and towards the Indian-Australian plate at c. 42 mm/yr (eg. DeMets et al. 1994) (Figure 2). Convergence between the two plates in central Hawke's Bay is at an oblique angle (with an inclination of about 50°) to the coast and to the trend of the Hikurangi trough offshore. The Pacific plate starts sliding beneath the Indian-Australian plate at the Hikurangi trough about 200 km east of Napier, and becomes progressively deeper below the surface to the west. The down-going plate dips gently (about 6°) immediately west of the trough (Reyners 1980; Bannister 1986), but steepens beneath central Hawke's Bay to about 25° (Adams and Ware 1977). The zone between the trough and the axial ranges of the North Island is a zone of intense deformation and is known variously as the East Coast Fold Belt (Katz 1974), Axial Tectonic Belt (Walcott 1978) and East Coast Deformed Belt (Spörli 1980; used within this report). Folding and faulting within the belt is caused by oblique contractional forces generated by the subduction process.

The East Coast Deformed Belt is characterised by a set of strike-slip faults in the west (including the Ruahine and Mohaka faults; Figure 1), and a reverse fault zone (including thrust faults) dipping away from the Hikurangi trough in the east (Spörli 1980; Figure 2).

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

The Heretaunga Plains represents a tectonic depression developed within the East Coast Deformed Belt during the last 1.5 million years between actively growing folds (Ravens 1990; 1991). Within the basin, up to 1 km of Pleistocene (post c. 2 million yrs) gravel, sand and silt overlie the limestone and sandstone that form the local bedrock. The thickness of the young (< 250 000 years) sediments (eg. 240 m minimum at Tollemarche Orchard drillhole) within the Heretaunga Plains depression illustrates on-going deformation.

Formation of the basin now filled with gravel comprising the Ruataniwha Plains has been in response to the activity of a series of west-dipping, NE-trending reverse faults in the area during the last 1.5 million years.

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

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

3.0 THE EARTHQUAKE HAZARD ESTIMATION PROCEDURE

This study has used the SEISRISK suite of earthquake hazard programs (Hanson *et al.*, 1992), developed by the U.S. Geological Survey for Macintosh personal computers, and is a development from the earlier SEISRISK III suite of programs written for IBM-type personal computers (Arnold, 1989). The procedure (Figure 3) initially produces a standard format for an historical earthquake catalogue for the region of interest. Based on the pattern of seismicity and other geological criteria, the region of interest is then divided into smaller sub-regions or source zones, within which the earthquake hazard can reasonably be expected to be uniform. A program then assigns portions of the earthquake catalogue to each of the subregions and calculates earthquake activity rates for a series of earthquake magnitude classes.

In the simplest form of the model, the hazard can be computed using the historical catalogue alone, and produces a very similar result to the procedure used by Smith (1978a). However, it has long been recognised that if the seismicity that has occurred in the historical period is not an accurate reflection of the long-term occurrence of large magnitude (M≥7) damaging earthquakes in particular, then the modelling of the future earthquake hazard will be deficient in most cases, resulting in an underestimate of the hazard. The historical catalogue in New Zealand extends back a maximum of about 150 years to around 1840 (Eiby, 1968), but geological information indicates that the return time for surface rupture of active faults (and thus the likely maximum magnitude earthquake recurrence interval) is commonly several hundred to several thousand years (Berryman & Beanland, 1988; Hull *et al.*, 1993). This deficiency in not sampling the large magnitude earthquakes in the historical period would not matter if the earthquake frequency – magnitude relationship (Gutenberg & Richter, 1949), that relates the rate and size of earthquakes in a region, could be extrapolated to estimate the occurrence of large earthquakes on particular faults. However, there is increasing doubt that the frequency-magnitude relationship can be extrapolated in this way (eg. Wesnousky *et al.*, 1983; Schwartz & Coppersmith, 1984, Stirling et al., 1996), and the frequency of large, shallow, earthquakes may be more accurately assessed from paleoearthquake studies on active faults. Smith & Berryman (1986) recognised this deficiency, but did not have a numerically robust procedure to include geologically-derived estimates of large earthquake occurrence with the historical seismicity catalogue.

The procedure used in this study overcomes this problem, and allows for further sets of seismic source zones (in addition to designated earthquake regions) in the form of line (fault) or area (subduction zone) sources. Therefore, geologically-determined rates and magnitudes for large earthquakes, which have caused surface fault rupture or regional uplift and subsidence in the past, can augment earthquake rate parameters determined from the historical earthquake catalogue. So as not to double-count the rate of seismicity at higher magnitudes, the contribution to the hazard model from historical seismicity can be truncated at an appropriate magnitude threshold where earthquakes of that magnitude could be expected to result in surface rupture in that tectonic province, and thus be preserved in the geological record. Earthquakes originating below about 30 km (or within the subducting Pacific plate in the case of the east coast of the North Island – see Section 3.1 for discussion) are not likely to result in surface faulting. For deep seismicity source zones we must rely on earthquake magnitude and rate estimates derived solely from the historical catalogue.

Once information on rates and magnitudes for each of the earthquake source zones are compiled, be they areas or line sources, then the actual hazard computation can be performed. The earthquake hazard can be described in terms of Modified Mercalli (MM) intensity , or Peak Ground Acceleration (PGA) – a measure often used by the engineering profession. For this study, the hazard has been computed in terms of MM intensity, and PGA because they are the most widely used measures in New Zealand. These measures can readily be used to relate the estimated earthquake hazard to possible building and ground damage during future earthquakes. The hazard computation is an integration process in which rates and strengths of earthquake ground motion from all seismic sources are assessed based on the rate of decay (attenuation) of MM intensity and PGA away from the locus of activity. Hazard is computed for a grid of specified shape and spacing, in terms of the probability of exceedance within specified time periods (eg. 10% in 50 years).

In this study the hazard, has been computed for 10% probability of exceedance in 15 years, in 50 years and in 500 years. The 142 year return time event (10% probability of exceedance in 15 years) is likened to the Operating Basis Event, in which there is expected to be significant damage in local areas, and some injuries, but there should not be widespread disruption to lifeline services or life risk. The 475 year return period corresponds to the New Zealand Loadings Standard (NZS4203:1992), and the 5000 year event is appropriate as a worst case scenario from a hazard mitigation and planning perspective, and is likened to the Maximum Design Event. Widespread damage, many injuries, and some deaths may be anticipated in the highest hazard areas in this event. The planning and hazard mitigation challenge in the Maximum Design Event is to ensure that critical structures and facilities such as hospitals, fire stations, and core lifeline services remain intact and operable if possible, and certainly not to fail in a catastrophic way.

The predicted values for MM intensity and PGA throughout this study are for average ground conditions, such as the firm alluvium that underlies many of the towns of the Hawke's Bay. A few parts of the region are on very firm sites that are likely to experience a lesser intensity of shaking than predicted in this study, but many places are underlain by soft ground that will amplify the intensity of earthquake shaking. Areas subject to permanent ground deformation due to soil liquefaction are described in Part 2 of this stage of the Earthquake Hazard Analysis Programme for Hawke's Bay Regional Council (Hengesh et al., 1996).

4.0 INPUT DATA

Assessment of the seismicity for the Hawke's Bay region involved analysis of the historical earthquake catalogue to estimate Gutenberg-Richter rate parameters "a" and "b", and characterising the recurrence interval and size of the maximum magnitude earthquakes likely to occur on shallow crustal faults in the region and on the subduction zone.

4.1 Earthquake Catalogue

The record of historical earthquakes provides information on the rate and size of earthquakes in the region, and provides a basis for subdividing the region into smaller source zones, within which the rate of earthquake activity may be assumed to be uniform. A search of the Institute of Geological and Nuclear Sciences earthquake database includes 1007 shallow earthquakes (events interpreted to be in the upper, Australian plate) of magnitude 4 and greater between 1840 and the end of 1994 in an area somewhat larger than the HBRC boundary (Figure 4). There have been 3 events of magnitude 7.0 to 7.9, 8 of magnitude 6.0 to 6.9, and 90 of magnitude 5.0 to 5.9. For earthquakes originating deeper in the subducted lower, Pacific plate in the same search area, 728 events of magnitude 4 or greater, and up to 100 km deep, have been recorded up to the end of 1994. There have been 3 events of magnitude 7.0 to 7.9, 18 of magnitude 6.0 to 6.9, and 75 of magnitude 5.0 to 5.9.

The earthquake hazard computation procedure requires aftershocks to be removed from the catalogue before earthquake rates are established for each of the earthquake source regions. This was done manually with aftershocks being identified as those shocks that occur within 0.5 degrees of the mainshock and within 6 months of mainshock events less than magnitude 6, and within 12 months of mainshock events of magnitude 6 or more. Within the HBRC catalogue 137 events from the 1007 total were removed as aftershocks from the upper plate source zones, and 17 events from the lower plate source zone. The majority of aftershocks were associated with: the June 1942, Wairarapa earthquake of M 7.2; intense moderate magnitude activity near Porangahau in 1984; aftershocks of the Edgecumbe earthquake of 1987, and in the Taupo area in general. The maximum magnitude event removed from the HBRC catalogue as an aftershock was the 13 February 1931 M 7.3 aftershock of the 1931 Hawke's Bay earthquake. Identification and removal of events from swarm sequences such as occurred near Porangahau in 1984, and the Taupo region is more difficult because of the lack of clear-cut mainshock events and the occurrence of many similar-sized moderate magnitude events. The effect of removal or non-removal of small magnitude earthquakes on the hazard calculations is not large, because in this study the occurrence rate of large magnitude events, which contribute the most to the cumulative earthquake hazard, is based on fault data, not an extrapolation of the Gutenberg-Richter frequency-magnitude relationship.

The distribution of upper plate historical seismicity in the Hawke's Bay Region with aftershocks removed is illustrated in Figure 4. Notable features of the earthquake distribution are: the occurrence of several moderate magnitude earthquakes in the Taupo region; the relatively low number of earthquakes in the inland part of the region (although with a relatively large number of M 6.0 to 6.9 events); and more earthquake activity in a coastal belt, which diminishes again offshore. These variations in the earthquake occurrence rate across the region in historical time provide the basis for the earthquake source regions depicted in Figure 2 and Table 1. In addition to the devastating Hawke's Bay event of 1931, major earthquakes occurred near Waipukurau in 1863, Wairoa in 1932, Pahiatua in 1934, and Masterton in 1942. Most of these earthquakes occurred prior to the establishment of a seismograph network so the epicentres have been located on the basis of how strongly the earthquakes were felt by the sparse population of the time. Thus, there is considerable uncertainty in the location of these events, and also in their magnitudes.

The 1863 event in southern Hawke's Bay is assigned a magnitude of M 7.5 with an epicentre within the area of most damage centred on Waipukurau. However preliminary interpretation of recently acquired historical information (G. Downes, *pers comm.*, 1993) suggests the earthquake may have been centred somewhat further north, between Waipawa and Hastings, where the occurrence of "rents and fissures" in reports of the day may be contemporary descriptions for surface fault rupture.

The location of the 1934 "Pahiatua" earthquake is also problematical. The earthquake was thought to be shallow, and located close to the Wellington fault, a few kilometres west of Pahiatua. However, the maximum MM intensity assigned to the earthquake is only MM 8, and although the earthquake was felt throughout most of New Zealand, which is indicative of a magnitude about M 7.6 (Dowrick & Smith 1990), the epicentre is in doubt because several metres of surface fault displacement is expected in an earthquake of this magnitude at shallow depth. Dowrick & Smith (1990) have suggested a focal depth of 45 km to alleviate the problem of lack of surface fault rupture, but there are some historical data to suggest the maximum felt effects of the earthquake were in Makuri and Pongaroa, some 30-40 km east of the indicated epicentre. Surface faulting was not documented in the Makuri - Pongaroa region in 1934, but much of the land in that area was covered in second-growth forest, and only sparsely settled, so surface fault rupture could easily have gone undetected.

Table 1 Seismicity Parameters of Earthquake Source Zones

	Taupo	Inland	Coastal	Offshore	Pacific
M_{max}	6.8	8.2	8.2	7.8	8.0
area (x10^3 sq km)	6.62	29.10	30.25	27.54	108.85
a value	5.521	4.149	4.753	4.884	5.797
b value	1.20	0.85	0.96	1.08	1.05
a_4 value	0.794	0.193	0.271	0.133	0.363
RI (yrs) for ≥ M 7 †	–§	1840	2803	13,060	3889
RI (yrs) for ≥ M 6 †	316	260	307	1086	347
RI (yrs) for ≥ M 5 †	20	37	34	90	31
RI (yrs) for ≥ M 4 †	1.3	5.2	3.7	7.5	2.7

† Per 10^3 sq km. RI is recurrence interval.
§ above M_{max} for this source region.

Masterton and Wellington suffered the most damage in the June, 1942 Wairarapa earthquake which has an assigned magnitude of M 7.2 (Dowrick & Smith, 1990), and an epicentre placed near Bideford, about 20 km northeast of Masterton. Neef (1976) proposed that some bedding-slip surface faulting occurred near Ihuarau in association with the August, 1942 M 7.0 earthquake. The evidence for surface faulting near Ihuarau in 1942 is circumstantial, based entirely on a fault trace with youthful appearance. It is possible that the fault trace is several hundred years old, dating from the most recent rupture of the Alfredton fault as determined by trenching studies near Alfredton (K. Berryman and S. Beanland, unpublished data).

From this commentary it is apparent that considerably more research is needed to document the location, effects, and geological significance of all the M>7 earthquakes that have occurred within or near to the Hawke's Bay Region in the historical period. The effect of these uncertainties on the hazard computations is difficult to determine, but may be small because the estimated recurrence rate of earthquakes above M 7 is, in this study, controlled from geological input data.

The distribution of earthquakes in the lower plate seismicity zone is spatially reasonably uniform, although decreasing to the southeast of a line about 30 km from the coastline. Because of their depth, these earthquakes make a relatively small contribution to the cumulative earthquake shaking hazard, and are included in the hazard model as two, northwest-inclined (at the same slope as the plate interface) zones extending from 40 to 60 km deep across the region and from 60 to 80 km deep across the region (Figure 5).

4.2 Shallow Crustal Faults

Geological information obtained from shallow crustal faults provides information on the frequency of occurrence, and magnitude of large, surface-rupturing, pre-historical earthquakes. The ages of these earthquakes, and amount of displacement per event, allows the average surface slip-rate of the fault to be calculated.

For this study, characteristics of 40 active fault or fault segment sources (Figure 6 & Table 2) have been utilised to constrain the size and frequency of major earthquakes within, and somewhat beyond, the Hawke's Bay Region. Several fault sources beyond the Regional Council boundary are included in the compilation because large earthquakes occurring on these fault sources contribute significantly to the cumulative regional hazard for distances up to at least 50 km from source.

Table 2 lists the fault or fold, and then the length, fault dip, assumed thickness of seismogenic crust, and single event displacement estimates, in order to calculate seismic moment. These data allow an estimate of the moment magnitude (M_W) of the maximum magnitude earthquake likely to be associated with that fault from the relation of Hanks & Kanamori (1979). Estimates of the recurrence interval for the maximum magnitude earthquake are also presented in Table 2, based on estimates of fault slip rate and single-event displacement. The estimates of earthquake magnitude and recurrence interval are the parameters used in the earthquake hazard model. There are only limited data available for even the most-studied of the fault sources (see references cited for each of the fault sources), and many values of the magnitudes and recurrence intervals for the fault sources are no more than estimates based on comparison with nearby faults from which a little more data are available, and the consensus among a number of specialist geologists. Mean recurrence interval and magnitude estimates are used in the preferred model of earthquake hazard. To assess the sensitivity of these data inputs to the hazard computations, the maximum magnitude and minimum recurrence intervals data have also been used as the basis of a likely maximum hazard (see Section 6.5).

