WESTERN BAY OF PLENTY lifelines ENGINEERING

Microzoning for Earthquake Hazards for the Western Bay of Plenty

STUDY REPORT
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Western Bay of Plenty Lifelines Group

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Study Report

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Abstract

The Western Bay of Plenty Engineering Lifelines Group is facilitating risk management for lifelines in the area comprising the Tauranga and Western Bay of Plenty Districts. As part of their strategy to promote the management of risks to lifelines, an earthquake microzoning of the area was carried out, and included an assessment of the liquefaction hazards.

Past investigation information on ground conditions was collated during the study, and was supplemented by a programme of site investigations carried out for this study to fill gaps identified in priority areas with key lifelines. Information on the geology, soils, active faults and landslides was also compiled. Simplified geology and ground class maps were derived based on this information. The geology of the area is complex with a range of volcanic soils and recent marine, estuarine and alluvial sediments.

Ground shaking hazards in terms of peak ground accelerations were derived for the study using the New Zealand National Seismic Hazard Model with the earthquake sources appropriate for the study area. Hazard maps are presented for uniform hazards of 10% probability of exceedance in 50 years and 2% probability of exceedance in 50 years, and also for four earthquake scenarios. The chosen scenarios are the Local Tauranga Source, the Mayor Island Fault, the Matata Fault and the Kerepehi South Fault scenarios. The maps present the variation in ground shaking assessed across the study area. The ground shaking assessed is somewhat higher than that given by the current loadings code (NZS 4203 : 1992). The current loadings code gives peak ground accelerations of 0.21g to 0.28g for the Western Bay of Plenty area, whereas the equivalent 10% in 50 years probability of exceedance peak ground accelerations from this study are about 0.25g to 0.35g.

The liquefaction hazards were assessed and mapped using the general approach described by Brabhaharan (1994). Magnitude-weighted peak ground accelerations were used in the assessment of liquefaction to account for the different magnitude earthquakes contributing to the hazard. The liquefaction hazard is variable with a high potential for liquefaction in the recent estuarine / marine / alluvial sediments and a low potential in the coastal sand deposits. The volcanic soils are generally resistant to liquefaction.

The damage to lifelines from liquefaction will depend on the consequential type and magnitude of ground damage that is likely. Therefore the liquefaction ground damage is also presented based on the subsidence and the lateral spreading displacements that could occur. Regional hazard maps are presented based on the point estimates of liquefaction, and the geology of the area.

The earthquake slope failure hazards are also important to consider the performance of the lifelines, and should be assessed using additional topographical information that is expected to become available soon.

Hazard maps have been compiled using an ArcView geographical information system (GIS), for ground shaking, liquefaction and liquefaction ground damage. The earthquake microzoning assessment and hazard maps provide a valuable basis for the assessment of the risk to lifelines during earthquakes.

1 Introduction

Opus International Consultants (Opus) and the Institute of Geological and Nuclear Sciences Limited (GNS) were engaged by the Tauranga District Council on behalf of the Western Bay of Plenty Lifelines Group to undertake earthquake microzoning for the lifelines study of the Western Bay of Plenty area. The microzoning study for earthquake hazards in the Western Bay of Plenty will provide information to help determine the effects of earthquakes on the lifelines in the region.

The Western Bay of Plenty Lifelines Group is co-ordinating the lifelines study, which is supported by :

- Tauranga District Council
- Western Bay of Plenty District Council
- Environment Bay of Plenty

John Scott of Tauranga District Council manages the lifelines project.

The study included collection of information from various sources, a review of the information, site investigations to supplement the available information and an assessment of the earthquake hazards in the area. The results of the site investigations were reported in a site investigation report by Opus International Consultants (2002). Earthquake hazard maps have been prepared based on this information. This report presents the methodology used for the study and the outcomes of the study.

2 The Study Area

The earthquake microzoning study was carried out for a study area which covers the :

- Tauranga District, and
- Western Bay of Plenty District.

The Western Bay of Plenty study area stretches from Waihi Beach in the west, to Maketu in the east, and is enclosed by the Kaimai Ranges along the southwestern edge, and by the Pacific Ocean to the northeast. Tauranga is the largest city in the area, and is situated in the centre of the region on a natural harbour. Other major towns include Waihi Beach, Katikati, Mount Maunganui, Papamoa, and Te Puke. Figure 1 shows an overview of the study area.

3 Previous Studies

A review of the existing natural hazards information for the Western Bay of Plenty was carried out by Johnston and Scott (2000). The review presented ground shaking from historical earthquakes in the area. This review is reproduced in Appendix A.

The review recommended a microzoning study to further assess ground shaking scenarios and liquefaction hazard.

4 Objectives of the Study

The purpose of the study is to develop earthquake microzoning maps suitable for assessing the risk to lifelines in the Western Bay of Plenty area (consisting of the Tauranga District Council and Western Bay of Plenty District Council areas).

The following hazards associated with earthquakes were assessed as part of the study:

(a) Active fault hazards

(b) Earthquake ground shaking hazards (including consideration of amplification effects)

(c) Earthquake induced liquefaction ground damage hazards

The impact of these hazards on lifelines in the area can be assessed using the information from this study. Tsunami hazards are being considered separately by the Lifelines Study Group, and do not form part of this study. Earthquake induced slope failure hazards will be considered in a separate study when more detailed topographical information is available.

The study focus was on areas where lifelines are present, which covers inhabited areas of the districts and road/power transmission line corridors.

5 Historical Earthquakes

A review of the available natural hazards information for the Western Bay of Plenty was carried out by Johnston and Scott (2000). This report provides a review of the historical earthquakes in the region, and made recommendations for the current study.

In recorded history (since c. 1840), the largest shallow earthquakes in this region were the 1891 Waikato Heads earthquake and the 1932 Bay of Plenty earthquake. Both these events had Richter magnitudes of about 6.0. The commonly reported Richter magnitude is a measure of the total energy released at the source of the earthquake. The 1932 Bay of Plenty earthquake caused Modified Mercalli V (MM 5) intensity in Tauranga. The Modified Mercalli (MM) scale of I – XII, describes the intensity of shaking felt at any given site and is governed by the magnitude of the earthquake, distance from the earthquake source and the ground conditions at the site.

Fairless (1984) compiled case histories of liquefaction throughout New Zealand. No records of liquefaction in the Western Bay of Plenty area were identified in that study.

6 Data Collection and Compilation

6.1 Approach

Data was collected from various sources to provide the base information for the study. Organisations holding known information were contacted with the assistance of the lifelines group project manager.

In addition, a search was carried out of Opus and GNS records to obtain information relevant to this study. The lifelines group project manager, John Scott, also collated relevant information from Tauranga Council records and other local organisations.

6.2 Lifelines

Lifeline data provided by the WBOP Lifelines Group includes:

- Road network
- Rail network
- Water reticulation
- Water supply pumping stations
- Cellular phone stations for the Vodafone network.

The lifelines information available has been used to focus the hazard assessments for these areas. Lifeline details that were not available for this study are the energy distribution networks for electrical power and natural gas, other telecommunications networks and the sewerage and stormwater networks.

6.3 Geology

For this project, the geology of the Western Bay of Plenty District and Tauranga District has been compiled from published geological maps. No new geological mapping has been carried out.

The following three published maps have been utilised:

- Geological Map of New Zealand, 1:250,000, Sheet 5 Rotorua (Healy et al, 1964)
- Geology of the Tauranga area, 1:50,000, Sheet U14 (Briggs et al, 1996) and
- Geology of the Auckland area, 1:250 000, Qmap Sheet 3 (Edbrooke, 2001).

These maps cover different parts of the study area. The last two were available in a digital form. However, as the maps of Briggs *et al* (1996) and Edbrooke (2001) do not cover all of the area of interest, the geology of the remaining area had to be digitised from Healey *et al* (1964).

6.4 Soil Maps

Soil maps were compiled for the SmartGrowth study by Landcare Research New Zealand (2002). These were compiled from a range of soil maps prepared for different parts of the Western Bay of Plenty study area. The soil map compiled for that study is reproduced in Figure 3. This map does not cover the whole study area.

The soil maps usually represent the characteristics of the near surface soils, generally within about 1 m depth. Therefore, they are of limited use for earthquake microzoning, where the earthquake effects such as ground shaking and liquefaction are dependent on the engineering characteristics of soils to significant depths.

6.5 Geotechnical Information

Geotechnical information is mainly contained within geotechnical reports prepared for infrastructure developments and other resource studies within the districts. A search for geotechnical information was carried out as follows :

(a) by John Scott of Tauranga District Council, of information held by Tauranga District Council, Western Bay of Plenty District Council and Environment Bay of Plenty, as well as other organisations such as Tranzrail.

(b) By Opus, of information from projects carried out for a variety of clients.

(c) By GNS, of information from previous studies.

A large amount of data was collated from (a) and (b) above and limited information from (c). Given the large amount of data available and the benefit from this information for the study, the study period was extended to enable collection of more information. The information varied from limited quality data from water well records held by EBOP to high quality information from recent geotechnical investigations for major projects.

A list of the reports collected for the study has been compiled and the locations of the reports are mapped onto a geographical information system (GIS) database. The locations of the past site investigations and reports collated are shown on Figure 2.

6.6 Identification of Gaps

The geotechnical information collated during this study was reviewed in relation to the known lifeline corridors, and gaps in the available information were identified.

A further search for information was carried out, targeting these gaps, by contacting organisations that may hold records. Additional information was collated and the locations were mapped in GIS. The remaining gaps were prioritised, and a programme of site investigations was developed to obtain additional information to reduce the gaps in the ground information along lifeline corridors.

6.7 Site Investigations

A programme of site investigations comprising 4 boreholes, nineteen Static Cone Penetration Tests (CPT) and laboratory classification tests were carried out during January to March 2002. The boreholes were drilled to a depth of 17 m to 22 m with Standard Penetration Tests and were logged by an engineering geologist from Opus. Standpipe peizometers were installed in the boreholes to allow monitoring of groundwater levels. Laboratory tests comprised Atterberg Limits, particle size distribution tests using wet sieving and hydrometer analyses and a solid density test.

The results of the site investigations are reported in a separate site investigation report (Opus International Consultants, 2002). The locations of the site investigations were compiled in GIS and the results were used in the earthquake hazard assessment.

6.8 Groundwater Information

For most of the significant parts of the area of interest, ground water levels are available from previous work undertaken for Tauranga District Council by CH2MBeca Ltd (2000), who modelled depths to groundwater from groundwater level data held by Environment Bay of Plenty.

6.9 Terrain Model

Two topographic data sets have been used. The first, covering all of the area of interest, is *NZ Topo* from Land Information New Zealand (LINZ). The second is a dataset supplied by EBOP, a laser aerial survey (LIDAR) derived dataset from AAM Geodan (Australia).

NZ Topo is vector data derived from the LINZ NZMS 260 topographic mapping programme. Data is suitable for use at a scale of 1:50,000. Height data is represented by turning points on contour vectors (with a contour interval of 20 m ± 10) and by spot heights. The contour basis of the height data means that height is under-sampled in areas of low gradient, as on coastal plains, and conversely and relatively, over-sampled in areas of steep gradient.

The LIDAR data set from AAM Geodan (Australia) was produced as part of a beach monitoring programme for Environment Bay of Plenty. Although the LIDAR data has high-resolution, with an intended scale of use of 1:500, it was noted that the definition of ground under trees may be less accurate and that the data had not been field tested for completeness. Some apparent anomalies in the LIDAR data elevations confirm that the data may not have been cleaned of "non-ground" values. Also a datum shift was evident, with the discrepancy increasing significantly towards the western margin of the LIDAR coverage.

Two digital terrain models (DTM's) have been built from each of the datasets (using ARC/INFO – TopoGrid). The intention was to use the LIDAR derived DTM for the area the LIDAR survey covered (coastal), and for the rest of the WBOP area of interest to use the *NZ topo* derived DTM.

However, because of the discrepancies and the likely availability of better topographical data later, further development and use of the topographical data and DTM's was not progressed any further.

6.10 Active Faults

Active faults are sources of earthquake and of intense ground displacement and deformation. The GNS Active Fault database and the geological maps of the area were examined for the project. Some possible faulting (eg as shown by Healy et al, 1964) was further investigated by aerial photo interpretation. No active faults have been identified in the study area.

Further studies to better map and define active faults is being carried out offshore as well as on land in the vicinity of the Western Bay of Plenty Study area. This new information is currently not available. When this becomes available, it would be prudent to review whether it would significantly change the active fault and ground shaking hazards in this area.

Known active faults exist immediately outside the study area, and include the Kerepehi Fault to the west, the Matata Fault zone to the east, and offshore faulting including the Mayor Island Fault. These and other faults have been used as earthquake sources in the assessment of ground motions, see Section 9. For this purpose, the compilation of active faults by Stirling *et al* (2000b) has been used.

6.11 Landslides

Two datasets of existing landslides are available. The first is the National Landslide database being actively compiled by GNS. The second is the verification of relic slips in Tauranga District prepared by Richards & Bell for Tauranga District Council. Additional reports on landslides have been identified but their compilation is beyond the scope of this project.

7 Geology

7.1 Data Sources

Three major sources of geological information for the project have been the published geological maps of Healy *et al* (1964), Briggs *et al* (1996) and Edbrooke (2001). The Briggs *et al* map has a scale of 1:50,000 while the other two are at a scale of 1:250,000. The geological maps of Briggs *et al* (1996), and Edbrooke (2001) do not provide the full coverage for the study area, but have been used in preference because they are more detailed than Healy *et al* (1964). Edbrooke (2001) has the greatest differentiation in the Quaternary and Holocene units, an important consideration when evaluating ground class. In addition, drillhole data has been used to confirm the near surface geology and to better assign ground classes. The data used was compiled as discussed in Section 6.5.

7.2 Compilation

To synthesise the three geological maps, the Healey *et al* (1964) map was digitised so that all map units were then available as digital polygons. All geological units from the three maps were tabulated. Where a geological unit had the same name on all maps (*e.g.* Mamaku Ignimbrite), the polygons were associated in the GIS coverage by assigning a common unit code to each. For the geological units that weren't common to all three maps, the legend of Edbrooke was adopted because of its finer subdivision of the geological units of the Quaternary and Holocene Age. The legend and text descriptions of Briggs *et al* (1996) and Healy *et al* (1964) were then evaluated with respect to the Edbrooke (2001) legend and assigned the unit code of Edbrooke (2001) that was judged most appropriate. From this the simplified geological legend of Table 1 was developed. This table provides the attributes of the compiled polygons of the geological units.

The resulting digital geological map provides the principal spatial database on which ground classification has been based. The geological map is shown on Figure 4.

Table 1 Simplified geological units of the Western Bay of Plenty region

Rock or soil type	Unit code	Unit description
Holocene sediments	Q1re	Fill
	Q1l	Landslide deposits
	Q1d	Dune sediments
	Q1b	Beach sediments
	Q1as	Peat
	Q1al	Alluvium
	Q1ae	Estuarine sediments
Late Quaternary sediments	lQa	Alluvium
	lQd	Dune sediments
Middle Quaternary sediments	mQm	Alluvium, estuarine sediments, undifferentiated ignimbrite and tephra
Early Quaternary sediments	eQa	Alluvium and colluvium
Differentiated ignimbrites	mam	Mamaku Ignimbrite (partially welded)
	mat	Matahina Ignimbrite (welded)
	ong	Ongatiti Ignimbrite (partially welded)
	pap	Papamoa Ignimbrite (partially welded)
	tep	Te Puna Ignimbrite (partially welded)
	ter	Te Ranga Ignimbrite (partially welded)
	wam	Waimakariri Ignimbrite (partially welded)
	wat	Waiteariki Ignimbrite (partially welded)
Ignimbrite/Pumice breccias	rb	Rotoiti Breccia - poorly compacted pumice breccia with basal siltstone
	Pho	Ohinemuri subgroup - pumice rich ignimbrite with local pumice breccia
	Mhc	Coroglen subgroup - lithic- and pumice-rich ignimbrite and local rhyolitic and obsidian-rich pumice breccia deposits and tuff.
Volcanic and sedimentary rocks	Mca	Andesite and dacite
	Mhm	Rhyolite
	ug	Greywacke
	mb	Basalt

8 Ground Classification

8.1 Class Definition

A five-step scale of ground class (Class A to Class E) is proposed in the draft Australia/ New Zealand Loadings Standard (Standards New Zealand, 2002). These ground classes are defined in Table 2.

Table 2 Ground class definitions

Class	Geological description	Engineering description
A	Strong rock	Sites with strong rock (ie material with a compressive strength of 20 MPa or greater) at the surface. Average shear wave velocities over the upper 30 m of greater than 760 m/s.
B	Weak rock	Sites with weak rock (ie material with a compressive strength between 1 MPa and 20 MPa) at the surface, or sites with a soil thickness not exceeding 3 m overlying rock.
C	Shallow soil	Sites with soil depths less than the limits defined in Table 3.
D	Deep or "Soft" soil	Soil sites with periods greater than 0.6 s, or with depths of soil greater than those defined in Table 3, but excluding Class E sites.
E	"Very Soft" soil	Sites with more than 10 metres of very soft cohesive soils with undrained shear strength less than 12.5 kPa, or with about 10 m or more of soil with shear-wave velocities less than 150 m/s, or with about 10 m or greater thickness of soils with SPT 'N' values less than 6.

The ground or site classes proposed in the draft Australia/ New Zealand Loadings Standard (Standards New Zealand, 2002) are similar to those of the three subsoil categories (a) to (c) of the current New Zealand Loadings Standard NZS 4203:1992 (Standards New Zealand, 1992). The current standard combines the proposed Class A *Strong Rock*, the Class B *Weak Rock*, and the Class C *Very Stiff Soils* (with estimated natural periods less than 0.25 s) into category (a). Catergory (b) *Intermediate Soil* sites of NZS 4203:1992 are those that do not fit catergories (a) or (c). This category is similar to the proposed Class C *Shallow Soil* sites, apart from the *Very Stiff Soil* sites of category (a). Site Category (c) of NZS 4203:1992 is carried over directly into the proposed Class D, except that *Very Soft Soil* sites are separated into the proposed Class E.

The Ground Class criteria of the draft Loadings Standard may change before the standard is finalised. This may alter the ground classes from that used in this study for the Western Bay of Plenty area, but is unlikely to alter the ground motion estimates presented in this report.

Table 3 Depth Limits for Ground Classes C and D

Soil type and description		Depth of soil (m)
Cohesive soil	*Representative undrained shear strengths (kPa)*	
Soft Firm Stiff Very stiff or hard	12.5-25 25-50 50-100 100-500	20 25 40 60
Cohesionless soil	*Representative SPT (N) values*	
Loose Medium dense Dense Very dense Gravels	4-10 10-30 30-50 >50 >30	40 45 55 60 100
▪ Depths no greater than those above qualify as Class C, greater depths qualify as Class D, except where Class E criteria apply. ▪ For layered sites, the ratios of the depth of each soil type to the limits of the table should be added, with a sum not exceeding 1.0 corresponding to Class C and greater sums to Class D.		

Only four classes (A, C, D and E) have been used in this study. For this project, Classes A and B are treated as producing the same earthquake motions. At present, Classes D and E share a common peak ground acceleration (pga) attenuation expression, but are modelled as producing different motions at intermediate to long spectral periods, beyond 0.5 s period.

8.2 Evaluation of Ground Class

The ground classification presented above was used for assigning ground class to the mapped geological units of Figure 4 and for the attenuation model used for assessing the earthquake ground shaking hazard in Section 9. The evaluation of ground class was carried out in two steps: -

1) Assignment of ground class to the geological units of Table 1, based on geological descriptions given in the geological maps.
2) Use of geotechnical properties obtained from reports and drillhole logs to review and modify the assignment of ground class as appropriate.

This process resulted in two major changes to the ground class between step 1 and step 2. The ignimbrites were assigned in step 1 to Class B, but on reviewing the geotechnical data it was found that greater than 3 metres of soil strength materials was often present. For this reason the ignimbrites were reclassified as Class C materials in step 2. Therefore, there are no Class B materials identified in the study area. The Holocene stream and river alluvium were initially assessed in step 1 as Class D, but review of the geotechnical data in step 2 showed Class E materials were often present - especially near the mouths of the rivers and streams. The resulting ground classes for the geological units are shown in Table 4. The ground class map is presented in Figure 5.

Table 4 Simplified Geological Units and Assignment of Ground Class

Rock or soil type	Unit code	Unit description	Ground Class
Holocene sediments	Q1re	Fill	C
	Q1l	Landslide deposits	C
	Q1d	Dune sediments	D
	Q1b	Beach sediments	D
	Q1as	Peat	E
	Q1al	Alluvium	E
	Q1ae	Estuarine sediments	E
Late Quaternary sediments	lQa	Alluvium	D
	lQd	Dune sediments	D
Middle Quaternary sediments	mQm	Alluvium, estuarine sediments, undifferentiated ignimbrite and tephra	C
Early Quaternary sediments	eQa	Alluvium and colluvium	C
Differentiated ignimbrites	mam	Mamaku Ignimbrite (partially welded)	C
	mat	Matahina Ignimbrite (welded)	C
	ong	Ongatiti Ignimbrite (partially welded)	C
	pap	Papamoa Ignimbrite (partially welded)	C
	tep	Te Puna Ignimbrite (partially welded)	C
	ter	Te Ranga Ignimbrite (partially welded)	C
	wam	Waimakariri Ignimbrite (partially welded)	C
	wat	Waiteariki Ignimbrite (partially welded)	C
Ignimbrite/ Pumice breccias	rb	Rotoiti Breccia - poorly compacted pumice breccia with basal siltstone	C
	Pho	Ohinemuri subgroup - pumice rich ignimbrite with local pumice breccia	C
	Mhc	Coroglen subgroup - lithic- and pumice-rich ignimbrite and local rhyolitic and obsidian-rich pumice breccia deposits and tuff.	C
Volcanic and sedimentary rocks	Mca	Andesite and dacite	A
	Mhm	Rhyolite	A
	ug	Greywacke	A
	mb	Basalt	A

9 Ground Shaking Hazards

9.1 Introduction

Ground shaking hazards in this study have been derived from the recently developed New Zealand National Seismic Hazard Model (NZNSHM) of Stirling et al. (2000a, 2000b and 2002). A brief description of the seismicity and attenuation model used is presented in Appendix A. While the published results of Stirling et al. are in terms of peak ground acceleration (pga) and 5% damped response spectral accelerations, the brief for the current study is restricted to pga only. It is noted that the NZNSHM has been used to derive the recommended spectra and zone factor maps for New Zealand in the draft Australian/New Zealand Loadings Standard (Standards Australia/Standards New Zealand, 2002).

The Western Bay of Plenty Lifelines Group is interested in two levels of earthquake-induced ground motions (J. Scott, pers com), namely those with return periods of:

1) Approximately 500 years
2) 2000 to 3000 years

Two different approaches have been used in addressing both of these return periods, giving uniform-hazard and single-scenario earthquake ground-shaking maps. Both uniform-hazard and single scenario earthquake ground shaking hazard maps are useful for the lifelines study. A description of the two types of maps and a comparison of the approaches are presented in Appendix A. The appendix also discusses the selection of appropriate hazard levels.

9.2 Selection of Uniform Hazard Levels and Scenarios for the Western Bay of Plenty

In this study, we have used both the uniform hazard and scenario approaches, to obtain the benefits of each approach. First a uniform hazard analysis has been performed for the Western Bay of Plenty study area to estimate the distribution of peak ground acceleration with 10% and 2% probabilities of exceedance in 50 years (corresponding to return periods of approximately 500 years and 2500 years) for each of three site classes that are available in the model. Then the map of the ground class in the study area (Figure 5) has been used in conjunction with the component earthquake ground-shaking maps for the three site classes to produce the overall ground shaking hazard maps, incorporating site conditions. These maps are presented in Figure 6 (10% probability of exceedance in 50 years) and Figure 7 (2% probability of exceedance in 50 years).

Single scenario earthquake ground shaking maps have then been developed that approximate the target 500-year or 2500-year peak ground accelerations over various parts of the Western Bay of Plenty study area. This has been achieved through the combination of the following two visual techniques to portray aspects of the hazard to aid in the selection of the scenarios:

- Maxium pga
- Deaggregation.

The selection of four appropriate earthquake scenarios for the Western Bay of Plenty study is discussed in detail in Appendix B. The component maps produced for the different ground classes for each of the uniform hazards levels of 10% and 2% probability in 50 years, are also presented in this appendix.

9.3 Fault Sources

The component pga maps presented in Appendix B show the fault sources nearest the WBOP Lifelines project's study area. The fault sources are simplified, for the purposes of seismic hazard analysis. Faults outside the mapped region and several sources representing the Hikurangi subduction zone were also included in the hazard analyses, but these made little contribution to the estimated hazard in the study area because of their distance from the region. The parameters of the fault sources neighbouring the study area have been adopted from the NZNSHM and are summarised in Table 5.

Table 5 Parameters used for Western Bay of Plenty Faults

Fault ID	Fault Name	Magnitude	Ave. Recurrence Interval of Rupture (years)	Fault Type
95	Kerepehi North-Central	6.7	2500	normal
96	Kerepehi Central	6.7	5000	normal
97	Kerepehi South	6.7	5000	normal
98	Mayor Island 1	7.0	4000	normal
99	Mayor Island 2	7.4	4000	normal
100	Mayor Island 3	7.1	4000	normal
101	Mayor Island 4	7.0	4000	normal
102	Tauranga	7.0	2000	normal
104	Matata	6.5	375	normal volcanic
105	Braemar	6.5	800	normal volcanic
106	Rotoiti	5.7	520	normal volcanic
107	Te Teko	5.7	340	normal volcanic
108	Onepu	5.8	250	normal volcanic
110	Edgecumbe 1987	6.5	1360	normal volcanic
111	Edgecumbe Coastal	6.0	175	normal volcanic
118	Rurima A	6.3	1080	normal volcanic

Note : From New Zealand National Seismic Hazard Model (Stirling et al, 2000b).

The "Fault ID" corresponds to the fault labels shown on the hazard maps. Some of the data on single-event displacements and segment lengths are poor. Of the listed parameters, probably the most reliable are the recurrence intervals for the Kerepehi Central and Kerepehi South fault segments. The estimated recurrence interval for the Kerepehi North-Central fault segment is likely to be too short, because of a suspected underestimate of single-event displacements. The locations of the endpoints of the five listed offshore faults, Fault IDs 98 to 102, are poorly known. The uncertainty in the lengths of the offshore faults affects the estimates of their magnitudes and average recurrence intervals, as well as their distances from locations in the Western Bay of Plenty. The listed recurrence intervals for the seven volcanic region faults are likely to be too short. Updating of the fault database and revision of the fault parameters is outside the scope of this study.

9.4 Uniform Hazard PGA Maps

Uniform-hazard peak ground acceleration maps for the Western Bay of Plenty are presented in Appendix B for each of the three site classes A/B, C and D/E of the attenuation model. The gridded data used to produce these maps were combined with the site classes in the region to produce maps of the hazard incorporating site conditions.

Uniform-hazard peak ground acceleration maps for the Western Bay of Plenty at 1:250,000 scale are presented in Figure 6 and Figure 7, corresponding to 10% and 2% probabilities of exceedance in 50 years, respectively.

The peak ground accelerations for rock (Class A/B) sites with 10% probability of exceedance in 50 years lie within the range 0.2g to 0.3g for most of the onshore region. Around the faults of the Taupo Volcanic Zone (TVZ), the rock pga values rise to a maximum of 0.4g. The areas with the highest acceleration lie outside the southeastern boundary of the Western Bay of Plenty, but affect transport routes into it from around Matata. For shallow soil sites (Class C), the pga values are higher than the rock pga values by a factor of 1.35, with most in the 0.25g to 0.35g range, rising to the 0.4g to 0.5g range around the TVZ faults. The pga values for Class D&E deep or soft soil sites show a more limited range. For most of the region, they lie in the range 0.25g to 0.3g, reaching a maximum in the 0.4g to 0.45g range around the TVZ faults. At lower pga values up to about 0.25g, the Class D/E values are amplified with respect to the rock values but less than the Class C values. The strongest Class D/E pga values, around the TVZ faults, are less than those for either Class A/B or C. This behaviour is in line with the discussion in Appendix A. Accelerations at longer spectral periods, such as 1s, would show strong amplification of Class C relative to rock, and even greater amplifications for Class D/E.

A feature of the maps showing pga values for probabilities of exceedance of 10% in 50 years is that apart from the very active TVZ faults to the south-east of the region, the influence of the modelled fault sources does not appear very marked. Even for the 2% in 50 years hazard level, corresponding to a return period of about 2500 years, the fault contributions don't appear very marked.

The maps presenting pga values with 2% probability of exceedance in 50 years show values that are typically in the 0.3g to 0.4g range for rock sites, peaking at 0.7g to 0.8g around the TVZ faults. Shallow soil values (Class C) are typically 0.3g to 0.4g, peaking at 0.7g to 0.8g. Values for deep or soft soil sites (Class D or Class E) are typically 0.3g to 0.4g, peaking in the 0.5g to 0.6g range.

9.5 Maps for Selected Scenarios

9.5.1 Selected Scenarios

Four earthquake scenarios have been chosen based on the consideration of maximum pga and the deaggregation analyses (see Appendix B). These are :

1) Local Source for Tauranga Scenario
2) Mayor Island Fault Scenario
3) Matata Fault Scenario
4) Kerepehi South Fault Scenario

The estimated 2500-year pga of 0.47g on shallow soil in Tauranga are not produced by 84-percentile scenarios on any of the modelled faults. The deaggregation studies show that they are contributed largely by the distributed seismicity gridpoints, with the fault sources estimated as producing only 4% of the rate of exceedance of 0.47g. Even a direct hit on Tauranga (i.e. an earthquake directly under it at 10 km depth) requires motions at just over the 90-percentile level to produce the estimated 2500-year motions.

9.5.2 Local Source for Tauranga Scenario

The deaggregation studies (Appendix B) show that distributed seismicity is the dominant contributor to the pga hazard for Tauranga. This has been taken into account in developing scenarios for the 475-year and 2500-year pga hazard in Tauranga, as it is not realistic to just consider scenarios based on the modelled fault sources.

The modal peak for the 475-year pga hazard for Tauranga corresponds to the 5.3-5.5 magnitude class at 0-20 km distance. The first scenario is selected to represent this type of earthquake affecting Tauranga. For constructing this scenario, a magnitude 5.4 normal-faulting earthquake with the top of its rupture surface at 10 km depth is modelled along an artificial fault of 8 km length, running from approximately from Tauriko on the Kaimai road to Omokoroa with a 65 degree strike. A normal-faulting mechanism is selected because it is the most common for earthquakes in this region, while the strike is approximately aligned with that of real faults in this area (e.g. Kerepehi South). The artificial fault is placed to the west of Tauranga, in that the Mayor Island Fault 1 scenario discussed below is centred to the east of Tauranga. The placement ensures that facilities to the west of Tauranga for which the pga from the Mayor Island Fault 1 scenario are less than the target 475-year values are subjected to at least the target pga in one of the scenarios.

The pga estimated for the scenario of 84-percentile motions from a magnitude 5.4 earthquake at 10 km depth about 10 km to the west of Tauranga are shown in Appendix B for the three site classes. These figures include the location of the artificial fault about which the scenario is constructed.

The ground shaking map for the Tauranga local source scenario is given in Figure 8.

9.5.3 Mayor Island Fault Scenario

As a second scenario for Tauranga, a Mayor Island Fault 1 earthquake is considered. This event has a magnitude of 7, a normal-faulting mechanism, and is assumed to rupture to the surface along the entire modelled length of the fault (number 98). These assumptions are all consistent with the modelling of the fault in the NZNSHM.

The ground shaking hazard map for the Mayor Island Fault scenario is given in Figure 9.

9.5.4 Matata Fault Scenario

The third scenario for the Western Bay of Plenty is selected as one producing 84-percentile motions in a magnitude 6.5 normal-faulting earthquake rupturing to the surface along the entire modelled length of the Matata fault (number 104). This corresponds to the type of earthquake that dominates the estimated hazard in Matata, and along the coastal route into the Western Bay of Plenty from the southeast.

The ground shaking hazard map for the Matata Fault scenario is presented in Figure 10.

9.5.5 Kerepehi South Fault Scenario

The fourth scenario considered consists of 84-percentile motions in a magnitude 6.7 normal-faulting earthquake rupturing to the surface along the south segment of the Kerepehi Fault (number 97).

The ground shaking hazard map for the Kerepehi South Fault scenario is presented in Figure 11.

9.6 Magnitude-weighted Peak Ground Accelerations

The magnitude-weighted peak ground accelerations recognise that for a given peak acceleration level, a larger magnitude earthquake is of more significance for liquefaction because of its greater duration and greater strength of long-period components.

For use in assessing the potential for liquefaction, Figures B12 and B13 in Appendix B show peak ground acceleration estimates scaled by the magnitude-weighting factors of Idriss (1985) for probabilities of exceedance of 10% and 2% in 50 years. Part (a) of each of these figures is for Site Class C (shallow soil), while part (b) is for Class D/E (deep or soft soil, or very soft soil). Class A/B (rock) sites are assumed not to be prone to liquefaction, so magnitude-weighted pga estimates are not relevant for this site class. The magnitude-weighting factors of $(M/7.5)^{1.285}$ are intended to convert pga produced by an earthquake of magnitude M into the pga value from a magnitude 7.5 earthquake that has equivalent effect in terms of liquefaction potential.

Maps incorporating magnitude-weighting are not shown for the scenarios. Since each of the scenarios is for a single magnitude, the scaling factors to account for magnitude-weighting can be calculated simply. They are presented in Table 6 for the four scenarios.

Table 6 Magnitude-Weighting Scaling factors

Scenario	Description	Magnitude	Scaling factor
1	Local Source at Tauranga	5.4 at 14 km distance from Tauranga	0.66
2	Mayor Island Fault 1 Scenario	7.04	0.92
3	Matata Fault Scenario	6.5	0.83
4	Kerepehi South Fault Scenario	6.7	0.87

The magnitude weighted pga values can be directly used in liquefaction analyses.

9.7 Estimation of Probabilities of Exceedance

The standard scenario approach assumes that the motions in a given earthquake are uniformly high or low with respect to the median motions at all locations i.e. in an 84-percentile scenario, the motions are at the 84-percentile level everywhere. This corresponds to all the random variability occurring between different earthquakes of the same magnitude and location (between-earthquake variation), and none of the random variability occurring between different locations within a single earthquake (within-earthquake variation). Modern attenuation relations indicate that, in contrast to the scenario assumption, most of the variation in fact consists of within-earthquake variation. Currently, scenario maps haven't been developed to show the joint probabilities of exceedance at multiple locations taking into account the split into within-earthquake and between-earthquake variability. However, Rhoades and McVerry (2001 and 2002) have developed a methodology to assess the joint probabilities of exceedance of given ground motions at multiple locations.

In general the joint probability of *exceedance* of the mapped motions at multiple locations is less than the probabilities of *exceedance* for the locations individually. The differences can be large. The situation of total within-earthquake variation corresponds to the joint probability of exceedance in the same earthquake being the product of the individual probabilities for the earthquake. The situation of total between-earthquake variability corresponds to the joint probability being the smaller of the individual probabilities of exceedance in the earthquake. The actual joint probability of exceedance lies between these two extremes. The joint-probability approach is useful if an initial analysis suggests that there are several critical locations in a lifeline network. Two situations particularly amenable to a joint-probability analysis are highly redundant systems for which the network fails only if there are failures at all critical locations, or non-redundant networks for which the network fails if there is failure at any individual critical location.

9.8 Ground Motions : Peak Ground Acceleration and Intensity

Ground shaking associated with historical earthquakes is often described in terms of felt intensity. For most of the English speaking world, this is typically in terms of the Modified Mercalli (MM) intensity scale and its revisions (see Dowrick 1996). The intensity is assessed from observations of the earthquake impact on people, fittings, structures, and the environment, by people present during the shaking, or from evidence, usually damage, that can be observed after the event. These subjective estimates reflect, at each location of the observations, the net effect of the earthquake's ground motion, its duration and frequencies, as well as the ground conditions and the response of people, fittings, and structures.

Rather than the subjective measure of felt intensity, this study uses peak ground acceleration (pga) as an indicator of possible earthquake ground motion for the two uniform hazards and the scenarios. Values of pga are useful in the design and performance assessment of lifelines and other utilities (better still would be to use estimates of response spectra or measures related to ground strain, but limitations on the study prevented this). The ground shaking hazard maps (Figure 6 to Figure 11) are presented in terms of pga.

Peak ground accelerations and Modified Mercalli intensities are not directly comparable. However, recent developments in the near instantaneous reporting of earthquake strong ground motion have led to publication of several correlations between pga and intensity, for Modified Mercalli intensity (MMI), and Japanese Metrological Agency intensity (JMA) e.g. Wald et al (1999), Shabestari & Yamazaki (2001), Davenport & Dowrick (2002). Wald et.al.'s (1999) results are shown in Table 7. Note the large range of pga for a given intensity and that for this study the correlation was reportedly not sensitive to ground class.

Table 7 Correlation of Intensity, PGA, and PGV

Instrumental Intensity (MMI)	Acceleration (% g)	Velocity (cm/s)	Perceived Shaking	Potential Damage
I	< 0.17	< 0.1	Not Felt	None
II – III	0.17 - 1.4	0.1 - 1.1	Weak	None
IV	1.4 - 3.9	1.1 - 3.4	Light	None
V	3.9 - 9.2	3.4 - 8.1	Moderate	Very light
VI	9.2 - 18	8.1 - 16	Strong	Light
VII	18 - 34	16 - 31	Very Strong	Moderate
VIII	34 - 65	31 - 60	Severe	Moderate to Heavy
IX	65 - 124	60 - 116	Violent	Heavy
X+	> 124	> 116	Extreme	Very Heavy

Wald et al (1999). Relationships between Peak Ground Acceleration, Peak Ground Velocity and Modified Mercalli Intensity in California, Earthquake Spectra, 15, 557-564

This Western Bay of Plenty study estimates pga maxima up to 0.8g. If we use the Californian relationship of Wald (1999), this equates to MMI IX. For comparison, the 1987 Edgecumbe earthquake had a reported maximum MMI of X (Lowry et al 1989), but revision by Dowrick (pers. com.) suggests the maximum was probably MMI IX.

9.9 Comparison with New Zealand Loadings Code NZS 4203 : 1992

The existing New Zealand Loadings Code gives peak ground accelerations of 0.21g to 0.28g (for zone factors of 0.8 to 1.0 for the Western Bay of Plenty District, and for a risk factor of 1.0 corresponding to an approximately 10% in 50 years probability of exceedance, ie return period of about 475 years). In comparison this regional study, which is based on the new New Zealand National Seismic Hazard Model (NZNSHM) and refined ground classes, gives 0.25g to 0.35g for a 10% in 50 year probability of exceedance. This gives 20% to 25% higher levels of shaking.

It should be noted that the loading code is currently being revised, and this could narrow the difference between the code and the specific study.

The current study also provides levels of shaking for a 2% in 50 years probability of exceedance and for specific scenarios. This additional information would be useful in the assessment of vulnerability and risk to lifelines under different levels of shaking and earthquake scenarios.

10 Liquefaction Hazards

10.1 Definition

Liquefaction includes all *"phenomena giving rise to a loss of shearing resistance or to the development of excessive strains as a result of transient or repeated disturbance of saturated cohesionless soils"* (National Research Council, 1985). American Society of Civil Engineers (1978) define liquefaction as *"the act or process of transforming cohesionless soils from a solid state to a liquefied state as a consequence of increased pore pressure and reduced effective stress"*.

10.2 Mechanism of Liquefaction

Ground shaking associated with earthquakes gives rise to an increase in the porewater pressure in saturated, loose, mainly cohesionless soils, leading to *earthquake induced liquefaction*. In soils where the increasing porewater pressures cannot dissipate rapidly, and become equal to the overburden stress, the soil particles no longer have inter-particular friction, and the soil liquefies, losing most of its strength. This state with a peak cyclic pore pressure ratio of 100%, is known as initial liquefaction. The soil is at a liquefied state. The strength of earthquake shaking has to be sufficient to cause significant increases in porewater pressures, and its duration has to be long enough for soils to reach this state.

Liquefaction most commonly occurs in saturated loose sands and silty sands. These were the only soil types thought to be prone to liquefaction. Increasingly it has become apparent from observations in earthquakes that loose sandy gravels and low plasticity sandy silts and silts also have liquefied (Brabhaharan et al, 1994).

While soils may develop initial liquefaction, their subsequent behaviour depends on many factors such as the soil characteristics, strength and duration of shaking and layering of the soil deposits. Soft cohesive soils such as clays and silty clays do not strictly undergo liquefaction, but could cause similar ground damage, such as lateral spreading, flow slides or failure of structures founded on them due to significant loss of strength during ground shaking.

10.3 Historical Evidence of Liquefaction

Fairless (1984) compiled case histories of liquefaction throughout New Zealand. However, no historical evidence of liquefaction in the Western Bay of Plenty study area was found. This could be attributed to the lack of strong earthquake shaking in the Western Bay of Plenty study area during the relatively brief recorded history of European settlement in New Zealand. However, there have been many historical records of liquefaction in New Zealand, including in the adjacent Whakatane District during the 1987 Edgecumbe Earthquake (Jennings et al, 1988, Pender and Robertson, 1987).

10.4 Liquefaction Assessment

10.4.1 Approach

Given the absence of historical records in the area, the liquefaction assessment has been based on consideration of the geology and ground conditions, estimated ground shaking hazards (see Section 9) and empirical methods developed internationally for the assessment of liquefaction.

The approach used for assessment and mapping of the liquefaction hazard is that developed by Brabhaharan (1994). This approach, tailored to suit this study, comprised :

- Identification of areas susceptible to liquefaction based on the geology
- Selection of key site investigation locations with good ground condition information
- Analyses of the potential for liquefaction using state-of-the-art empirical methods
- Mapping the liquefaction hazard using the point assessments and the geology maps

10.4.2 Liquefaction Susceptibility based on Geology

The liquefaction susceptibility of the study area was considered using the geology map developed for the study, see Figure 4. Areas with recent sediments were chosen for collection of additional site investigation information as discussed in Section 6.6. This was focussed on lifeline corridors.

<u>Estuarine Deposits</u>

Significant areas of fine grained soils are present in the Western Bay of Plenty study area. While the fine grained soils are generally considered to be resistant to liquefaction, the ground damage observations in Wellington during the 1855 Wairarapa Earthquake indicate that fine grained soils can liquefy (Brabhaharan et al, 1994).

Even when liquefaction of very soft fine grained soils does not occur, these soft soils can undergo severe loss of strength during ground shaking, and can give rise to ground strains and lateral spreading similar to ground damage experienced due to classic liquefaction.

The estuarine deposits in the study area vary from sands and silts to clays. The dominant materials are silts and sands and these are considered to be susceptible to liquefaction. A thickness of 5 m to 20 m or more of loose sediments are present in these areas.

<u>Volcanic Ash Deposits</u>

The terrace areas in Tauranga to Katikati are covered with volcanic ash deposits, which are generally clays, silts and some sand layers. These are generally firm to stiff or medium dense. These materials are generally considered to be resistant to liquefaction due to the fine grained plastic nature and the presence of some "welding effects" due to their volcanic origin. However, some localised loose sand layers may undergo minor liquefaction under strong ground shaking.

Older Terrace Deposits

The older terrace deposits such as in the Te Puke area include sand deposits, which are moderately dense and are of limited thickness. Also the older deposits tend to have a lower susceptibility to liquefaction due to ageing effects, which could lead to some inter-particle bonding. These areas can liquefy only in larger events and the thickness of liquefaction is smaller than other areas.

Coastal Sand Deposits

The coastal sand deposits comprise sands but these are generally medium dense to dense, consistent with their higher energy depositional environment. These are generally resistant to liquefaction, but may experience some liquefaction in large events.

Ignimbrite Areas

The areas shown as various ignimbrite sheets are generally completely weathered and are indicated to be clays and sands. There is limited information from these areas to assess the liquefaction. Some sites do have loose sands and silts which are likely to be susceptible. However, these may be localised and the predominant weathered ignimbrite soils are likely to be resistant to liquefaction. Given that there are limited lifelines through these areas, this uncertainty is less important.

10.4.3 Selection of Key Site Investigation Locations

About 75 site investigation locations were chosen from the large database of ground investigation information. The locations are indicated on Figure 2. The information was chosen in areas susceptible to liquefaction, in the vicinity of lifeline corridors and from adequate quality investigations with geotechnical information. However, given that the information of suitable quality with the necessary geographical spread was not available, some assumptions were made to supplement the factual information.

10.4.4 Liquefaction Analyses

The liquefaction analysis was carried out with the aid of software, using the Seed and Idriss approach as refined by the Robertson and Wride (1998) method for liquefaction assessment, presented by NCEER (1997). The method is based on empirical correlation of cyclic stress ratio and Standard Penetration Test 'N' values and Static Cone Penetration Test cone resistances, for soils which liquefied and those which did not liquefy in past earthquakes. The correlations are based on a large database of records.

$$\text{cyclic stress ratio} = 0.65 \,.\, a_{max} \,.\, \sigma_o \,.\, r_d \,/\, \sigma'_o .\, g$$

where,

	a_{max}	peak ground acceleration
	σ_o	total overburden stress at the depth under consideration
	r_d	stress reduction factor that reduces from 1 at the ground surface
	σ'_o	effective overburden stress at the same depth
	g	gravitational acceleration

The penetration test values were corrected for overburden pressure. The fines content of the soils were used (where not available assumed) to make allowance for the increased liquefaction resistance associated with the proportion of fines in the soils.

The liquefaction hazard was assessed for the two uniform hazard levels of :

- 10% probability in 50 years (475 year return period), and
- 2% probability in 50 years (2,500 year return period).

Given that the contribution to these hazards comes from a variety of earthquake events with different magnitudes, it would be difficult to use the peak ground accelerations and magnitude in the liquefaction assessment. Therefore, magnitude-weighted peak ground accelerations, derived as discussed in Section 9.6, were used in the liquefaction analysis. Maps showing the magnitude-weighted peak ground accelerations assessed for the 10% in 50 years and 2% in 50 years hazard levels are given in Appendix B (Figures B12 and B13). These also allow for amplification or attenuation of ground motions based on the ground class in different areas identified in Figure 5.

The assessment at each key investigation location identified the potential for liquefaction and the thickness and depth of the soil horizons likely to liquefy.

10.5 Liquefaction Hazard Mapping

The liquefaction hazard was then mapped by considering the point assessments of liquefaction potential and the extent of liquefaction based on the geographical spread of the point estimates and the geological extent of the soils.

The liquefaction potential has been mapped into five classes depending on the likelihood of liquefaction in different uniform ground shaking hazard levels, the depth of liquefaction and extent of associated ground deformation. The classes are presented in Table 8.

Table 8 Liquefaction Potential Classes

Class	Liquefaction Potential	Description
1	No Liquefaction	Liquefaction unlikely in any scenario, except locally such as in stream deposits or fill.
2	Localised liquefaction	Liquefaction is generally unlikely but there may be limited areas that are likely to liquefy in a large earthquake event.
3	Minor Liquefaction	No liquefaction likely in a 10% in 50 year earthquake shaking, but liquefaction of limited layers may occur in a larger 2% in 50 year earthquake event.
4	Moderate Liquefaction	Liquefaction is likely in both 10% and 2% in 50 year earthquake shaking, in localised areas or are associated with limited ground damage.
5	Widespread Liquefaction	Liquefaction is likely to be extensive in both 10% and 2% in 50 year earthquake shaking and could lead to significant ground damage.

The liquefaction hazard classes present the potential for liquefaction in both 10% and 2% in 50 years uniform hazard shaking levels. This has enabled the liquefaction hazards to be presented in one map for both hazard levels. This is considered more appropriate for the liquefaction hazard maps, than preparing different hazard maps for the two uniform hazard levels such as those presented for the ground shaking hazard maps which present numerical peak ground accelerations for each of the hazard levels.

The liquefaction hazard has been mapped as shown on Figure 12 to a scale of 1:250,000. A 1:50,000 enlargement for the Tauranga urban area is presented on Figure 13.

10.6 Liquefaction Induced Ground Damage

10.6.1 Consequences of Liquefaction

Liquefaction can lead to the following effects, that can cause damage to lifelines :

- Ground damage – subsidence, lateral spreading, flow failure, slope failure
- Bouyancy of buried services, tanks and chambers (manholes)
- Foundation failure due to reduction / loss of bearing capacity
- Settlement of structures on liquefied materials

10.6.2 Types of Ground Damage

The liquefaction induced ground damage is of importance for most lifeline networks, as ground damage causes damage and disruption to most lifelines.

Liquefaction can lead to ground damage in the form of subsidence, failure of sloping ground, flow failure and lateral spreading of ground towards natural banks and embankments built on liquefiable ground. The presence of a surface layer that is resistant to liquefaction could reduce the ground damage at the surface due to the liquefaction of underlying layers. However, where lateral spreading is likely, the presence of a non-liquefiable layer may not preclude ground damage. In addition, recent studies have indicated that the presence of lower permeability layers overlying liquefiable soil layers, may lead to the formation of water films at the interface, leading to significant lateral spreading (Kokusho, 1999) and liquefaction of overlying denser layers.

The actual ground damage will depend on the liquefiable soils, their thickness, and the topography of the area. The possible ground damage has been assessed based on the subsidence analysis, literature and engineering judgement.

10.6.3 Ground Subsidence

The ground subsidence has been assessed based on the method of Ishihara and Yoshimine (1992) for each key site investigation location chosen for liquefaction assessment. These very approximate subsidence estimates range from less than 10 mm to over 1000 mm.

Indicative ground subsidence for the different liquefaction potential classes in a 10% in 50 year earthquake shaking are given in Table 9.

Table 9 Liquefaction Induced Subsidence

Class	Liquefaction Potential	Order of Magnitude of Subsidence (mm)
1	No Liquefaction	None
2	Localised liquefaction	Variable but likely to be small.
3	Minor Liquefaction	Less than 100 mm
4	Moderate Liquefaction	100 mm to 300 mm
5	Extensive Liquefaction	Greater than 300 mm and possibly over 1000 mm in places.

10.6.4 Slope Failures

Most areas likely to liquefy in the Western Bay of Plenty study area are in relatively flat areas. Liquefaction is therefore likely to cause slope failures predominantly along the banks of water courses and coastal banks. These are lateral spreading type failures and are discussed in Section 10.6.5.

10.6.5 Lateral Spreading

Lateral spreading could occur along river / stream banks and coastal areas, where the liquefied ground could displace towards the free surface. Any embankments or bridge abutments built on liquefiable ground are also likely to be affected.

The simple rules in Table 10 were developed to give an indication of the degree and extent of liquefaction-induced lateral spread, recognising that the extent is likely to be variable.

Table 10 Liquefaction Induced Lateral Spreading Assumptions

Liquefaction Potential Zone	Distance from bank/ shore	10% in 50 years	2% in 50 years
1		No liquefaction ground damage	
2 and 3		No significant ground damage or uncertain.	
4	Within 50 m	Significant ground damage	Extensive ground damage
	50 m to 100 m	Minor ground damage	Significant ground damage
5	Within 50 m	Extensive ground damage	Extensive ground damage
	50 m to 200 m	Significant ground damage	Significant ground damage

Notes : Ground deformation definitions

- Minor 10s of millimetres to 200 mm
- Significant 100s of millimetres to 1 metre
- Extensive few metres

While these assumptions are approximate only, they could provide a basis for identifying areas where lateral spreading damage to lifelines need to be considered.

10.6.6 Mapping Liquefaction Ground Damage Hazards

The ground damage (subsidence and lateral spreading) assessments have been used to map the liquefaction ground damage hazards, based on the liquefaction hazard and the proximity of river / stream banks and shorelines. The classification of the liquefaction ground damage hazards is presented in Table 11.

Table 11 Liquefaction Ground Damage Classification

Liquefaction Ground Damage Zone	Class Description	10% in 50 years	2% in 50 years
A	None	No liquefaction ground damage	
B	Localised minor	Localised minor subsidence	
C	Minor	Minor subsidence (less than 100 mm)	
D	Limited	Moderate subsidence (say 100 mm to 300 mm)	
E	Moderate	Large Subsidence (say greater than 300 mm)	
F	Large	Minor lateral spreading and moderate subsidence	Significant lateral spreading and moderate subsidence
G	Major	Significant lateral spreading and large subsidence	
H	Widespread	Significant lateral spreading and moderate subsidence.	Extensive lateral spreading and moderate subsidence
I	Extensive	Extensive lateral spreading and large subsidence	

Notes : Lateral spreading definitions

- Minor 10s of millimetres to 200 mm
- Significant 100s of millimetres to 1 metre
- Extensive up to few metres

The subsidence and lateral spreading ground damage estimates have been used to map the liquefaction induced ground damage hazards, and are presented in Figure 14 for the study area at 1:250,000 scale. A 1:50,000 scale enlargement for the Tauranga urban area is presented on Figure 15.

The liquefaction and ground damage hazard maps provide a valuable resource for the assessment and management of risk to lifelines (Brabhaharan, 2000).

10.7 Limitations

The liquefaction assessment has been carried out as a regional hazard assessment based on the available information and within the available time and resources. It should not be considered as a substitute for site-specific site investigations and geotechnical engineering assessment for any project.
The following specific limitations apply for the products of this study :

(a) While the zones of liquefaction potential have been shown on the map, there is no certainty of liquefaction in a particular area due to an earthquake of any size.

(b) It is possible that liquefaction could occur in some isolated areas not shown to have liquefaction potential, for example near streams.

(c) The classification of liquefaction potential is indicative only, and does not imply any level of damage to particular structures or lifelines.

(d) The magnitudes of ground damage suggested in the report are indicative only.

(e) The boundaries of the various liquefaction zones are approximate only based on a regional study and should be used with caution.

(f) There is limited amount of information in parts of the study area, and the liquefaction hazard suggested is indicative based on the geology only.

(g) Site-specific assessment should be undertaken for the performance at a particular site.

11 Slope Failure Hazards

An assessment and mapping of earthquake induced slope failure hazards was planned as part of this study. The following data was compiled to facilitate this assessment :

(a) Map of relic landslides in the Tauranga area

(b) Geology of the area

(c) Groundwater conditions in the area

(d) Topography of the area as digital terrain models.

The digital terrain model was developed as a combined coverage comprising the LINZ data and LIDAR data from a coastal survey. However, as discussed in Section 6.9, the more accurate LIDAR data was found to contain non-ground information making it unusable for this study, and the terrain model available from the LINZ database was found to be of inadequate accuracy at 20 m contours given the limited relief associated with the terrain in the important urban area and lifeline corridors.

It is understood that data of better accuracy would become available later. Therefore, it was decided that slope failure hazard assessment and mapping would be deferred and carried out as a separate study.

Earthquake induced slope failures can cause major damage to lifelines, and should be assessed and mapped for use in the assessment of the performance of lifelines, and management of the risk.

12 Mapping

12.1 Geographical Information Systems Approach

All the component maps and hazard maps have been produced using a geographical information system database, as coverages. This has facilitated derivation of the hazard maps and would also be available as digital data, which can be used in considering the risks during the lifeline study.

The maps have been produced as GIS coverages using the ARC/INFO and ArcView systems.

12.2 Map Scale

The maps have been produced at 1:250,000 scale in the report. Larger scale maps of the liquefaction hazard to 1:50,000 scale are presented for the Tauranga urban area.

13 Summary

1) The earthquake hazards in the Western Bay of Plenty study area have been assessed using available information.
2) Additional active fault information and study of the characteristics is being carried out by various organisations and these may become available later.
3) A large database of ground information was compiled from existing site investigation reports from various sources including Opus and Tauranga District Council records. All the investigation reports were compiled into a GIS database.
4) Some additional site investigations were carried out and additional information was obtained through some site investigations that included four boreholes and 20 Static Cone Penetration Tests.
5) The area was characterised and mapped into five ground classes, A to E, which are consistent with the draft Australia / New Zealand loadings standard.
6) There are no active faults in the study area, and therefore there are no known fault rupture hazards in the study area. But there are faults outside the area, which can lead to earthquake shaking in the study area.
7) The ground shaking has been assessed using the New Zealand National Seismic Hazard Model, and the active faults and distributed seismicity sources.
8) The assessment makes allowance for amplification of ground shaking with deep sediments and attenuation of peak ground accelerations in very soft ground conditions.
9) The ground shaking hazard maps have been derived using the assessed peak ground accelerations for the 10% and 2% in 50 year uniform hazard levels and in four scenarios, and the ground class characterisation of the study area.
10) The ground shaking hazards have been assessed for two uniform-hazard levels, 10% probability in 50 years (475 year return period) and 2% probability in 50 years (2500 year return period).
11) The ground shaking hazard in the study area is a combination of a number of fault sources and distributed seismicity, and no one source dominates the hazard.
12) The ground shaking hazard has also been assessed for four scenarios – a local source near Tauranga, the Mayor Island Fault, the Matata Fault and the South Kerepehi Fault scenarios.
13) The hazard estimates are presented in terms of peak ground accelerations, which are appropriate for many lifeline structures and components. The pga cannot be scaled to other spectral periods, because the relationships of spectral accelerations to pga vary with site condition, and magnitude and distance of the earthquakes contributing to the hazard. For some structures, it may be necessary to derive spectral accelerations from specific studies, and this is possible from the New Zealand National Seismic Hazard Model.

14) The ground shaking assessed is shown on Figure 6 to Figure 11, and is summarised below for the main centres of the study area :

	Peak Ground Acceleration (g)				
	Waihi Beach	**Kati Kati**	**Tauranga**	**Mt Maunganui**	**Te Puke**
Uniform Hazard 10% in 50 years	0.2 to 0.3	0.25 to 0.35	0.25 to 0.35	0.25 to 0.3	0.25 to 0.3
Uniform Hazard 2% in 50 years	0.3 to 0.5	0.35 to 0.5	0.4 to 0.5	0.35 to 0.45	0.35 to 0.45
Scenario: Tauranga Local Source	Up to 0.2	Up to 0.25	0.2 to 0.35	Up to 0.25	Up to 0.2
Scenario : Mayor Island Fault	0.2 to 0.3	0.2 to 0.3	0.25 to 0.4	0.25 to 0.35	0.2 to 0.3
Scenario : Matata Fault	Up to 0.2				
Scenario : Kerepehi South Fault	Up to 0.25	0.2 to 0.35	Up to 0.25	Up to 0.2	Up to 0.2

15) There are no known historical records of liquefaction in the area, probably a reflection of the lack of significant earthquake events in the area during the last 150 years since European settlement.

16) The liquefaction hazard has been mapped using the assessed liquefaction potential, ground subsidence and the geology of the study area, and is presented in Figure 12.

17) There are significant liquefaction hazards in the study area.

18) The potential ground damage from liquefaction is presented in Figure 14.

19) The slope failure hazard assessment has been deferred due to the lack of good terrain model information, and the likely availability of this information soon.

20) The hazard maps have been prepared as ArcView geographical information system coverages.

21) The earthquake microzoning presented has been assessed on a regional scale and the limitations of the maps are outlined.

22) The earthquake microzoning maps and report provide a good basis for the assessment of the risk to the lifelines in the study area. The maps present potential hazards and it is important to assess the effects of these hazards on each particular lifeline, the potential for damage and the consequences. This will enable an assessment of the risk and development of risk management measures.

14 Recommendations

The following recommendations are made based on this study :

(a) The earthquake hazard maps presented in Figure 6 to Figure 15 be used as a basis for the lifelines study.

(b) That the earthquake hazards be presented and explained by the authors of this report to the lifelines group in a workshop to help them better appreciate the use and limitations of this study for their further risk evaluation.

(c) The earthquake induced slope failure hazards should be assessed and mapped to facilitate the assessment of the risk to lifelines from these hazards. Further more accurate topographical information should be collated to facilitate this assessment.

(d) The earthquake hazards should be reviewed periodically to update the hazards when further significant information becomes available. In particular, when additional new offshore fault information becomes available, the significance of this be reviewed, and if significant, the earthquake hazards assessed in this study be updated.

(e) A better digital terrain model be developed and used for assessment and mapping of the earthquake induced slope failure hazards for the study area.

(f) The ground information database and GIS coverage be structured and kept up to date for future studies.

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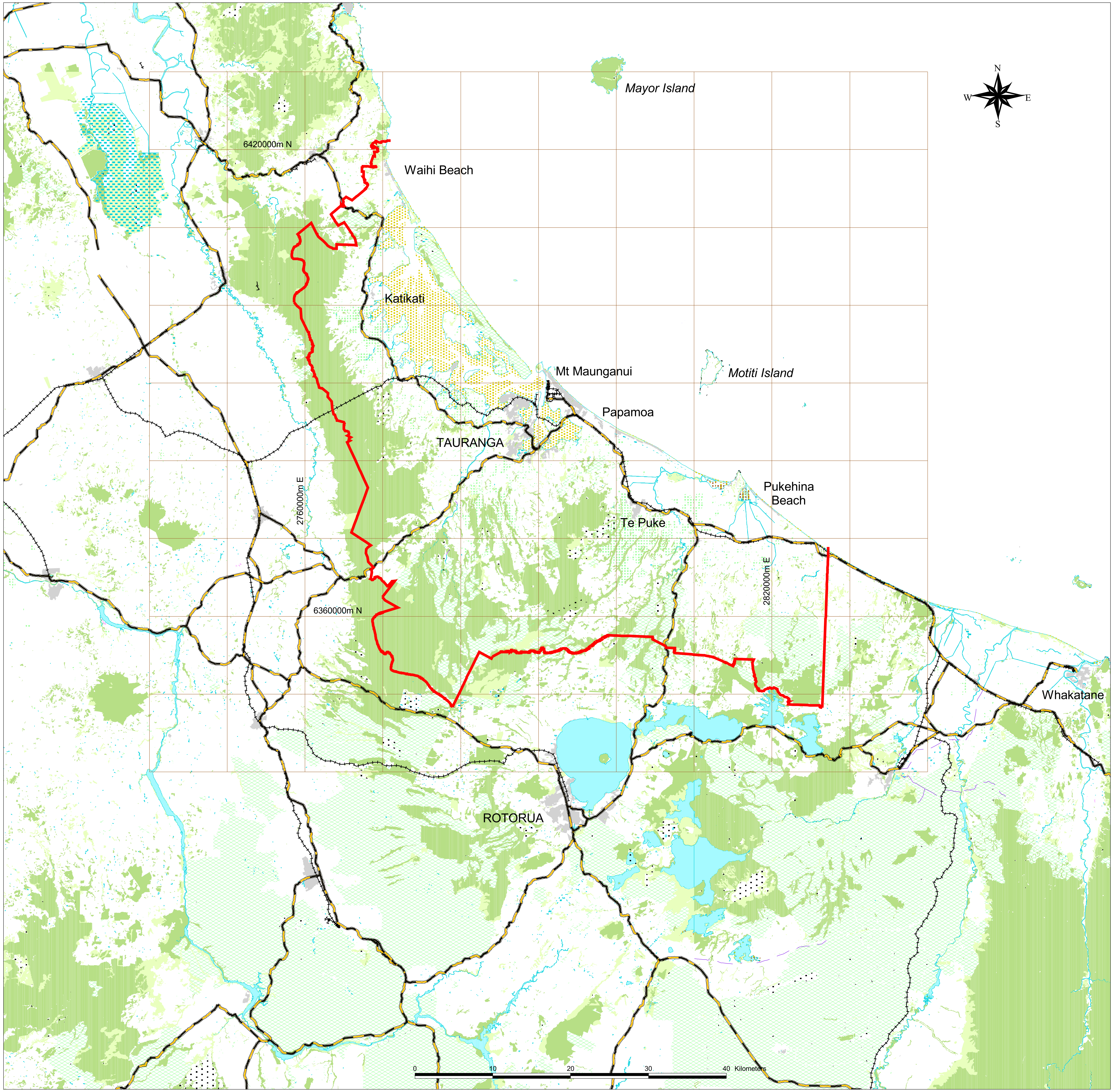
The contributions of the following organisations and staff to this project is acknowledged :

- Tauranga District Council
- Western Bay of Plenty District Council
- Environment Bay of Plenty
- Earthquake Commission
- Opus International Consultants, Hamilton
- Institute of Geological and Nuclear Sciences
- Port of Tauranga
- Transit New Zealand
- Montgomery Watson, Hamilton
- Natural Gas Corporation
- Pacific Health
- Gull Petroleum Ltd
- Perry Drilling Limited
- Smithbridge New Zealand
- Beca Carter Hollings & Ferner, Tauranga (& Marianne O'Halloran)
- CH2M BECA, Auckland
- Connell Wagner, Tauranga
- Harrison & Grierson, Tauranga
- Smithbridge New Zealand
- Shrimpton & Lipinski
- Marine Parade Motel

Figures



Title: The Study Area

Project: Western Bay of Plenty Lifelines Study
Microzoning for Earthquake Hazards