Table 2 Parameters of fault sources for Hawkes Bay earthquake hazard model

Fault No	Fault	Length (km)	Fault Type	Dip (deg)	Crustal depth (km)	Fault Width (km)	Average Displ (m)	M_o x10^{20}Nm^{-2}		M_W		Mean RI (years)
								mean	max	mean	max	
1	Taupo Fault belt NE	17	NOR	60±15	8±2	9.2 +4.9/ -3.0	1.5±1.0	0.07	0.17	6.5	6.7	200±100
2	Taupo Fault belt NE	15	NOR	60±15	8±2	9.2 +4.9/ -3.0	1.5±1.0	0.06	0.17	6.4	6.7	200±100
3	Taupo Fault belt NE	15	NOR	60±15	8±2	9.2 +4.9/ -3.0	1.5±1.0	0.06	0.17	6.4	6.7	200±100
4	Turangi NE	17	NOR	60±15	8±2	9.2 +4.9/ -3.0	1.5±1.0	0.07	0.17	6.5	6.7	200±100
5	Turangi SW	17	NOR	60±15	8±2	9.2 +4.9/ -3.0	1.5±1.0	0.07	0.17	6.5	6.7	200±100
6	Kaweka	32	SS	80±10	13±5	13.2 +5.9/ -5.0	3.0±1.5	0.38	0.83	7.0	7.2	2000±500
7	Waiohau	73	SS	80±10	13±5	13.2 +5.9/ -5.0	3.0±1.5	0.86	1.88	7.2	7.4	3000±1500
8	Ruahine NE Seg.	69	SS	80±10	13±5	13.2 +5.9/ -5.0	4.0±1.0	1.09	1.97	7.3	7.5	2000±1000
9	Ruahine Central NE Seg.	50	SS	80±10	13±5	13.2 +5.9/ -5.0	4.0±1.0	0.79	1.46	7.2	7.4	2000±1000
10	Ruahine Central SW Seg.	26	SS	80±10	13±5	13.2 +5.9/ -5.0	3.0±1.0	0.31	0.74	6.9	7.2	2000±1000
11	Ruahine SW Seg.	51	SS	80±10	13±5	13.2 +5.9/ -5.0	4.0±1.0	0.79	1.46	7.2	7.4	2000±1000
12	Whakatane	68	SS	80±10	13±5	13.2 +5.9/ -5.0	3.0±1.5	0.81	1.75	7.2	7.4	3000±1500
13	Ruatahuna	47	SS/NOR	80±10	13±5	13.2 +5.9/ -5.0	3.0±1.5	0.56	1.21	7.0	7.3	2000±1000
14	Mohaka NE Seg	57	SS	80±10	13±5	13.2 +5.9/ -5.0	4.0±1.0	0.90	1.63	7.3	7.4	1000±500
15	Mohaka Central Seg.	45	SS	80±10	13±5	13.2 +5.9/ -5.0	4.0±1.0	0.71	1.29	7.2	7.4	1000±500
16	Mohaka SW Seg.	59	SS	80±10	13±5	13.2 +5.9/ -5.0	4.0±1.0	0.90	1.63	7.3	7.4	1000±500
17	Waimana	58	SS	80±10	13±5	13.2 +5.9/ -5.0	3.0±1.5	0.69	1.49	7.2	7.4	5000±2000
18	Potaka -Rangiora	62	SS	80±10	13±5	13.2 +5.9/ -5.0	4.0±1.0	0.90	1.63	7.3	7.4	1000±500
19	Waikaremoana	23	SS	80±10	13±5	13.2 +5.9/ -5.0	3.0±1.5	0.27	0.59	6.9	7.1	5000±2000
20	Wakarara rangefront 1	33	REV	50±15	13±5	16.9 +14.4/ -8.1	3.0±2.0	0.50	1.23	7.0	7.4	5000±2000
21	Wakarara rangefront 2	31	REV	50±15	13±5	16.9 +14.4/ -8.1	3.0±2.0	0.50	1.23	7.0	7.4	5000±2000
22	Taniwha	24	REV	60±10	13±5	15.0 +8.5/ -6.5	3.0±2.0	0.32	0.85	6.9	7.2	5000±2000
23	Oruawharo	23	SS/REV	60±10	13±5	15.0 +8.5/ -6.5	3.0±2.0	0.32	0.85	6.9	7.2	3000±1500
24	Wairarapa	81	SS	60±10	13±5	15.0 +8.5/ -6.5	8.0±2.0	2.92	5.71	7.6	7.8	2000±500
25	Waipukurau	19	SS/REV	60±10	13±5	15.0 +8.5/ -6.5	4.0±2.0	0.34	0.80	6.9	7.2	2000±500
26	Poukawa	35	REV	40±10	13±5	20.2 +15.8/ -7.7	7.0±2.0	1.48	3.40	7.4	7.6	3000±1000
27	Napier	90	REV	40±10	13±5	20.2 +15.8/ -7.7	6.0±2.0	3.27	7.77	7.6	7.9	3000±1000
28	Haumoana	16	NOR	60±15	10±3	11.5 +6.8/ -4.3	1.5±1.0	0.08	0.22	6.5	6.9	3000±1000
29	Tukituki/Middle Rd	30	REV	40±15	12±3	18.7 +16.8/ -3.8	6.0±2.0	1.01	2.55	7.3	7.5	5000±2000
30	Otane	18	REV	40±10	13±5	20.2 +15.8/ -7.7	4.0±2.0	0.43	1.16	7.0	7.3	5000±1000
31	Weber	19	SS	70±15	13±5	13.8 +8.1/ -5.8	3.0±2.0	0.24	0.62	6.9	7.1	2000±1000
32	Saunders Road	40	SS/NOR	70±15	13±5	13.8 +8.1/ -5.8	3.0±2.0	0.49	1.31	7.0	7.4	2000±1000

33	Elsthorpe	18	NOR	60±10	8±4	9.2 +6.4/ -5.0	3.0±2.0	0.15 0.42	6.7 7.0	5000±2000
34	Craggy Range Road	18	NOR	60±10	8±4	9.2 +6.4/ -5.0	3.0±2.0	0.15 0.42	6.7 7.0	2000±1000
35	Maraetotara	22	NOR	60±10	8±4	9.2 +6.4/ -5.0	1.5±1.0	0.09 0.26	6.6 6.9	2000±1000
36	Kidnappers Anticline	51	REV	40±10	12±3	18.7 +11.3/ -3.8	5.0±1.5	1.43 2.98	7.4 7.6	1500±500
37	Hawkes Bay shelf	45	REV	40±10	12±3	18.7 +11.3/ -3.8	5.0±1.5	1.26 2.63	7.4 7.6	1500±500
38	Motukura	51	REV	40±10	12±3	18.7 +11.3/ -3.8	5.0±1.5	1.43 2.98	7.4 7.6	1000±500
39	Lachan Anticline	108	REV	40±10	12±3	18.7 +11.3/ -3.8	5.0±1.5	3.02 6.31	7.6 7.8	1000±500
40	Gisborne Water Supply	17	NOR	60±10	10±2	11.5 +4.1/ -3.0	1.5±1.0	0.08 0.19	6.5 6.8	1000±500
41	Subduction Thrust zone	200	REV	20±5	8-30 km	100	13	102.6	8.3	2500/1000
42	Subduction Thrust zone	120	REV	20±5	8-25 km	65	5/13	57.6	8.1	2500/1000
43	Subduction Thrust zone	120	REV	20±5	8-25 km	65	5/13	57.6	8.1	2500/1000

Notes
(i) Crustal depth means the estimated thickness of the seismogenic crust.
(ii) NOR is normal fault, SS is strike-slip fault, REV is reverse fault.

The computer programs require the activity rate of earthquakes to be expressed as annual probabilities of occurrence so the recurrence interval estimates were inverted. This procedure tacitly assumes the faulting process is a random (Poisson) process, in which the past behaviour of the fault has no bearing on future activity. This assumption is not accepted by many geologists (eg Schwartz & Coppersmith, 1984), especially when considering the hazard posed by an individual fault. However, the areal smoothing that is a feature of this regional study overcomes much of this potential shortcoming in the modelling. Some preliminary trials investigating the sensitivity of the hazard computation to models of fault behaviour (Berryman, unpublished data) indicate the assumption of Poisson processes is adequate, provided the earthquake hazard is not dominated by a single fault source, and the study is regional (such as the present study) rather than local (city size or smaller) in scale.

Table 2 illustrates that there is a large variation in the activity rates of active structures both within the Hawke's Bay Region, and beyond its boundaries. The highest activity rates are on faults in the active volcano-tectonic zone of the Taupo region, and on faults of the North Island shear belt that extends through the western part of the Hawke's Bay region, southwestward into the Wairarapa. Because the Taupo zone is outside the HBRC boundary, the activity on the many faults there is represented as a single source with a shorter recurrence interval. In terms of earthquake hazard this approximation will influence the western part of the HBRC region in the same way that many individual faults would. This has been done as a convenience to compilation of the input hazard model. The net recurrence time of a maximum magnitude event of M_W 6.5 to 6.7 in this zone is assessed at 100 years. The rate of activity and size of earthquake are based on the assessment for the northeast end of the Taupo zone (Berryman & Beanland, 1989).

4.3 Subduction Zone

The subduction zone provides the third principal component of our model of earthquake occurrence along the east coast of the North Island, together with the major fault sources and the distributed lower magnitude seismicity. This feature occurs where the Pacific plate is forced beneath the overlying Australian plate. Around the margin of the Pacific plate there are many large earthquakes related to the rupture of the large fault that constitutes the interface between the two plates. The largest known earthquake, the M_W 9.4 Chile earthquake of 1960, occurred on the subduction zone between the Pacific plate and the overlying South American plate. However, not all subduction zones around the Pacific margin produce earthquakes this large, and in some settings the two plates currently appear to be moving past each other in a

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There are few data from New Zealand earthquakes to determine whether the plate interface is locked and storing energy to be released in a major earthquake, or is generally slipping with only minor coupling and moderate to small magnitude earthquakes. The 1966 Gisborne earthquake (M_L 6.2), and the Weber earthquake of May 1990 (M_L 6.2) occurred on or very close to the plate interface (Webb *et al.*, 1985; Smith, 1990). Therefore, it is reasonable to presume at least a part of the ca. 45 mm/yr average relative plate movement will be released by major subduction earthquakes.

For this study a variety of scenarios were considered to address the question of the size and recurrence of subduction zone earthquakes. Critical components of the scenarios are: (i) relative plate motion in the region and how it is accommodated at the plate boundary; (ii) the proportion of the relative plate motion that is accomplished by seismic release of accumulated strain versus stable sliding without major earthquakes; (iii) the likely length, width and displacement that might occur in typical maximum magnitude subduction events; and (iv) the recurrence interval for the maximum magnitude earthquake. A consensus approach was used to determine appropriate input parameters. Weightings that were assigned to possible options of each of these parameters resulted in a probability distribution for each of the critical parameters for the earthquake hazard model. From these probability distributions "best estimate" and conservative values that may be likened to the mean plus standard deviation level were selected.

Key parameters and their weightings are as follows:

(i) Relative plate motion of about 45 mm/yr can be partitioned into contractional and translational components. The translational component is largely accounted for by upper plate faulting and rotation. The contractional component is about 29 mm/yr.

(ii) The literature on seismic coupling efficiency was reviewed (including Begg *et al.*, 1995) and for the Hawke's Bay sector of the Hikurangi margin a 30 % coupling efficiency was assigned a 0.7 weighting and a 50% coupling efficiency was assigned a 0.3 weighting. Thus, of the 29 mm/yr contraction at the plate margin the model expects that 10-15 mm/yr will be accommodated as slip during earthquakes.

(iii) The Hikurangi subduction margin is likely to be broken into relatively small blocks because of the rapid variation along the length of the margin from the pinned, no-slip situation at Kaikoura to relatively rapid plate slip at East Cape. Thus, very long ruptures of the plate interface such as occurred in Chile in 1960 and Alaska in 1964 are judged to be unlikely. Taking these views into account and noting the length of fault rupture or aftershock zone of major earthquakes in the upper plate, such as the 1855 Wairarapa and the 1931 Hawke's Bay earthquakes (both about 100-120 km long), which may be "seeing" the dimensions of the broken-up Pacific plate, provides some basis for assigning a subduction length value of 120 km. In seeking to evaluate another, somewhat more conservative scenario (ie. producing a larger earthquake and larger ground motions) a model with subduction rupture length of 200 km was also promulgated. These options, 120 km and 200 km, were weighted 0.8 and 0.2 respectively.

The down-dip width of the subduction zone has been evaluated from two viewpoints. Both the geological evidence of where contractional deformation is occurring in the upper plate, and seismological evidence of where the concentration of seismicity occurs within the lower plate may be interpreted as the region in which the interface is strongly coupled. These dimensions, either 65 km or 100 km wide respectively, were weighted equally at 0.5.

Figure 6 indicates the dimensions and the depth to the subduction interface that has been modelled for this study. The depths and position of the subduction fault has been compiled from earthquake studies by Reyners (1983; 1989), Ansell and Bannister (1996), and Begg *et al.* (1995).

The amount of average slip occurring on the interface in these postulated subduction events was assessed from seismological considerations and from modelling of average slip over the fault area for major reverse faulting events in the upper plate. Seismological data indicates a relationship between the rupture area and slip (Kanamori & Anderson, 1975), which in the Hawke's Bay case suggests about 5 m of slip per event. This has been weighted at 0.5. Forward dislocation modelling of the 1855 Wairarapa earthquake (Darby and Beanland, 1992), and the 1931 Hawke's Bay earthquake (Haines and Darby, 1987) suggest an average of 9 m and 13 m slip on the fault surface. These events were within the upper plate, so they are not direct analogies for interface events, but provide a basis for evaluating large slip per event possibilities for inferred similar fault dimensions. The 9 m and 13 m options are each weighted at 0.25.

These values for fault area and average slip over the fault area allow the calculation of the moment magnitude from the equation of Hanks and Kanamori (1979) for the postulated plate interface events. They range from M_W 7.9 with a 0.12 weighting to M_W 8.5 with a 0.06 weighting. The maximum likelihood value is M_W 8.1 with a weighting of about 0.3, while the

84th percentile is less than about M_W 8.3. A best estimate value of M_W 8.1, and an upper bound estimate (approximately mean plus σ) of M_W 8.3, are therefore accepted for this study.

(iv) The possible range and weighting of average recurrence intervals of the subduction earthquake were assessed from estimates of seismic coupling efficiency, the proportion of the rate of contractional plate motion in the margin that is taken up on upper plate structures, and the amount of slip per event. In the discussion above, the seismic efficiency was assessed at 30 or 50 percent, upper plate deformation may account for 6 or 9 mm/yr of the 9.7-14.5 mm/yr seismically released relative plate motion, and single event displacement on the interface was assessed at 5 m, 9 m, or 13 m. Combining these values with appropriate weightings indicates a range of recurrence interval from as short as about 600 years with a 0.08 weighting to as long as 18,500 years, also with a weighting of 0.08. The probability distribution is severely skewed with some likelihood that very long recurrence intervals may be possible. The best estimate value for the recurrence of an M_W 8.1 event is 2500 years, which correspond to the 50 percentile of the distribution. An upper bound hazard estimate for an M_W 8.3 earthquake with an average recurrence interval of 1000 years (approximately mean plus σ) has been estimated as the 16 percentile of the distribution.