Prepared for: Western Bay of Plenty lifelines Engineering

Prepared by: OPUS; Institute of Geological & Nuclear Sciences Limited

Job No:	Date:	Figure:
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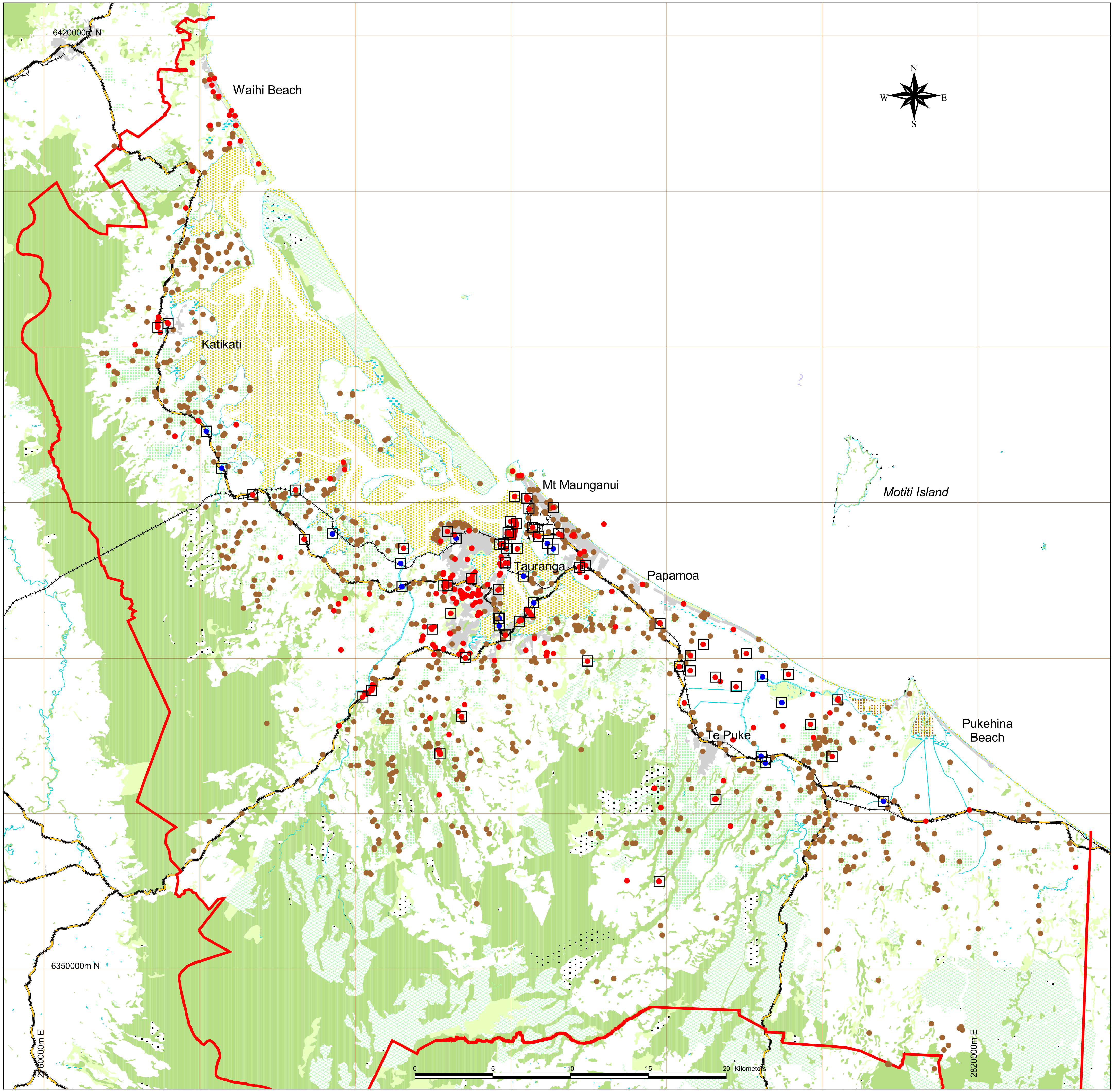


LEGEND

- Key locations chosen for liquefaction assessment
- Locations of past investigations
- Locations of wells - EBOP
- Locations of investigations this study
- Study Area

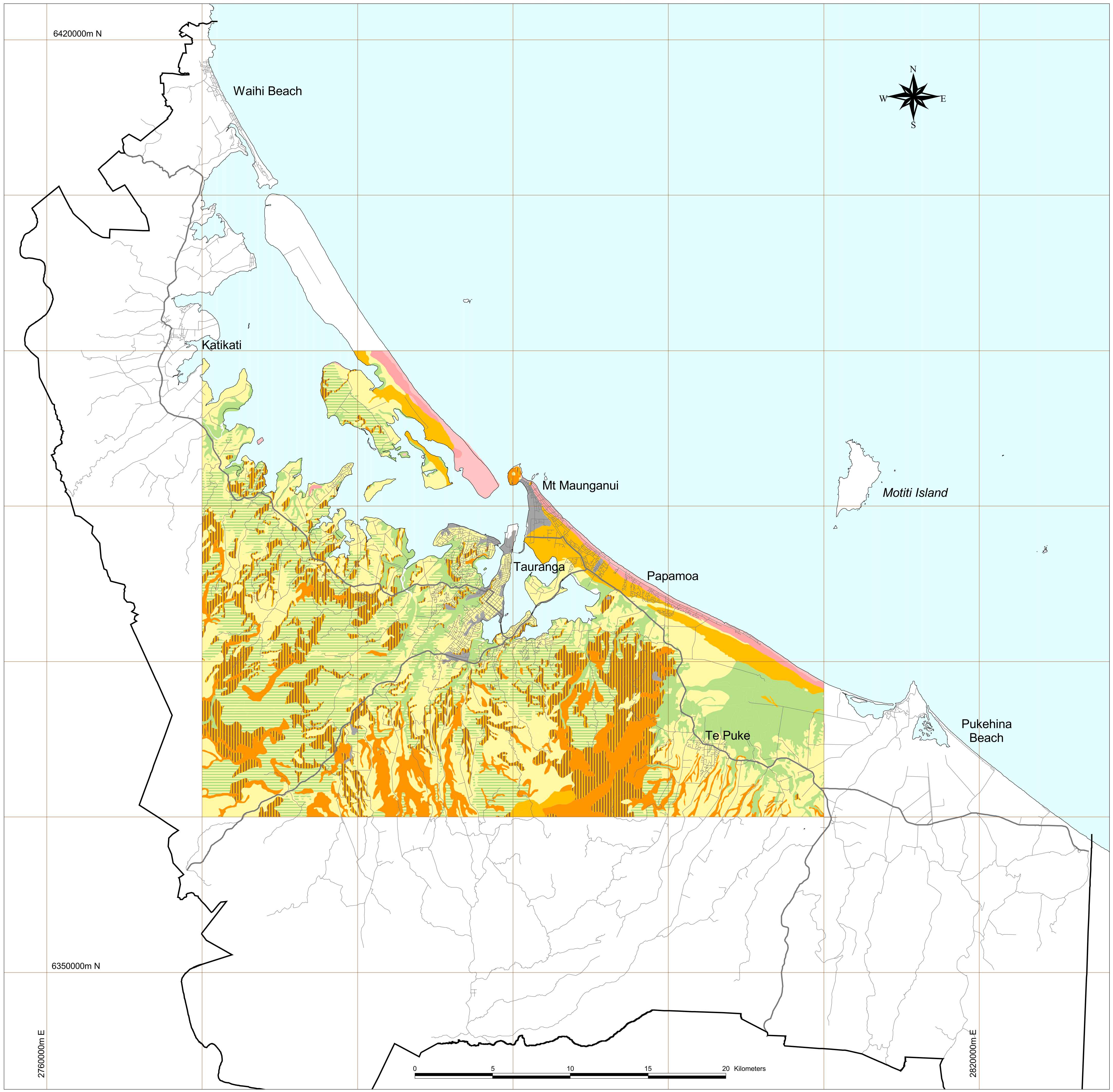
Title:
Locations of Past Site Investigations

Project:
Western Bay of Plenty Lifelines Study
Microzoning for Earthquake Hazards

Prepared for:
WESTERN BAY OF PLENTY lifelines ENGINEERING

Prepared by:
OPUS
Institute of Geological & Nuclear Sciences Limited

Job No:	Date:	Figure:
5C2931.00	December 2002	2



LEGEND

Study Area

Soil Classification

- Katikati sandy loam
- Katikati sandy loam, rolling phase
- Manoeka fine sandy loam
- Omarumutu sandy loam
- Paengaroa sandy loam
- Parawhenuamea sandy loam
- Parton fine sandy loam
- Pukeroa sandy loam
- Te Puke sandy loam
- Te Puke sandy loam, rolling phase
- Waipumuka sandy loam
- Whakamarama fine sandy loam
- Whakamarama sandy loam, rolling phase
- Wharere sandy loam
- Kopuroa silt loam
- Muriwai silt loam
- Ohineangaanga silt loam
- Pahoia silt loam
- Raparapahoe silt loam
- Te Matai silt loam
- Te Puna silt loam
- Waiari silt loam
- Man-made soils
- Ohope sand
- Papamoa loamy sand
- Kairua loamy sand
- Oropi loamy sand
- Katikati hill soils
- Te Puke hill soils
- Whakamarama hill soils
- Otanewainuku steepland soils

From Lancare Research New Zealand Limited, 2002

Title:

Soil Map

Project:
Western Bay of Plenty Lifelines Study
Microzoning for Earthquake Hazards

Prepared for:

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Job No:	Date:	Figure:
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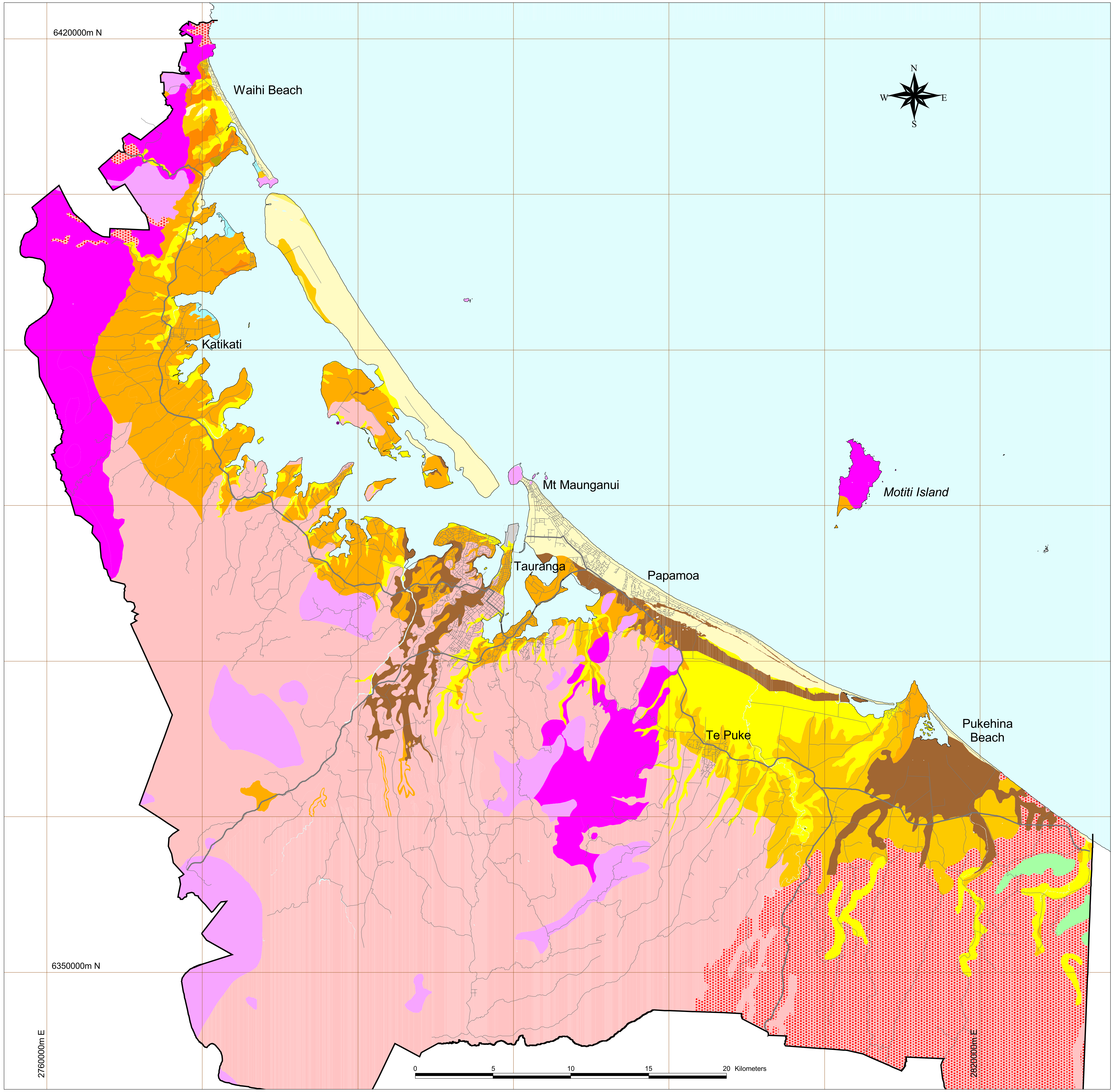

LEGEND

Study Area

Geology

- Fill
- Landslide deposits
- Dune sediments
- Beach sediments
- Peat
- Alluvium
- Estuarine sediments
- Late Quaternary sediments
- Alluvium, estuarine sediments
- Alluvium and colluvium
- Differentiated ignimbrites
- Ignimbrite/Pumice breccias
- Andesite and dacite
- Rhyolite
- Basalt
- Greywacke
- Water

Title:

Geological Map

Project:
Western Bay of Plenty Lifelines Study
Microzoning for Earthquake Hazards

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Job No:	Date:	Figure:
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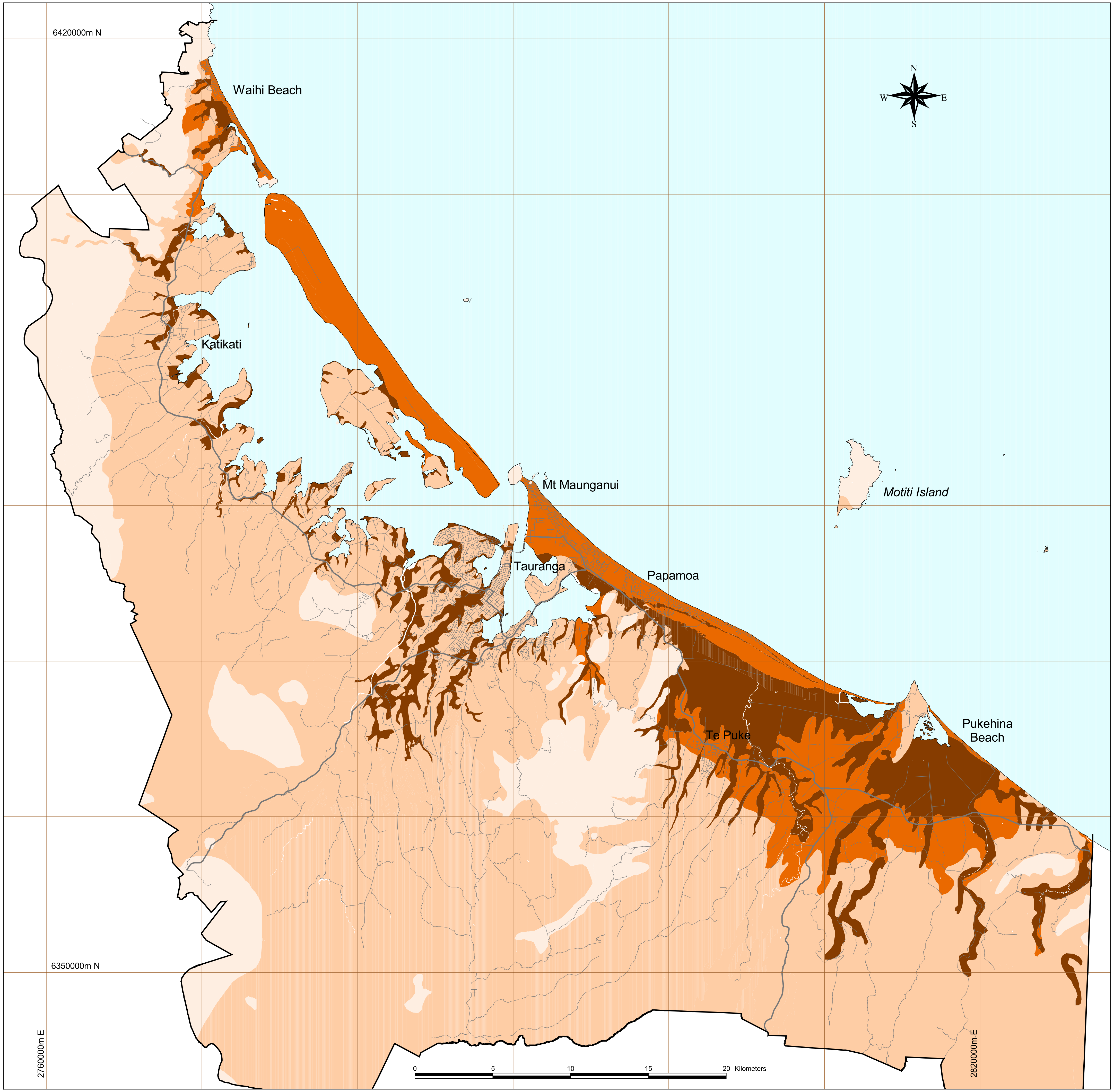

LEGEND

Study Area
Ground Class
Class A - Strong rock
Class C - Shallow stiff soil
Class D - Deep or soft soil
Class E - Very soft soil

Title:

Ground Class Map

Project:
Western Bay of Plenty Lifelines Study
Microzoning for Earthquake Hazards

Prepared for:

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Job No:	Date:	Figure:
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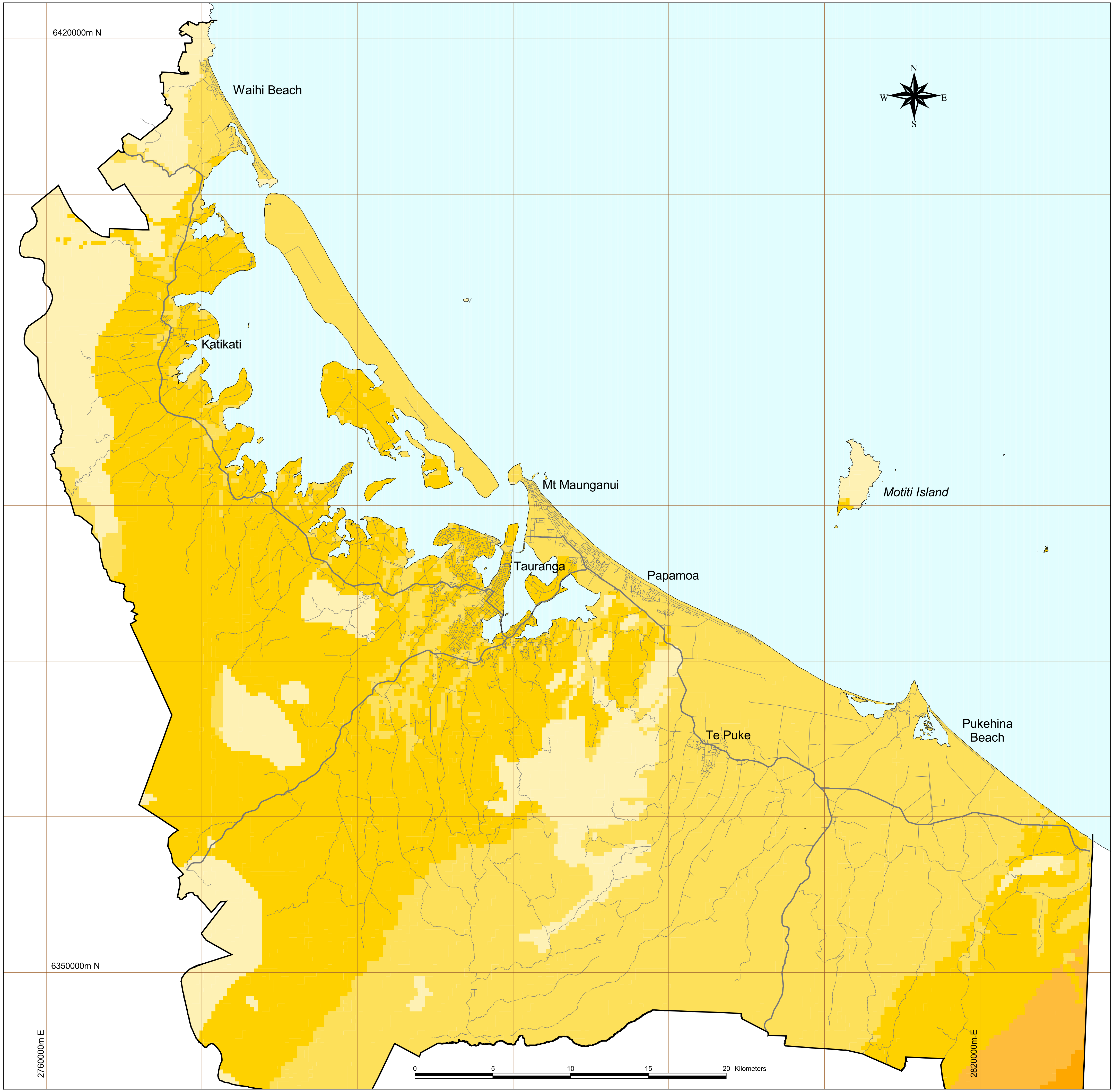

IMPORTANT NOTES

Accompanying Report

This map should be used in conjunction with the report "Western Bay of Plenty Lifelines Study : Microzoning for Earthquake Hazards" (Opus International Consultants, 2002).

Limitations

The zone boundaries on this map are approximate only and have been determined with the aid of a national seismic hazard model, regional geological maps and available borehole data. Accuracy can vary from few tens of metres to few hundreds of metres.

Localised areas of enhanced hazard may be present within areas identified as having a low hazard, and also the hazard may be lower in some sections identified as having a high hazard.

Site-specific assessment of the hazard (such as ground shaking or liquefaction) based on site-specific investigations and risk should be considered for assessing the performance or design of a specific facility.

LEGEND

Study Area

Peak Ground Acceleration (g)

- 0.01 - 0.2
- 0.2 - 0.25
- 0.25 - 0.3
- 0.3 - 0.35
- 0.35 - 0.4
- 0.4 - 0.45
- 0.45 - 0.5
- 0.5 - 0.6
- 0.6 - 0.85

Title:

Ground Shaking Hazard Map 10% Probability in 50 Years

Project:
Western Bay of Plenty Lifelines Study
Microzoning for Earthquake Hazards

Prepared for:
WESTERN BAY OF PLENTY lifelines ENGINEERING

Prepared by:
OPUS
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Job No:	Date:	Figure:
5C2931.00	December 2002	6

IMPORTANT NOTES

Accompanying Report

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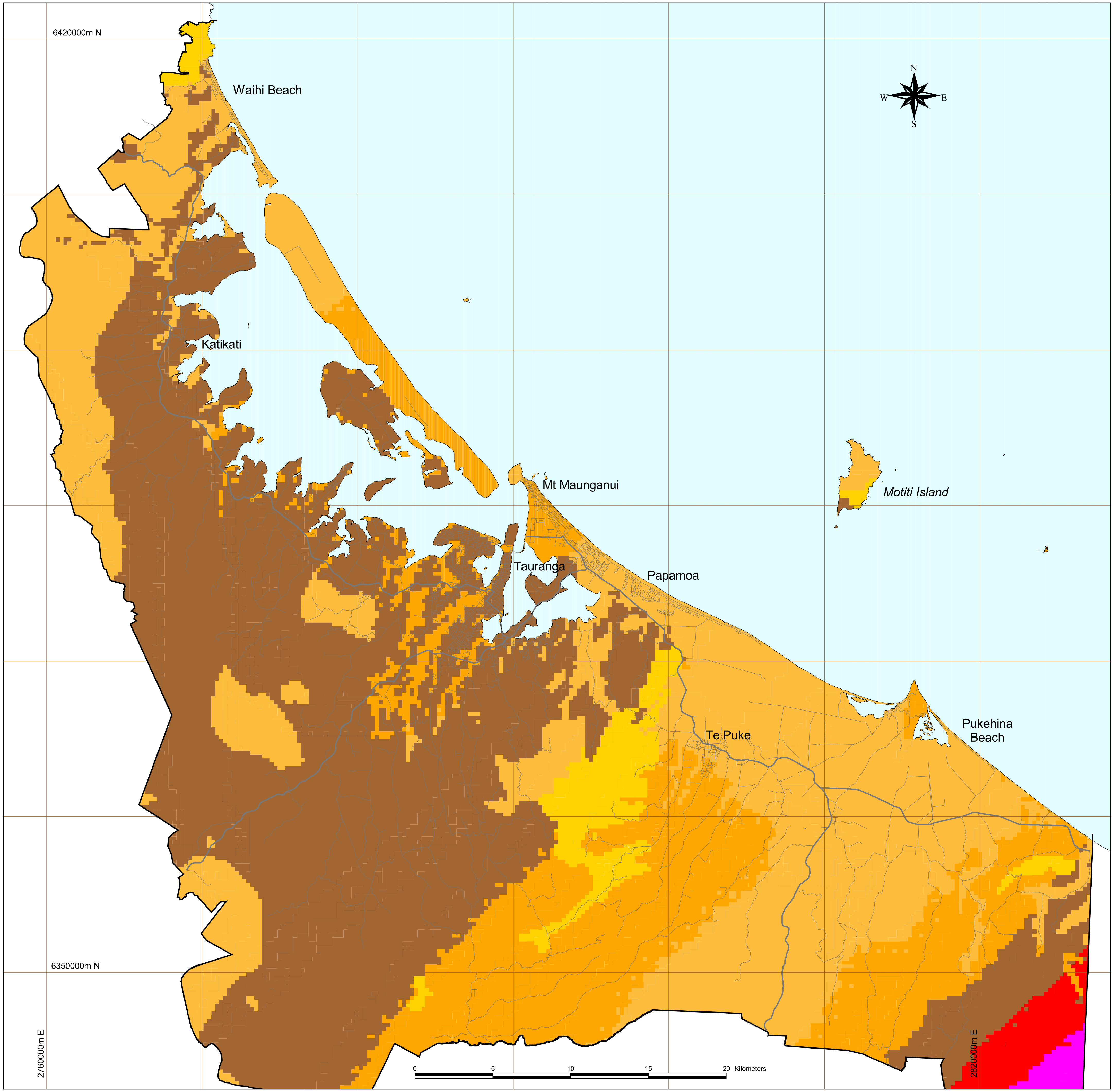

LEGEND

Study Area

Peak Ground Acceleration (g)

- 0.01 - 0.2
- 0.2 - 0.25
- 0.25 - 0.3
- 0.3 - 0.35
- 0.35 - 0.4
- 0.4 - 0.45
- 0.45 - 0.5
- 0.5 - 0.6
- 0.6 - 0.85

Title:

Ground Shaking Hazard Map 2% Probability in 50 Years

Project:

Western Bay of Plenty Lifelines Study
Microzoning for Earthquake Hazards

Prepared for:

WESTERN BAY OF PLENTY lifelines ENGINEERING

Prepared by:

OPUS

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Job No:	Date:	Figure:
5C2931.00	December 2002	7

IMPORTANT NOTES

Accompanying Report

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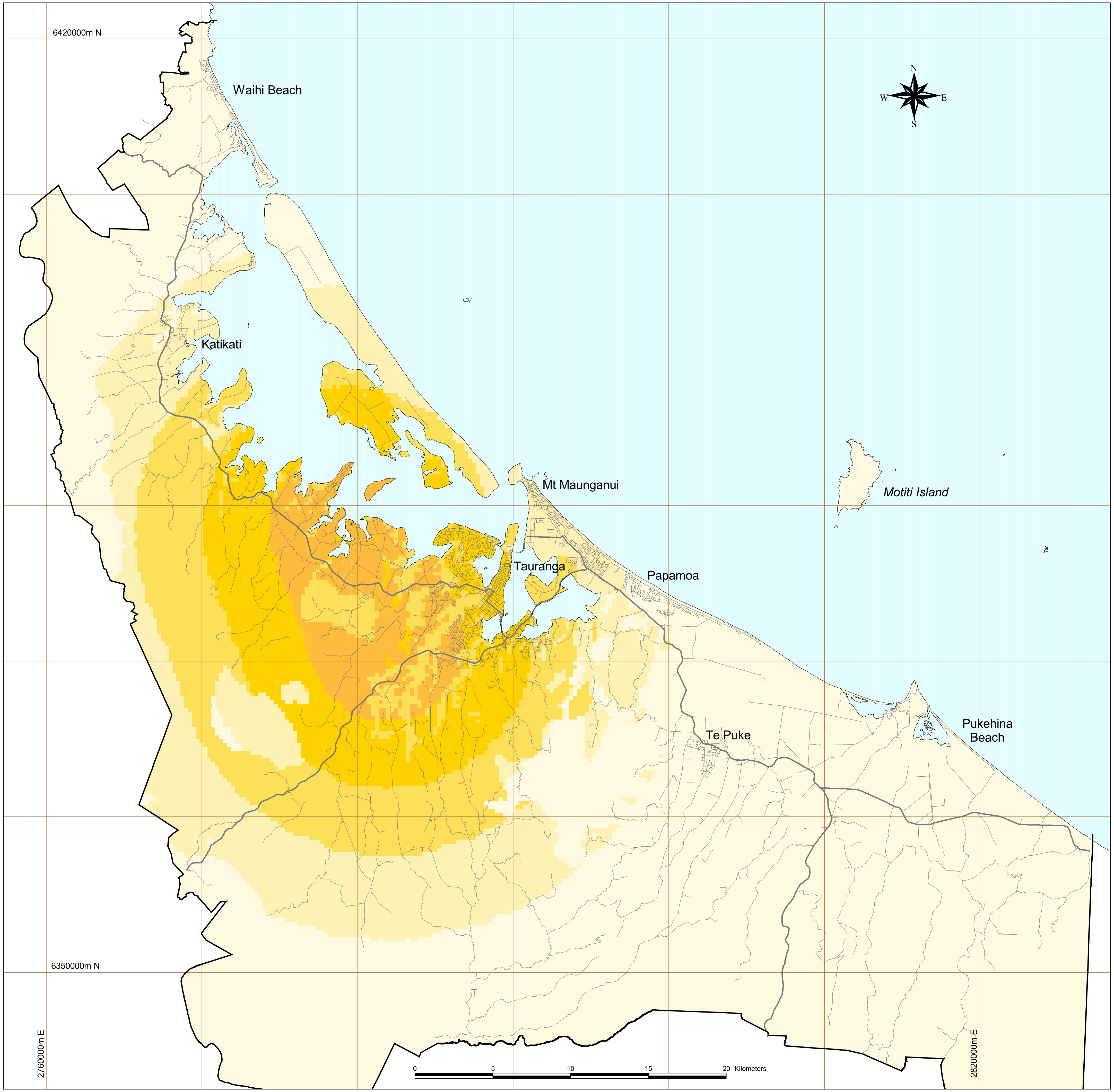

LEGEND

Study Area

Peak Ground Acceleration (g)

- 0.01 - 0.2
- 0.2 - 0.25
- 0.25 - 0.3
- 0.3 - 0.35
- 0.35 - 0.4
- 0.4 - 0.45
- 0.45 - 0.5
- 0.5 - 0.6
- 0.6 - 0.85

Title:

Ground Shaking Hazard Map
Tauranga Local Source Scenario

Project:
Western Bay of Plenty Lifelines Study
Microzoning for Earthquake Hazards

Prepared for:

WESTERN BAY OF PLENTY lifelines ENGINEERING

Prepared by:

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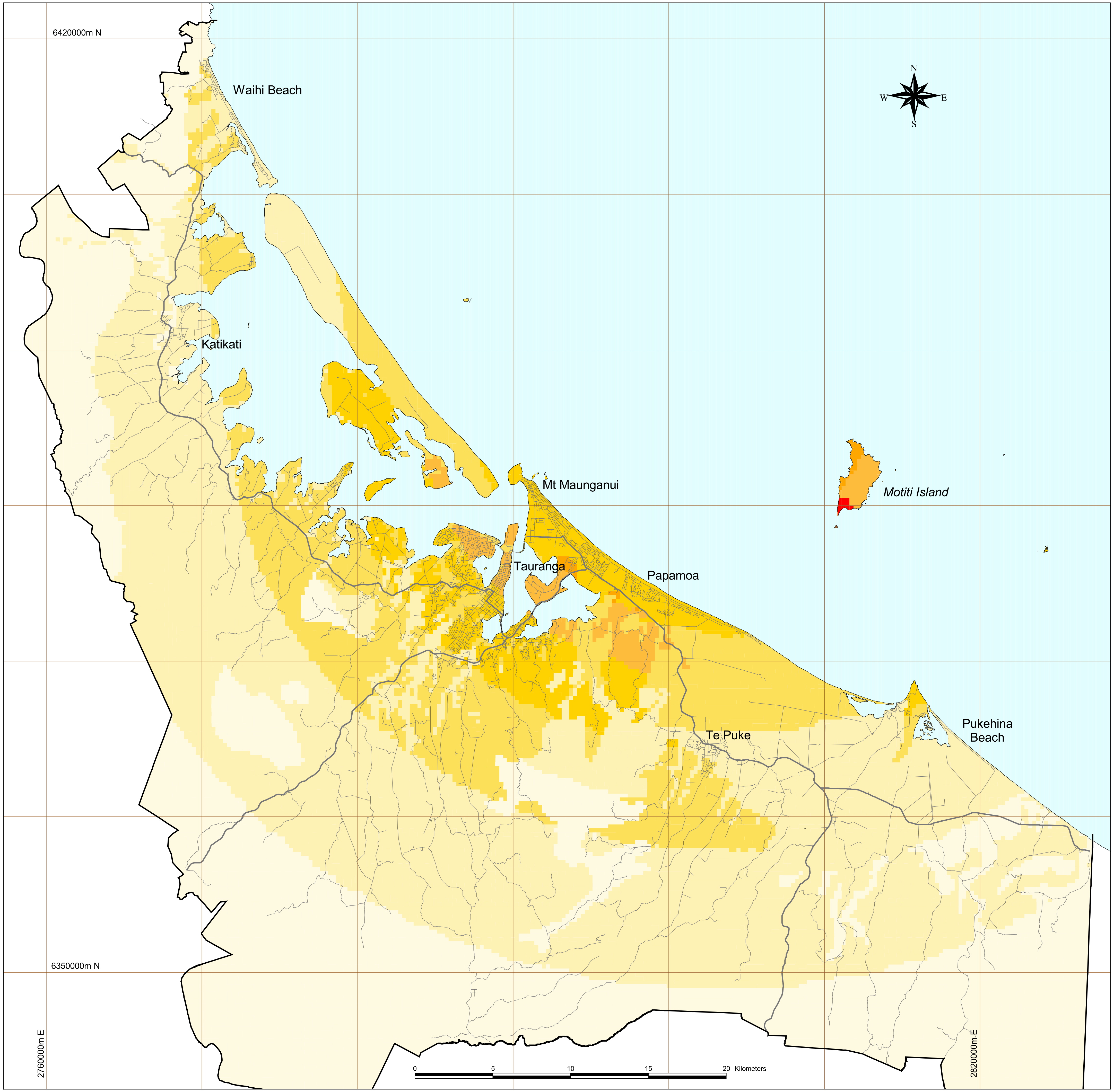
Institute of Geological & Nuclear Sciences Limited

Job No:	Date:	Figure:
5C2931.00	December 2002	8



IMPORTANT NOTES

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Site-specific assessment of the hazard (such as ground shaking or liquefaction) based on site-specific investigations and risk should be considered for assessing the performance or design of a specific facility.

LEGEND

Study Area

Peak Ground Acceleration (g)

- 0.01 - 0.2
- 0.2 - 0.25
- 0.25 - 0.3
- 0.3 - 0.35
- 0.35 - 0.4
- 0.4 - 0.45
- 0.45 - 0.5
- 0.5 - 0.6
- 0.6 - 0.85

Title:
Ground Shaking Hazard Map
Mayor Island Fault Scenario

Project:
Western Bay of Plenty Lifelines Study
Microzoning for Earthquake Hazards

Prepared for:

WESTERN BAY OF PLENTY lifelines ENGINEERING

Prepared by:

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Job No:	Date:	Figure:
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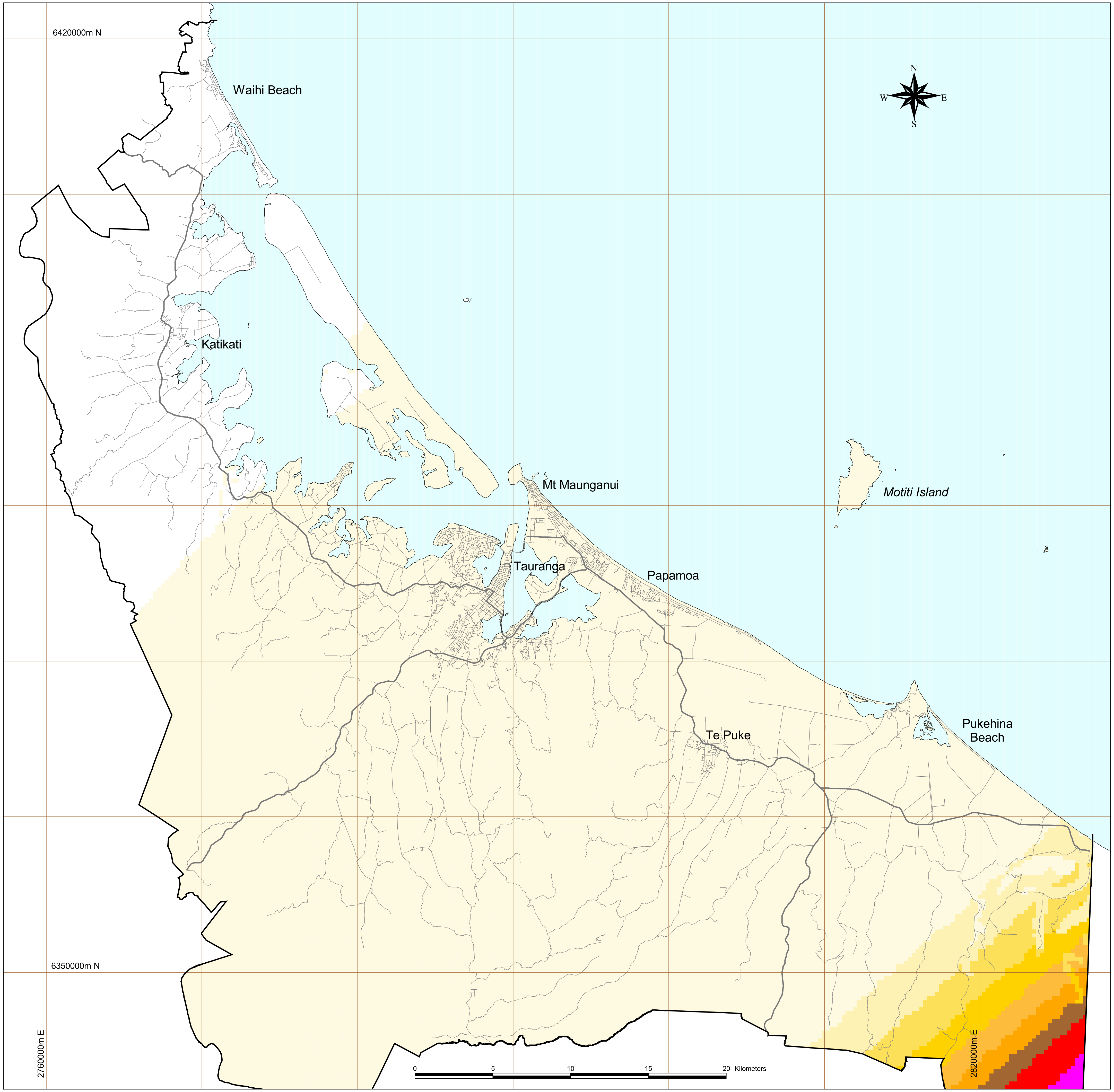

IMPORTANT NOTES

Accompanying Report

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Limitations

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Site-specific assessment of the hazard (such as ground shaking or liquefaction) based on site-specific investigations and risk should be considered for assessing the performance or design of a specific facility.

LEGEND

Study Area

Peak Ground Acceleration (g)

- 0.01 - 0.2
- 0.2 - 0.25
- 0.25 - 0.3
- 0.3 - 0.35
- 0.35 - 0.4
- 0.4 - 0.45
- 0.45 - 0.5
- 0.5 - 0.6
- 0.6 - 0.85

Title:

Ground Shaking Hazard Map
Matata Fault Scenario

Project:

Western Bay of Plenty Lifelines Study
Microzoning for Earthquake Hazards

Prepared for:

WESTERN BAY OF PLENTY lifelines ENGINEERING

Prepared by:

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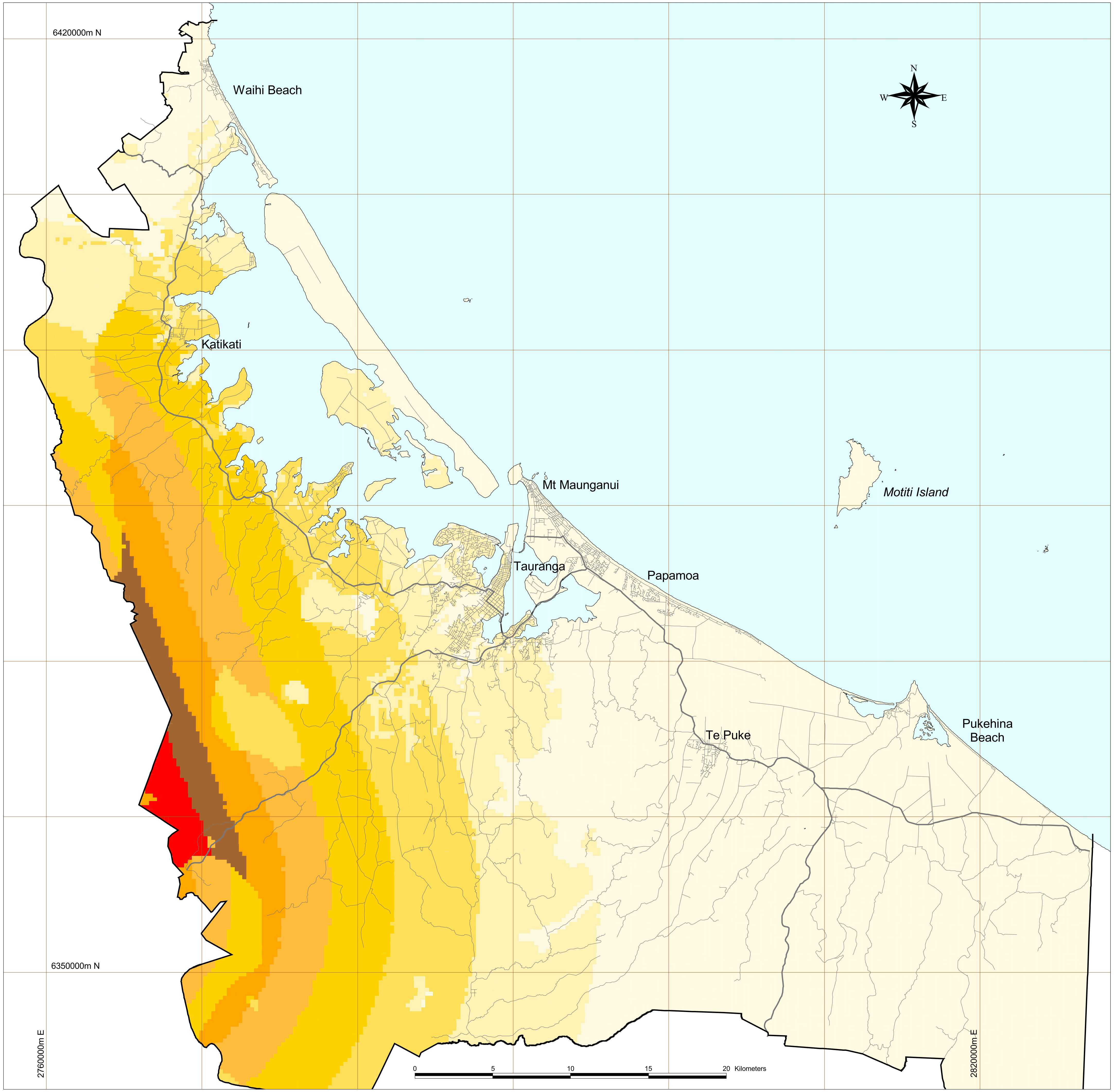
Institute of Geological & Nuclear Sciences Limited

Job No:	Date:	Figure:
5C2931.00	December 2002	10



IMPORTANT NOTES

Accompanying Report

This map should be used in conjunction with the report "Western Bay of Plenty Lifelines Study : Microzoning for Earthquake Hazards" (Opus International Consultants, 2002).

Limitations

The zone boundaries on this map are approximate only and have been determined with the aid of a national seismic hazard model, regional geological maps and available borehole data. Accuracy can vary from few tens of metres to few hundreds of metres.

Localised areas of enhanced hazard may be present within areas identified as having a low hazard, and also the hazard may be lower in some sections identified as having a high hazard.

Site-specific assessment of the hazard (such as ground shaking or liquefaction) based on site-specific investigations and risk should be considered for assessing the performance or design of a specific facility.

LEGEND

Study Area

Peak Ground Acceleration (g)

- 0.01 - 0.2
- 0.2 - 0.25
- 0.25 - 0.3
- 0.3 - 0.35
- 0.35 - 0.4
- 0.4 - 0.45
- 0.45 - 0.5
- 0.5 - 0.6
- 0.6 - 0.85

Title:

Ground Shaking Hazard Map
Kerepehi South Fault Scenario

Project:
Western Bay of Plenty Lifelines Study
Microzoning for Earthquake Hazards

Prepared for:

WESTERN BAY OF PLENTY lifelines ENGINEERING

Prepared by:

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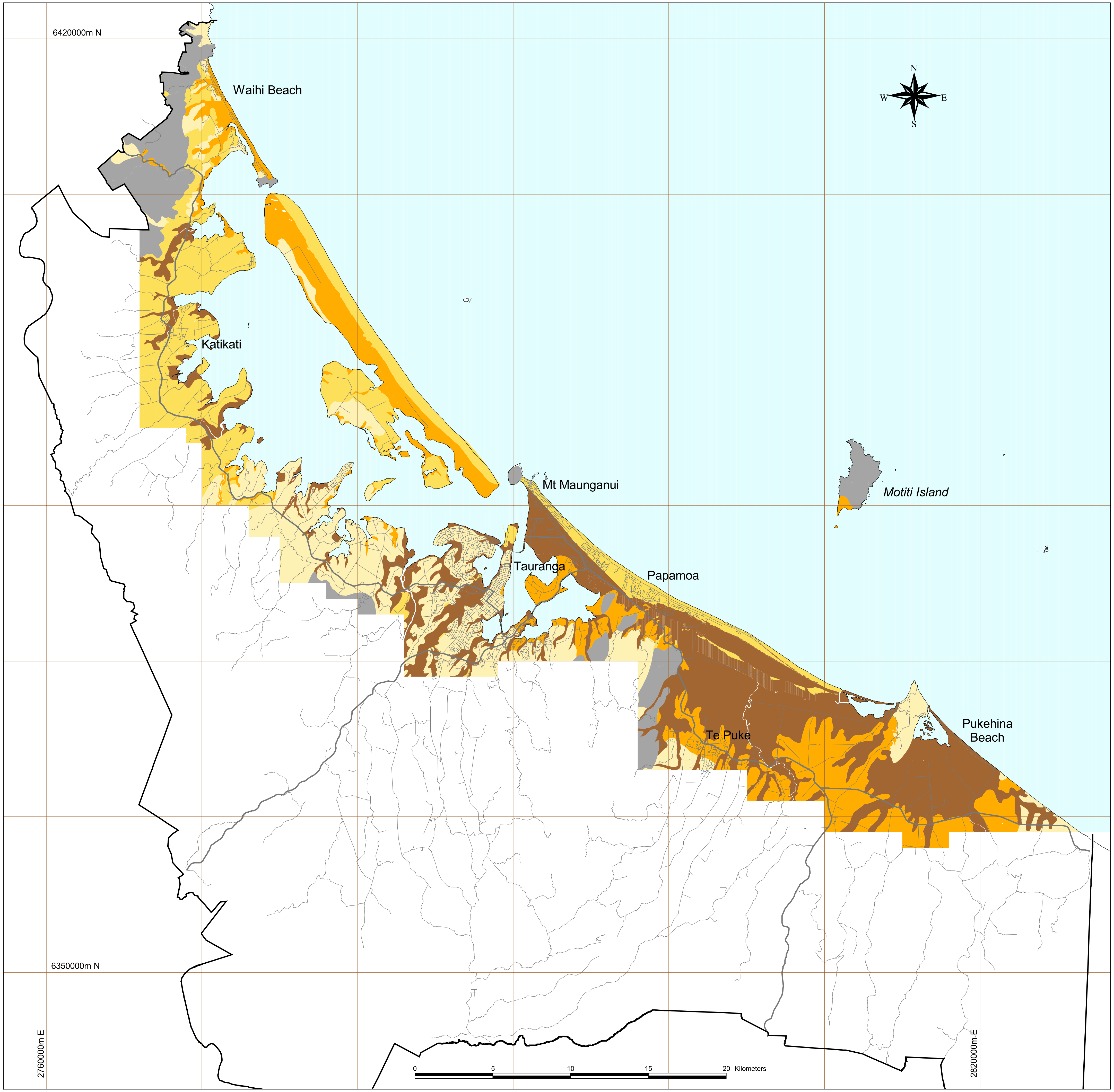
Institute of Geological & Nuclear Sciences Limited

Job No:	Date:	Figure:
5C2931.00	December 2002	11



IMPORTANT NOTES

Accompanying Report

This map should be used in conjunction with the report "Western Bay of Plenty Lifelines Study : Microzoning for Earthquake Hazards" (Opus International Consultants, 2002).

Limitations

The zone boundaries on this map are approximate only and have been determined with the aid of a national seismic hazard model, regional geological maps and available borehole data. Accuracy can vary from few tens of metres to few hundreds of metres.

The classification of the liquefaction hazard is indicative only, and the level of damage to any facility will depend on a variety of factors such as the potential for liquefaction, the thickness and depth of liquefying layers and their relationship to other layers, and the topography and the nature of the facility itself. Further limitations are given in the report.

Localised areas of enhanced hazard may be present within areas identified as having a low hazard, and also the hazard may be lower in some sections identified as having a high hazard.

Site-specific assessment of the hazard (such as ground shaking or liquefaction) based on site-specific investigations and risk should be considered for assessing the performance or design of a specific facility.

LEGEND

Study Area

Liquefaction Hazard

	No Liquefaction	Liquefaction unlikely in any scenario, except locally such as stream deposits or fill.
	Localised Liquefaction	Liquefaction is generally unlikely but there may be limited areas that are likely to liquefy in a large earthquake event.
	Minor Liquefaction	No liquefaction likely in a 10% in 50 year earthquake shaking, but liquefaction of limited layers may occur in a larger 2% in 50 year earthquake event
	Moderate Liquefaction	Liquefaction is likely in both 10% and 2% in 50 year earthquake shaking, in localised areas or are associated with limited ground damage
	Widespread Liquefaction	Liquefaction is likely to be extensive in both 10% and 2% in 50 year earthquake shaking and could lead to significant ground damage

Title:

Liquefaction Hazard Map

Project:
Western Bay of Plenty Lifelines Study
Microzoning for Earthquake Hazards

Prepared for:

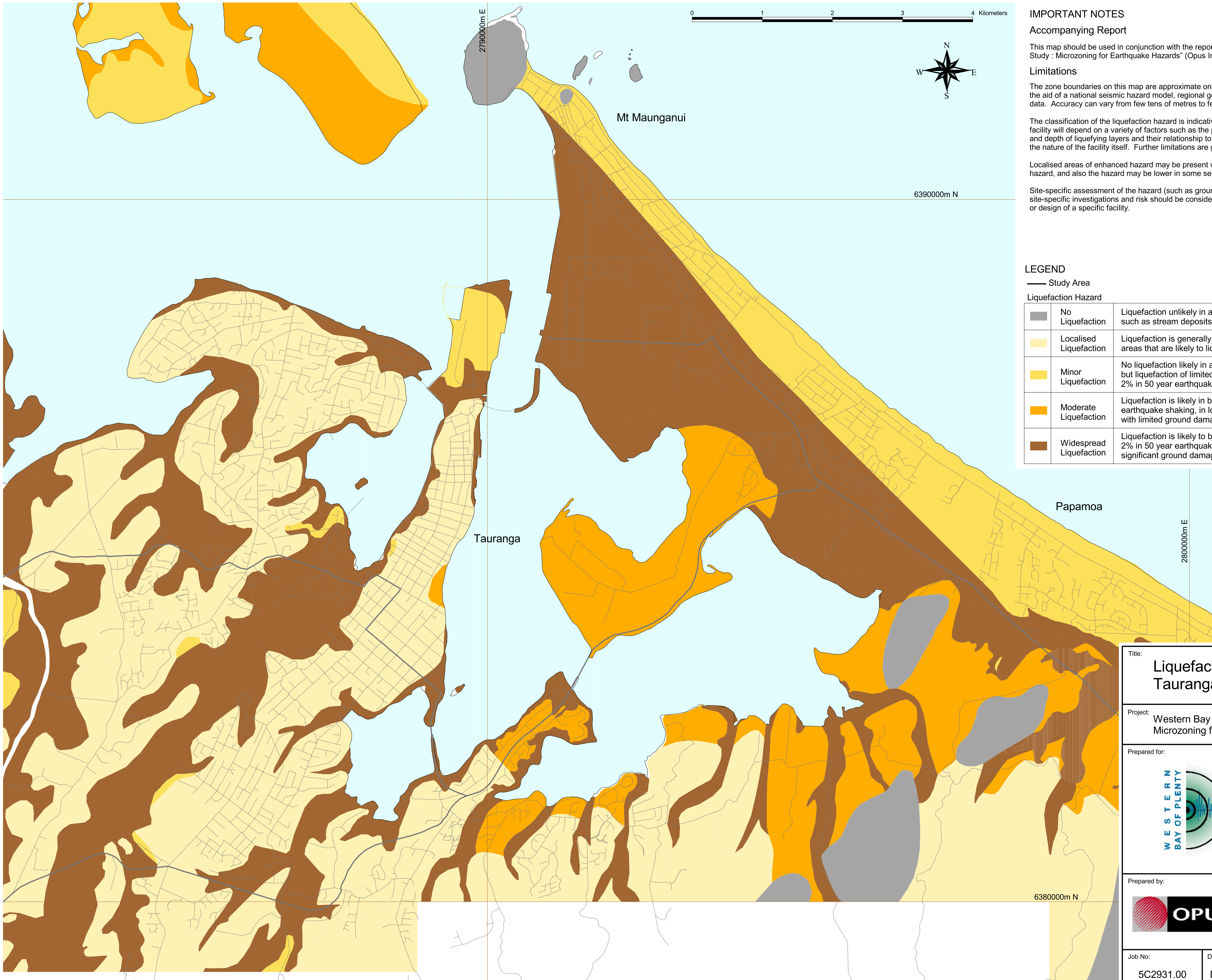
WESTERN BAY OF PLENTY lifelines ENGINEERING

Prepared by:

OPUS

Institute of Geological & Nuclear Sciences Limited

Job No:	Date:	Figure:
5C2931.00	December 2002	12



IMPORTANT NOTES

Accompanying Report

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Site-specific assessment of the hazard (such as ground shaking or liquefaction) based on site-specific investigations and risk should be considered for assessing the performance or design of a specific facility.

LEGEND

—— Study Area

Liquefaction Hazard

	No Liquefaction	Liquefaction unlikely in any scenario, except locally such as stream deposits or fill.
	Localised Liquefaction	Liquefaction is generally unlikely but there may be limited areas that are likely to liquefy in a large earthquake event.
	Minor Liquefaction	No liquefaction likely in a 10% in 50 year earthquake shaking, but liquefaction of limited layers may occur in a larger 2% in 50 year earthquake event
	Moderate Liquefaction	Liquefaction is likely in both 10% and 2% in 50 year earthquake shaking, in localised areas or are associated with limited ground damage
	Widespread Liquefaction	Liquefaction is likely to be extensive in both 10% and 2% in 50 year earthquake shaking and could lead to significant ground damage

Title:

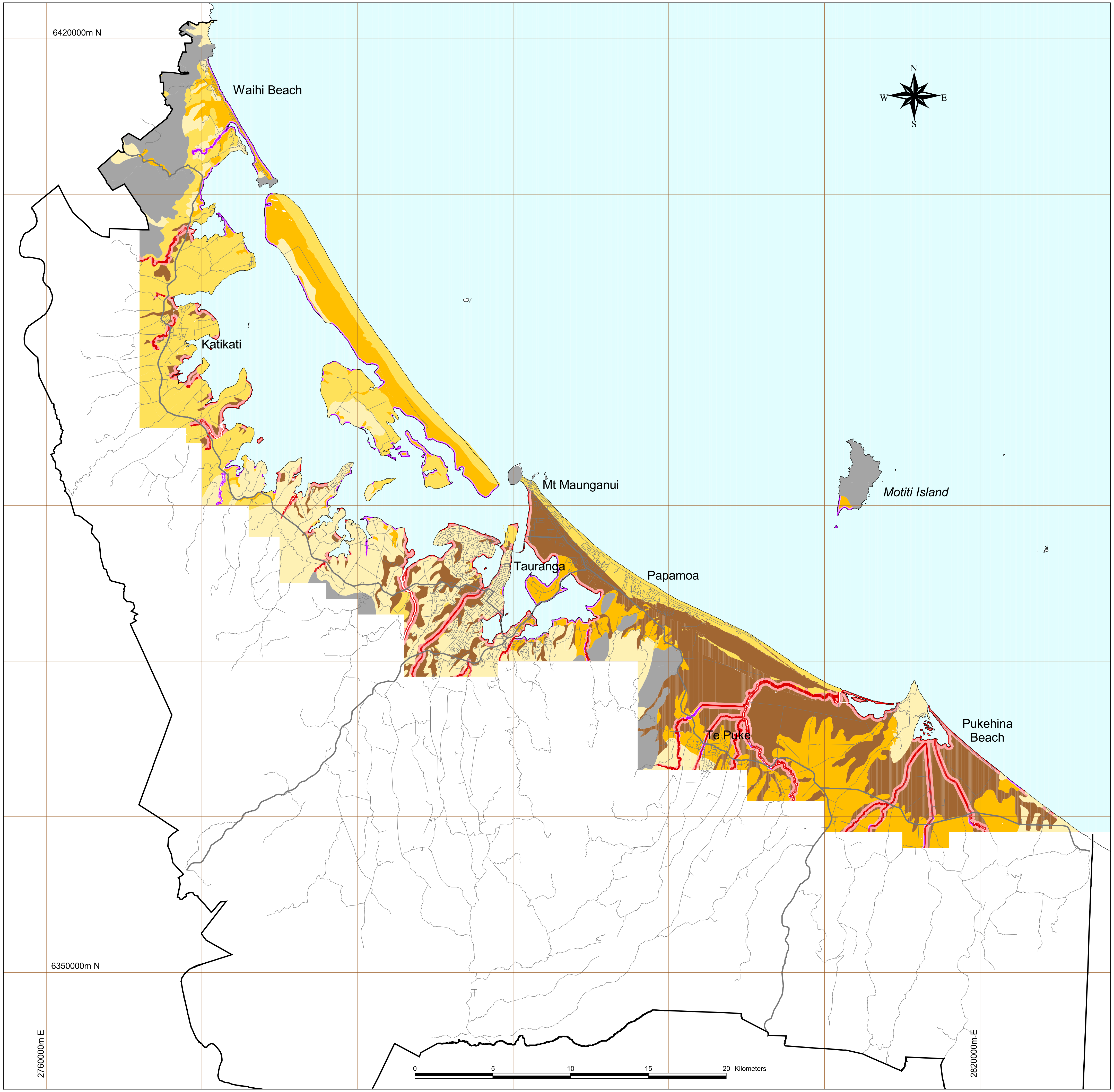
Liquefaction Hazard Map
Tauranga Urban Area

Project: Western Bay of Plenty Lifelines Study
Microzoning for Earthquake Hazards

Prepared for: Western Bay of Plenty lifelines Engineering

Prepared by: OPUS; Institute of Geological & Nuclear Sciences Limited

Job No:	Date:	Figure:
5C2931.00	December 2002	13



IMPORTANT NOTES

Accompanying Report

This map should be used in conjunction with the report "Western Bay of Plenty Lifelines Study : Microzoning for Earthquake Hazards" (Opus International Consultants, 2002).

Limitations

The zone boundaries on this map are approximate only and have been determined with the aid of a national seismic hazard model, regional geological maps and available borehole data. Accuracy can vary from few tens of metres to few hundreds of metres.

The classification of the liquefaction hazard is indicative only, and the level of damage to any facility will depend on a variety of factors such as the potential for liquefaction, the thickness and depth of liquefying layers and their relationship to other layers, and the topography and the nature of the facility itself. Further limitations are given in the report.

Localised areas of enhanced hazard may be present within areas identified as having a low hazard, and also the hazard may be lower in some sections identified as having a high hazard.

Site-specific assessment of the hazard (such as ground shaking or liquefaction) based on site-specific investigations and risk should be considered for assessing the performance or design of a specific facility.

LEGEND

—— Study Area

Liquefaction Ground Damage

Liquefaction Ground Damage Zone	Earthquake Shaking: 10% in 50 years	Earthquake Shaking: 2% in 50 years
None	No liquefaction ground damage	
Localised minor	Localised minor subsidence	
Minor	Minor subsidence (less than 100mm)	
Limited	Moderate subsidence (say 100mm to 300mm)	
Moderate	Large subsidence (say greater than 300mm)	
Large	Minor lateral spreading and moderate subsidence	Significant lateral spreading and moderate subsidence
Major	Significant lateral spreading and large subsidence	
Widespread	Significant lateral spreading and moderate subsidence	Extensive lateral spreading and moderate subsidence
Extensive	Extensive lateral spreading and large subsidence	

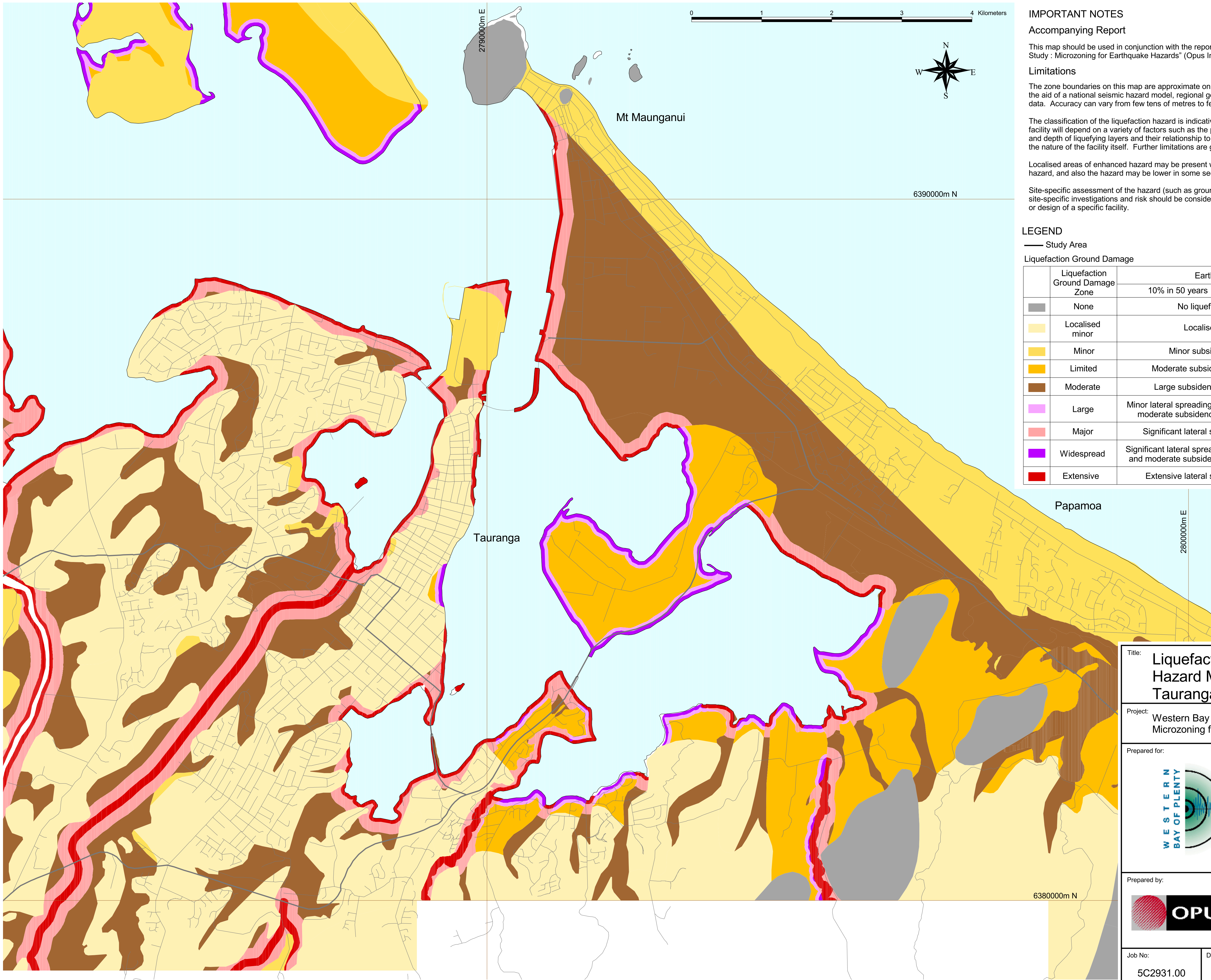
Title:
Liquefaction Ground Damage Hazard Map

Project:
Western Bay of Plenty Lifelines Study
Microzoning for Earthquake Hazards

Prepared for:
WESTERN BAY OF PLENTY lifelines ENGINEERING

Prepared by:
OPUS
Institute of Geological & Nuclear Sciences Limited

Job No:	Date:	Figure:
5C2931.00	December 2002	14



IMPORTANT NOTES

Accompanying Report

This map should be used in conjunction with the report "Western Bay of Plenty Lifelines Study : Microzoning for Earthquake Hazards" (Opus International Consultants, 2002).