5.0 ATTENUATION OF EARTHQUAKE SHAKING WITH DISTANCE

In this study, ground motions were calculated for Modified Mercalli (MM) intensity (see Appendix 1 for a description of the scale), and for Peak Ground Acceleration (PGA). The expression of attenuation of MM Intensity developed by Dowrick (1991) from New Zealand data for normal and strike-slip earthquakes, and the expression of PGA attenuation of McVerry et al (1993, 1995), also from New Zealand data, but compared with several overseas studies, have been used (equations 1 and 2 below, respectively). For the subduction zone beneath the region, an attenuation expression developed by Crouse (1991) specifically for subduction source zones was used in some of the hazard models (equation 3 below). The equations take the following forms :

$$I = 2.18 + 1.411\,M_S - 0.00439\,r - 2.709\,\log_{10} r \qquad \sigma_I = 1.0 \qquad (1)$$

$$\log_{10} PGA\,(g) = 0.309M_W - 0.00297\,r - 0.618\log_{10} r - 1.810 \qquad \sigma = 0.252 \qquad (2)$$

$$\ln PGA\,(\text{gals}) = 6.36 + 1.76M_W - 2.73\,\ln(r + 1.58\,e^{0.608M}) + 0.00916\,h \qquad \sigma = 0.773 \qquad (3)$$

where I is the MM intensity, M_S is surface wave magnitude, M_W is moment magnitude, r is the distance (in km) from the site to the rupture surface at the presumed centre of energy release (the centroid depth) at depth h (in km). For the subduction interface, the seismogenic part of the interface is inferred to extend from 8-22 km depth, with a centroid depth of 14 km. The centroid depth for upper plate fault sources and the distributed seismicity in the upper plate has been set at 5 km, inferring rupture of at least the upper 10 km of the brittle crust in a surface-rupture event. The standard deviation for each of the attenuation expressions is shown with the equations.

The standard deviation of equation (2) has been reduced for the preferred hazard model, as indicated in the Tables summarising results. Some recent studies (e.g. Idriss, 1985, 1991; Sadigh et al., 1986; Youngs et al., 1990, 1995; Campbell & Bozorgnia, 1993) have shown that the standard deviations of PGA attenuation models becomes less with increasing magnitude. The New Zealand study contained few data from large earthquakes, and assumed a constant standard deviation for all magnitudes. The value of 0.252 of equation (2) lies toward the small magnitude (high standard deviation)) end of the range of the relations noted above. For the longer return periods (475 and 5000 years) of this study, the contribution to the hazard is dominated by large magnitude earthquakes on the major fault sources, so it is appropriate to use standard deviations more relevant to large magnitudes. The value of 0.252 has been reduced to 0.150 (ln variability of 0.35) in preferred models of the hazard. This is the value specified for magnitudes larger than 7.0 by Idriss (1985), and is close to the value of 0.38 for the ln variability given by Youngs et al. (1990), and adopted in several other recent studies. The reduced variability leads to lower PGA estimates at long return periods, although it can increase the ground motion estimates for short return periods.

Dowrick (1991) did not report a standard deviation for his MM intensity attenuation expression. However, there is an approximately linear relationship between mean value intensities and PGA's estimated from the attenuation expression for various combinations of magnitude and distance. The increase in PGA associated with one standard deviation of the PGA attenuation expression suggests that the corresponding standard deviation of the MM intensity attenuation expression should be slightly greater than 1.0. A value of $\sigma_I = 1.0$ has been used in this study.

6.0 RESULTS

Hazard results were calculated for a variety of input seismological and geological parameters, as well as for several sensitivity tests on attenuation expressions, for two measures of ground motion (MM intensity and PGA), for three return periods (142, 475, and 5000 years).

6.1 Operating Basis Event Hazard

The 142 year return period (10% probability of exceedance in 15 years) hazard is presented because this return period is commonly used as the appropriate hazard level for an Operating Basis Event (OBE) where minor damage could be expected in such an event, but not to the extent that life safety, functionality of a structure, or service are impaired.

The preferred model for the 142 year hazard uses historical seismicity represented by a Gutenberg and Richter recurrence relation (Table 1), mean fault activity data, a 2500 year recurrence interval for a M 8.1 earthquake accompanying rupture of the subduction zone, and the attenuation expressions for MM Intensity or PGA as input data. Average ground conditions are assumed everywhere. The results are illustrated in Tables 3 & 4. MM intensities of 7.4-8.1[1] are predicted (using the mean value attenuation expression) for towns and cities in the region (Model 1 of Table 2). Taking into account the standard deviation of the MM intensity attenuation relationship results in preferred estimates of MM intensity of MM 8.5-8.9 (Model 2 of Table 3). Comparison of Models 1 and 3 show little difference indicating that active fault location is of little significance in the hazard at short return period, and the hazard is derived almost exclusively from the more frequent occurrence of small and moderate magnitude earthquakes. Mean predicted values in Napier and Hastings in this study are very similar to those derived by Smith and Berryman (1986) - (comparison of Models 3 & 4), but are a little higher than for their 1992 assessment - (Model 5 of Table 2). A plot of the preferred Model 2 is presented in Figure 7.

PGA has been calculated for both the mean value attenuation expression, and in a fully probabilistic manner using distributions with the standard deviations, i.e. incorporating variability. PGA estimates incorporating variability (Table 4 and Figure 8) range from about

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[1] Decimalised MMI values from computations are presented, but they should not be regarded as having precision of this order. They have been presented in this form to allow the computational path to be audited, and to indicate whether the computed MMI values are more appropriately rounded up or rounded down to whole-number intensities so as to forecast future earthquake effects.

0.26g to 0.40g across the region with a tendency for lower values in eastern coastal areas at the north and south of the region. Values of about 0.3 g are predicted for Napier and Hastings (for average ground conditions), and higher values occur to the west where there are several closely spaced strands of the strike-slip fault belt, and the rate of distributed seismicity is higher than in areas to the east. Te Pohue, located between the Mohaka fault and Patoka-Rangiora fault, appears to be the locality with the highest hazard within the HBRC region.

6.2 Design Level Event Hazard

The 475 year return period (10% probability of exceedance in 50 years) hazard is presented because this return period is commonly used as the appropriate hazard level for a Design Level Event (DLE), and coincides with the hazard level of the New Zealand Loadings Code (NZS4203:1992) for earthquake resistant design of risk factor R=1 structures. The preferred hazard model for 475 years return period uses the same input data as for the 142 year model.

MM Intensities in the range 7.9 to 9.1 are predicted for Model 1 (Table 3), which uses the mean value attenuation expression and MM 9.1-9.7 for the preferred estimate of hazard that incorporates variability in the attenuation relationship (Model 2 - Table 3, and Figure 9). There is less variation in the ground motion estimates of Model 3 (historical seismicity alone) which smoothes the hazard evenly across each of the source regions. MM intensities about one unit lower are predicted in Model 3 at Te Pohue which is close to active faults, than in Model 1. The hazard estimates for Model 3 (our preferred estimates are much higher) are lower than the Smith and Berryman (1986 & 1992) result for Napier and Hastings, but our preferred estimate is only slightly higher than their 1986 estimate (Table 3).

Estimates of PGA for the 475 year return period, incorporating variability (the preferred estimate of hazard) in the attenuation expression, using a standard deviation thought to be relevant to larger magnitude earthquakes, range from 0.36 g to 0.63 g for towns and cities in the HBRC region (Table 4 & Figure 10). Predicted ground motions for the major population centres are about 0.5 g, with a large region above 0.6 g about 40 km west of Napier where the strike-slip fault zone extends through the region (Figure 10). In the offshore area, and Mahia Peninsula, the predicted ground motions are above 0.5 g as a consequence of major offshore faults, and the shallow depth of the subduction interface beneath this part of the region. In general, the hazard posed by the subduction interface does not dominate any of the estimates of hazard, because although the maximum magnitude of the earthquake from this source is larger than other fault sources, the recurrence interval is generally longer, and the depth is greater than the distance from population centres to active faults in the upper plate.

Table 3 MM Intensities calculated for cities and towns of the Hawke's Bay region from earthquake hazard modelling

Hazard Model	1	2	3	4	5	1	2	3	4	5	1	2
Return Period (yrs)	142	**142**	142	150	150	475	**475**	475	500	500	5000	**5000**
Location												
Napier	7.7	**8.8**	8.0	8.1	7.7	8.2	**9.4**	8.3	9.1	8.7	9.8	**10.5**
Hastings	7.8	**8.8**	8.0	8.1	7.7	8.3	**9.4**	8.2	9.1	8.7	9.9	**10.7**
Havelock North	7.9	**8.8**	8.0			8.5	**9.4**	8.2			9.3	**10.5**
Wairoa	7.4	**8.5**	7.9			7.9	**9.1**	8.1			8.5	**10.0**
Nuhaka	7.5	**8.5**	7.8			8.0	**9.1**	8.1			8.6	**10.1**
Tutira	7.9	**8.8**	8.0			8.6	**9.4**	8.2			9.2	**10.6**
Te Pohue	8.1	**8.9**	8.0			9.1	**9.7**	8.2			9.8	**11.0**
Onga Onga	7.9	**8.7**	7.9			8.2	**9.4**	8.2			8.8	**10.4**
Waipawa	7.7	**8.7**	7.9			8.4	**9.4**	8.2			9.6	**10.6**
Waipukurau	7.7	**8.7**	7.8			8.5	**9.4**	8.1			9.6	**10.7**
Takapau	7.9	**8.7**	7.8			8.4	**9.4**	8.1			9.0	**10.4**
Porangahau	7.5	**8.5**	7.7			7.9	**9.1**	8.1			8.8	**10.0**

Notes:

Model 1; historical seismicity plus mean hazard estimates of active fault data above a presumed surface rupture threshold, and M_{max} of 8.1 on the subduction zone. Mean attenuation expression.

Model 2; same seismicity and fault data as model 1. Attenuation including variability. This is the preferred estimate of hazard.

Model 3; historical seismicity rates to maximum magnitudes (no fault sources). This model is comparative with Smith and Berryman (1986, 1992). Mean attenuation expression.

Model 4 are values from Smith & Berryman (1986). No variability in Smith (1978) attenuation expression.

Model 5 are values from Smith & Berryman (1992). No variability in Smith (1978) attenuation expression.

Table 4 Peak Ground Acceleration values calculated for cities and towns of the Hawke's Bay region from earthquake hazard modelling.

	Ground Motion (g)		
Location	142 yrs RP incl variability	475 yrs RP incl variability	5000 yrs RP incl variability
Napier	0.33	0.48	0.99
Hastings	0.34	0.52	1.06
Havelock North	0.35	0.53	0.99
Wairoa	0.26	0.36	0.68
Nuhaka	0.28	0.41	0.80
Tutira	0.33	0.52	0.91
Te Pohue	0.40	0.63	1.06
Onga Onga	0.35	0.50	0.80
Waipawa	0.33	0.49	0.95
Waipukurau	0.32	0.49	0.93
Takapau	0.35	0.52	0.84
Porangahau	0.26	0.37	0.71

Notes

(i) RP is return period

(ii) The model uses the McVerry et al., (1993) attenuation expression with ln variability of 0.35, for all source zones comprising historical seismicity plus mean hazard estimates of active fault data above a presumed surface rupture threshold, and M_{max} of 8.1 at 2500 year recurrence interval on the subduction interface.

An estimate of the 475 year PGA may be obtained from the NZS4203:1992 Loadings Standard for comparison with this study from the product $C_h(T=0s, \mu=1)Z$ for subsoil category (b). This product produces a value of 0.42 × 1.2 g = 0.50 g for anywhere in Hawke's Bay. The hazard calculations that formed the basis for the Loadings Code included the effects of variability, although using a standard deviation of 0.275 rather than the reduced value of 0.15 used here. The recommended 475 year PGA estimates of this study, with variability included, give very similar values to those of the code for the cities and larger towns of Hawke's Bay. This study predicts larger values for locations such as Te Pohue that are very close to major active faults. The code commentary recognises that "the motions in the vicinity of surface fault rupture could considerably exceed those provided for in this Standard" (NZS4203:1992 Commentary Clause C4.6.2).

6.3 Maximum Design Event Hazard

The hazard at the 5000 year return period is presented as it probably represents a worst-case scenario, similar to what is known as a Maximum Design Event (MDE), where substantial damage and loss of functionality for non-critical structures and services may be expected, but collapse and other life-threatening damage must be avoided. We recommend that in this level of event, critical structures and services, particularly in terms of threat to life, and to emergency response in a large earthquake, must remain operable. Thus, hospitals, ambulance and fire service facilities, police stations, school buildings used as emergency centres, basic communications, alternative electricity supply facilities, and containment structures for toxic substances should, in our opinion, be capable of withstanding the ground motions predicted for this return period.

The New Zealand Loadings Standard makes no mention of 5000 year return period motions. For ultimate limit state, the more severe of the two limit states addressed in the Standard which is "intended to protect life and to ensure that the structure will not collapse in a major earthquake" (NZS4203:1992, commentary clause C4.2.2), the assessed return period is 450 years. For Category 1 buildings, "buildings dedicated to the preservation of human life or for which the loss of function would have a severe impact on society" (NZS4203:1992, Table 2.3.1), the basic hazard coefficient is factored up by a value of 1.3. According to figure C4.6.1 in the Commentary to the Standard, a factor of 1.3 is equivalent to extending the 475 year return period to a little over 1000 years. Thus, the Loadings Standard does not directly address requirements for earthquake motions with return periods above about 1000 years, a likelihood of exceedance of 5% in 50 years or 10% in 100 years, no matter how critical the structure or facility may be. We suggest that consideration of the 5000 year return period ground motions is more appropriate for such structures and facilities for an anti-collapse limit state.

Fortunately, for at least some types of modern structures, this level of performance is likely to be achieved for 5000 year return period motions. Influential New Zealand researchers whose thinking has guided some of the materials codes recognise that an annual probability of exceedance of about 0.0002 (ie. 5000 year return period) is appropriate for the "survival limit state". This situation is one where "loss of life should be prevented during the strongest ground shaking feasible for the site" and is achieved by requiring that "collapse must not occur (Paulay & Priestley, 1992 p10 and p65). For a return period similar to that assigned to the ultimate limit state in the Loadings Standard, they consider a "damage control limit state" for which "it is expected that after an earthquake causes this or lesser intensity ground shaking, the building can be successfully repaired and reinstated to full service". Paulay & Priestley associate a nominal annual probability of exceedance of approximately 0.002 (ie. a return period of 500 years) with this limit state for office buildings and the like, with lower risk values for buildings such as hospitals. Paulay & Priestley adopt a design approach that is intended to ensure that the survival limit state criteria are met. Thus, designs that follow their philosophy and satisfy code level design should survive at the MDE (5000 year return period level), even though the Loadings Standard does not explicitly address 5000 year return period earthquake motions.

Estimates of MM Intensity and PGA for the 5000 year return period are shown in Tables 3 and 4. Felt intensity of MM 8.8-9.8 for the mean estimate of hazard (Model 1 of Table 3) or MM intensity 10-11 (Model 2 of Table 3, Figure 11) when variability is considered is predicted throughout the region. High values in Napier and Hastings occur as a consequence of expected rupture on nearby faults in this period (essentially a repeat of the 1931 Hawke's Bay earthquake), as well as a contribution from the subduction zone. At these long return times the hazard is higher in the big towns and cities of Hawke's Bay than localities like Te Pohue (the reverse of the 475 and shorter return period events), because although Te Pohue is located close to active faults, their maximum magnitude is smaller than the Napier fault or the subduction zone, which are expected to produce their maximum magnitude earthquake in any 5000 year interval.

Estimates of PGA follow the same trends as for MM intensity. Preferred estimates of ground motion incorporating variability in the attenuation relationship range from 0.68 g to 1.06 g for the cities and towns of the Hawke's Bay region, with values of about 1.0 g predicted for Napier, Hastings and Havelock North, and about 0.95 g for Waipawa and Waipukurau (Figure

12). These high estimates of ground motion infer that earthquake resistant design levels for critical structures, and services in the region need to be of the very highest standard.