Limitations

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The classification of the liquefaction hazard is indicative only, and the level of damage to any facility will depend on a variety of factors such as the potential for liquefaction, the thickness and depth of liquefying layers and their relationship to other layers, and the topography and the nature of the facility itself. Further limitations are given in the report.

Localised areas of enhanced hazard may be present within areas identified as having a low hazard, and also the hazard may be lower in some sections identified as having a high hazard.

Site-specific assessment of the hazard (such as ground shaking or liquefaction) based on site-specific investigations and risk should be considered for assessing the performance or design of a specific facility.

LEGEND

Study Area

Liquefaction Ground Damage

	Liquefaction Ground Damage Zone	Earthquake Shaking	
		10% in 50 years	2% in 50 years
	None	No liquefaction ground damage	
	Localised minor	Localised minor subsidence	
	Minor	Minor subsidence (less than 100mm)	
	Limited	Moderate subsidence (say 100mm to 300mm)	
	Moderate	Large subsidence (say greater than 300mm)	
	Large	Minor lateral spreading and moderate subsidence	Significant lateral spreading and moderate subsidence
	Major	Significant lateral spreading and large subsidence	
	Widespread	Significant lateral spreading and moderate subsidence	Extensive lateral spreading and moderate subsidence
	Extensive	Extensive lateral spreading and large subsidence	

Title: Liquefaction Ground Damage Hazard Map Tauranga Urban Area

Project: Western Bay of Plenty Lifelines Study Microzoning for Earthquake Hazards

Prepared for: WESTERN BAY OF PLENTY lifelines ENGINEERING

Prepared by: OPUS Institute of Geological & Nuclear Sciences Limited

Job No:	Date:	Figure:
5C2931.00	December 2002	15

Appendix A

Seismicity Model and Approach

Appendix A – Seismicity Model and Approach

A1 New Zealand National Seismic Hazard Model

The hazard maps provided in this study are derived from the recently developed New Zealand National Seismic Hazard Model (NZNSHM) of Stirling et al. (2000a, 2000b and 2002). The NZNSHM comprises both seismicity model and attenuation model components. While the published results of Stirling et al. are in terms of peak ground acceleration (pga) and 5% damped response spectral accelerations, the brief for the current study is restricted to pga only. It is noted that the NZNSHM has been used to derive the recommended spectra and zone factor maps for New Zealand in the draft Australian/New Zealand Loadings Standard (Standards Australia/Standards New Zealand, 2002).

A1.1 The Seismicity Model

The seismicity model specifies the location of earthquake sources and the frequency with which they produce earthquakes, as a function of magnitude. The model combines individual fault sources, with parameters estimated from geological studies, and a grid of distributed seismicity sources based on the catalogue of historical earthquakes in New Zealand. The distributed seismicity component models the earthquakes that have been observed historically but which are not associated with the modelled fault sources. The use of the historical catalogue in conjunction with the geologically-based fault catalogue recognises that many earthquakes are not associated with surface fault rupture and that the compilation of faults may be incomplete. There are few faults that have ruptured in the historical period against which to calibrate the geological model, while the length of the historical seismicity catalogue is short compared to the return periods of interest, and very short in geological terms.

The distributed seismicity is represented by point earthquake sources across a uniform three-dimensional grid. These earthquake sources are generally of small to moderate magnitude, up to 7 in the Bay of Plenty region. Each grid source point is associated with earthquakes that have a Gutenberg-Richter distribution of magnitudes, truncated at the maximum magnitude for the grid point. In the distributed seismicity model, all crustal earthquakes in the Taupo Volcanic Zone, Bay of Plenty, Coromandel, Taranaki, Waikato, Auckland and Northland regions are assumed to have normal mechanisms, the predominant mechanism observed throughout these regions.

In the NZNSHM, each modelled fault source segment is represented as producing a single magnitude of earthquake. The magnitudes have been determined from the magnitude of historical events in the few cases where they have occurred. More commonly, the magnitudes have been determined from correlations between magnitude and single-event displacements and/or fault dimensions derived from geological studies where they have been performed. There is also a slip type associated with each fault, and an associated average recurrence rate that is used in a Poisson model for earthquake occurrence, based on either geologically observed inter-event times or slip-rates. In the absence of data on particular faults, the fault parameters are based on analogies with similar nearby faults.

The uniform-hazard and scenario maps presented later show the fault sources nearest the WBOP Lifelines project's study area. The fault sources are simplified, for the purposes of seismic hazard analysis. Faults outside the mapped region and several sources representing the Hikurangi subduction zone were also included in the hazard analyses, but these made little contribution to the estimated hazard in the study area because of their distance from the region. The parameters of the fault sources neighbouring the area of interest have been adopted from the NZNSHM and are summarised in Table - A 1.

Table - A 1 Parameters used for Western Bay of Plenty Faults

Fault ID	Fault Name	Magnitude	Ave. Recurrence Interval of Rupture (years)	Fault Type
95	Kerepehi North-Central	6.7	2500	normal
96	Kerepehi Central	6.7	5000	normal
97	Kerepehi South	6.7	5000	normal
98	Mayor Island 1	7.0	4000	normal
99	Mayor Island 2	7.4	4000	normal
100	Mayor Island 3	7.1	4000	normal
101	Mayor Island 4	7.0	4000	normal
102	Tauranga	7.0	2000	normal
104	Matata	6.5	375	normal volcanic
105	Braemar	6.5	800	normal volcanic
106	Rotoiti	5.7	520	normal volcanic
107	Te Teko	5.7	340	normal volcanic
108	Onepu	5.8	250	normal volcanic
110	Edgecumbe 1987	6.5	1360	normal volcanic
111	Edgecumbe Coastal	6.0	175	normal volcanic
118	Rurima A	6.3	1080	normal volcanic

Note : From New Zealand National Seismic Hazard Model (Stirling et al, 2000b).

The "Fault ID" corresponds to the fault labels shown on the hazard maps. Some of the data on single-event displacements and segment lengths are poor. Of the listed parameters, probably the most reliable are the recurrence intervals for the Kerepehi Central and Kerepehi South fault segments. The estimated recurrence interval for the Kerepehi North-Central fault segment is likely to be too short, because of a suspected underestimate of single-event displacements. The locations of the endpoints of the five listed offshore faults, Fault IDs 98 to 102, are poorly known. The uncertainty in the lengths of the offshore faults affects the estimates of their magnitudes and average recurrence intervals, as well as their distances from locations in the Western Bay of Plenty. The listed recurrence intervals for the seven volcanic region faults are likely to be too short. Updating of the fault database and revision of the fault parameters from those used in the NZNSHM is outside the scope of this study.

A1.2 The Attenuation Model

The New Zealand National Seismic Hazard Model incorporates the latest ground motion attenuation relationships for New Zealand (McVerry et al., 2000). The attenuation relationships take into account the different tectonic types of earthquakes in New Zealand (i.e. crustal, subduction interface, and dipping slab). The attenuation relationships for crustal earthquakes have further subdivisions, through mechanism terms, for different types of fault rupture (strike-slip, normal, oblique/reverse and reverse). The attenuation expressions have been derived from a database incorporating all available New Zealand strong-motion response-spectral data supplemented by a representative selection of overseas near-source peak ground acceleration data. Both the crustal and subduction zone attenuation relationships have been derived by modifying models from other parts of the world to obtain better fits to the supplemented New Zealand database. The crustal model was modified from the Abrahamson & Silva (1997) model that was derived from mainly western US data, while the subduction zone expression was modified from the Youngs et al. (1997) expression derived from subduction zone earthquakes around the world.

An important feature for the Western Bay of Plenty region is that the attenuation model incorporates a more rapid rate of decay of the strength of shaking with distance for earthquake sources (both faults and distributed seismicity grid points) in the Taupo Volcanic Zone (TVZ) than for sources elsewhere in New Zealand. Fault sources affected by this increased attenuation rate are labelled "normal volcanic" in Table - A 1. The TVZ distributed seismicity gridpoints affected are immediately to the southeast of the Western Bay of Plenty study area. A small area near the eastern boundary of the Western Bay of Plenty region lies within the TVZ, while, standard attenuation rates apply within the rest of the study area.

A1.3 Features of Site Response in the Attenuation Model

Although a five-step site class scale has been used in this study, the same earthquake motions are modelled for the two rock classes, A and B (although no Class B materials are identified in the study area).

The attenuation model also does not distinguish between Classes D and E for peak ground accelerations. Classes D and E will not necessarily give rise to the same motions, but at present a separate model for Class E is not available because data from Class E sites have not been used in the analysis for developing the attenuation model. Peak ground accelerations may well be similar for Class D and Class E sites, but the "softer" Class E sites will probably produce stronger long-period components of motion.

A feature of the peak ground acceleration (pga) attenuation expression used in this study is that it has a non-linear site response term for Class D, which is a function of the expected rock (Site Class A & B) pga. This behaviour gives an ordering of the pga for the site classes that changes with the strength of motion, which can be summarised as:

Low pga: Site Class D&E pga > Site Class C pga > Site Class A&B pga

Moderate pga: Site Class C pga > Site Class D&E pga > Site Class A&B pga

High pga: Site Class C pga > Site Class A&B pga > Site Class D&E pga

In effect the moderate to high pga values are attenuated for Class D&E sites, due to the non-linear effects. The non-linearity is expected to be less pronounced for longer period motions, and the Class D&E long-period motions are expected to be relatively stronger with respect to Classes A&B and C than suggested by the pga model. For longer periods, the Class D&E motions are strongest, followed by Class C, with Class A&B motions the weakest. For example, for the response spectrum acceleration (SA) at 1s, SA(1s), the motions become more amplified going from rock to shallow soil to deep or soft soil:

All levels of motion: Site Class D&E SA(1s) > Site Class C SA(1s) > Site Class A&B SA(1s)
The amplifications in the attenuation model used in this study are listed in Table - A 2.

Table - A 2 Predicted Amplification with respect to the Rock Class for Two Measures of Earthquake Motions

	Class C Stiff Shallow Soils	Class D Deep or Soft Soils					Class E Very Soft Soils
Ground-motion measure		Rock PGA					
		0.01g	0.1g	0.2g	0.4g	0.6g	
PGA [1]	1.35	1.53	1.16	1.02	0.88	0.81	As for Class D
SA(1s) [1]	1.22	2.35					As for Class D

Note : [1] PGA and SA(1s) amplifications from McVerry et al. (2000) New Zealand response spectrum acceleration attenuation model.

The dependence of ordering of the strength of motion for the different site classes on the spectral period, is in line with both instrumental recordings of earthquake motions and damage observations in New Zealand. Generally, Class D&E sites are expected to experience intensities that are larger than for Class C sites, and Class A&B is expected to produce smaller intensities than Class C. However, the intensities and damage will depend on the type of structure, especially for site classes D&E. Short-period structures may experience less damage for Site Classes D&E, especially for very strong shaking, than for Site Class C and perhaps even than for Site Class A&B. For example, this type of behaviour was observed in housing damage in Napier in the 1931 earthquake (Dowrick *et al.*, 1995).

A2 Uniform Hazard versus Scenario Approaches

Two common methods of portraying earthquake ground-shaking hazard are uniform hazard maps and earthquake scenario maps. Both types of map are of use in hazard assessments for lifelines. Uniform hazard maps define the levels of ground shaking likely for a given probability at any location in the map area, but not the level of shaking from a single earthquake. Scenario maps show the motions that are likely to occur together across a region (and a lifelines network) for a specific earthquake.

A2.1 Uniform Ground-shaking Hazard Maps

Uniform hazard maps show the ground motions at each location that have the same estimated *probability of exceedance* in a stated time period (T), e.g. 10% probability of exceedance in 50 years, or, in other words, have the same *return period* (t) e.g. 475 years. The return period is the reciprocal of the annual frequency of exceedance, with the return period (t) and the probability of exceedance p(t) in time (T) related by the Poisson formula

$$p(T) = 1 - e^{-T/t}$$

Uniform hazard maps include the contributions to the estimated hazard at each location from all possible earthquakes represented in the hazard model. For this reason, they are sometimes referred to in the lifelines literature as multi-earthquake hazard maps. Their main disadvantage for assessing lifelines networks is that the earthquakes that are the principal contributors to the hazard may vary between different locations. Unless there is a single major highly-active fault that dominates the hazard at all locations in a region, the mapped values at different locations in a region are likely to be produced by different earthquakes.

A2.2 Scenario Ground-shaking Hazard Maps

For consideration of lifelines systems, the levels of shaking that are likely to occur in the same earthquake at different locations in the system are required. This requirement can be addressed through a scenario approach. Particular earthquake events are selected as the scenario earthquakes, that approximate over parts of the area of interest the “target motions”, i.e. the ground shaking associated with the return periods of interest. Different scenarios are likely to be required for different parts of the area.

The levels of shaking at different locations within the study area, for a given scenario, may have vastly different return periods. The target motions for a given return period are usually satisfied only over a limited region, unless the earthquake hazard over the area of interest is dominated by a single earthquake event (e.g. an earthquake rupturing the entire Wellington-Hutt Valley segment of the Wellington Fault for Wellington).

The selection of scenarios is subjective, in that for a given location several scenarios may produce the target motions.

Scenario maps show the strength of ground shaking at each location expected at some percentile level in a given earthquake event. The percentile level is the *probability of non-exceedance* in the particular scenario (e.g. the 84-percentile ground motions for a magnitude 6.0 earthquake on the Kerepehi South fault) at individual locations. Scenario maps are most commonly prepared for 50-percentile and 84-percentile motions. A 50-percentile level map shows the median motions expected for the scenario earthquake, the motions that are expected one time in two. The 84-percentile level is reached only about one time in six, and corresponds to one standard deviation above the mean for normal distributions. Other percentile levels are sometimes selected, including cases where the percentile-level is calculated so that the scenario motions match the target motions at some location of particular interest.

A2.3 Comparison of Uniform Hazard and Scenario Hazard Maps

When a uniform-hazard map and a scenario map give the same strength of motion at a particular location, the distribution of shaking shown over the study area is usually different for the two types of map. The difference in the distribution of shaking for a single earthquake event and for a given return period raises questions as to which is the relevant approach for estimating hazard in a region for a particular purpose: a scenario or a return period approach?

In some applications, it is the level of hazard at individual locations that is relevant, without regard to the level of hazard at other locations in a region. This may be the case in selecting levels of earthquake motion for design of individual facilities. For example, the zone factors of the current New Zealand Loadings Standard NZS 4203:1992 are based on a uniform hazards approach. Even then, often a dual approach is taken for very important structures. In the dual approach, motions for a selected return period are first estimated as the basis for design. Then the uniform hazard results are anchored to a particular scenario earthquake that gives rise to this level of motion as a physical realisation of the type of event corresponding to the particular return period. The selection of a scenario is often not unique, in that there may be several or many earthquake events that contribute to the hazard at a location that can give rise to the motions associated with a given return period. The choice of return period also varies depending on the importance of the facility, and the hazard posed by its failure.

For evaluating the response of networks or of facilities distributed across a number of locations, a scenario approach is often used. This approach recognises that to evaluate the performance of the network, it is the range of motions that may occur across the area of the network from one event that are important. Lifeline systems are required to have a high level of reliability in strong earthquake shaking. The shaking that should be considered for lifelines systems is likely to arise only in the larger earthquakes that may affect a region. High levels of shaking are unlikely to occur throughout the area of interest unless the seismicity includes very large magnitude events with recurrence intervals of no more than a few thousand years. In many regions, the selection of appropriate scenarios is achieved best by first performing a uniform hazard analysis, to establish the strength of earthquakes motions with the target probability of exceedance. This is followed by a "deaggregation analysis" (see below) to determine the relative contributions of various earthquake sources to the rates of occurrence of these levels of motion.

Scenario approaches are a straightforward way of portraying the earthquake ground-shaking hazard in places like Wellington where the hazard is dominated by a single fault. Although there are other major earthquake sources in the Wellington region, such as the Wairarapa Fault that ruptured in 1855, the Ohariu Fault, and the subduction interface, they are at sufficient distance or have long enough recurrence intervals that their contribution to the estimated hazard for Wellington City is small. The Wellington Fault is estimated to contribute about 70 per cent of the occurrences of motions with return periods in the 475-year to 2500-year range in Wellington City. In this situation, a scenario map gives a reasonable approximation to the strength of shaking expected at different locations for the return period associated with the scenario event.

For much of the Western Bay of Plenty, and in particular for the largest population centre of Tauranga, the situation is complicated because there are many potential earthquake sources but not one dominates the hazard. There may be several scenarios that match the target motions at any one locality but give very different motions elsewhere. The selection of a scenario becomes subjective. Even at a particular location or in a relatively small part of the overall region, such as Tauranga, there are likely to be several earthquake sources contributing to the overall hazard rather than a single dominant source.

For situations like the Western Bay of Plenty it is important that several scenarios are considered. For the Western Bay of Plenty, unlike for Wellington City, it is not possible to develop a single scenario for a given return period and have confidence that it will lead to appropriate conclusions about the performance of lifeline systems affecting even a single urban centre such as Tauranga, let alone the whole of the region. The users and scenario developers need to work together to consider the layout of various networks, the location of their critical elements, and the location of geological hazards that may affect the lifeline. This is needed before selecting the scenarios most relevant to the evaluation of the various components of the lifeline infrastructure.

A3 Selection of Appropriate Hazard Level

Another issue irrespective of whether a scenario or uniform hazard approach is adopted is the selection of the appropriate hazard level to consider for lifelines systems or individual facilities within them. The strength of motion to be specifically considered in the design of "standard" structures (e.g. office buildings) according to the New Zealand Loadings Standard NZS 4203:1992 (Standards New Zealand, 1992) corresponds to a nominal return period of 450 years, or approximately a 10% probability of exceedance in 50 years. The design requirements of the New Zealand Loadings Standard are intended to ensure that structures specifically designed for 450-year return period motions *survive without collapse* in even stronger motions, corresponding to return periods of about 2500 years to 5000 years or more. Often essential lifeline facilities are designed *to remain functional* in return periods of 2000 years or 2500 years, corresponding to probabilities of exceedance of 2% to 2.5% in 50 years. (eg. see AS/NZS 1170.0:2002). A *minimum* return period of 1000 years is to be specifically considered in design for important structures "for which the loss of function would have a severe impact on society" according to the Loadings Standard (NZS 4203:1992). This class includes structures such as essential hospital and medical facilities, radio and television transmitting facilities, telephone exchanges, and power stations and sub-stations.

The Maximum Design Earthquake (MDE) motions for a facility are those corresponding to the maximum return period or lowest probability of occurrence that is deemed appropriate (e.g. 2500 years or 2% probability in 50 years may be deemed sufficient for critical lifelines facilities). The earthquake(s) associated with the MDE motions may differ from the Maximum Credible Earthquake (MCE) for a region, which may have too long a recurrence interval (e.g. 20,000 years) to be considered in the design of a particular facility. In other cases, the MCE event for a region (e.g the one with the largest magnitude) may not be the one that gives the most critical motions for a given return period at a particular location. Stronger motions may be produced at a particular location by lower magnitude earthquakes that are closer than the MCE event. In addition, a single event associated with the MDE motions may be difficult to define, in that the hazard is produced by the contributions of many moderate magnitude earthquakes rather than a single clearly identifiable event. The contributions from each of these moderate magnitude earthquakes may be at low probability levels. Contributions up to 3 standard deviations above the median are usually included in probabilistic analyses, while the probability levels associated with analyses for scenario events are often restricted to the 84-percentile level, only one standard deviation above the median.

All these issues arise in the Western Bay of Plenty. In much of the region, the major fault sources are associated with long average recurrence intervals. Except within a few kilometres of the faults, the estimated 84-percentile motions from the fault sources are less than even the 10% in 50 years motions, let alone the 2500-year return period motions often considered for critical lifelines facilities. At most locations, the main contributions to the 2500-year motions come from moderate magnitude earthquakes, but at levels well beyond one standard deviation above the median motions.

Appendix B

Selection of Ground Shaking Scenarios

Appendix B – Selection of Ground Shaking Scenarios

B1 Approach to Select Scenarios

For the Western Bay of Plenty study, both the uniform hazard and scenario approaches have been used, to obtain the benefits of each approach. First a uniform hazard analysis has been performed for the Western Bay of Plenty study area to estimate the distribution of peak ground acceleration with 10% and 2% probabilities of exceedance in 50 years (corresponding to return periods of approximately 500 years and 2500 years) for each of three site classes that are available in the model. Then the map of the ground class in the study area has been used in conjunction with the component earthquake ground-shaking maps for the three site classes to produce the overall ground shaking hazard maps, incorporating site conditions.

Single scenario earthquake ground shaking maps have then been developed that approximate the target 500-year or 2500-year peak ground accelerations over various parts of the Western Bay of Plenty study area. This has been achieved through the combination of the following two visual techniques to portray aspects of the hazard to aid in the selection of the scenarios:

- Maxium pga
- Deaggregation.

B1.2 Maximum pga

As an aid for the selection of scenarios, maps were prepared showing the maximum 50- and 84-percentile pga at each location for all of the fault sources included in the NZNSHM. These percentile levels correspond to probabilities of *non-exceedance* of 50 and 84 per cent. These percentile levels have been chosen because they correspond to the hazard levels used for most scenario maps. The resulting maps are essentially a supposition of the maximum motions at that exceedance level from all the possible fault scenarios. By overlaying the fault locations on these maps, it is simple to identify the critical fault scenarios at either the 50- or 84-percentile levels for any location in the region.

However, because these maps take no account of the average recurrence intervals of rupture for the fault sources, the fault giving rise to the maximum 50- or 84-percentile motions at a location is not necessarily the source that contributes most to the motions for a target return period. A more active fault with a shorter recurrence interval producing somewhat lesser 50- or 84-percentile motions may contribute more to the hazard because it ruptures more frequently. Also, the earthquake source model (“seismicity model”) used to obtain the uniform hazard earthquake ground-shaking estimates includes both fault sources and a distributed seismicity component. In some parts of the Western Bay of Plenty, including Tauranga, it is earthquakes from the distributed seismicity grid that dominates the estimated hazard.

B1.3 Deaggregation

Deaggregation breaks down the estimated hazard at particular locations into contributions by different earthquake sources. These sources include both the modelled faults and the uniformly gridded (distributed seismicity) point sources. In deaggregation, the rates of exceedance of the target acceleration level at a location of interest are calculated for each source, for every magnitude level associated with each source. These rates for the location of interest are plotted as a three-dimensional block diagram that gives the rate of exceedance of the particular acceleration level (e.g., 10% in 50-years pga) for various magnitude-distance cells, either in absolute or percentage form. Inspection of this diagram reveals the magnitude-distance combinations that contribute most to the estimated rate of exceedance of the chosen hazard measure. These magnitude-distance cells can be interpreted in terms of particular fault sources and/or distributed seismicity grid-points. The combination giving the largest contribution is referred to as the modal magnitude-distance contribution. In some situations, these plots show multiple peaks. These lower peaks are referred to as the second, third, fourth etc modal contributions.

Such a deaggregation analysis provides a rational basis for the selection of the appropriate scenarios that contribute significantly to a selected level of hazard at any particular location, as well as providing information on what fraction of the overall rate of the hazard level of interest is contributed by the selected scenario at the particular site. It also shows where there are multiple scenarios that should be evaluated at a given location, or whether different scenarios are required for different parts of the study area. The appropriate scenario in a given location may also vary with the return period of interest. Moderate-magnitude earthquakes may contribute most of the relatively weak earthquake motions corresponding to short return periods for which full functionality should be required of the system. For more extreme motions, larger-magnitude earthquakes are likely to contribute most to the hazard.

B2 Uniform Hazard PGA Maps

Uniform-hazard peak ground acceleration maps for the Western Bay of Plenty are presented in Appendix B (Figures B1(a)-(c) and B2(a)-(c)) for each of the three site classes of the attenuation model. Figures B1 and B2 correspond to 10% and 2% probabilities of exceedance in 50 years, respectively. Parts (a) to (c) correspond to the site classes A/B, C and D/E. The gridded data used to produce these maps were combined with the site classes in the region to produce maps of the hazard incorporating site conditions.

Offshore faults in the region, as shown in Figures B1 to B4 and B8 to B11, were included in the hazard analysis, together with faults that lie outside the mapped region. The faults are those of the NZNSHM, their identification numbers shown on the figures correspond to those in Table - A 1 in Appendix A.

From Figure B1(a), it can be seen that the peak ground accelerations for rock (Class A/B) sites with 10% probability of exceedance in 50 years lie within the range 0.2g to 0.3g for most of the onshore region. Around the faults of the Taupo Volcanic Zone (TVZ), the rock pgas rise to a maximum of 0.4g. The areas with the highest acceleration lie outside the southeastern boundary of the Western Bay of Plenty, but affect transport routes into it from around Matata. For shallow soil sites (Class C), the pga values are higher than the rock pgas by a factor of 1.35, with most in the 0.25g to 0.35g range, rising to the 0.4g to 0.5g range around the TVZ faults. The pgas for Class D&E deep or soft soil sites show a more limited range. For most of the region, they lie in the range 0.25g to 0.3g, reaching a maximum in the 0.4g to 0.45g range around the TVZ faults. At lower pgas up to about 0.25g, the Class D/E values are amplified with respect to the rock values but less than the Class C values. The strongest Class D/E pgas, around the TVZ faults, are less than those for either Class A/B or C. This behaviour is in line with the discussion in Appendix A. Similar maps for the accelerations at longer spectral periods, such as 1s, would show strong amplifications of Class C with respect to rock, and even greater amplifications for Class D/E.

A feature of the maps for pgas with probabilities of exceedance of 10% in 50 years is that apart from the very active TVZ faults to the south-east of the region, the influence of the modelled fault sources does not appear very marked. This is because the average recurrence intervals (RIs) of rupture of the faults in the region are 2000 years to 5000 years. For motions with 10% probability of exceedance in 50 years, for which the return period is 475 years, their recurrence intervals mean that individual faults can contribute at most 475/RI of the hazard rate i.e. a maximum of about 25%. Even for the 2% in 50 years hazard level, corresponding to a return period of about 2500 years, the fault contributions don't appear very marked.

The maps for pgas with 2% probability of exceedance in 50 years show values that are typically in the 0.3g to 0.4g range for rock sites, peaking at 0.7g to 0.8g around the TVZ faults. Shallow soil values (Class C) are typically 0.3g to 0.4g, peaking at 0.7g to 0.8g. Values for deep or soft soil sites (Class D or Class E) are typically 0.3g to 0.4g, peaking in the 0.5g to 0.6g range.

B3 Superposition of Fault Scenario Motions

Figures B3 and B4 present maps for the shallow soil class showing the maximum pgas at the 50-percentile and 84-percentile levels estimated at each location from all fault sources included in the NZNSHM. A feature is that there are only very few locations in the region where the maximum 50-percentile pgas from the modelled rock sources reach the range of 0.25g to 0.35g that is typical for 10% in 50 year motions. For example, the maximum 50-percentile pgas for shallow soil sites in Tauranga are in the 0.2g to 0.25g range. The 0.25g to 0.4 g range is only reached in Tauranga and Mt Maunganui with 84-percentile motions. From the distribution of the patterns around faults for the 50- and 84-percentile motions, it is apparent that of the modelled fault sources the one that can potentially produce the strongest pgas in Tauranga and Mt Maunganui is Mayor Island Fault 1 (labelled "98" in the maps). The 84-percentile pgas estimated to be produced in Tauranga and Mt Maunganui by this fault correspond approximately to the 10% in 50 year motions for these locations.

None of the modelled faults are estimated to produce 84-percentile pgas in Tauranga or Mt Maunganui that approach the 0.45g to 0.50g range for shallow soils corresponding to 2% in 50 year motions for these localities.

B4 Deaggregation Analyses

B4.1 Deaggregation Analyses for Tauranga and Matata

The maps of the maximum 50- and 84-percentile fault pga take no account of the recurrence intervals of rupture of the faults. Recurrence intervals need to be considered to determine whether a fault scenario that produces the target level of motions for a given hazard level (i.e. return period) in an area is a significant contributor to the hazard for that return period. This has been investigated through deaggregation.

Deaggregation plots for 10% and 2% in 50 year pga on shallow soil (Class C) are shown in Figure B5 for Tauranga, and in Figure B6 for Matata.

B4.2 Deaggregation plots of PGA for Tauranga

The plots for Tauranga show that the largest peak for both return periods occurs for the cell corresponding to magnitude 5.3 to 5.5 and distance 0 to 20 km. This cell contributes 18% of the rate of exceedance of the 475-year shallow soil (Class C) pga of 0.30g, and 26% of the rate of exceedance of the 2550-year value of 0.47g. None of the modelled fault sources correspond to this magnitude-distance combination, with the closest fault being Mayor Island 1 at a distance of 18 km from Tauranga. This fault appears as the relatively minor, but second modal, peak at 0-20 km distance and magnitude 6.9-7.1. This fault contributes about 3% of both the 475-year and 2500-year pga hazard.

The plots for pga understate the contribution to the overall hazard of fault sources, in that strong pga can be produced by relatively small magnitude earthquakes at short distances. However, at longer spectral periods, the influence of magnitude is greater, and large motions generally require moderate to large magnitudes. This is shown in the deaggregation plots for the SA(1s) values with 10% and 2% probability of exceedance in 50 years on shallow soil (Class C) in Tauranga (Figure B7). The largest peak is for the magnitude 6.9-7.1 class at 0-20 km distance, followed by the magnitude 6.9-7.1 class at 40-60 km distances. These cells correspond to Mayor Island Fault 1 (number 98), and the combination of Mayor Island Faults 3 and 4 (numbers 100 and 101) and the Tauranga Fault (number 102). These are all offshore faults. Local distributed seismicity ranks with the central (fault 96) and southern segments (fault 97) of the Kerepehi Fault (magnitude 6.7-6.9 cell at 20-40 km), Mayor Island Fault 2 (number 99, magnitude 7.1-7.3 at 40-60 km) and the Hikurangi subduction zone in the magnitude 7.7-8.1 range at distances of 140-160 km. The deaggregation of the 2500 year SA(1s) hazard is made up of a similar mix of the principal contributing sources, but Mayor Island Fault 1 is a more dominant contributor. An important feature is that the contributions to the SA(1s) hazard are spread over many sources, with the largest contributions from any magnitude-distance cell being only about 5% and 15% for the 475-year and 2500-year pga, from the cell corresponding to Mayor Island Fault 1.

B4.3 Deaggregation plots of PGA for Matata

The deaggregation plots of pga for Matata (Figure B6) are very different in character from those for Tauranga. Even for the 475-year pga, they are dominated by a single magnitude-distance cell, magnitude 6.3-6.5 at 0-20 km distance (there are similar results for SA(1s) so these are not shown for Matata). This dominant cell corresponds to the contributions of the Matata Fault (number 104), 30% of the rate of exceedance of this pga, and the Rurima A Fault (number 118, unlabelled offshore extension of the Matata Fault), contributing about 15% of the rate. For the 2500-year pga, this magnitude-distance cell is even more dominant, with 40% of the hazard rate coming from the Matata Fault and 25% from the Rurima A Fault. These percentages show that visually these plots tend to overemphasize the dominance of the largest peaks. The impression from inspection of the plot is that the one magnitude-distance cell completely dominates the contributions, but in fact over a third of the total hazard come from other magnitude-distance combinations. Nevertheless, the large contribution makes the selection of an appropriate pga scenario for Matata straightforward.

B5 Selected Scenarios

B5.1 Four Scenarios

Four earthquake scenarios have been chosen based on the consideration of maximum pga and the deaggregation analyses. These are :

5) Local Source for Tauranga Scenario
6) Mayor Island Fault Scenario
7) Matata Fault Scenario
8) Kerepehi South Fault Scenario

The estimated 2500-year pga of 0.47g on shallow soil in Tauranga are not produced by 84-percentile scenarios on any of the modelled faults. The deaggregation studies show that they are contributed largely by the distributed seismicity gridpoints, with the fault sources estimated as producing only 4% of the rate of exceedance of 0.47g. Even a direct hit on Tauranga (i.e. an earthquake directly under it at 10 km depth) requires motions at just over the 90-percentile level to produce the estimated 2500-year motions.

B5.2 Local Source for Tauranga Scenario

The deaggregation studies show that distributed seismicity is the dominant contributor to the pga hazard for Tauranga. This needs to be taken into account in developing scenarios for the 475-year and 2500-year pga hazard in Tauranga. It is not realistic to just consider scenarios based on the modelled fault sources.