Near source recordings in recent moderate to large magnitude earthquakes have repeatedly produced very strong accelerations, and offer support to the calculations made for Hawke's Bay. For example, in the magnitude M_W 6.7 Northridge earthquake of 1994, a contour map drawn using recorded accelerations indicates that an area of 150 km^2 experienced PGA exceeding 1.0 g, with 450 km^2 having accelerations in excess of 0.5 g. The Kobe 1995 earthquake of M_W 6.9, produced many records exceeding 0.5 g, up to a maximum of 0.85g. Many of the faults listed in Table 1 are expected to produce earthquakes with magnitudes greater than those of the Northridge and Kobe earthquakes, so their zones of strong shaking are likely to be comparable or even larger. For a return period of 5000 years, which equals or exceeds the estimated mean recurrence intervals of rupture estimated for 43 sources listed in Table 1, the areas of Hawke's Bay where active faults have been located can be expected to experience ground motions similar to those in the near-source zones of the Kobe or Northridge earthquakes.

7.0 SENSITIVITY OF HAZARD ESTIMATION TO VARIATION IN INPUT DATA

Testing the sensitivity of hazard estimates to variation in input data is an important component of this earthquake hazard study because only through this procedure can the reliability and robustness of the results be assessed. Sensitivity analysis also provides a procedure to identify which components of the hazard model require most refinement for improved hazard estimation.

The range of sensitivity testing for each of the components of the hazard model are listed below:

(i) Seismological data.

- hazard models with and without subduction earthquakes were assessed.
- hazard models with differing magnitude and recurrence intervals of subduction earthquakes were assessed.
- a hazard model for which the fault sources were removed and distributed seismicity was extended to maximum magnitude in source regions (Table 3) was evaluated.

(ii) Geological data.

- hazard models using mean recurrence interval and mean magnitude on fault sources, as well as maximum hazard derived from minimum recurrence interval and maximum magnitude were assessed.

(iii) Attenuation expressions.

- hazard models using the McVerry et al. (1993) PGA attenuation for all sources were assessed.
- hazard models using McVerry et al., PGA attenuation for upper plate sources, Crouse (1991) PGA attenuation for the subduction zone, and McVerry et al. for lower plate sources were assessed.
- hazard models were also developed using Idriss (1985, 1987) attenuation expressions to assess the sensitivity of the PGA estimates to different attenuation expressions, and using epicentral and hypocentral distance measures in the attenuation expression.

- the effects of using a magnitude-dependent standard deviation of the attenuation relationship was investigated for the McVerry et al. attenuation relationship.
- the sensitivity of hazard results to near field ground motions was investigated by truncating PGA estimates at distances of less than 10 km from source.

Some of these variations are illustrated in terms of MM intensity in Figure 13.

7.1 Seismological Data

This study has characterised the rate of seismicity within the Pacific plate as it is subducted to depths of 100 km beneath the Hawke's Bay region (Figure 3). However, examination of MM intensity attenuation with depth indicates that for earthquakes that originate at 40 km depth only earthquakes of $M \geq 7$ will result in MM 8 intensity at the surface. Only the very largest earthquakes ($M \geq 8.5$) at 100 km depth will result in MM 8 intensities at the ground surface. This study predicts that shallow earthquake sources produce MM 8 or greater across the whole of the Hawke's Bay region in a 150 year return period, so deep earthquake sources do not add significantly to the hazard.

In Section 3.3 there is substantial discussion of the procedure for evaluating the hazard posed by major earthquakes on the subduction interface. The best estimate is that the Hawke's Bay region is underlain by two sectors of the subduction zone, each capable of producing a M_W 8.1 earthquake at an average recurrence interval of 2500 years. A more hazardous possibility evaluated as something akin to the 84th percentile is for a single larger sector of the subduction zone capable of producing a M_W 8.3 earthquake with an average 1000 year recurrence interval.

These earthquakes have also been evaluated using two ground motion attenuation relationships - Crouse (1991) and McVerry et al. (1993). The findings are that, at return periods as short as 1000 years, rupture of the subduction interface is not a major contributor to the hazard in onshore parts of the HBRC region. However, it must be stressed that the evaluation of the earthquake potential of the plate interface is imprecise because of the paucity of appropriate data. If the subduction interface were in fact capable of producing a major earthquake with an average recurrence interval of just a few hundred years, then it would be the major contributor to the hazard at short return periods, and the ground motion values presented here would be significantly too low.

A high priority for future research efforts will be to obtain data to better define the earthquake hazard associated with subduction.

As discussed in Section 3.1 of this report, the location, and perhaps magnitude, of many of the large historical earthquakes is uncertain, especially those that occurred in the last century, and also those in the period prior to a significant upgrade of the seismograph network in 1940. However, for the preferred hazard models presented in this study, the recurrence interval and location of major earthquakes have been estimated from the active fault data, and thus the uncertainty in location of the 1863 Waipawa and 1934 Pahiatua earthquakes, for example, should not have significantly affected the hazard estimation.

It remains critical however to study in more detail the major earthquakes that have occurred in the historical period. Investigating the amount of damage for particular ground conditions in major earthquakes, and relating surface fault rupture parameters with particular earthquakes provide key information to improve the estimation of earthquake hazard, and the likely effects of future major earthquakes.

7.2 Geological Data

Because of incomplete information on the pre-historical rupture history of the active faults, and the magnitude of earthquakes associated with these events, the estimation of large magnitude earthquake recurrence interval in this study has uncertainties. In Table 1, the range of, and mean, recurrence intervals for best estimate and upper bound maximum magnitude events on each of the active faults and folds was assigned. We consider the ranges to represent something similar to 95% confidence limits on the recurrence intervals. From these considerations, we have combined maximum magnitude and minimum recurrence interval data in some hazard models to investigate the possible variation in hazard in response to maximum likely variation in fault rupture and associated large earthquake parameters. Results from these models indicate that the use of maximum earthquake magnitude with minimum recurrence increases the hazard estimates by about 0.1g at the 5000 year return period, while producing estimates insignificantly larger for the 144 and 475 year return periods.

A hazard model compiled solely from shallow historical seismicity predicts mean estimates of MM intensity of 7.7-8.0 for the twelve cities and towns in the region for 142 year return periods, and MM intensity 8.1-8.3 for the 475 year return period. These values are similar for most sites to those predicted from models of the hazard which use the combination of distributed historical seismicity up to M 6.5, and fault sources for larger events. However, for the 475 year return period at sites in close proximity to faults (eg. Te Pohue), and consistently at the 5000 year return period, the model that includes fault sources (Model 1 of Table 3) gives MM intensities that are consistently one-half to a one unit above the models using distributed seismicity alone.

This sensitivity of the assessed hazard to proximity of major active faults is unsurprising given the assumption in the preferred hazard models that major earthquakes will occur on known active faults. The indication is that use of the active fault data consistently predicts at least equal, and often higher, hazard than the historical record of seismicity.

7.3 Attenuation Models

This study discusses earthquake hazard in terms of two measures of ground motion - MM intensity and PGA. The formulation of expressions of the MM intensity and PGA attenuation both involve scatter in the data used to establish the regressions, and quantified by standard deviation of the data about the mean regression expression. The variability expressed by the standard deviation is usually incorporated into probabilistic assessment of hazard, and is routinely done so for PGA. However this has not been the case for hazard calculations of MM intensity in New Zealand (eg. Smith, 1978; Smith & Berryman, 1986, 1992; Dowrick, 1991). This study does incorporate variability in the hazard assessment and the impact is illustrated in Table 3 and Figure 13. Hazard models that incorporate variability produce MM intensities about one unit higher for all return periods, and PGA's about 0.05g higher for the 142 year return period, 0.05-0.1g higher for the 475 year return period, and 0.1-0.2g higher for the 5000 year return period.

Measurement and attenuation of strong ground motion in close (<20 km) proximity to large magnitude earthquakes is poorly constrained, and thus there is uncertainty in the near-fault ground motions predicted for this and indeed all ground motion hazard studies. To assess the sensitivity of the hazard estimate to ground motion attenuation we have compared McVerry et al. (1993) with Idriss (1985, 1987), considering both epicentral and hypocentral distance measures. We favour the use of the McVerry et al relationship because it has been developed from New Zealand data. However, it is weakly constrained for large near-field events and predicts, for example, PGA of about 0.80g for a M 8.0 earthquake at 10 km. In contrast the Idriss (1985) relationship developed from western North America data predicts only 0.46g from the same event. This difference in attenuation results in higher estimates of PGA of about 0.05g for the 142 year return period at the twelve cities and towns listed in Table 4, about 0.1g for the 475 year return period, and 0.2-0.3g for the 5000 year return period.

Single attenuation expressions are also used to characterise a number of different source types, for example large shallow earthquakes on faults that have surface rupture, and moderate- and small-magnitude earthquakes that have no surface rupture, and possible earthquakes on a very shallow-dipping subduction zone. In attempting to characterise the reduction in ground motion with distance, no account is usually taken of whether a large component of the energy is released near surface, such as during a surface fault rupture event, or at greater depth. We have investigated the effect of source depth by comparing hazard estimates produced from the Idriss (1985) attenuation expression by taking the distance term in the expression combining the shortest horizontal source-to-site distance with the depth component, taken as either zero (perhaps appropriate for large earthquakes associated with surface fault rupture) or focal depth (perhaps appropriate for deeper earthquake sources). Naturally the model using only the horizontal component of distance always predicts higher ground motions - by about 0.05g for the 142 year return period, by 0.07-0.15g (higher for sites closer to fault sources) for the 500 year return period, and by 0.15-0.25 g (again higher for sites closer to fault sources) for the 5000 year return period. Thus, the depth assessment of the principal contributor to the hazard at a site, can produce a significant variation in hazard estimation, but not as large as the differences between some attenuation expressions.

Because of the uncertainty of near-field peak ground motions, a hazard model that truncates the maximum PGA estimated from the McVerry et al. (1993) mean value attenuation expression to 0.95g was also assessed. We found that the truncation in maximum PGA had very little effect (reduction of 0.04g for 5000 year return period) in towns such as Porangahau where there are no nearby fault sources, but resulted in a reduction of 0.1g for the 500 year return period and 0.14g for the 5000 year return period in Napier where nearby fault sources make a major contribution to the hazard.

7.4 Summary

Individually, uncertainty in each input parameter commonly introduces a sensitivity to the estimate of hazard of between one-half and one MM intensity unit, and commonly about 0.1g, but up to 0.4 g in extreme cases (Table 5). Hazard estimates are generally insensitive to reasonable variation in input parameters for the 144 year return period, but are increasingly sensitive at longer return periods. Variation in models of earthquake attenuation, particularly for near-field peak ground motion, in appropriate variability factors for attenuation of large magnitude earthquakes, and maximum magnitude estimates for some of the fault sources are the most likely factors to produce variation in hazard estimates. Now that the characteristics of the Poukawa-Napier fault system has been evaluated (Begg et al., 1995), the main uncertainty concerning major earthquake occurrence close to Napier and Hastings is the characterisation of the Maraetotara and Haumoana fault zones, and the subduction zone. These are areas of high priority study for earthquake hazard characterisation in the Hawke's Bay region.

Table 5 Summary of Input Parameter Sensitivity Testing

Parameter	MM Intensity 142RP	 475 RP	 5000 RP	PGA 144 RP	 475 RP	 5000 RP
Pacific plate seismicity*	little or no contribution to the hazard			little or no contribution to the hazard		
subduction earthquakes†	+ 0.5 unit	+ 0.1 to 0.5 unit	+ 0.3 to 1.0 unit	+ 0.02g	+ 0.03g	+ 0.06 to 0.10g
historical seismicity to M_{max}§	- 0.5 to 0.7 unit	- 0.2 to 0.8 unit	- 0.4 to 1.5 unit	NA	NA	NA
maximum fault hazardø	+ 0.4 to 0.8 unit	+ 0.6 to 0.8 unit	+ 0.7 to 1.0 unit	+ 0.02 g	+ 0.03 to 0.07g	+ 0.03 to 0.12g
attenuation variability‡	+ 0.5 to 0.9 unit	+ 0.7 to 1.0 unit	+ 0.5 to 1.3 unit	+ 0.05g	+ 0.07 to 0.12g	+ 0.09 to 0.33g
epicentral/hypocentral distance#	NA	NA	NA	+ 0.04 to 0.07g	+ 0.09 to 0.15g	+ 0.13 to 0.30g
Idriss attenuation£	NA	NA	NA	- 0.04 to 0.08g	- 0.04 to 0.12g	- 0.12 to 0.29g
truncation of max. PGA in attenuation∂	NA	NA	NA	- 0.02g	- 0.03 to 0.06g	- 0.04 to 0.16g

Notes

variations are compared with respect to the preferred model, positive values indicate variation above the preferred value or the contribution that parameter makes to the preferred model

RP Means return period in years.

NA Means not assessed

* Refers to seismicity in the historical catalogue inferred to be within the subducted Pacific plate.

† Subduction earthquakes are assessed to make this contribution over and above other sources.

§ This is the value for the distributed seismicity model compared with the preferred model in Table 3.

ø This is the model using maximum fault hazard parameters compared with the preferred model of Table 4.

‡ These values indicate the effect of incorporating variability in the attenuation expression in the hazard estimate. This factor is as important as any other single factor, and is recommended as the single step of conservatism in the hazard estimation process.

This has been assessed using horizontal and depth-included distance terms in the Idriss (1985) attenuation expression.

£ This compares the hazard estimate derived using the Idriss (1985) attenuation expression compared with the preferred model which uses the McVerry et al. (1993) attenuation expression.

∂ This illustrates the effect of truncating the largest mean PGA in the McVerry et al. (1993) attenuation relationship to 0.95g. The truncation affects earthquakes of M 8.0 and above at epicentral distances of 10 km and less.

Some progress has been made in understanding the sensitivity of the hazard to the input data, but the results are not fully quantitative. The indications are that there is an average uncertainty of about one half an MM intensity unit and 0.1 g for the 142 year return period, and up to one MM Intensity unit and generally 0.15-0.3 g for the 500 and 5000 year return period hazard when the uncertainty and sensitivity of input parameters are taken into account. Hazard estimates are more sensitive to variation in input parameters for sites in close proximity to fault sources.

We recommend the use of the results generated with the McVerry et al. (1993) attenuation expression because the maximum values from this expression match more closely some of the very high recorded ground motion in recent earthquakes in Japan and USA, better than equivalent values from the Idriss (1985) relationship, for example. For our best estimates we recommend the incorporation of variability in the hazard estimate as the single step in conservatism because it is applied uniformly across the region, and increases the hazard estimate by about the same amount as any of the other variables assessed above. The incorporation of variability in MM intensity hazard estimation is recommended, but with more caution. Although some progress has been made by Dowrick (1996) in assigning criteria to MM11 and MM12, there remains considerable uncertainty because there have not been many examples in New Zealand of earthquake damage to buildings that have specific earthquake resistant design.

8.0 LIMITATIONS OF THE STUDY

There are two main areas that present limitations to this study. These are:

8.1 Incomplete Data Sources.

Neither the historical catalogue of earthquakes, nor the geological data on the occurrence of major earthquakes in pre-historical times, is complete. This study has relied upon the historical rate of magnitude M 4 to M 6 earthquakes to define the distributed, background level of seismicity. In parts of the study area there have been many earthquakes, and the rate estimates are judged to be reasonable. However, in the offshore earthquake source zone there are fewer historical earthquakes, and the catalogue is likely to be deficient because of the difficulty of recording and locating events beyond the network.

There remains much to investigate about the location, magnitude and effects of many of the M≥7 earthquakes in the historical catalogue.

The geologically-derived database on pre-historical large earthquake occurrence is not complete, although, with the exception of the offshore area, the location of the main active faults and folds is generally well established in the region. The delineation of active faults in the offshore area is rudimentary and can only be regarded as a minimum estimate of the number of large earthquake sources. Recurrence intervals and maximum magnitudes of earthquake associated with fault rupture are not well established for any of the structures, and for some apparently quite active structures there are no data at all. Rate parameters and earthquake magnitudes for these structures have been assigned by comparison with other better-known structures. The hazard established from geologically-derived data will usually be a minimum dataset because of the possibility that surface fault scarps have been removed from the landscape by erosion, or human modification. Therefore the hazard computed in this study is probably a minimum estimate of the hazard, although, as the sensitivity assessment has shown, the hazard estimates are quite stable for modest changes in the geologically-derived earthquake rate parameters.

8.2 Variation in Ground Conditions

This study has predicted levels of MM Intensity and PGA hazard for average ground conditions. Because there are large variations in the ground conditions across the Hawke's Bay Region, the results of this study can only be used as a general indication for all except firm soil sites. Specific study of the extent and amplification (or reduction) factors of various ground types will be assessed in a further stage of the HBRC Earthquake Hazard Project and will be used to refine the results of this study.

9.0 CONCLUSIONS

This study is the most comprehensive assessment of earthquake hazards completed in the Hawke's Bay region, and is an advance on the estimation of hazard available from existing New Zealand-wide studies (eg. Smith and Berryman, 1986, 1992). This study is more comprehensive for the following reasons: (1) the region has been more finely divided into distinct source zones; (2) active fault data has been used in a quantitative way to supplement the short-term historical seismicity catalogue; and (3) the sensitivity of the hazard estimates to variation in parameters in the hazard computation has been assessed for the first time.

The results of this study indicate in the cities and towns of Hawke's Bay a MM intensity using the mean-value attenuation expression of 7.4-8.1 (MM intensity 8.5-8.9 including variability), and PGA (including variability) of 0.26-0.40 g across the region for the 142 year return period (10% probability of exceedance in 15 years) hazard. This time period is likened to a operating basis event, and at MM Intensity 8 damage to modern structures should be minimal, but serious damage could occur to older unreinforced masonry, poorly reinforced structures, and well constructed buildings on ground suffering cracking and collapse (see Appendix 1 for description of damage likely at various MM Intensity). Because of the high probability of occurrence of this level of shaking, all structures should be examined to make sure they perform well at this level of hazard.

The MM Intensity and PGA across the region for a 475 year return period (10% probability of exceedance in 50 years) is estimated to range from MM intensity 7.9-9.1 for the mean-value attenuation expression (MM intensity 9.1-9.7 including variability), and 0.36-0.63g (including variability). These hazard estimates represent a revision of the level of ground shaking corresponding to code return periods. The seismic coefficients of NZS4203:1992 code correspond approximately to a PGA of 0.5g throughout the Hawke's Bay region.

The MM Intensity and PGA in the cities and towns of the region for a 5000 year return period (10% probability of exceedance in 500 years) is estimated to range from MM Intensity 8.5-9.9 using the mean-value attenuation expression (MM intensity 10.0-11.0 including variability), and 0.71-1.06 g (including variability). These hazard estimates correspond to a maximum design event, and are particularly sensitive to the choice of attenuation expression in the ground motion calculation.

Because the hazard varies throughout the region, there is a variation in susceptibility to earthquake damage within the region for a given return period, but this depends also on the style, age, and maintenance of buildings, and facilities, and on variation in ground conditions.

10.0 RECOMMENDATIONS

It is recommended that all critical facilities including, schools, hospitals, major industrial plants, fire and ambulance stations, and gas, water and electricity distribution systems, be inspected and assessed as to their likely damage and serviceability at the 142, 475, and 5000 year return period levels of earthquake shaking.

Improvements to the hazard assessment in the major urban centres of Hawke's Bay will be achieved with more certain information about the seismogenic potential of the subduction zone beneath the region, and the zone of normal faults in the Te Awanga-Maraetotara-Elsthorpe area. Further studies of these zones are recommended.

This report documents the earthquake hazard within the HBRC region. The hazard will be refined when variations in ground conditions are taken into account. This study provides information on one component, the hazard, of the earthquake risk equation:

$$\text{Risk} = \text{Hazard} \times \text{Vulnerabilty}$$

When the vulnerability has been assessed, then the risk can be calculated. Effective strategies and policies for risk avoidance or reduction can only occur after complete formulation of the risk equation.

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APPENDIX 1 MODIFIED MERCALLI INTENSITY SCALE - NZ 1996

MM1 *People*

Not felt except by a very few people under exceptionally favourable circumstances..

MM2 *People*

Felt by persons at rest, on upper floors or favourably placed.

MM3 *People*

Felt indoors; hanging objects may swing, vibration similar to passing of light trucks, duration may be estimated, may not be recognised as an earthquake.

MM4 *People*

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

Fittings

Doors and windows rattle. Glassware and crockery rattle. Liquids in open vessels may be slightly disturbed. Standing motorcars may rock.

Structures

Walls and frame of buildings, and partitions and suspended ceilings in commercial buildings, may be heard to creak.

MM5 *People*

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

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).

MM6 *People*

Felt by all.

People and animals alarmed.

Many run outside.*

Difficult 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.

Very 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.

Windows Type I* broken.

Damage to a few weak domestic chimneys, some may fall.

Environment

Trees and bushes shake, or are heard to rustle.

Loose material may be dislodged from sloping ground, e.g. existing slides, talus slopes, shingle slides.

MM7 *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.

Substantial damage to fragile* contents of buildings.

Structures

Unreinforced stone and brick walls cracked.

Buildings Type I cracked some with minor masonry falls.

A few instances of damage to Buildings Type II.

Unbraced parapets, unbraced brick gables, and architectural ornaments fall.

Roofing tiles, especially ridge tiles may be dislodged.

Many unreinforced domestic chimneys damaged, often falling from roof-line.

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. Suspended ceilings damaged.

Environment

Water made turbid by stirred up mud.

Small slides such as falls of sand and gravel banks, and small rock-falls from steep slopes and cuttings.

Instances of settlement of unconsolidated or wet, or weak soils.

Some fine cracks appear in sloping ground. A few instances of liquefaction (ie small water and sand ejections).

MM8 *People*

Alarm may approach panic.

Steering of motorcars greatly affected.

Structures

Building Type I, heavily damaged, some collapse*.

Buildings Type II damaged, some with partial collapse*.

Buildings Type III damaged in some cases.

A few instances of damage to Structures Type IV.

Monuments and pre-1976 elevated tanks and factory stacks twisted or brought down.

Some pre-1965 infill masonry panels damaged.

A few post-1980 brick veneers damaged.

Decayed timber piles of houses damaged.

Houses not secured to foundations may move.

Most unreinforced domestic chimneys damaged, some below roof-line, many brought down.

Environment

Cracks appear on steep slopes and in wet ground.

Small to moderate slides in roadside cuttings and unsupported excavations.

Small water and sand ejections and localised lateral spreading adjacent to streams, canals, lakes, etc.

MM9 *Structures*

Many Buildings Type I destroyed*.

Buildings Type II heavily damaged, some collapse*.

Buildings Type III damaged, some with partial collapse*.

Structures Type IV damaged in some cases, some with flexible frames seriously damaged.

Damage or permanent distortion to some Structures Type V.

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 and more widespread, with large lateral spreading and flow sliding adjacent to streams, canals, lakes, etc.

MM10 *Structures*

Most Buildings Type I destroyed*.

Many Buildings Type II destroyed*.

Buildings Type III heavily damaged, some collapse*.

Structures Type IV damaged, some with partial collapse*.

Structures Type V moderately damaged, but few partial collapses.

A few instances of damage to Structures Type VI.

Some well-built* timber buildings moderately damaged (excluding damage from falling chimneys).

Environment

Landsliding very widespread in susceptible terrain, with very large rock masses displaced on steep slopes. Landslide dams may be formed.

Liquefaction effects widespread and severe.

MM11 *Structures*

Most Buildings Type II destroyed*.

Many Buildings Type III destroyed*.

Structures Type IV heavily damaged, some collapse*.

Structures Type V damaged, some with partial collapse.

Structures Type VI suffer minor damage, a few moderately damaged.

MM12 *Structures*

Most Buildings Type III destroyed.

Many Structures Type IV destroyed.

Structures Type V heavily damaged, some with partial collapse.

Structures Type VI moderately damaged.

(Items marked * in the scale are defined below).

Construction Types:

Buildings Type I (Masonry D in the NZ 1965 MM scale)

Buildings with low standard of workmanship, poor mortar, or constructed of weak materials like mud brick or rammed earth. Soft storey structures (e.g. shops) made of masonry, weak reinforced concrete, or composite materials (e.g. some walls timber, some brick) not well tied together. Masonry buildings otherwise conforming to Buildings Types I - III, but also having heavy unreinforced masonry towers. (Buildings constructed entirely of timber must be of extremely low quality to be Type I).

Buildings Type II (Masonry C in the NZ 1966 MM scale)

Buildings of ordinary workmanship, with mortar of average quality. No extreme weakness, such as inadequate bonding of the corners, but neither designed nor reinforced to resist lateral forces. Such buildings not having heavy unreinforced masonry towers.

Buildings Type III (Masonry B in the NZ 1966 MM scale)

Reinforced masonry or concrete buildings of good workmanship and with sound mortar, but not formally designed to resist earthquake forces.

Structures Type IV (Masonry A in the NZ 1966 MM scale)

Buildings and bridges designed and built to resist earthquakes to normal use standards, i.e. no special collapse or damage limiting measures taken (mid-1930's to c. 1970 for concrete and to c. 1980 for other materials).

Structures Type V

Buildings and bridges, designed and built to normal use standards, i.e. no special damage limiting measures taken, other than code requirements, dating from since c. 1970 for concrete and c. 1980 for other materials.

Structures Type VI

Structures, dating from c. 1980, with well-defined foundation behaviour, which have been specially designed for minimal damage, e.g. seismically isolated emergency facilities, some structures with dangerous or high contents, or new generation low damage structures.

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) More likely to be used for historical events.

Other Comments:

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

"Many run outside" (MM6) variable depending on mass behaviour, or conditioning by occurrence or absence of previous quakes, i.e. may occur at MM5 or not till MM7.

"Fragile Contents of Buildings". Fragile contents include weak, brittle, unstable, unrestrained objects in any kind of building.

"Well-built timber buildings" have: wall openings not too large; robust piles or reinforced concrete strip foundations; superstructure tied to foundations.

Δ Buildings Type III - V at MM10 and greater intensities are more likely to exhibit the damage levels indicated for low-rise buildings on firm or stiff ground and for high-rise buildings on soft ground. By inference lesser damage to low-rise buildings on soft ground and high-rise buildings on firm or stiff ground may indicate the same intensity. These effects are due to attenuation of short period vibrations and amplification of longer period vibrations in soft soils.

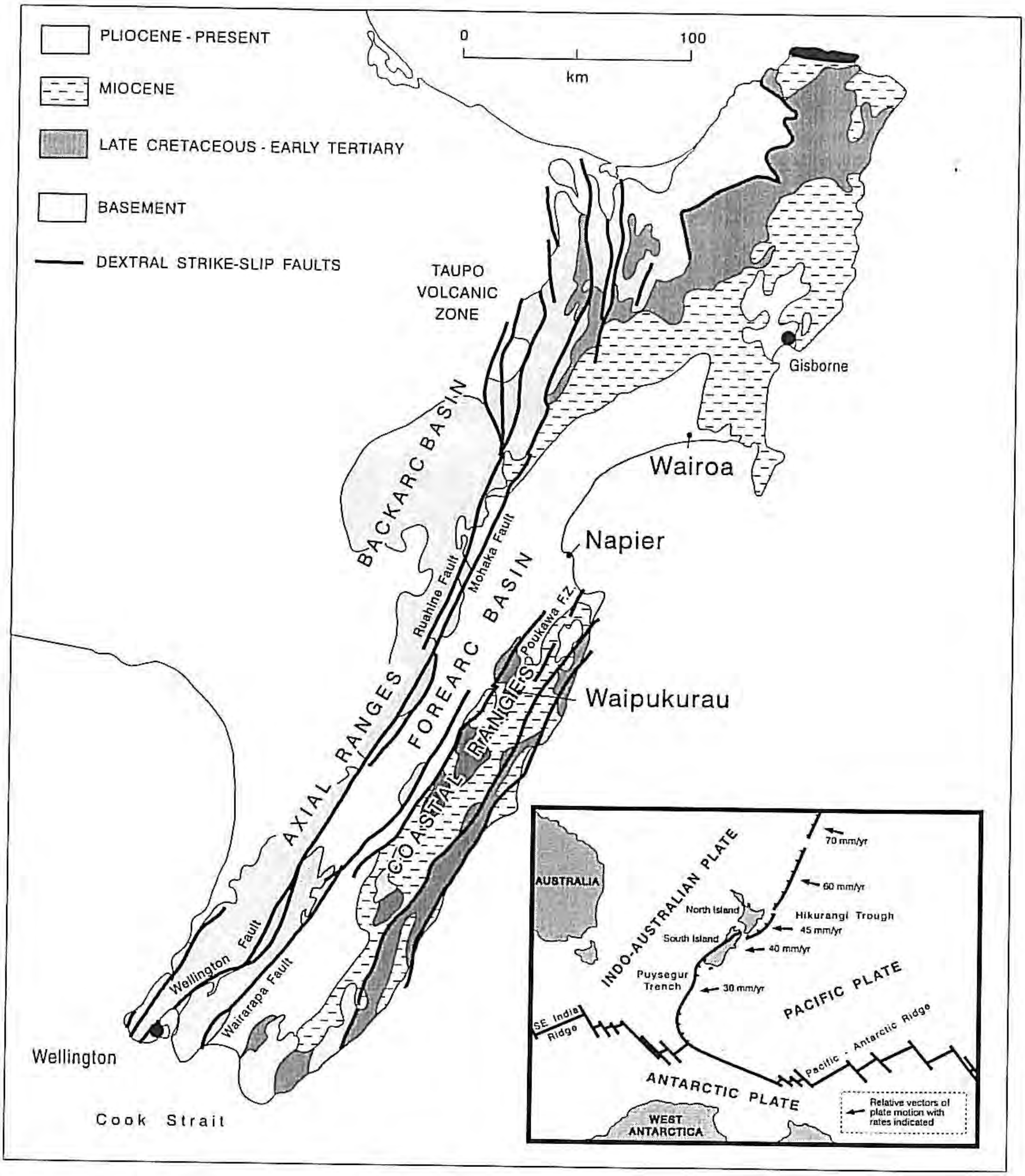


Figure 1. Generalised geology of eastern North Island showing major zones of active faulting. Inset shows plate tectonic setting with the rate and orientation of relative motion between the Pacific and Australian plates.

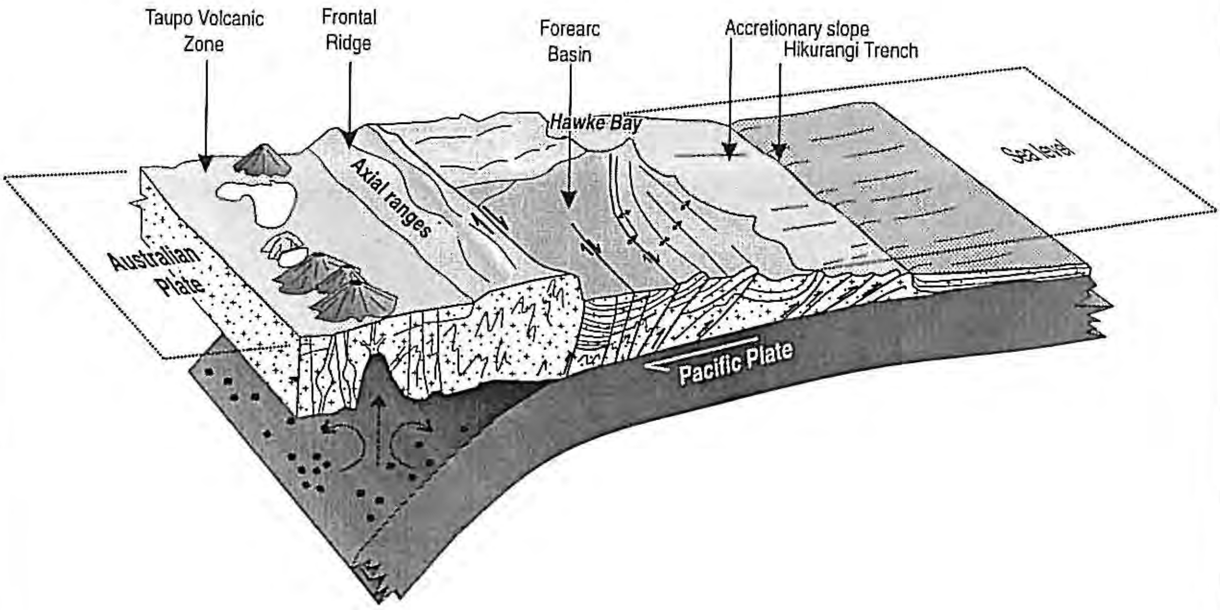


Figure 2. Perspective of the 3-dimensional structure and tectonics in the region of Hawke's Bay.