The modal peak for the 475-year pga hazard for Tauranga corresponds to the 5.3-5.5 magnitude class at 0-20 km distance. The first scenario is selected to represent this type of earthquake affecting Tauranga. In constructing the scenario representing this contribution, it needs to be noted that all the contributions actually arise from the 10 km to 20 km distance range, in that the shallowest layer of the distributed seismicity grid is at 10 km depth, which is therefore the minimum source-to-site distance for grid points. A selection of an event at 10 km depth and 10 km horizontal distance from Tauranga, corresponding to a source-to-site distance of about 14 km, seems reasonable, in that this corresponds to a distance that is near the middle of the real distance range corresponding to this cell. In the distributed seismicity grid, all earthquakes associated with gridpoints are treated as point-source events. To give more reality to the scenario, a local compact source is considered for this project. For constructing this scenario, a magnitude 5.4 normal-faulting earthquake with the top of its rupture surface at 10 km depth is modelled along an artificial fault of 8 km length, running from approximately from Tauriko on the Kaimai road to Omokoroa with a 65 degree strike. A normal-faulting mechanism is selected because it is the most common for earthquakes in this region, while the strike is approximately aligned with that of real faults in this area (e.g. Kerepehi South). The artificial fault (number 400 in Figures B8(a)-(c)) is placed to the west of Tauranga, in that the Mayor Island Fault 1 scenario discussed below is centred to the east of Tauranga. The placement ensures that facilities to the west of Tauranga for which the pga from the Mayor Island Fault 1 scenario are less than the target 475-year values are subjected to at least the target pga in one of the scenarios. Calculations for a magnitude 5.4 normal faulting earthquake at a distance of 14 km show that the target 475-year pga of 0.3g for Tauranga corresponds almost exactly one standard deviation above the mean i.e. 84-percentile values, the same as considered for the fault scenarios.

The pga estimated for the scenario of 84-percentile motions from a magnitude 5.4 earthquake at 10 km depth about 10 km to the west of Tauranga are shown in Figures B8(a) to B8(c) for the three site classes. These figures include the location of the artificial fault about which the scenario is constructed. Close to the fault, the pga reaches the 0.35g to 0.4g range for shallow soil sites, higher than the target range of 0.3g to 0.35g. Tauranga lies within the 0.3g to 0.35g band, the target range, while Mt Manganui is in the 0.25g to 0.3g band, slightly below the target range. The maps for the other site conditions show a similar relationship to the target pga ranges.

B5.2 Mayor Island Fault Scenario

As a second scenario for Tauranga, a Mayor Island Fault 1 earthquake is considered. This event has a magnitude of 7, a normal-faulting mechanism, and is assumed to rupture to the surface along the entire modelled length of the fault (number 98). These assumptions are all consistent with the modelling of the fault in the NZNSHM. The motions for this scenario are taken at the 84-percentile level (Figures B9(a)-(c)). The target 0.3g to 0.35g range on shallow soil is met in the western and southern parts of Tauranga, with motions further north-west slightly exceeding the target range.

B5.3 Matata Fault Scenario

The third scenario for the Western Bay of Plenty is selected as one producing 84-percentile motions in a magnitude 6.5 normal-faulting earthquake rupturing to the surface along the entire modelled length of the Matata fault (number 104, Figures B10(a)-(c)). This corresponds to the type of earthquake that dominates the estimated hazard in Matata, and along the coastal route into the Western Bay of Plenty from the southeast. The 84-percentile shallow soil pga of 0.47g in Matata for this event lies between the estimated 475-year pga of 0.41g and the 1000-year value of 0.50g for Matata.

B5.4 Kerepehi South Fault Scenario

The fourth scenario considered consists of 84-percentile motions in a magnitude 6.7 normal-faulting earthquake rupturing to the surface along the south segment of the Kerepehi Fault (number 97, Figure B11(a)-(c)). This scenario provides a target 475-year pga of 0.3g to 0.35g on shallow soil along the eastern flanks of the Kaimai Range, in a band around Lower Kaimai.

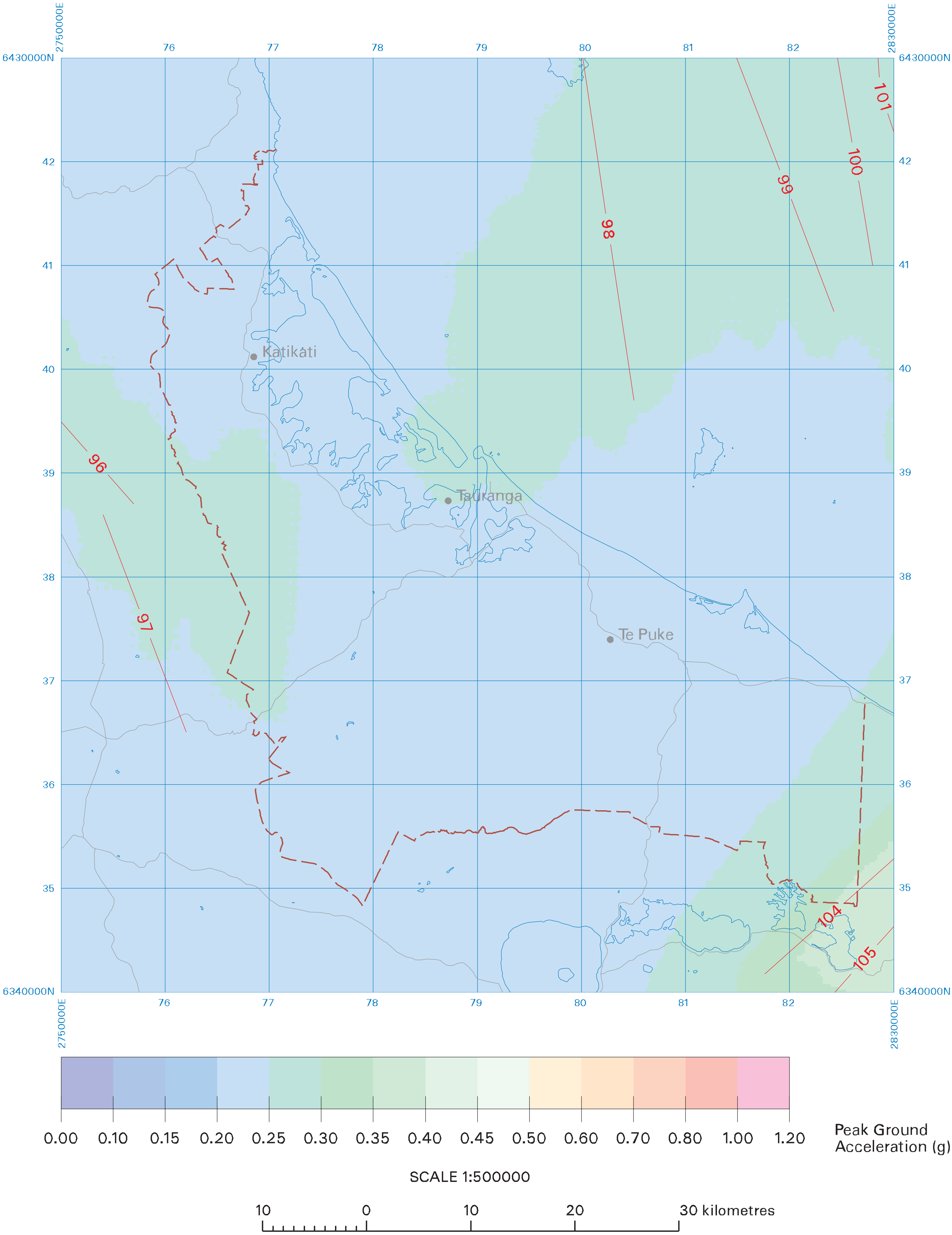


Figure B1(a) Uniform hazard peak ground acceleration, 10% probability of exceedance in 50 years, site class A/B.

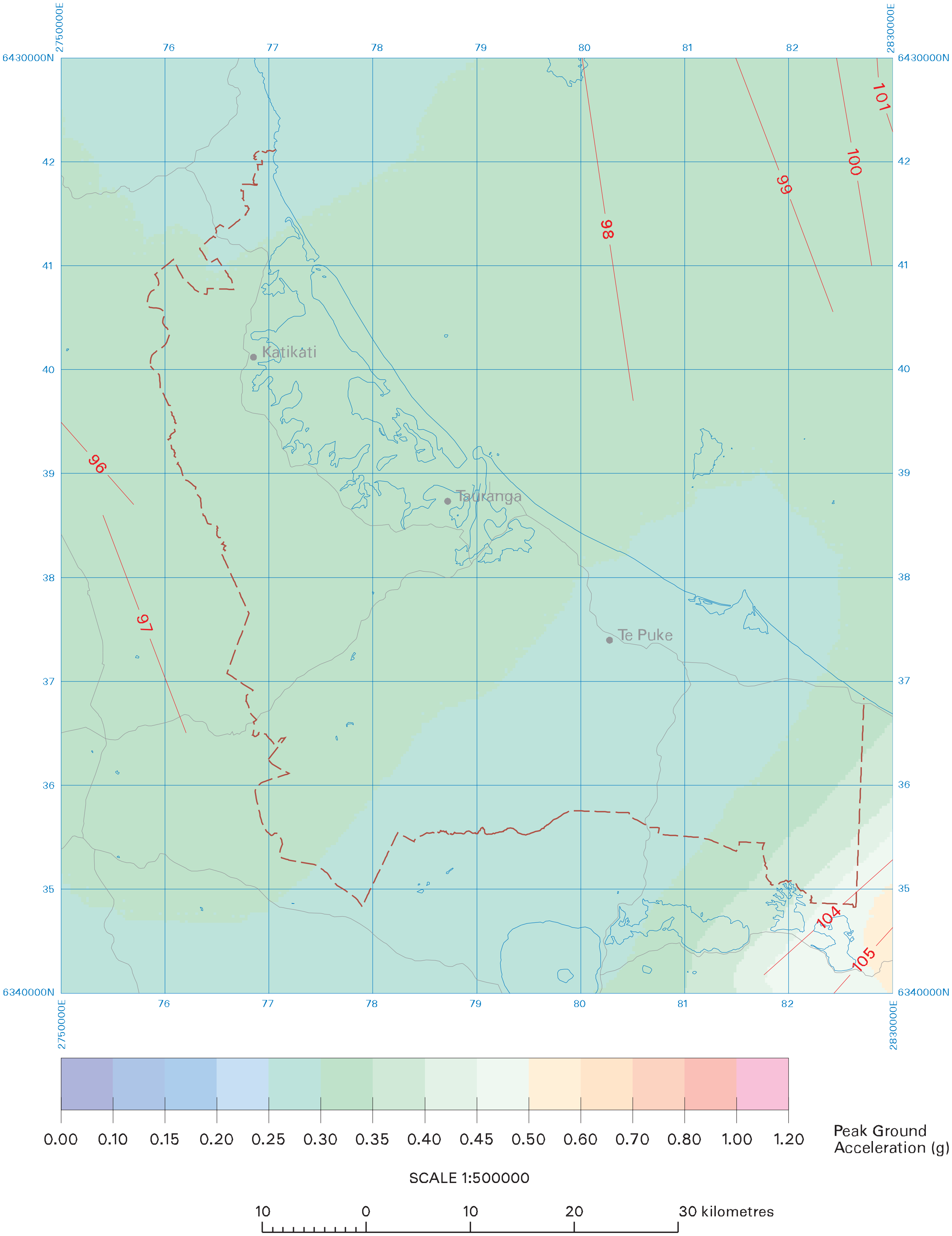


Figure B1(b) Uniform hazard peak ground acceleration, 10% probability of exceedance in 50 years, site class C.

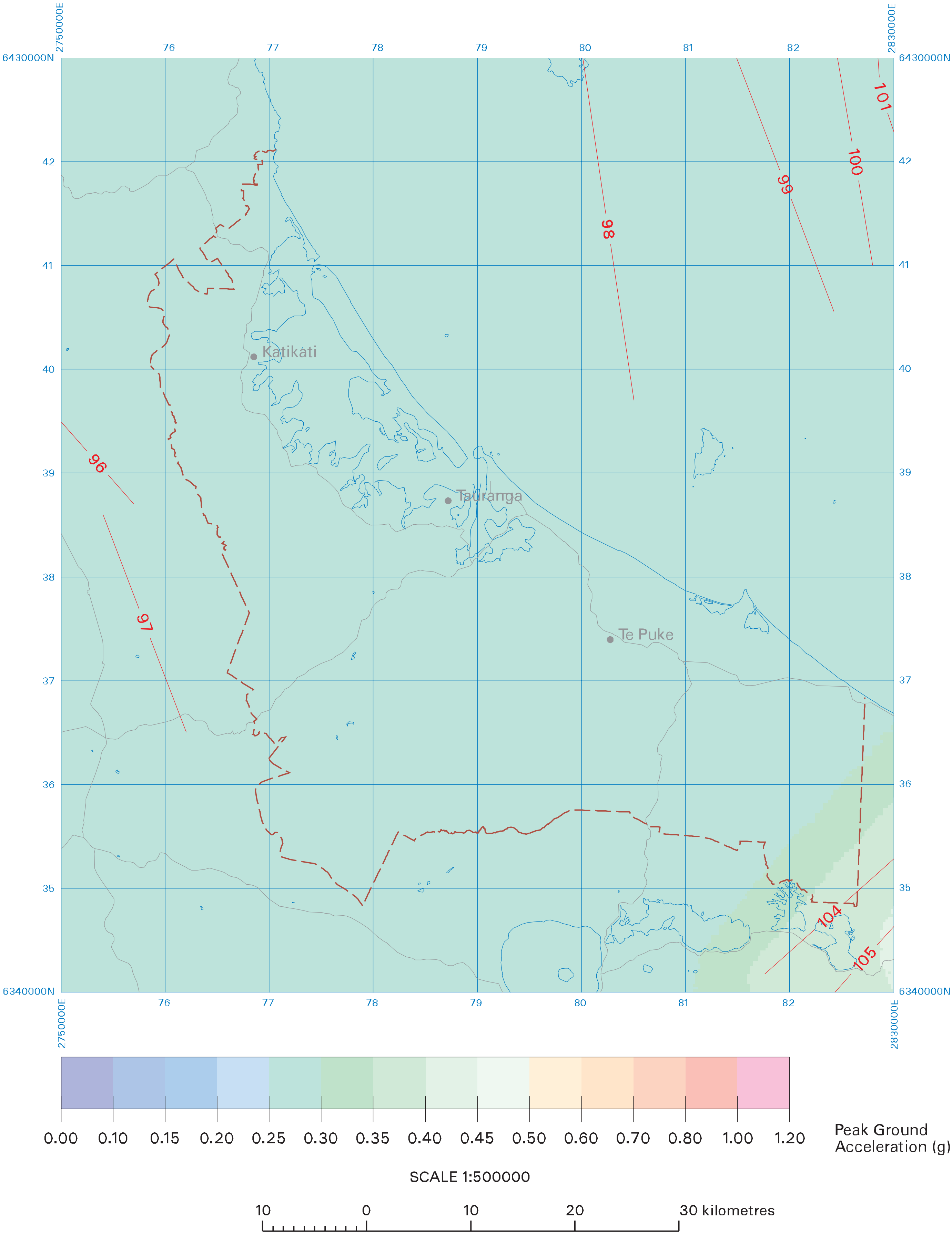


Figure B1(c) Uniform hazard peak ground acceleration, 10% probability of exceedance in 50 years, site class D/E.

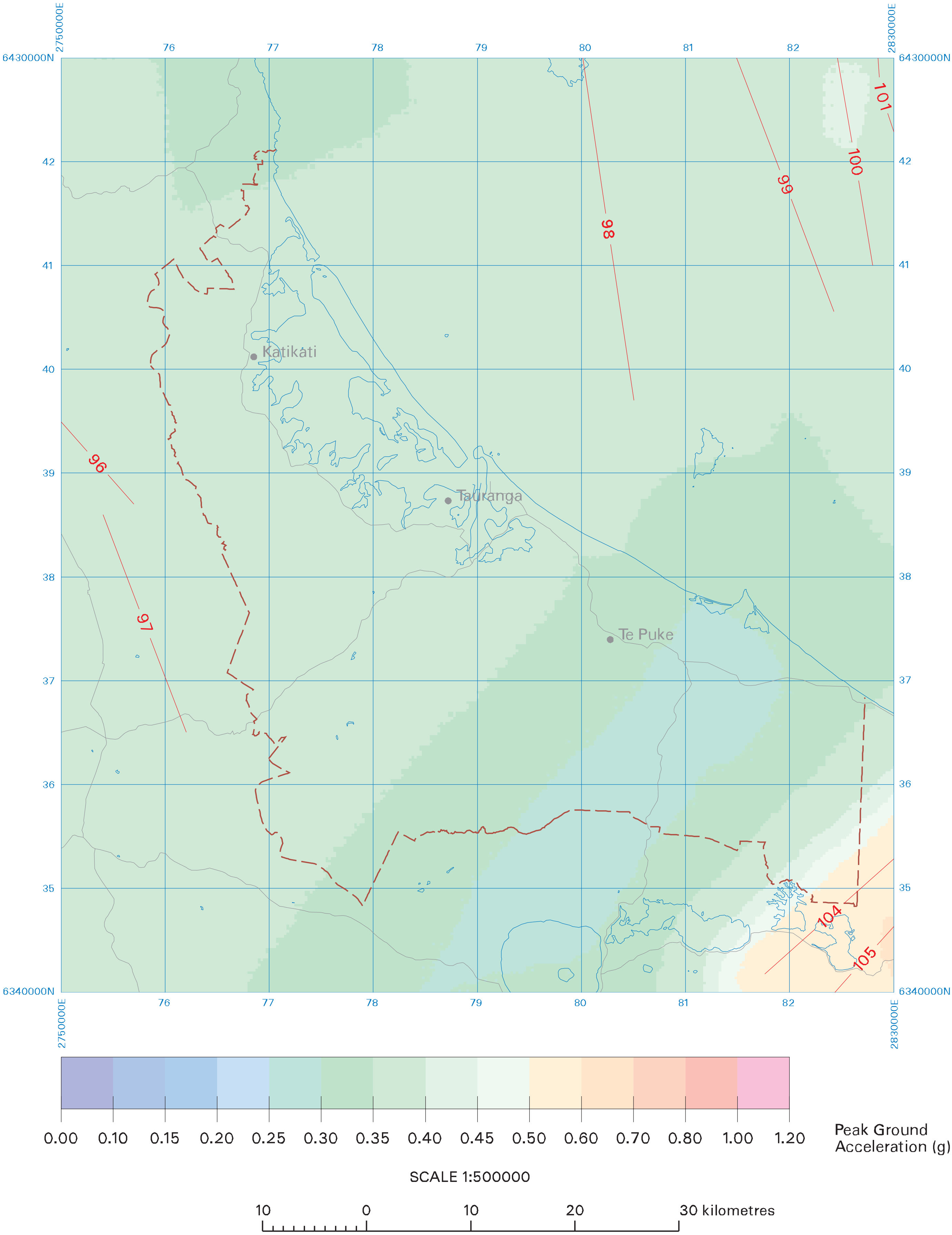


Figure B2(a) Uniform hazard peak ground acceleration, 2% probability of exceedance in 50 years, site class A/B.

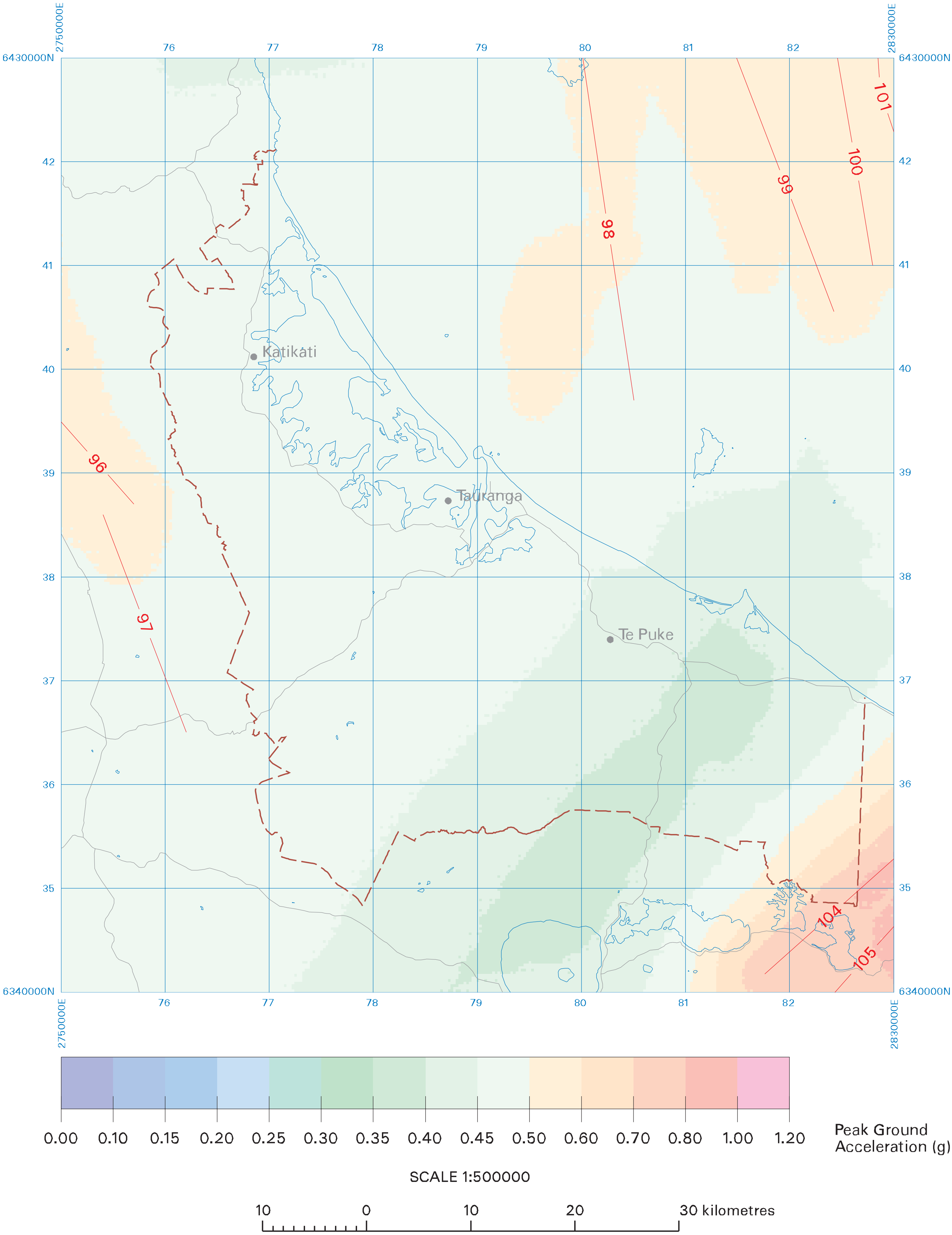


Figure B2(b) Uniform hazard peak ground acceleration, 2% probability of exceedance in 50 years, site class C.

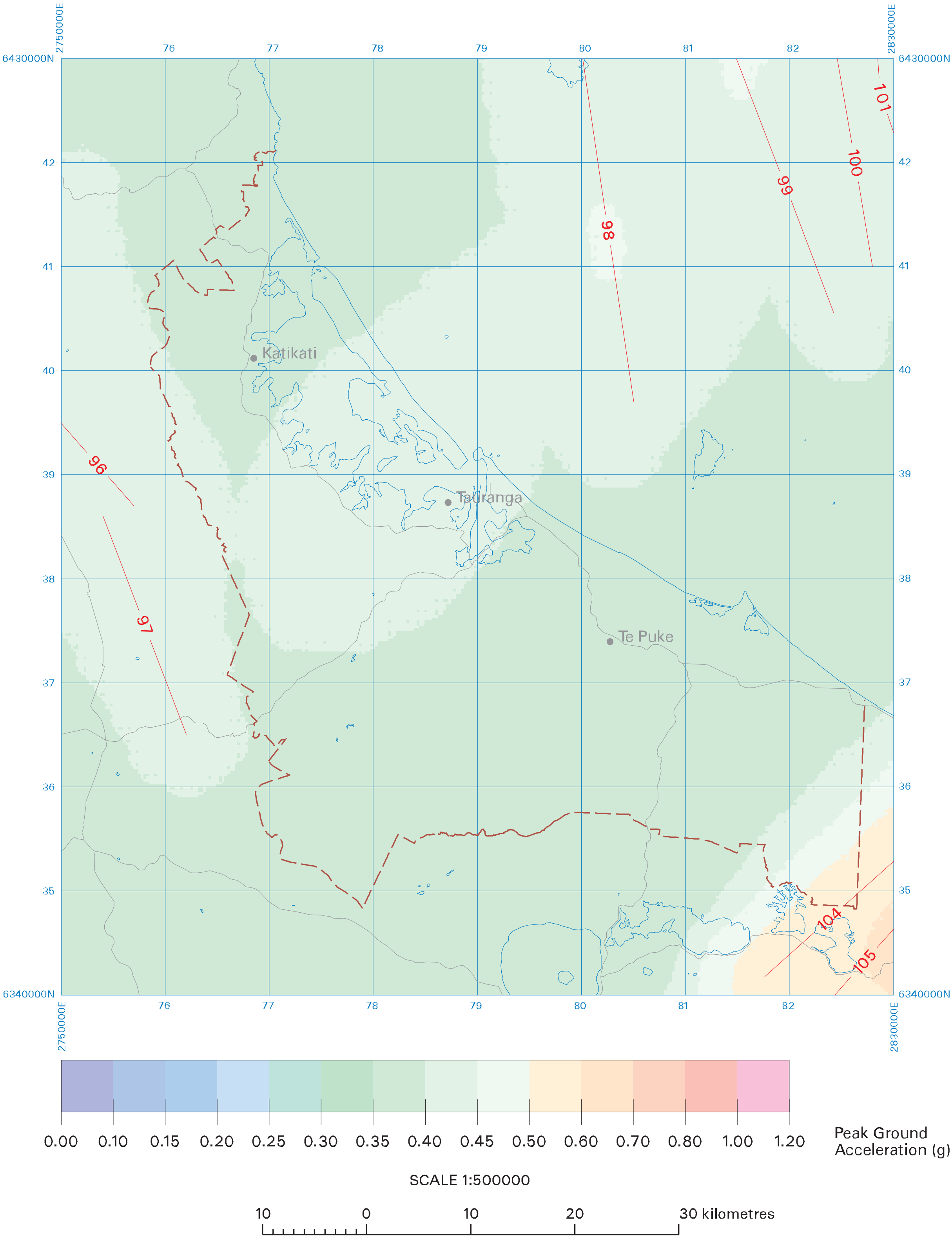


Figure B2(c) Uniform hazard peak ground acceleration, 2% probability of exceedance in 50 years, site class D/E.

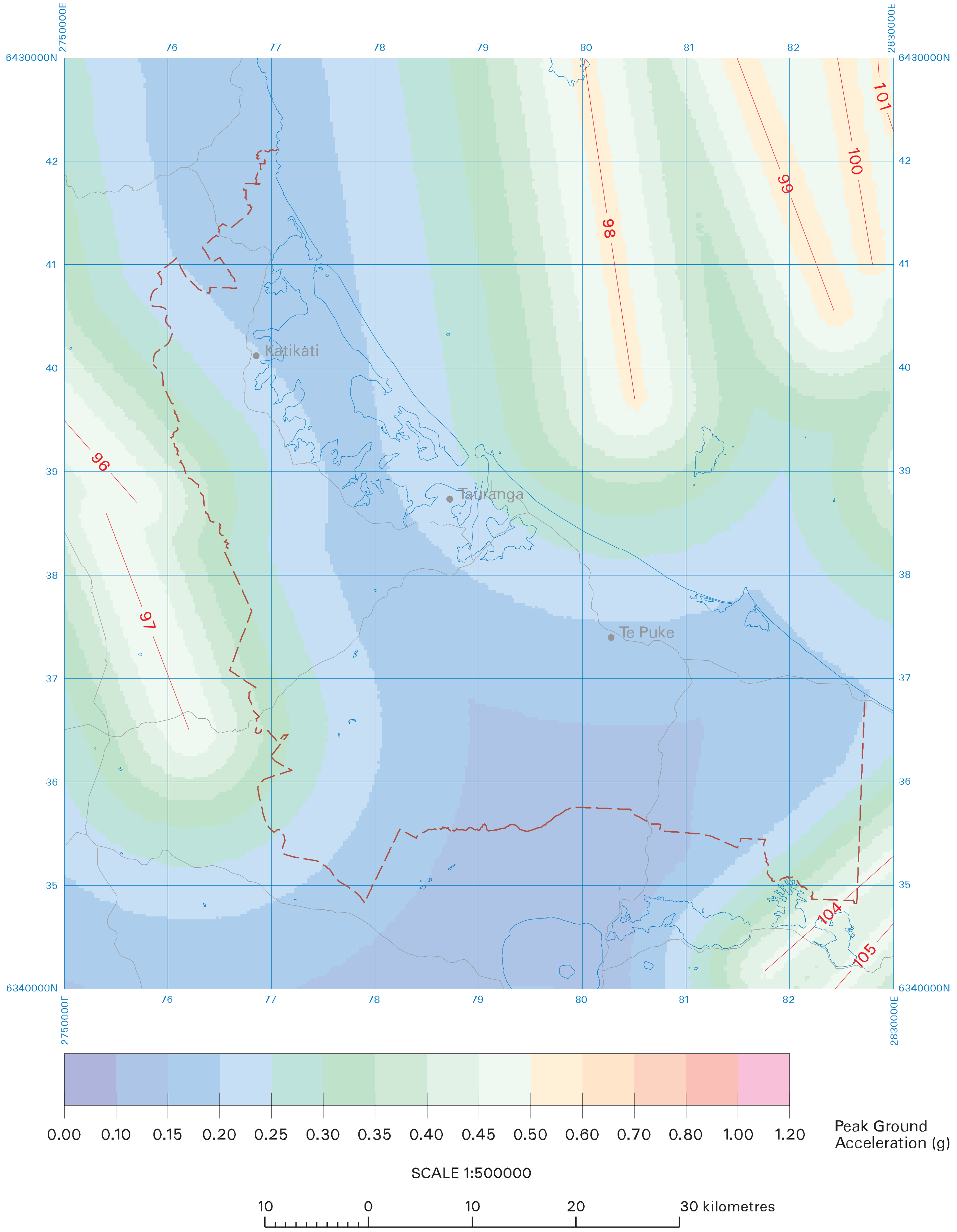


Figure B3 Maximum peak ground accelerations from all sources, 50-percentile level, for ground class C.