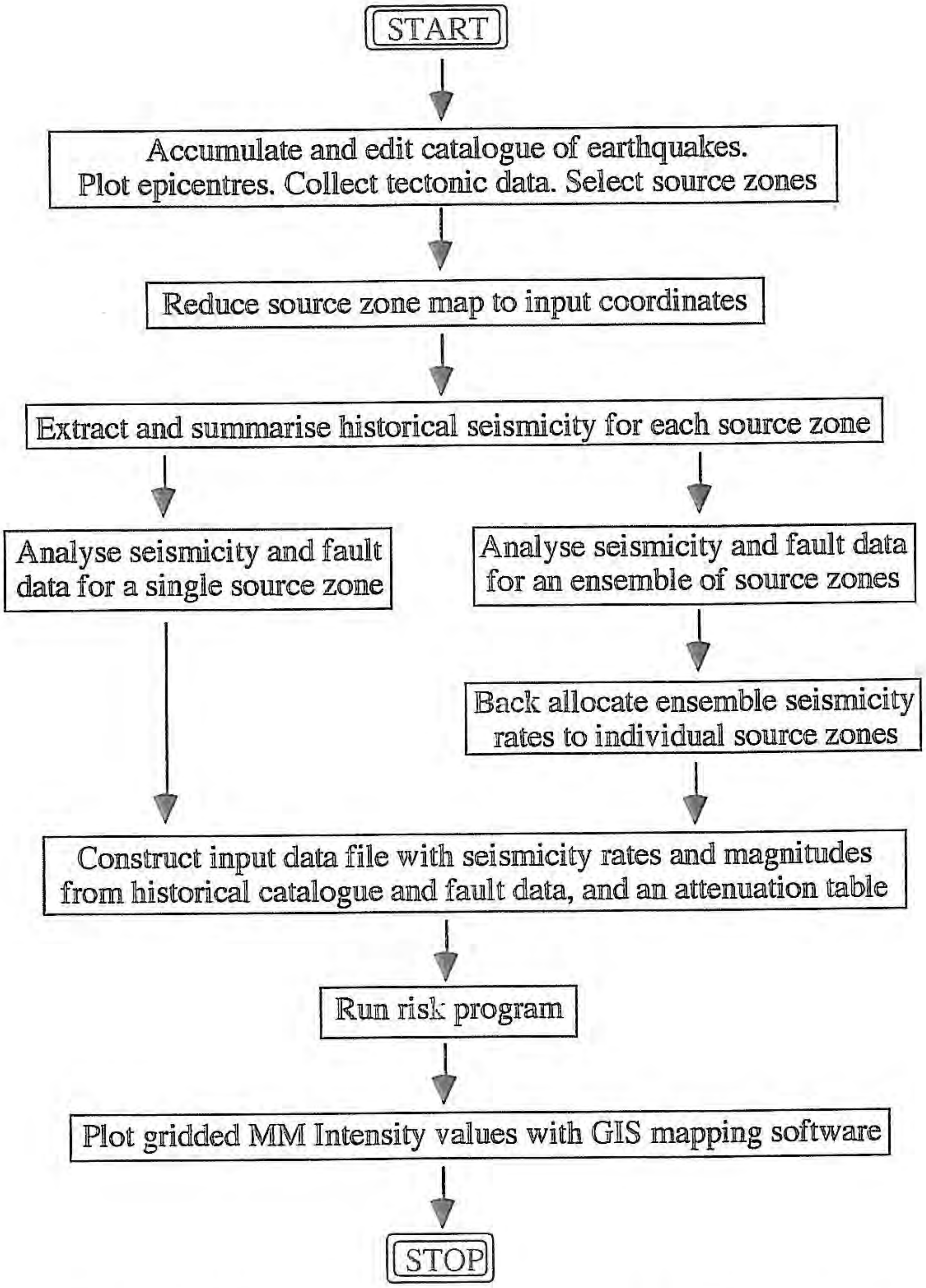


Figure 3. Flow-chart of the steps in editing data, compiling an input file, and running SEISRISK, the USGS earthquake hazard mapping program.

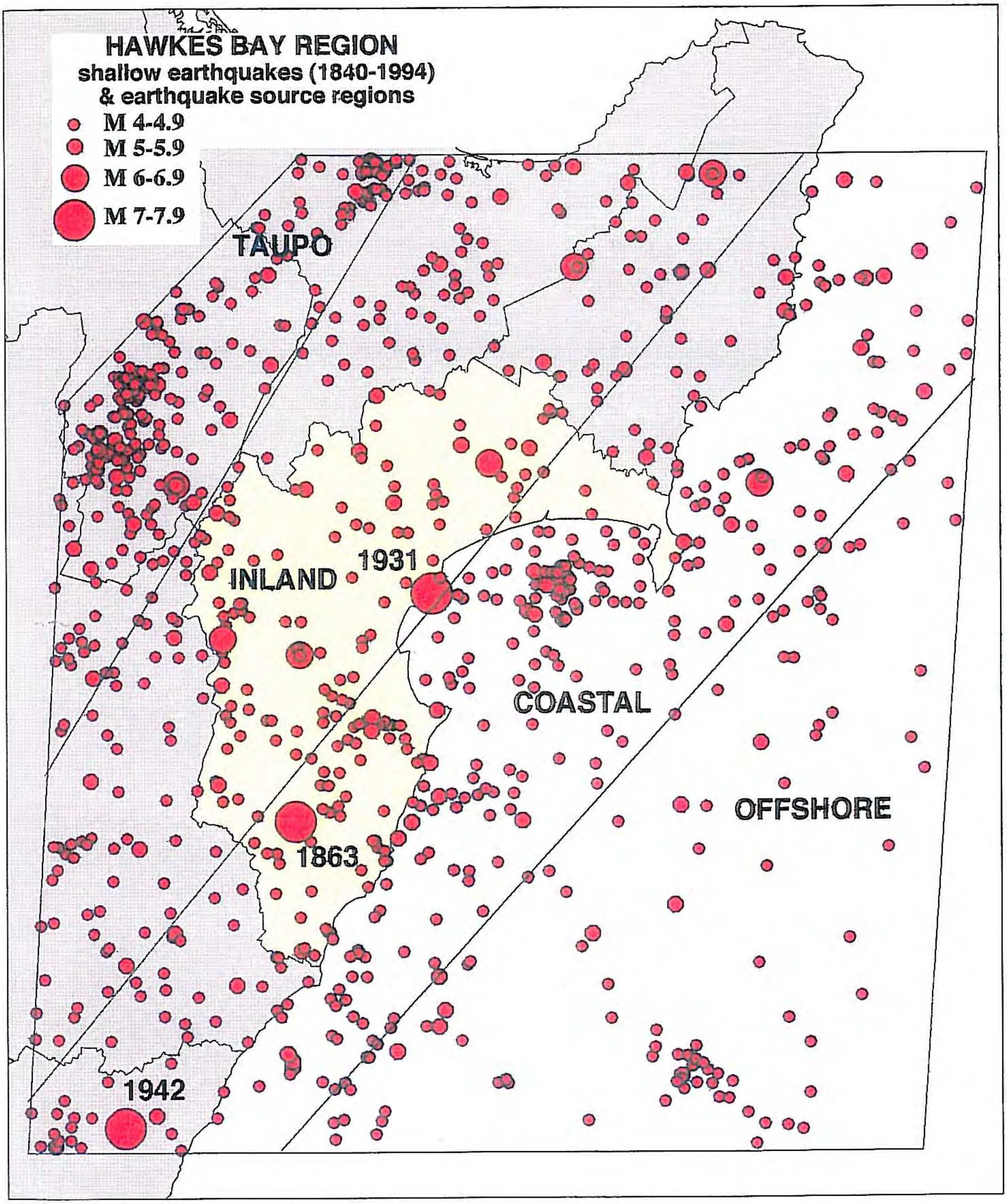


Figure 4. Seismicity plot of shallow earthquakes (with aftershocks removed) of the Ausralian plate from 1840-1994. Magnitude 7+ earthquakes are indicated by date. Earthquake source regions are labelled. Hawke's Bay region shown in yellow.

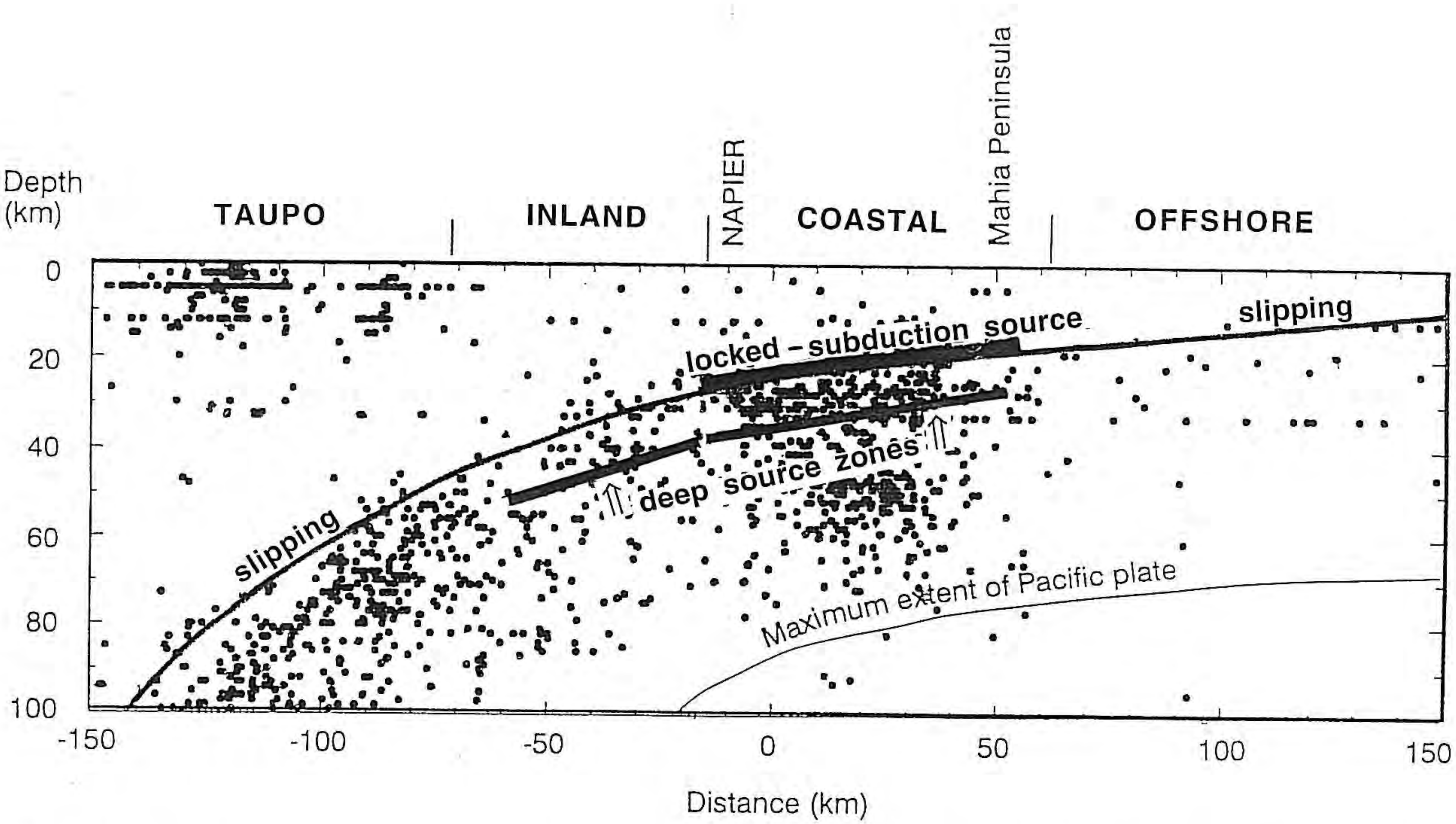


Figure 5. Earthquake hypocentres plotted on a NW-SE oriented section through Hawke's Bay from the Taupo area to offshore east of Napier. The dense pattern of earthquakes define the top of the Pacific plate. Also shown are the extent of upper plate source zones (Taupo, Inland, Coastal, Offshore), the extent of the inferred locked and therefore seismogenic part of the subduction interface, and the depth of planar earthquake source zones used in the hazard models to incorporate the deep (lower plate) seismicity. After Begg et al. (1995).

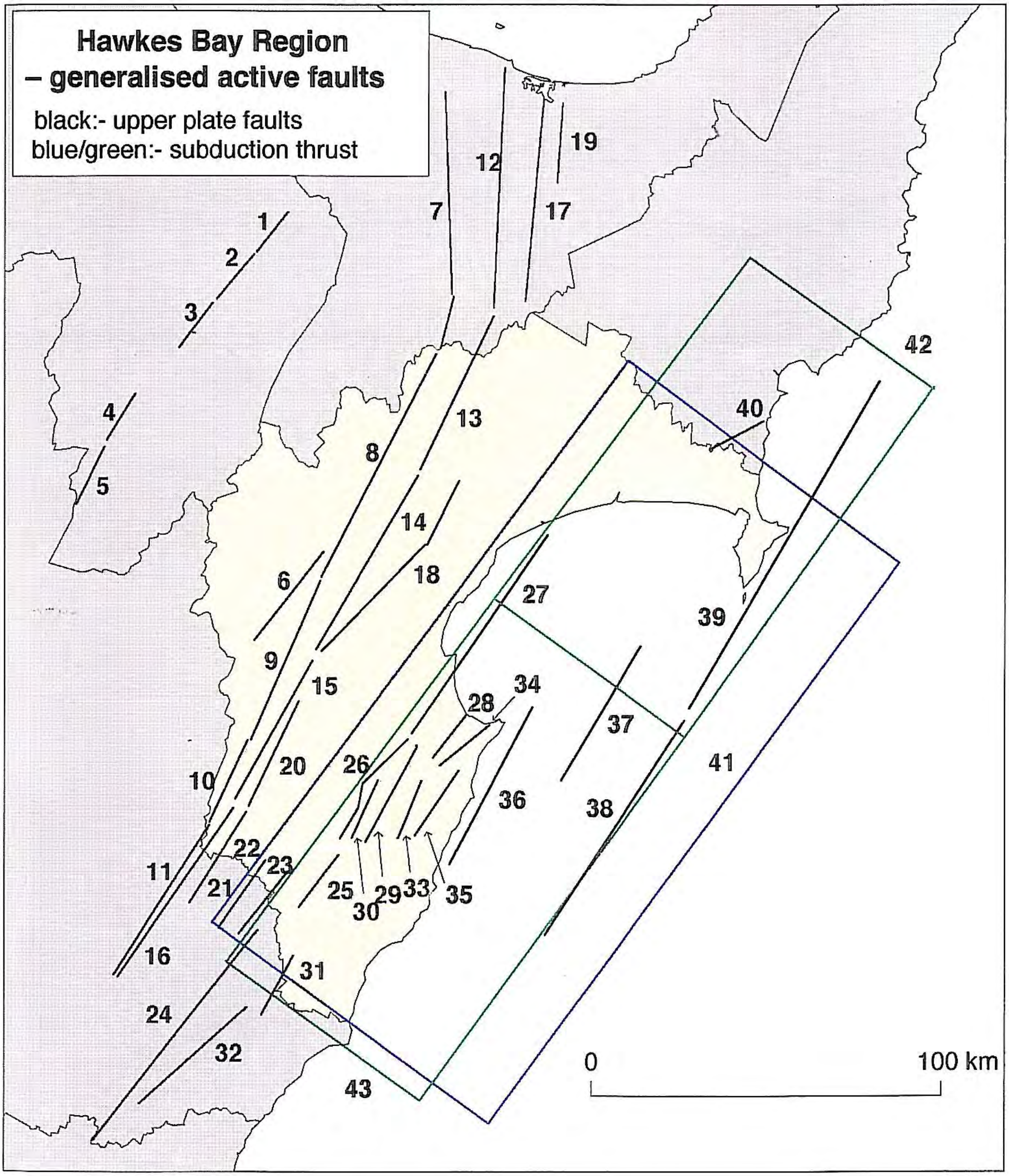


Figure 6. Generalised plot of active faults and fault segments incorporated into the hazard model. Numbers refer to faults and segments as listed in Table 2. Faults 41, 42, and 43 are area sources representing alternative subduction interface rupture scenarios. The smaller zones (areas 42 and 43) are for the preferred model of two regions producing M_W 8.1 earthquakes. The alternative larger fault (area 41) is for an M_W 8.3 earthquake.