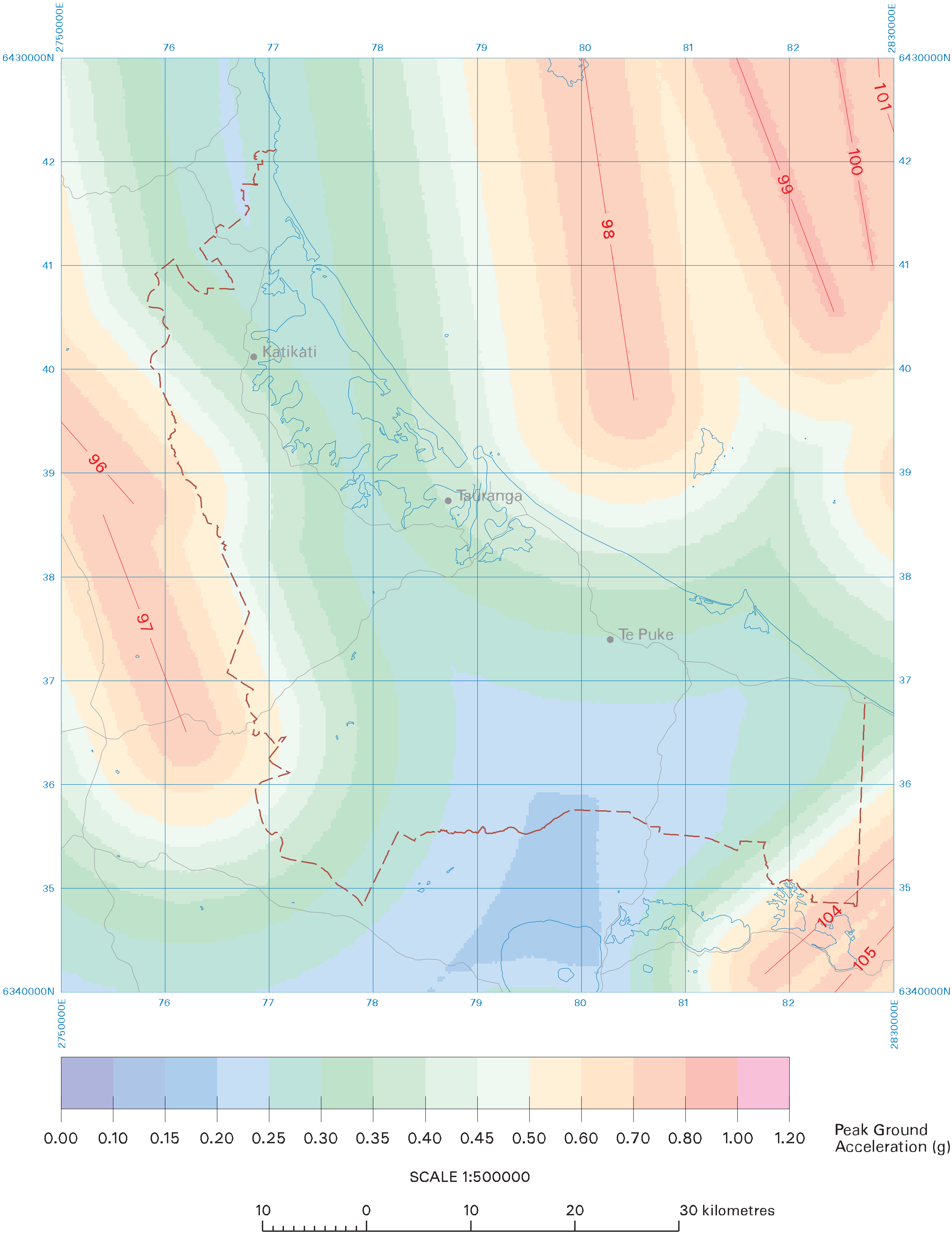
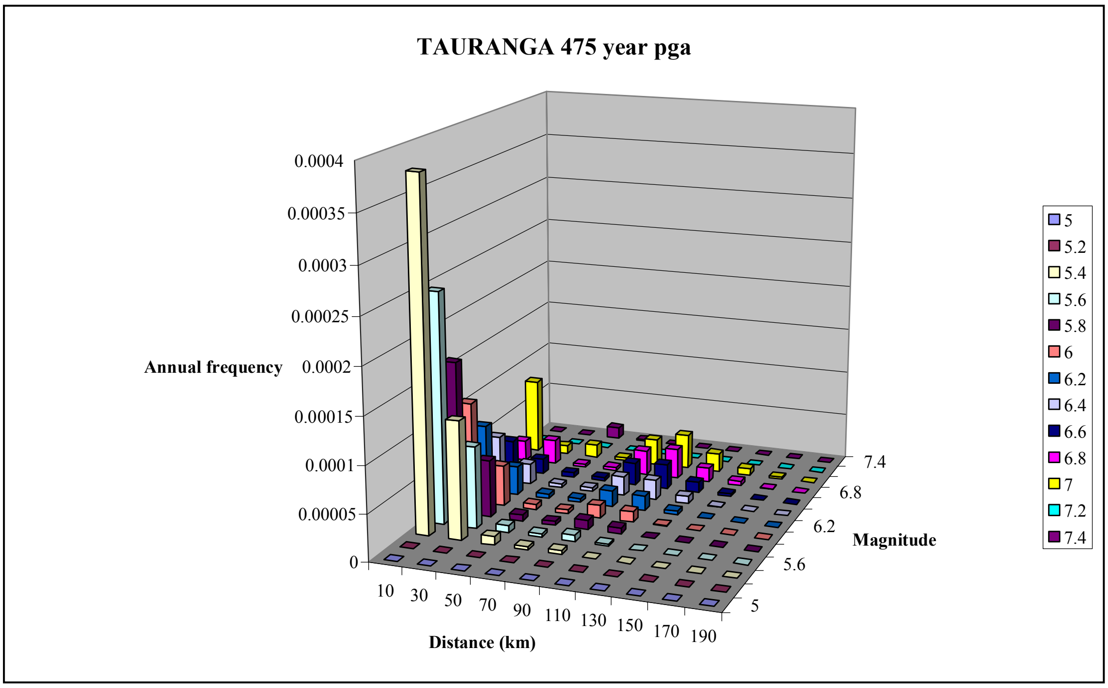


Figure B4 Maximum peak ground accelerations from all fault sources, 84-percentile level, ground class C



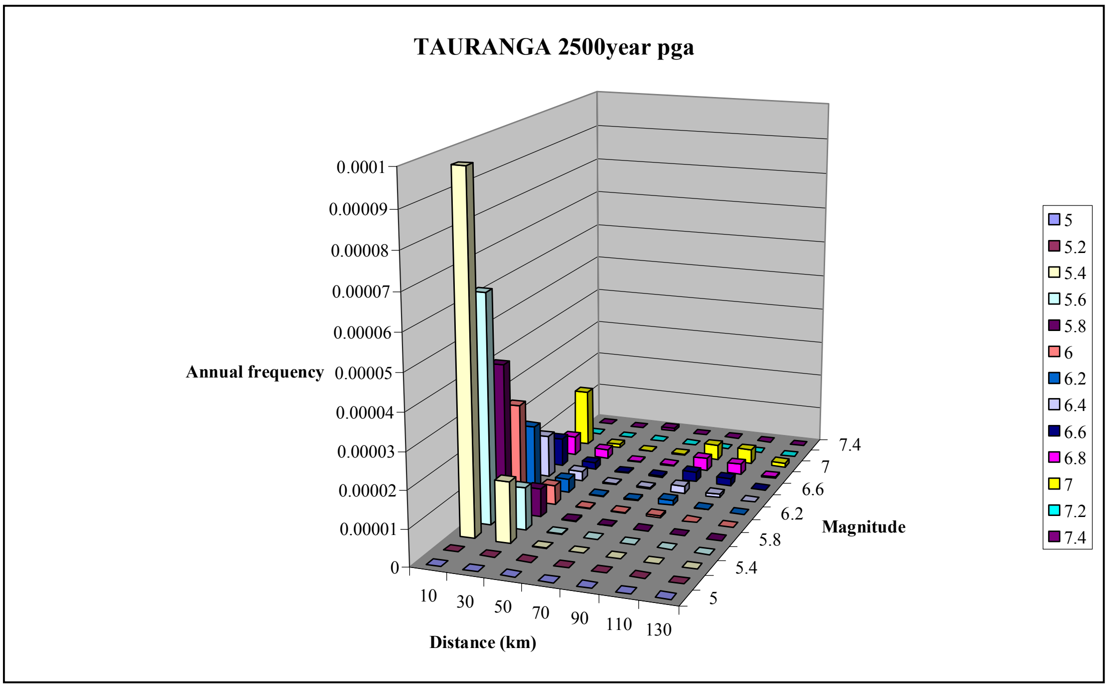
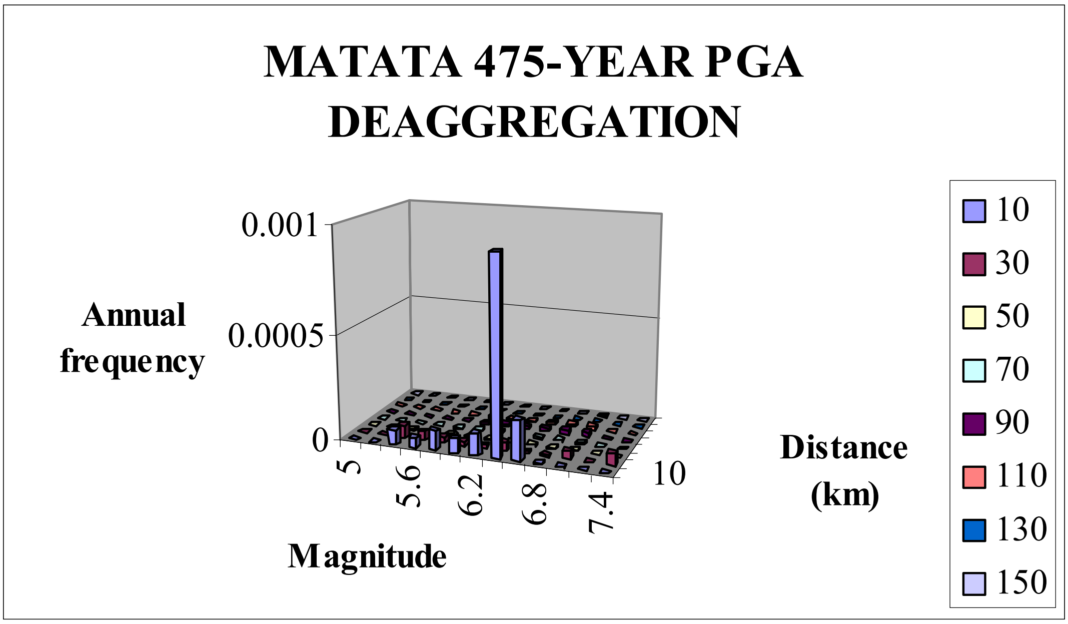


Figure B5 Deaggregation plots for peak ground accelerations of 10% and 2% probabilities of exceedance in 50 years on shallow soil (ground class C) for Tauranga.



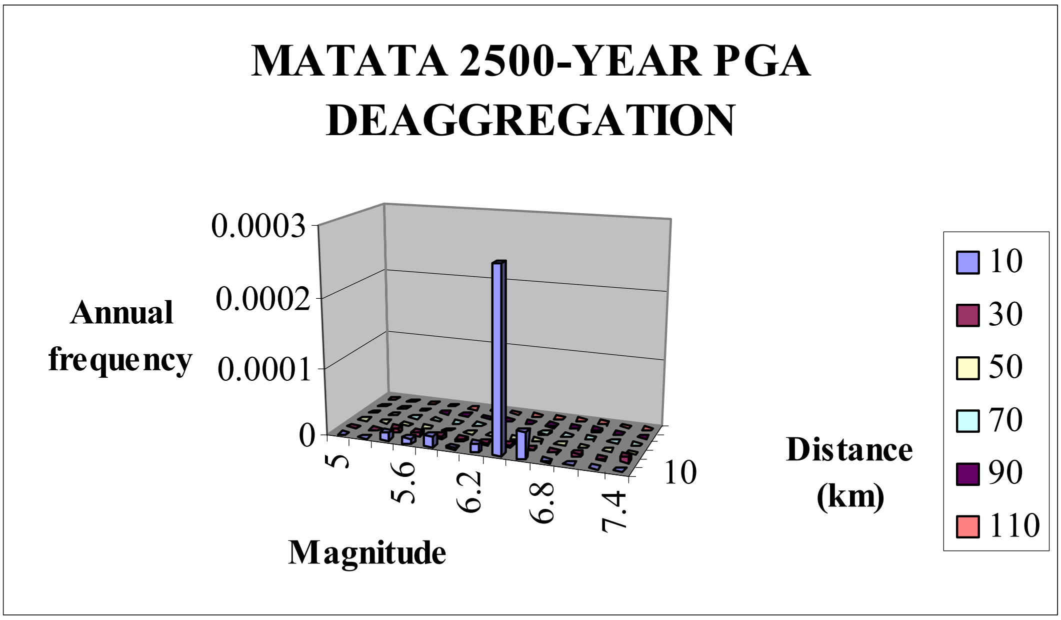
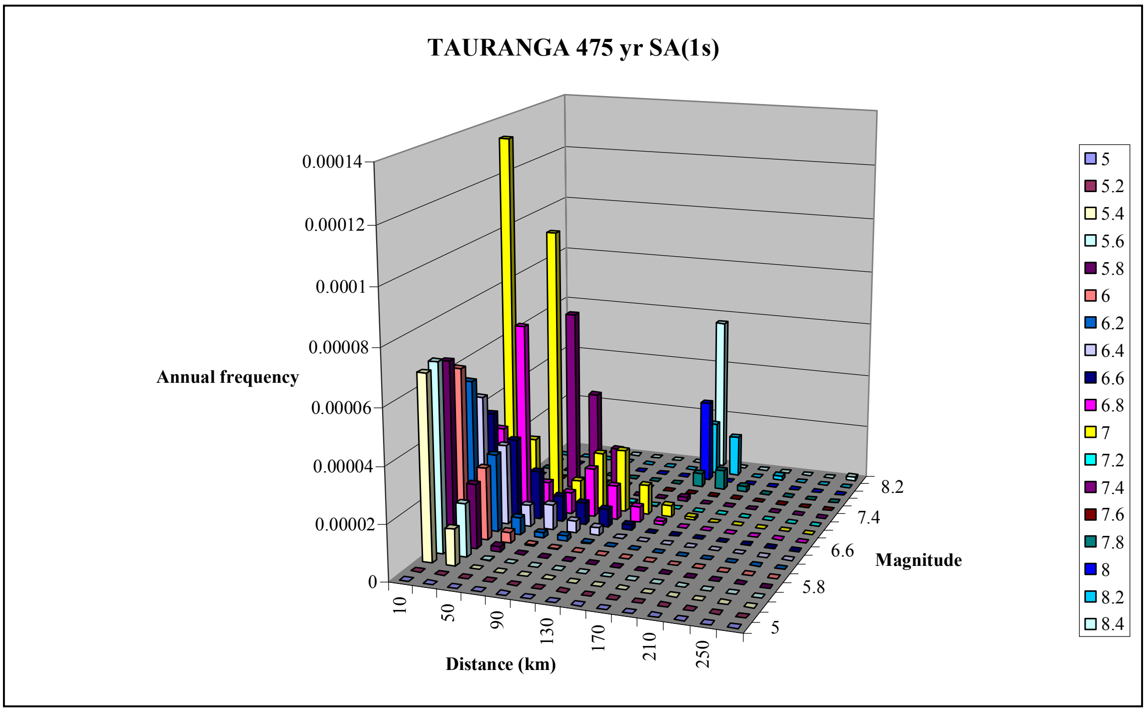


Figure B6 Deaggregation plots for peak ground accelerations of 10% and 2% probabilities of exceedance in 50 years on shallow soil (ground class C) for Matata.



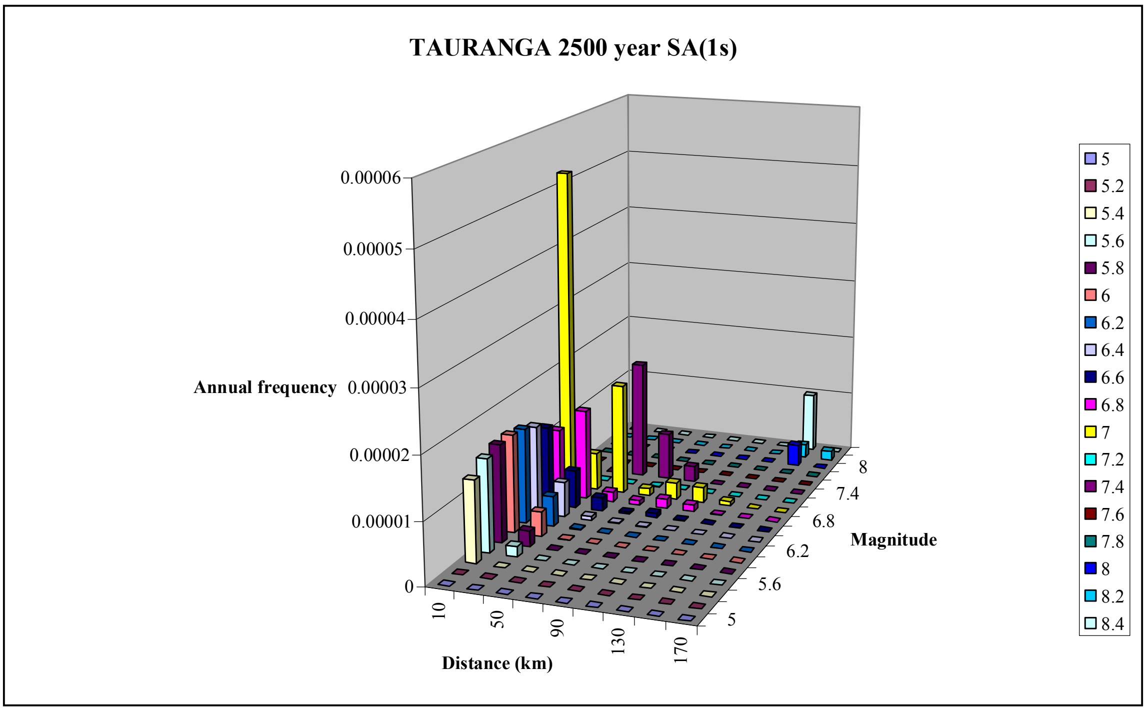


Figure B7 Deaggregation plots for spectral accelerations (SA (1s)) accelerations of 10% and 2% probabilities of exceedance in 50 years on shallow soil (ground class C) for Tauranga.

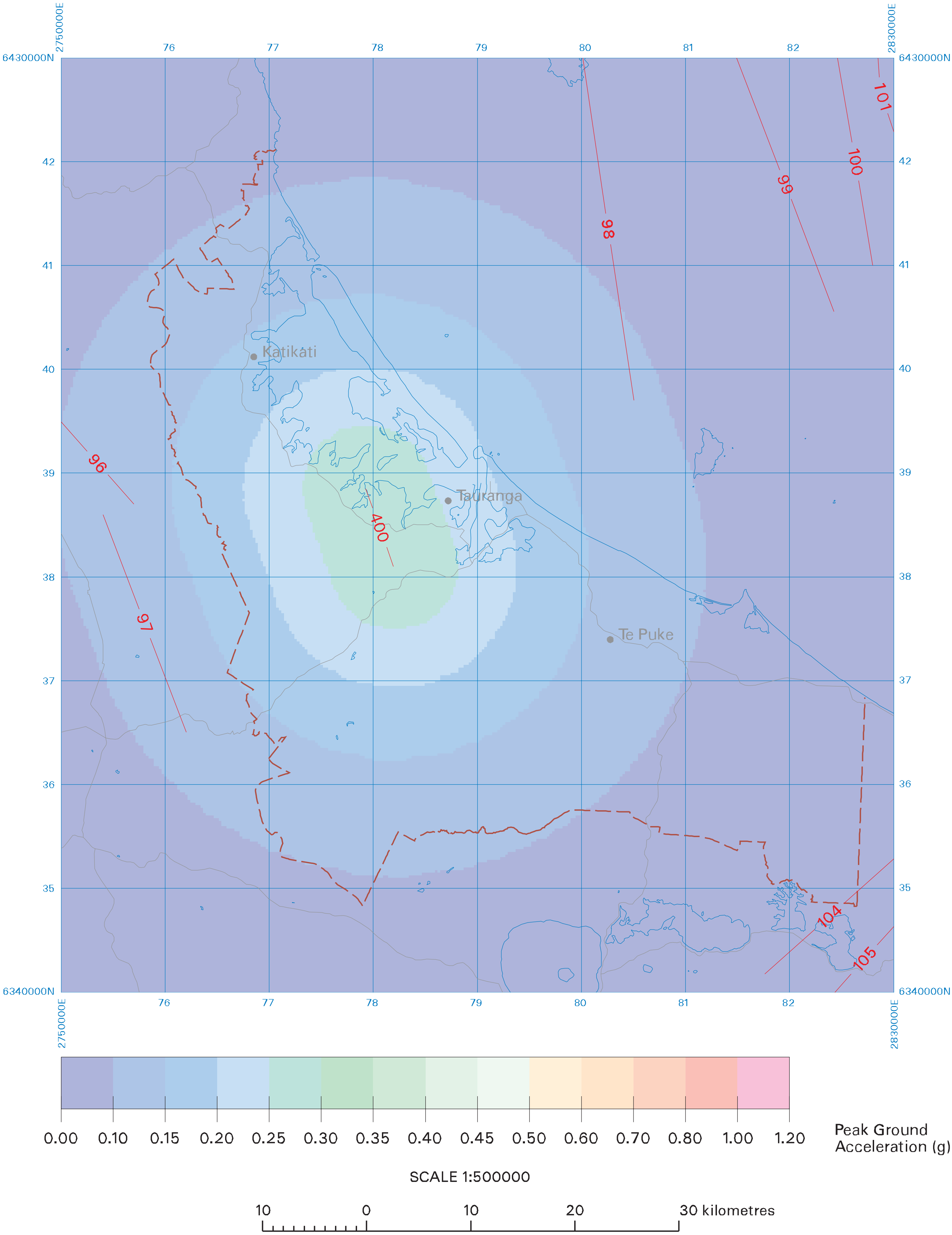


Figure B8(a) Peak ground accelerations estimated for the Tauranga scenario of 84-percentile motions from a magnitude 5.4 earthquake at 10 km depth about 10 km west of Tauranga, for site class A/B.

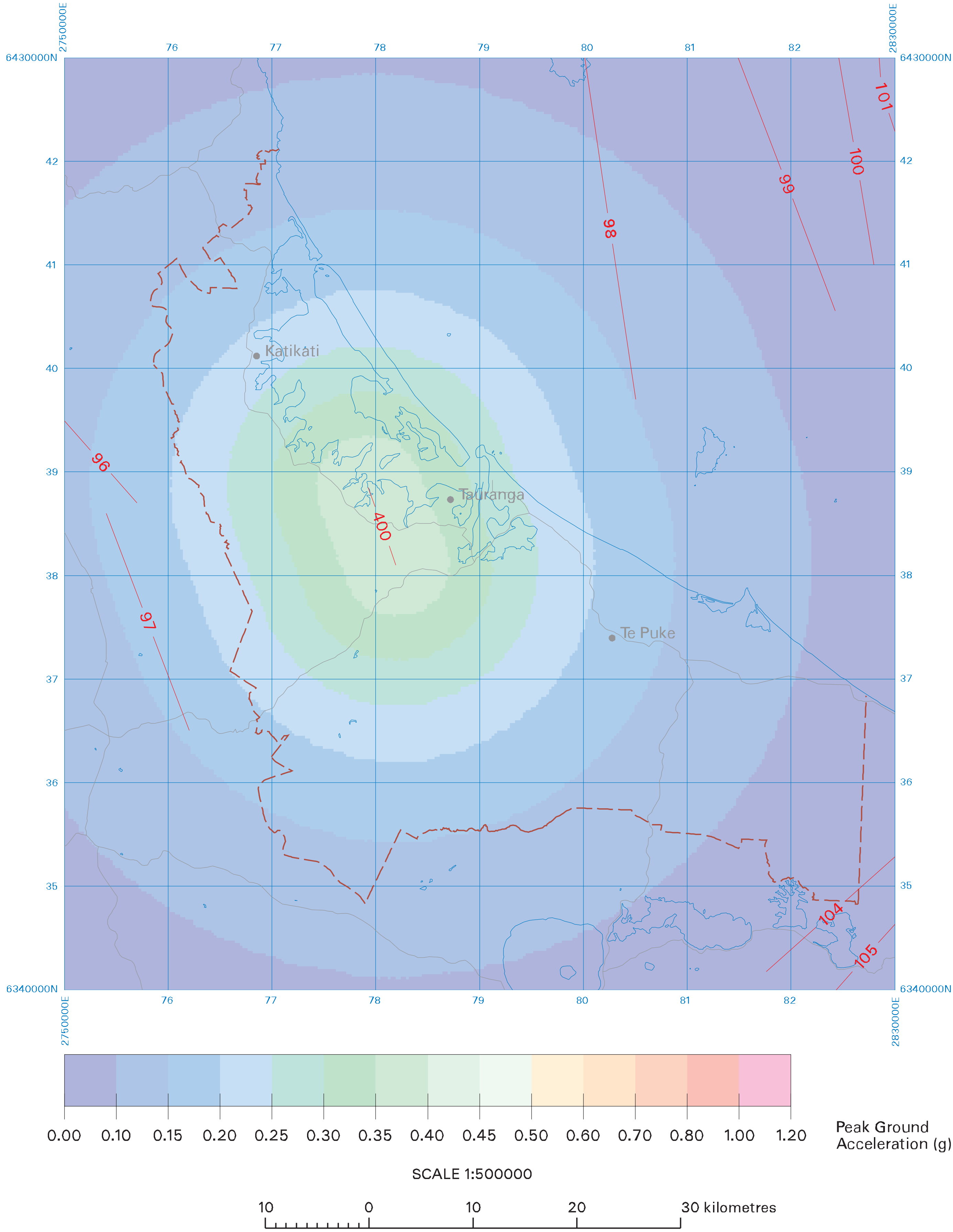


Figure B8(b) Peak ground accelerations estimated for the Tauranga scenario of 84-percentile motions from a magnitude 5.4 earthquake at 10 km depth about 10 km west of Tauranga, for site class C.

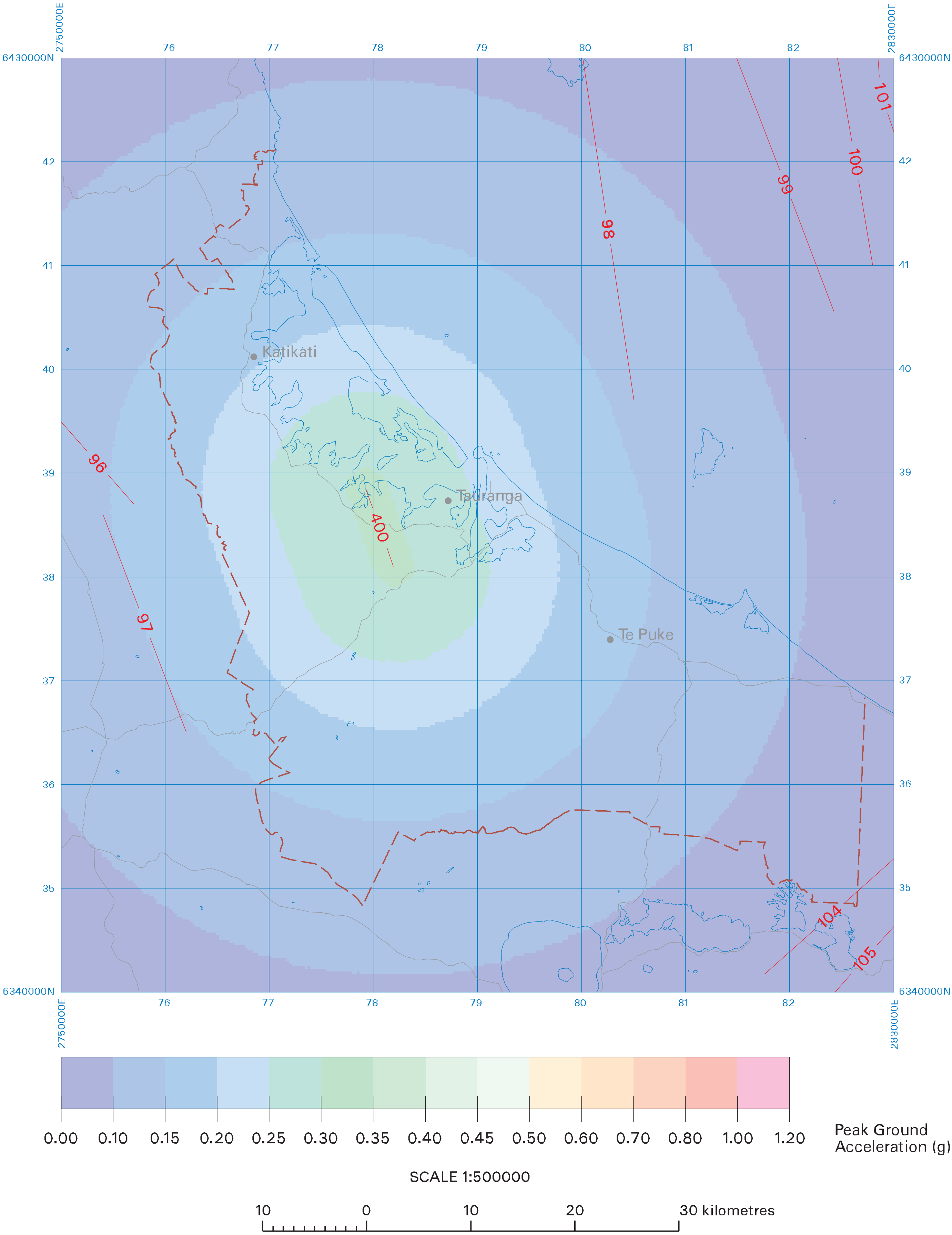


Figure B8(c) Peak ground accelerations estimated for the Tauranga scenario of 84-percentile motions from a magnitude 5.4 earthquake at 10 km depth about 10 km west of Tauranga, for site class D/E.

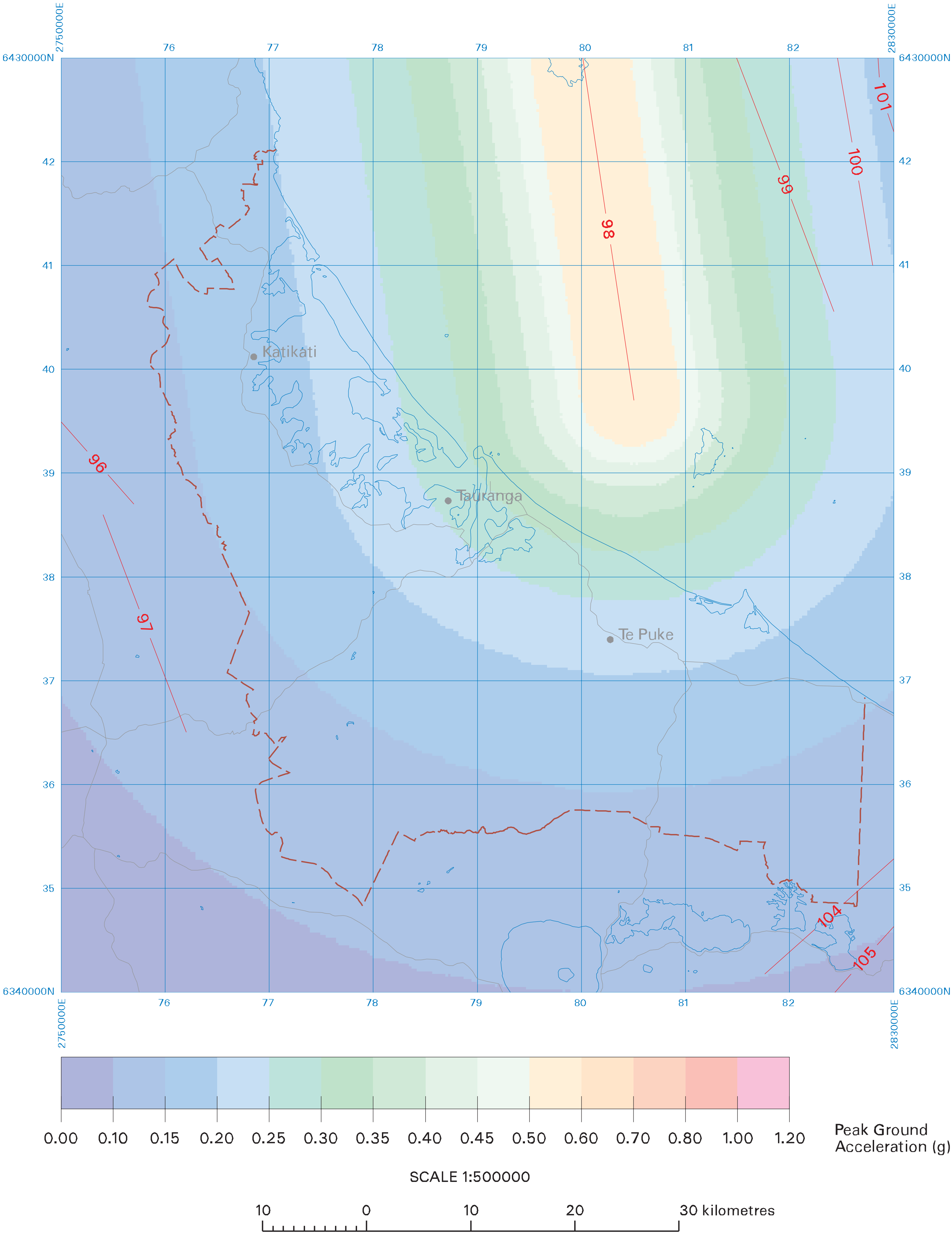


Figure B9(a) Peak ground accelerations estimated for the Tauranga scenario of 84-percentile motions from a magnitude 7 earthquake on the Mayor Island Fault 1, for site class A/B

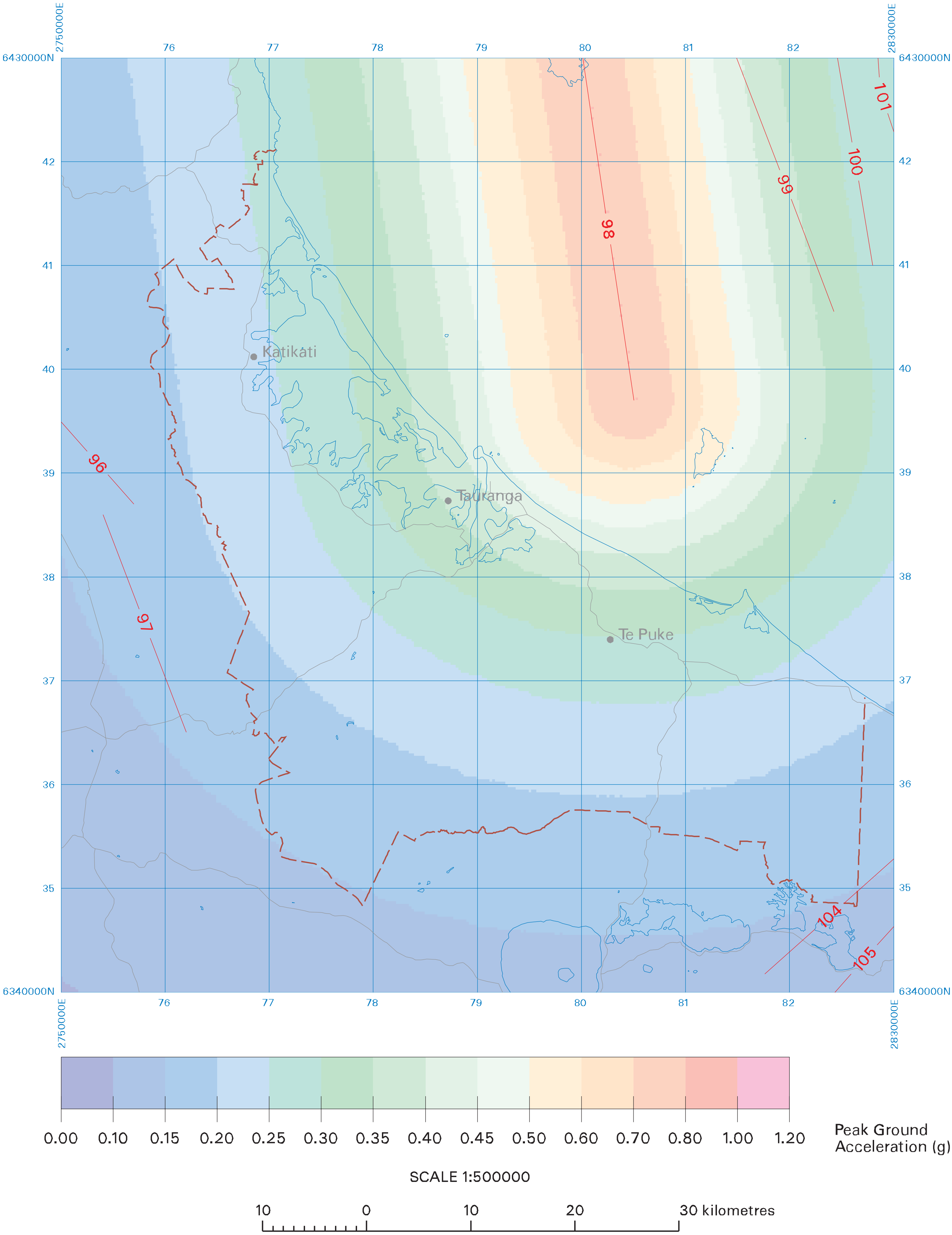


Figure B9(b) Peak ground accelerations estimated for the Tauranga scenario of 84-percentile motions from a magnitude 7 earthquake on the Mayor Island Fault 1, for site class C.