FIGURE 7

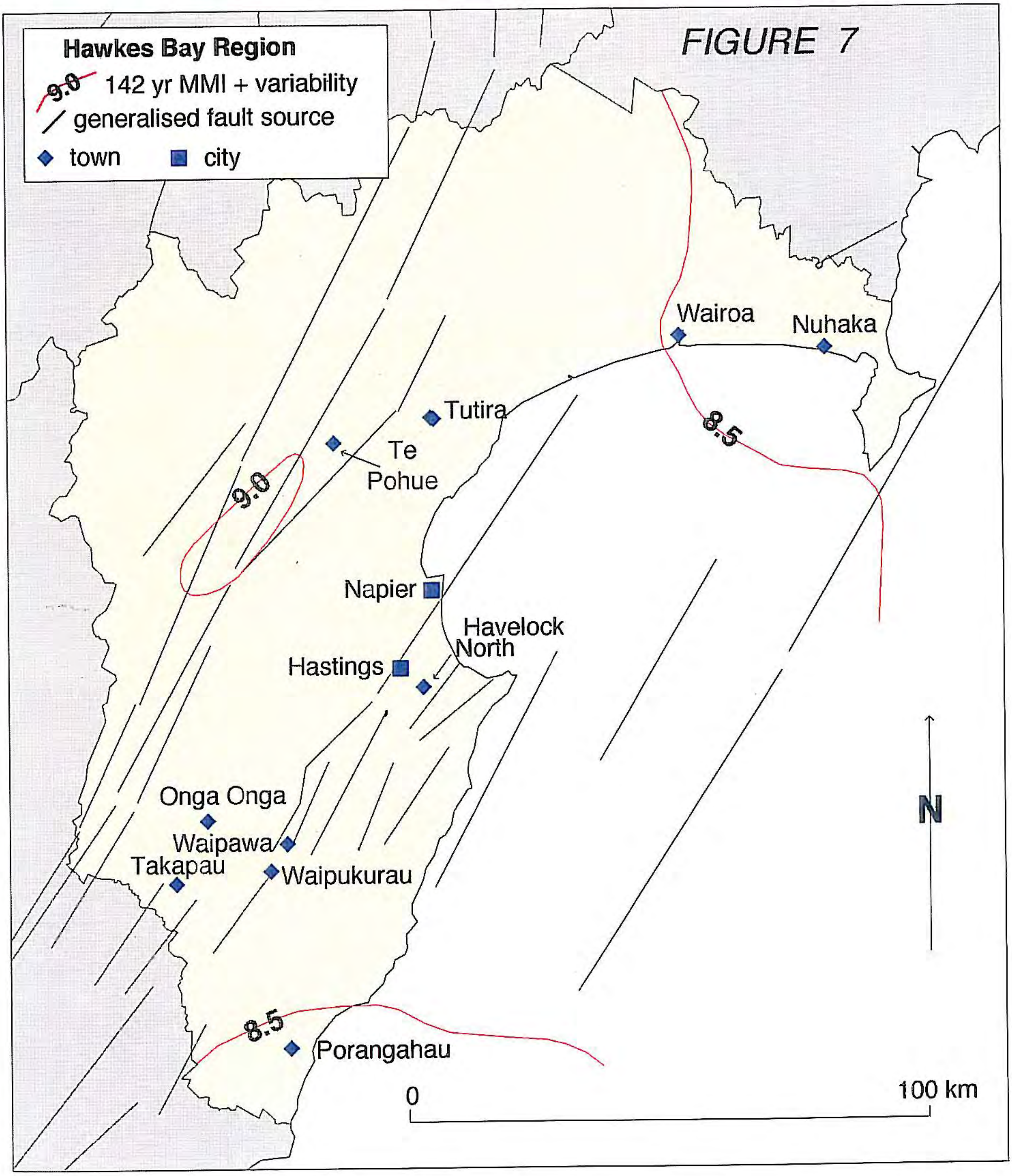

Hawkes Bay Region
9.0 142 yr MMI + variability
generalised fault source
town
city
Wairoa
Nuhaka
Tutira
Te Pohue
9.0
8.5
Napier
Havelock North
Hastings
Onga Onga
Waipawa
Takapau
Waipukurau
N
8.5
Porangahau
0
100 km

FIGURE 8

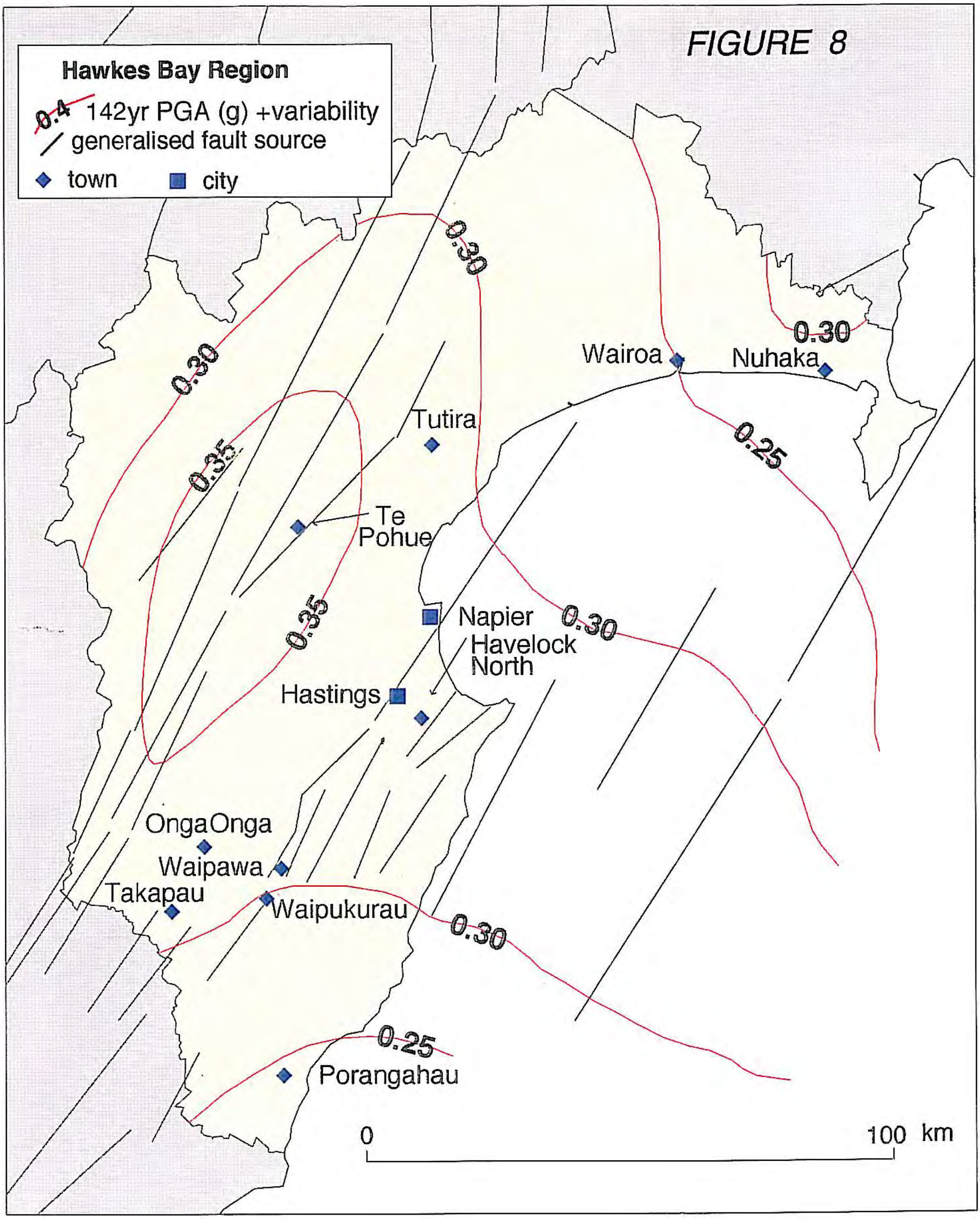
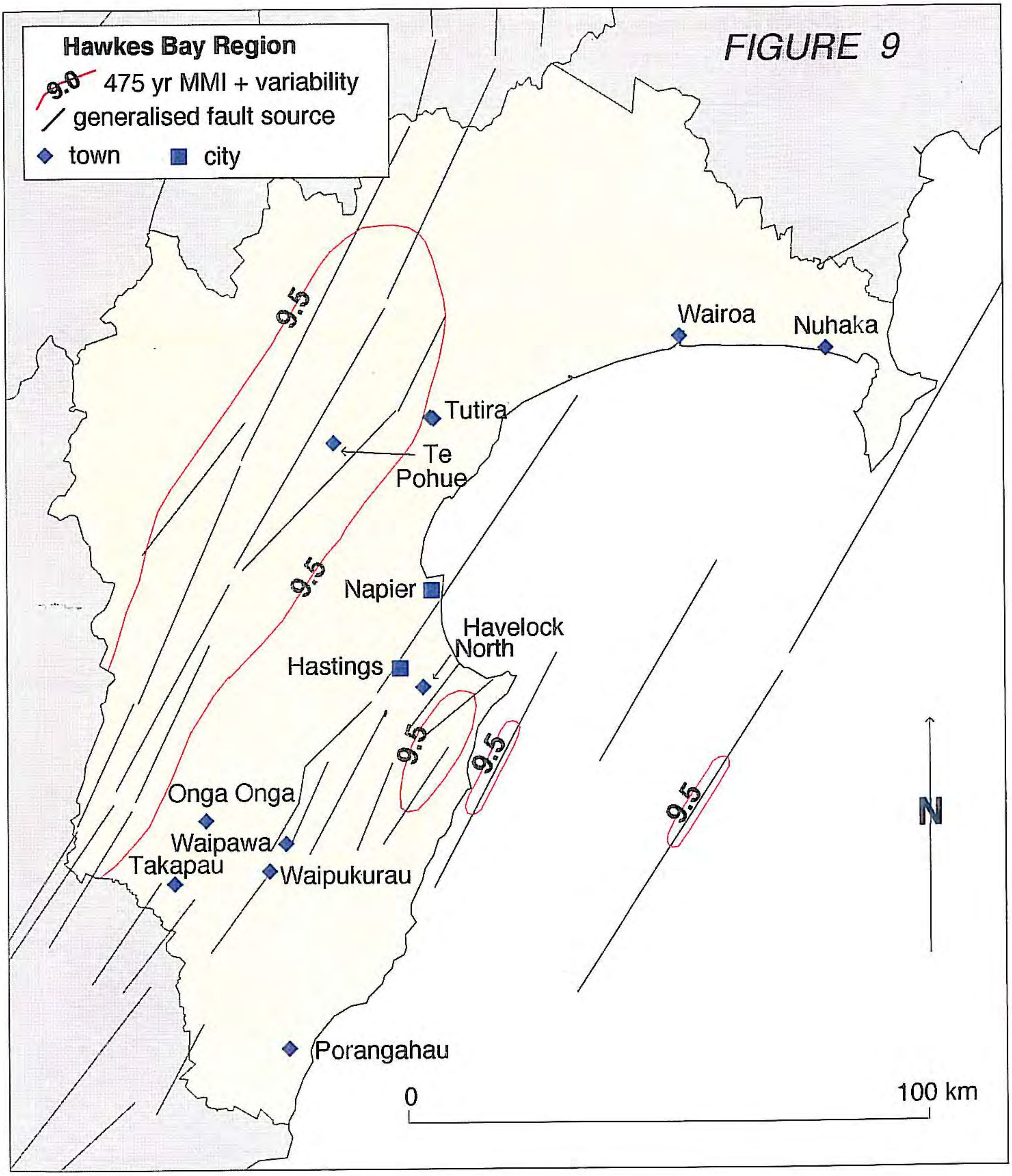

Hawkes Bay Region
0.4 142yr PGA (g) +variability
generalised fault source
town
city
0.30
0.30
0.35
0.35
0.30
0.25
0.30
0.30
0.25
Wairoa
Nuhaka
Tutira
Te Pohue
Napier
Havelock North
Hastings
OngaOnga
Waipawa
Takapau
Waipukurau
Porangahau
0
100 km

FIGURE 9


Hawkes Bay Region
9.0 475 yr MMI + variability
generalised fault source
town
city
9.5
9.5
9.5
9.5
9.5
Wairoa
Nuhaka
Tutira
Te Pohue
Napier
Havelock North
Hastings
Onga Onga
Waipawa
Takapau
Waipukurau
Porangahau
N
0
100 km

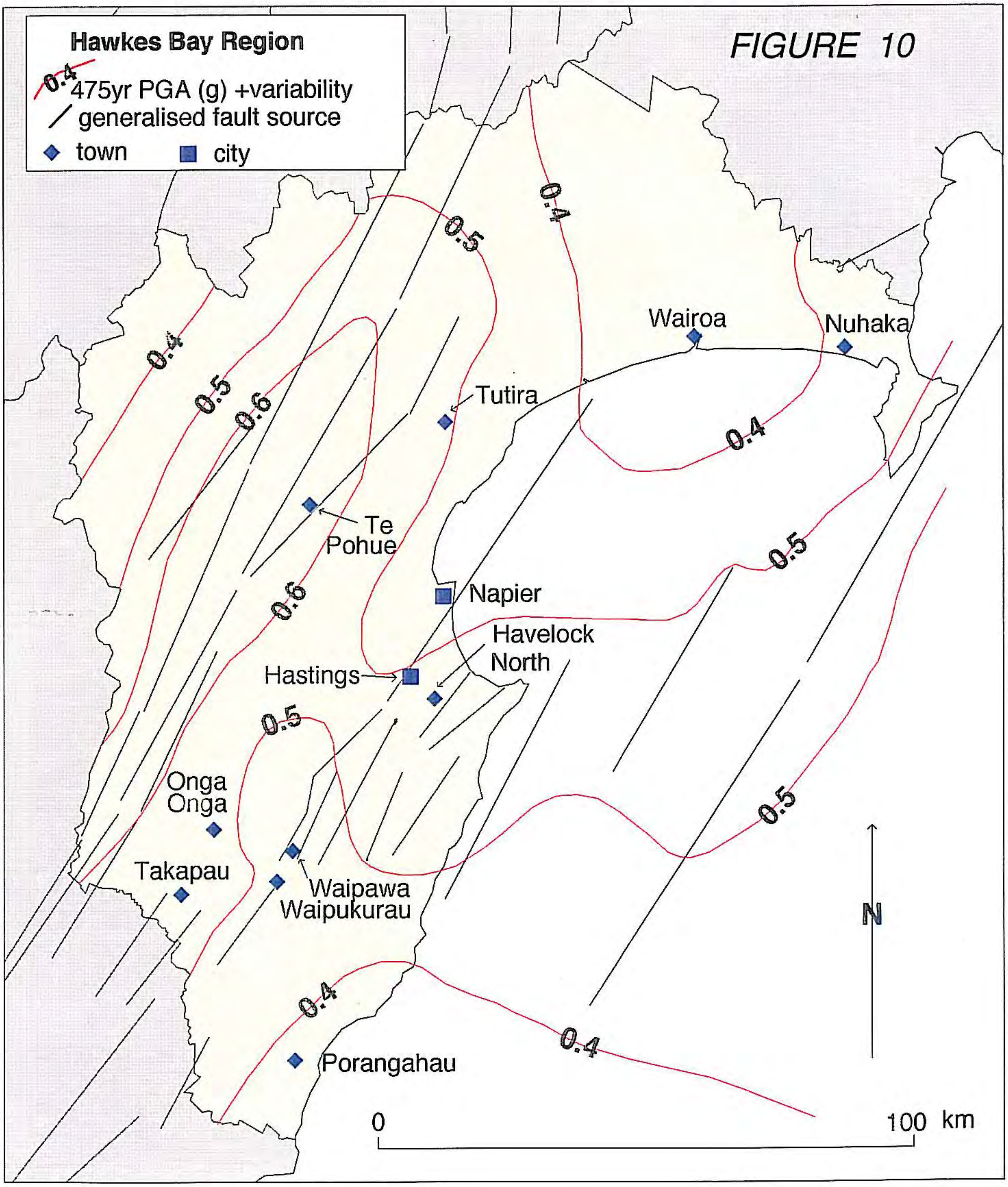
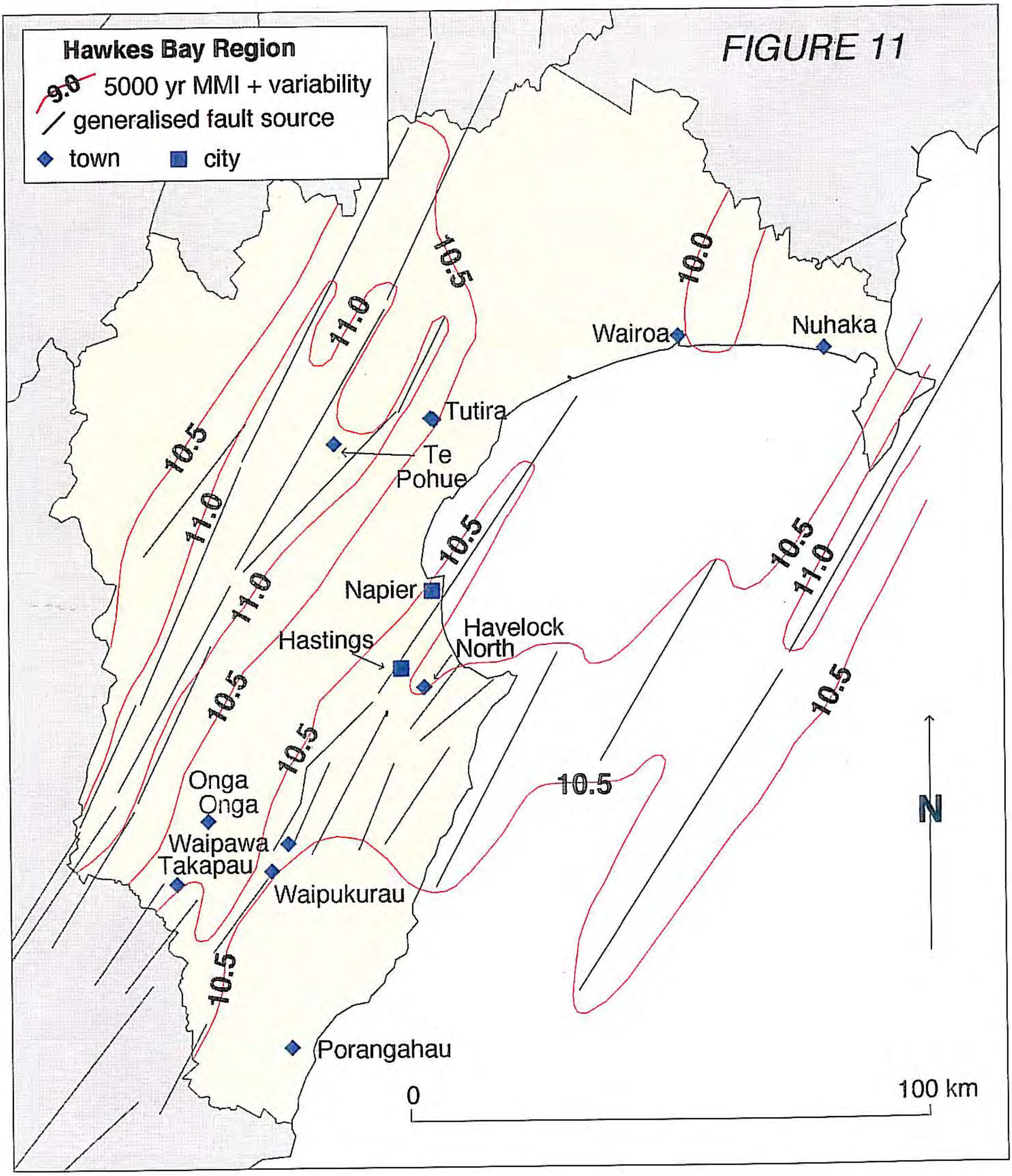


FIGURE 10

Hawkes Bay Region
0.4 475yr PGA (g) +variability
generalised fault source
town
city
0.4
0.5
0.6
Wairoa
Nuhaka
Tutira
Te Pohue
Napier
Havelock North
Hastings
Onga Onga
Takapau
Waipawa
Waipukurau
Porangahau
N
0
100 km

FIGURE 11


Hawkes Bay Region
9.0 5000 yr MMI + variability
generalised fault source
town
city
10.5
11.0
10.5
10.0
Wairoa
Nuhaka
Tutira
Te
Pohue
10.5
11.0
11.0
10.5
11.0
Napier
Hastings
Havelock
North
10.5
10.5
10.5
Onga
Onga
Waipawa
Takapau
Waipukurau
10.5
N
10.5
Porangahau
0
100 km

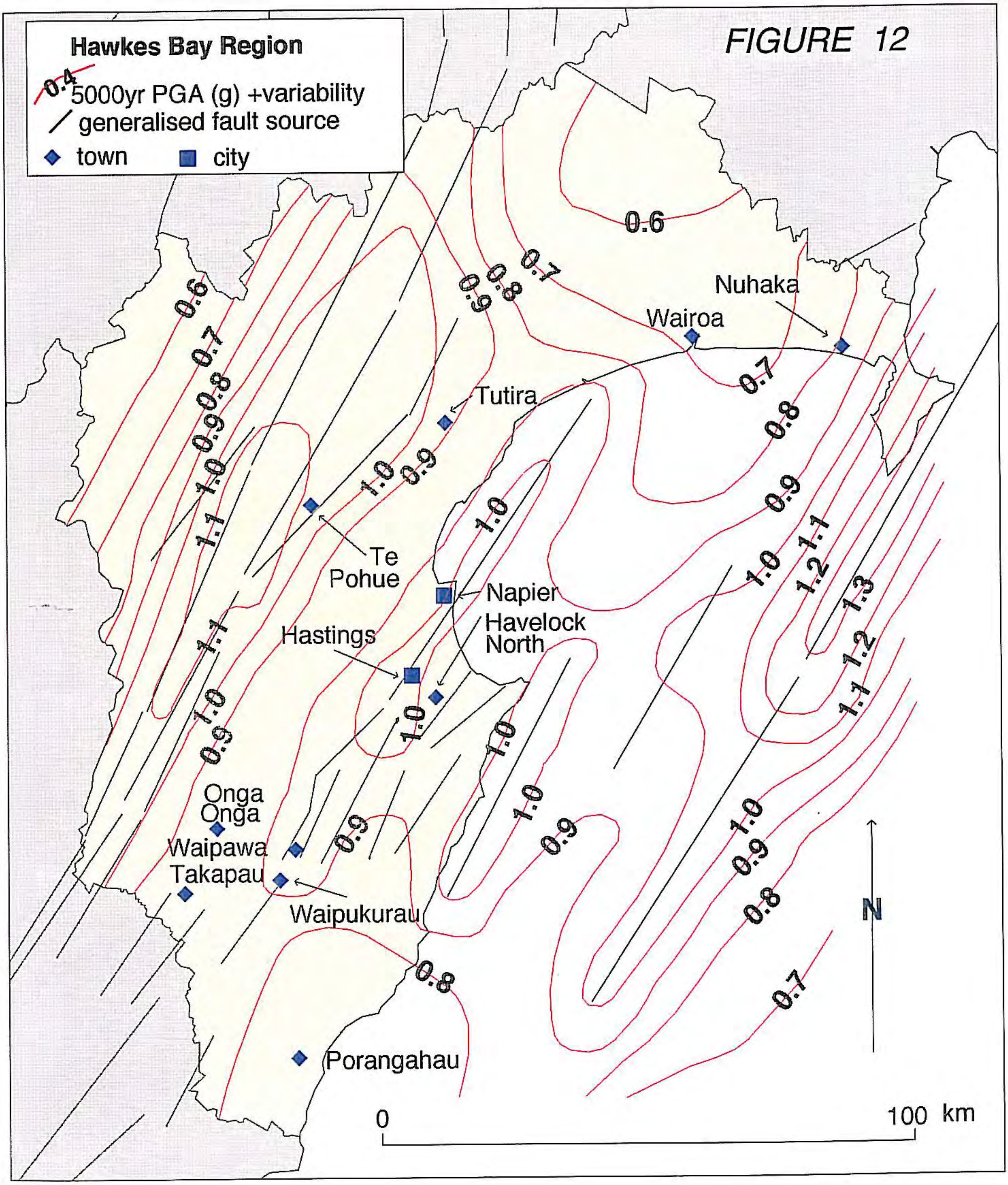


FIGURE 12

Hawkes Bay Region
0.4 5000yr PGA (g) +variability
generalised fault source
town
city
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
Nuhaka
Wairoa
Tutira
Te Pohue
Napier
Havelock North
Hastings
Onga Onga
Waipawa
Takapau
Waipukurau
Porangahau
N
0
100 km

NAPIER/HASTINGS

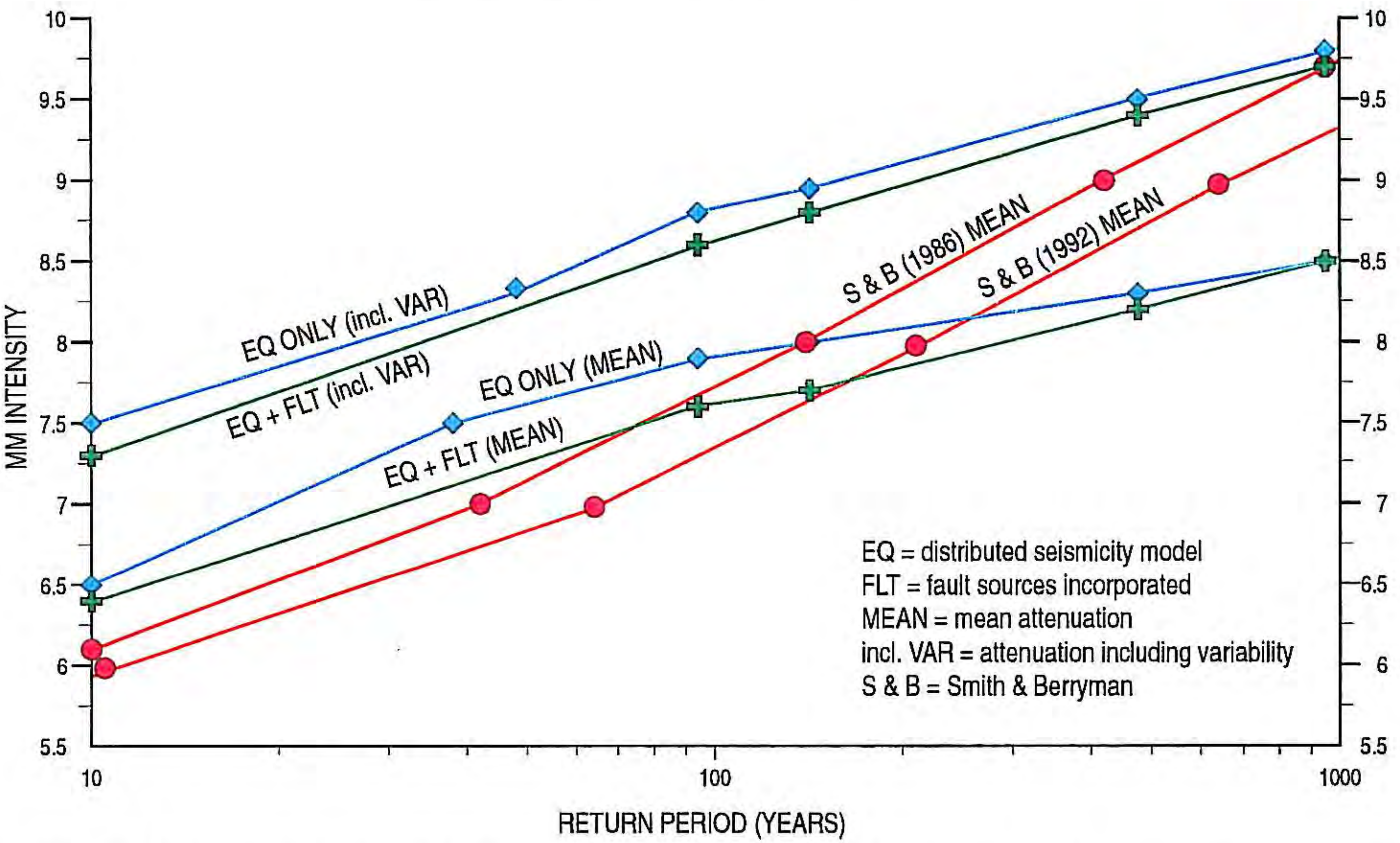


Figure 13: Comparison of MM intensity return times for the Napier/Hastings area as derived from previous estimates by Smith & Berryman (1986, 1992), and in this study. Plots of both mean attenuation expression and attenuation including variability are shown for hazard models incorporating earthquake and fault data (Model 1 & 2 of Table 3), or the historical earthquake catalogue alone (Model 3 of Table 3).

INSTITUTE OF GEOLOGICAL & NUCLEAR SCIENCES LIMITED

Corporate Services
Gracefield Road
PO Box 30 368
Lower Hutt
New Zealand
Phone +64-4-570 1444
Fax +64-4-569 0600

30 Gracefield Road
PO Box 31 312
Lower Hutt
New Zealand

Phone +64-4-569 0637
Fax +64-4-569 0657

State Insurance Building
Andrews Avenue
PO Box 30 368
Lower Hutt
New Zealand
Phone +64-4-569 9059
Fax +64-4-569 5016

32 Salamanca Road
Kelburn
PO Box 1320
Wellington
New Zealand
Phone +64-4-473 8208
Fax +64-4-471 0977

Wairakei Research Centre
State Highway 1, Wairakei
Private Bag 2000
Taupo
New Zealand
Phone +64-7-374 8211
Fax +64-7-374 8199

Crown Research Dunedin
764 Cumberland Street
Private Bag
Dunedin
New Zealand
Phone +64-3-477 4050
Fax +64-3-477 5232