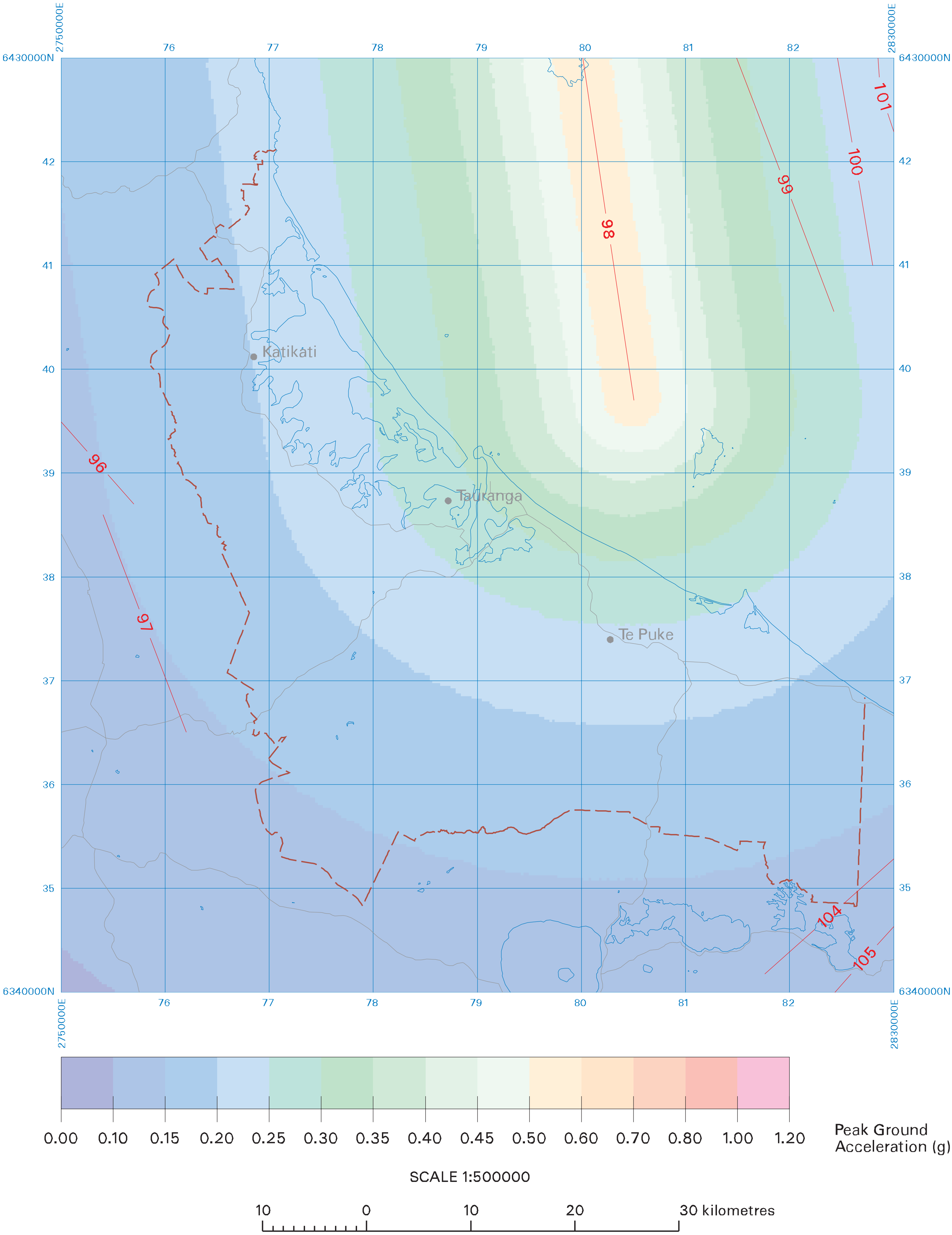


Figure B9(c) Peak ground accelerations estimated for the Tauranga scenario of 84-percentile motions from a magnitude 7 earthquake on the Mayor Island Fault 1, for site class D/E.

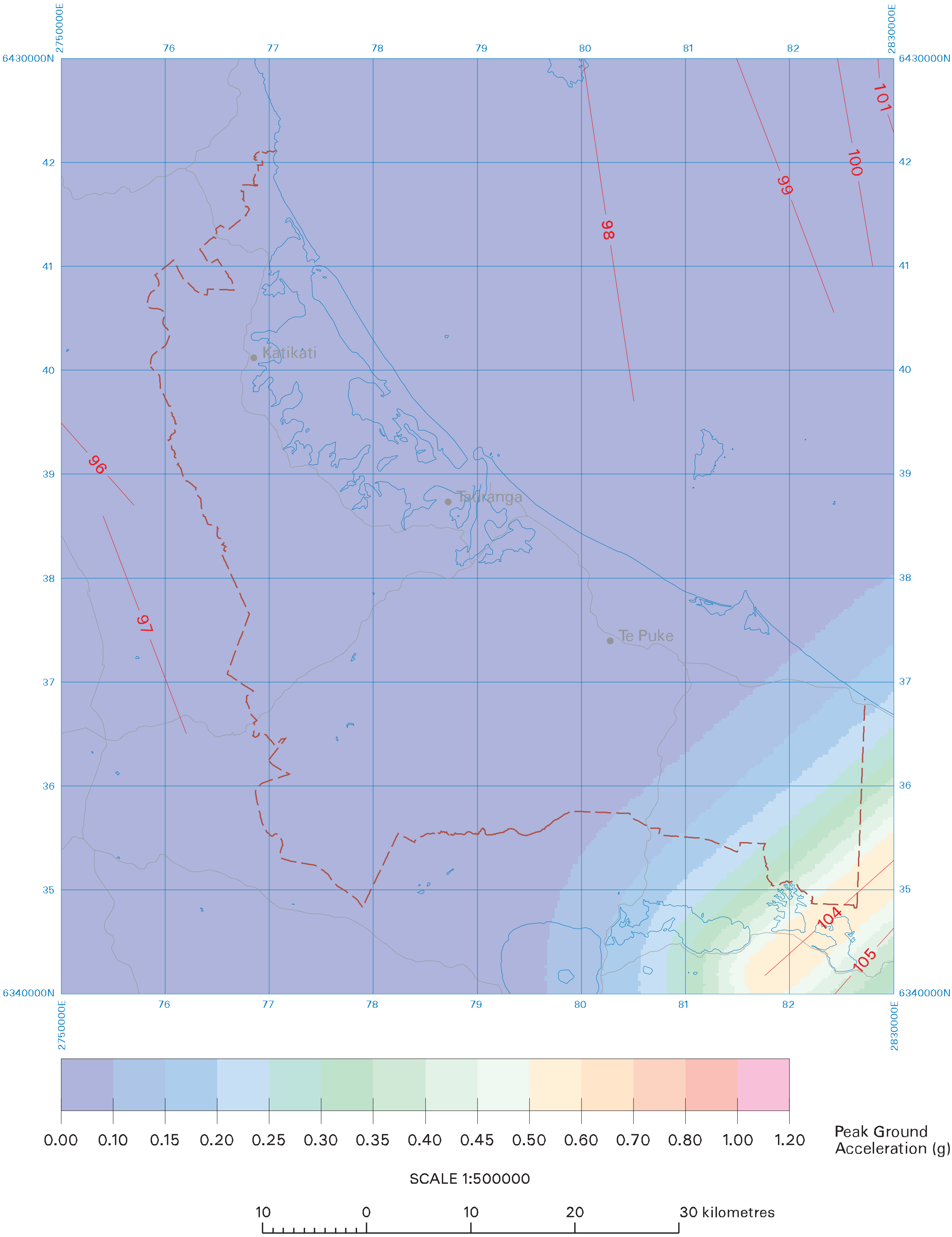


Figure B10(a) Peak ground accelerations estimated for the Matata scenario of 84-percentile motions from a magnitude 6.5 earthquake on the Matata Fault, for site class A/B

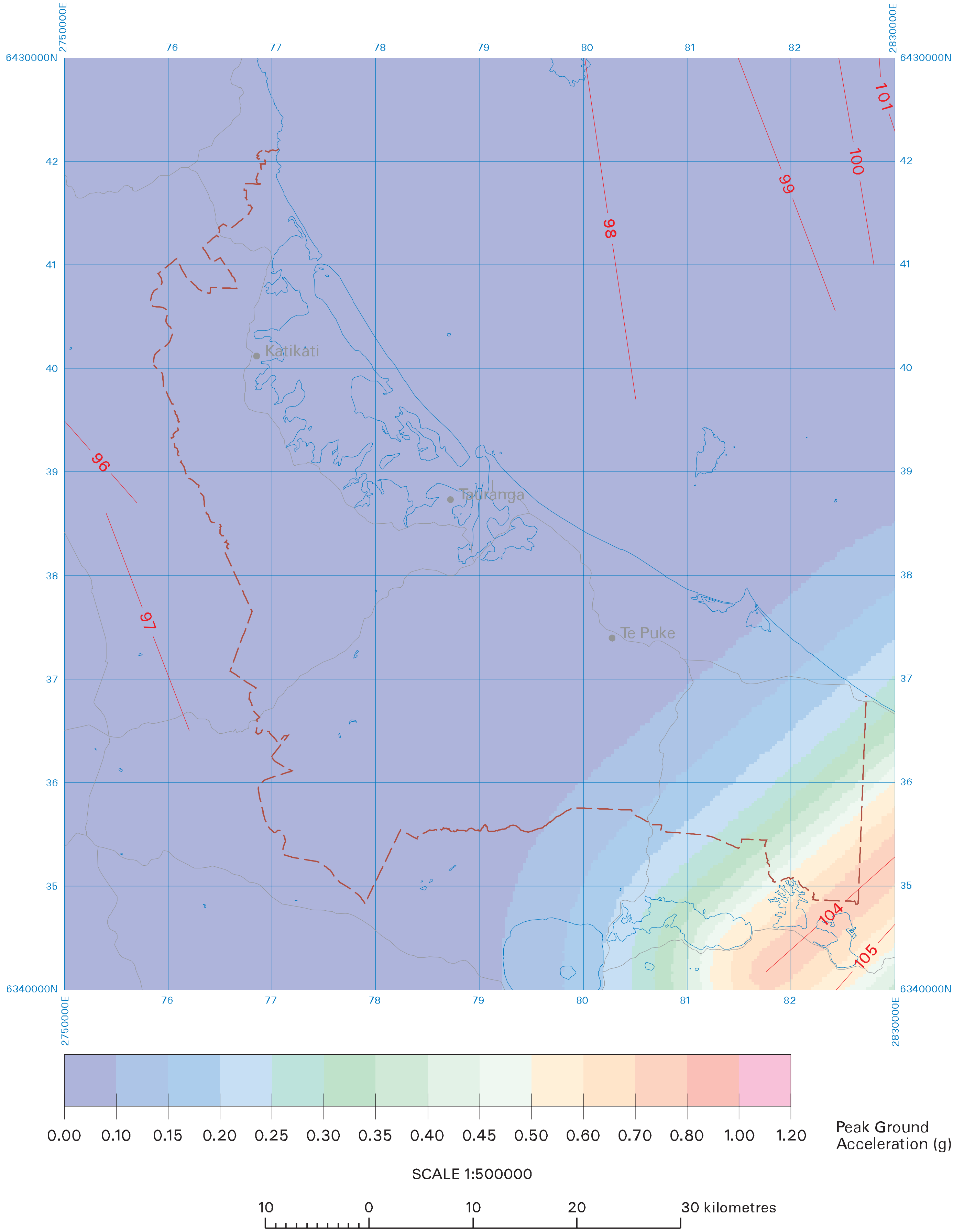


Figure B10(b) Peak ground accelerations estimated for the Matata scenario of 84-percentile motions from a magnitude 6.5 earthquake on the Matata Fault, for site class C.

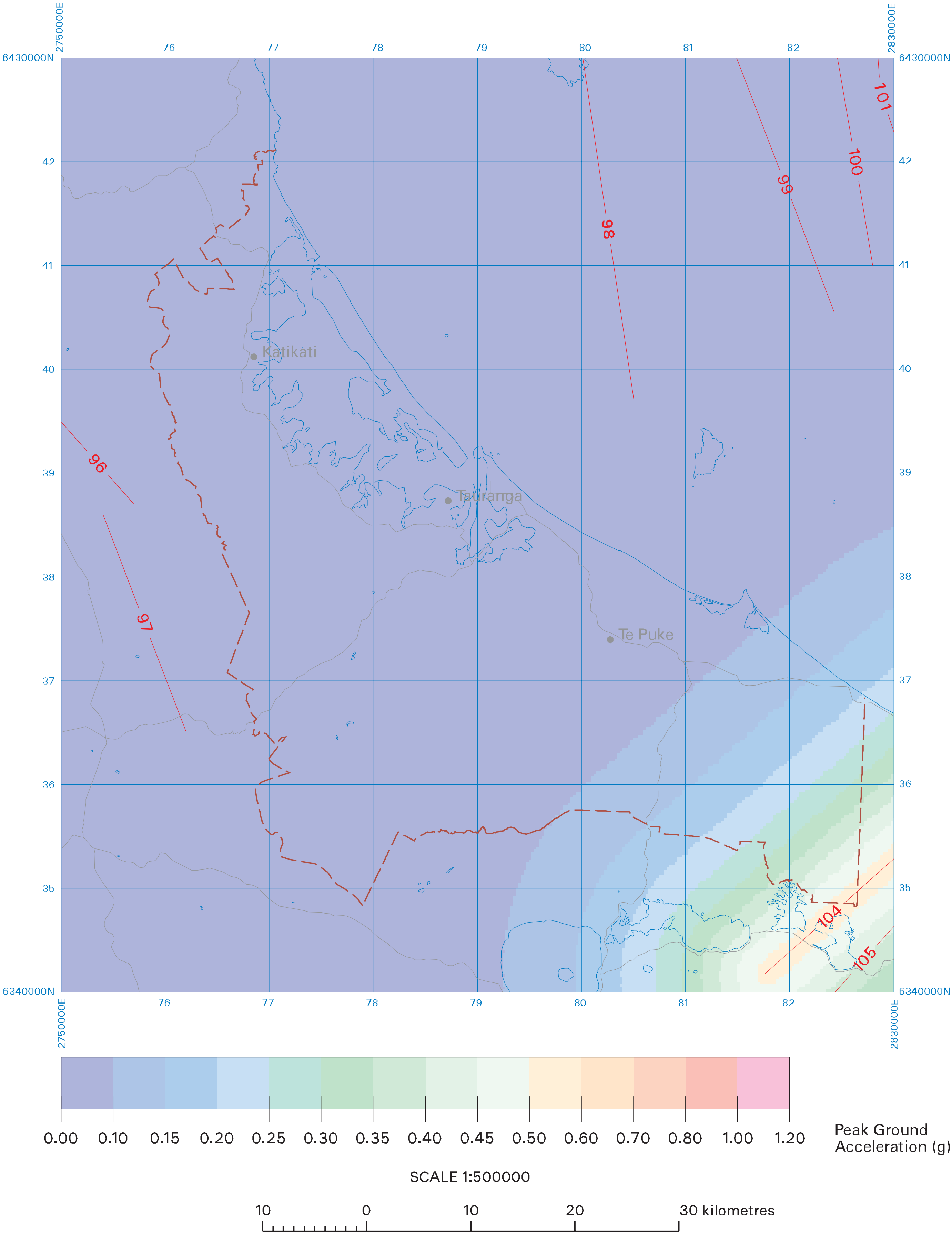


Figure B10(c) Peak ground accelerations estimated for the Matata scenario of 84-percentile motions from a magnitude 6.5 earthquake on the Matata Fault, for site class D/E.

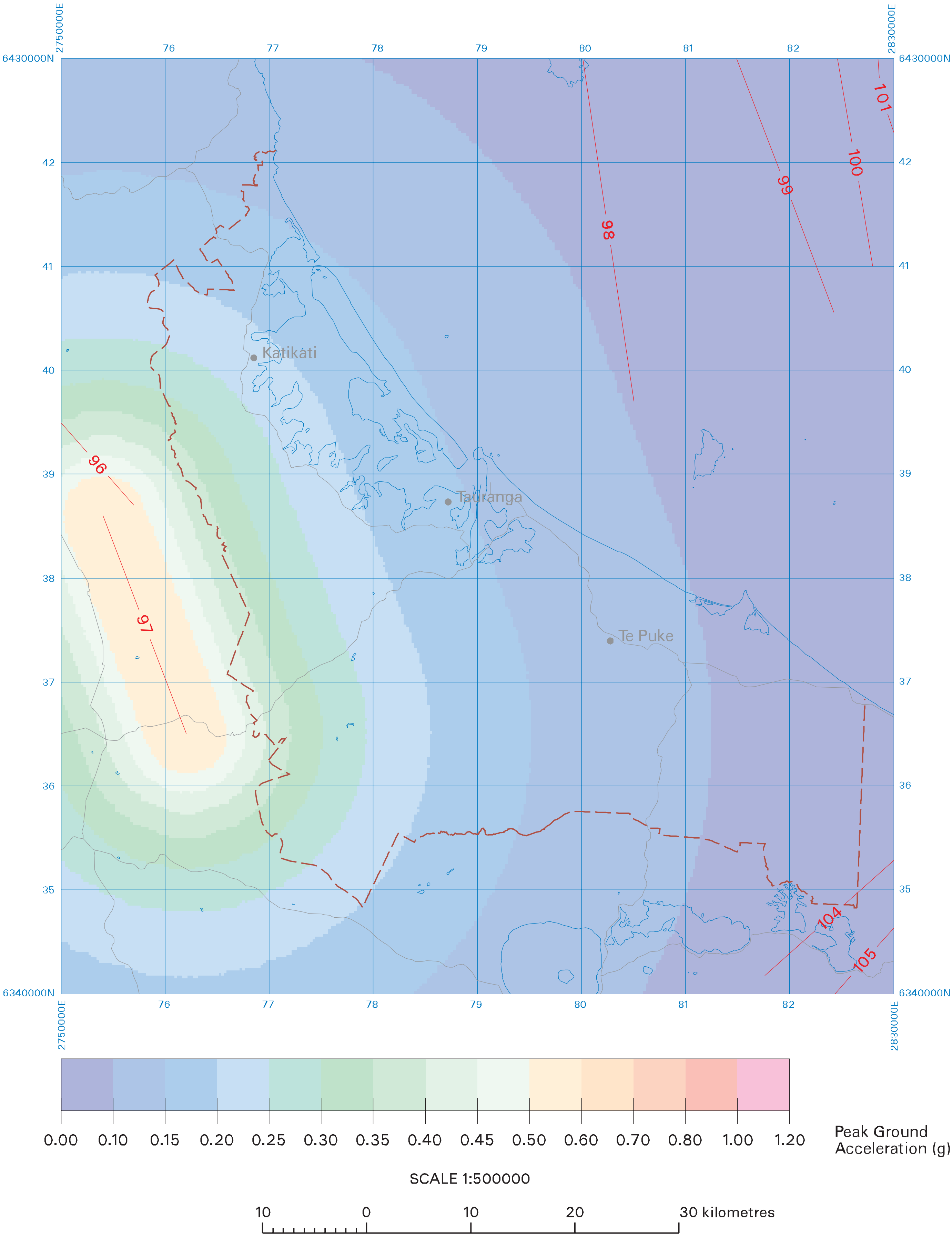


Figure B11(a) Peak ground accelerations estimated for the Lower Kaimai scenario of 84-percentile motions from a magnitude 6.7 earthquake on the south segment of the Kerepehi Fault, for site class A/B

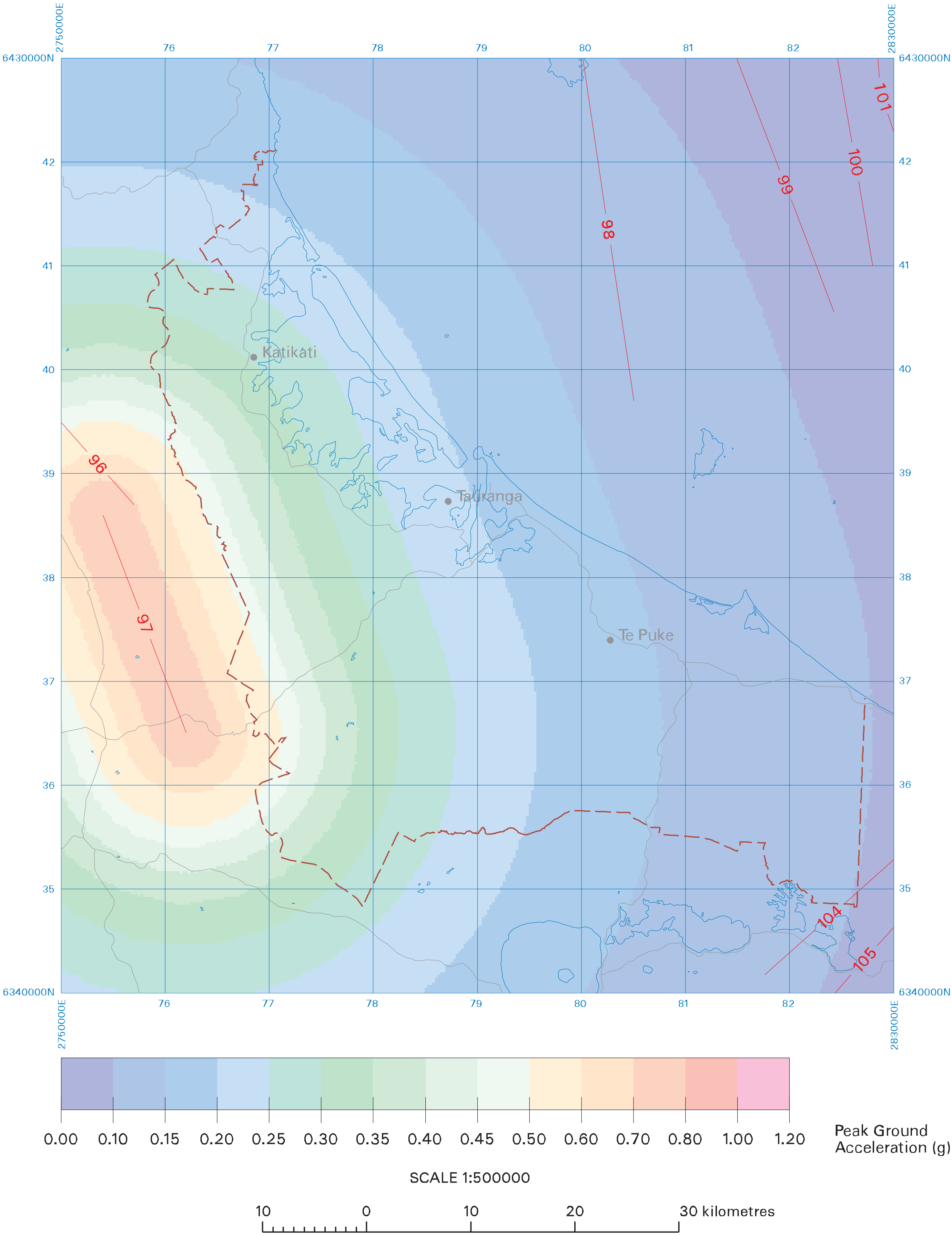


Figure B11(b) Peak ground accelerations estimated for the Lower Kaimai scenario of 84-percentile motions from a magnitude 6.7 earthquake on the south segment of the Kerepehi Fault, for site class C.

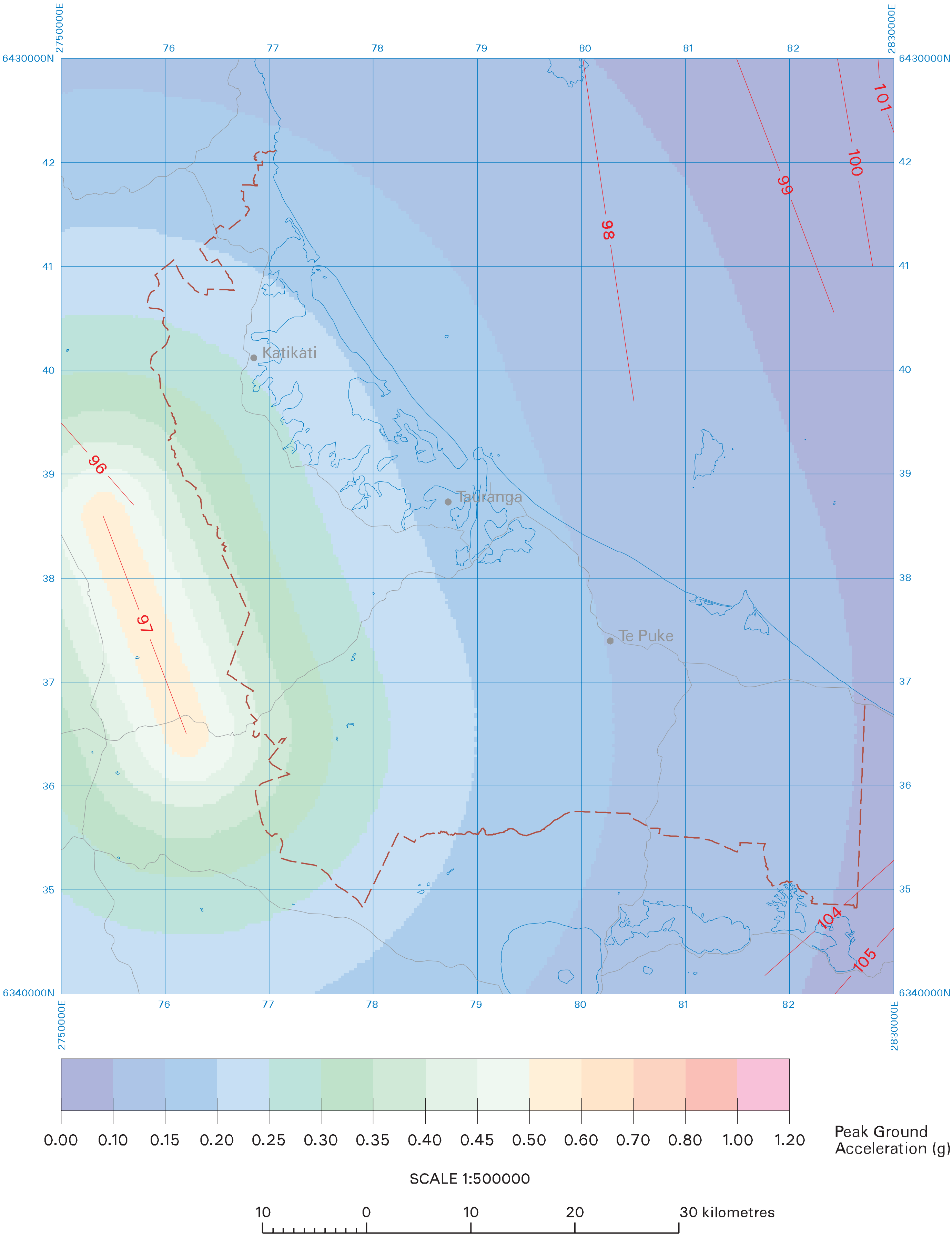


Figure B11(c) Peak ground accelerations estimated for the Lower Kaimai scenario of 84-percentile motions from a magnitude 6.7 earthquake on the south segment of the Kerepehi Fault, for site class D/E.

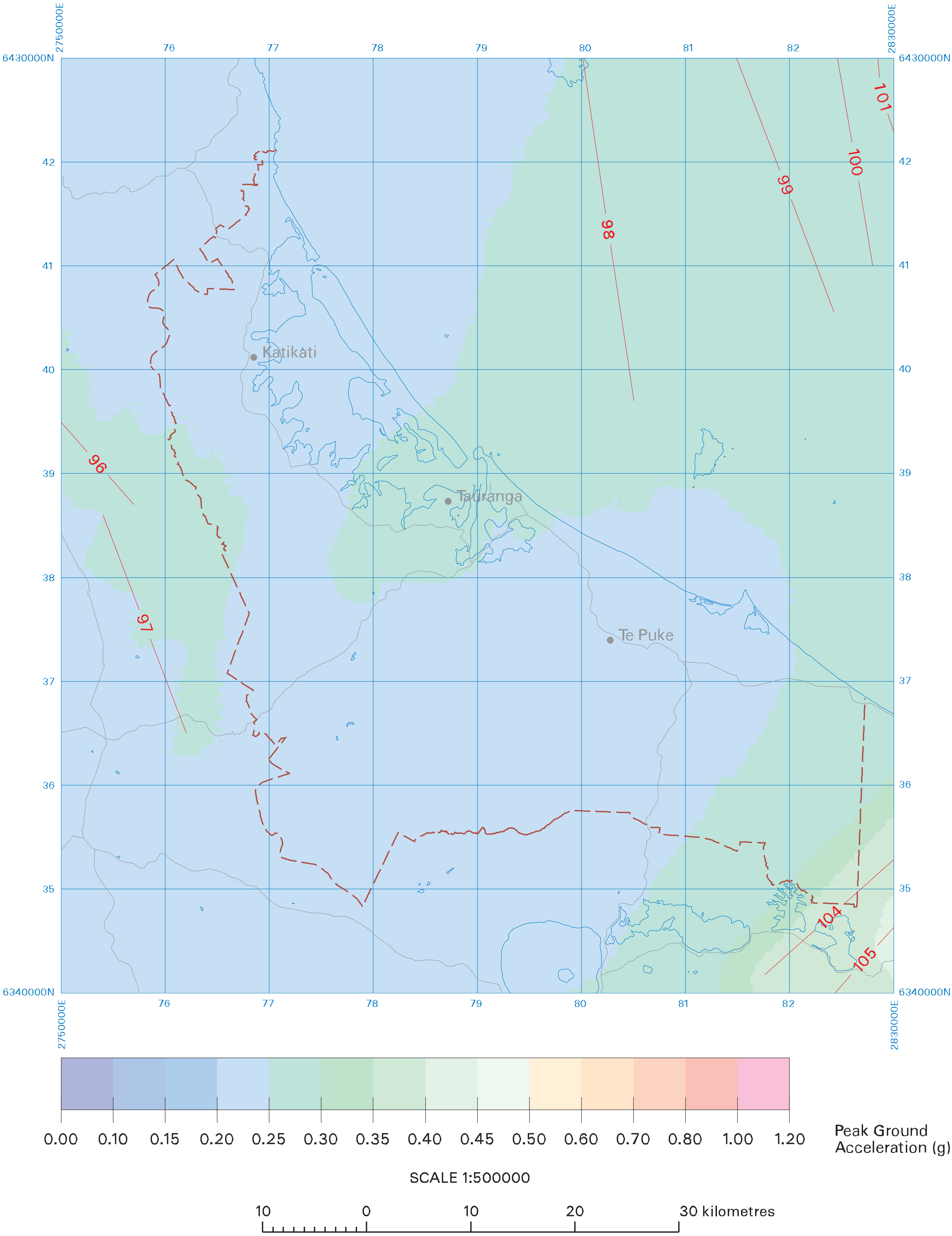


Figure B12(a) Magnitude Weighted peak ground accelerations, 10% probability of exceedance in 50 years, site class C.

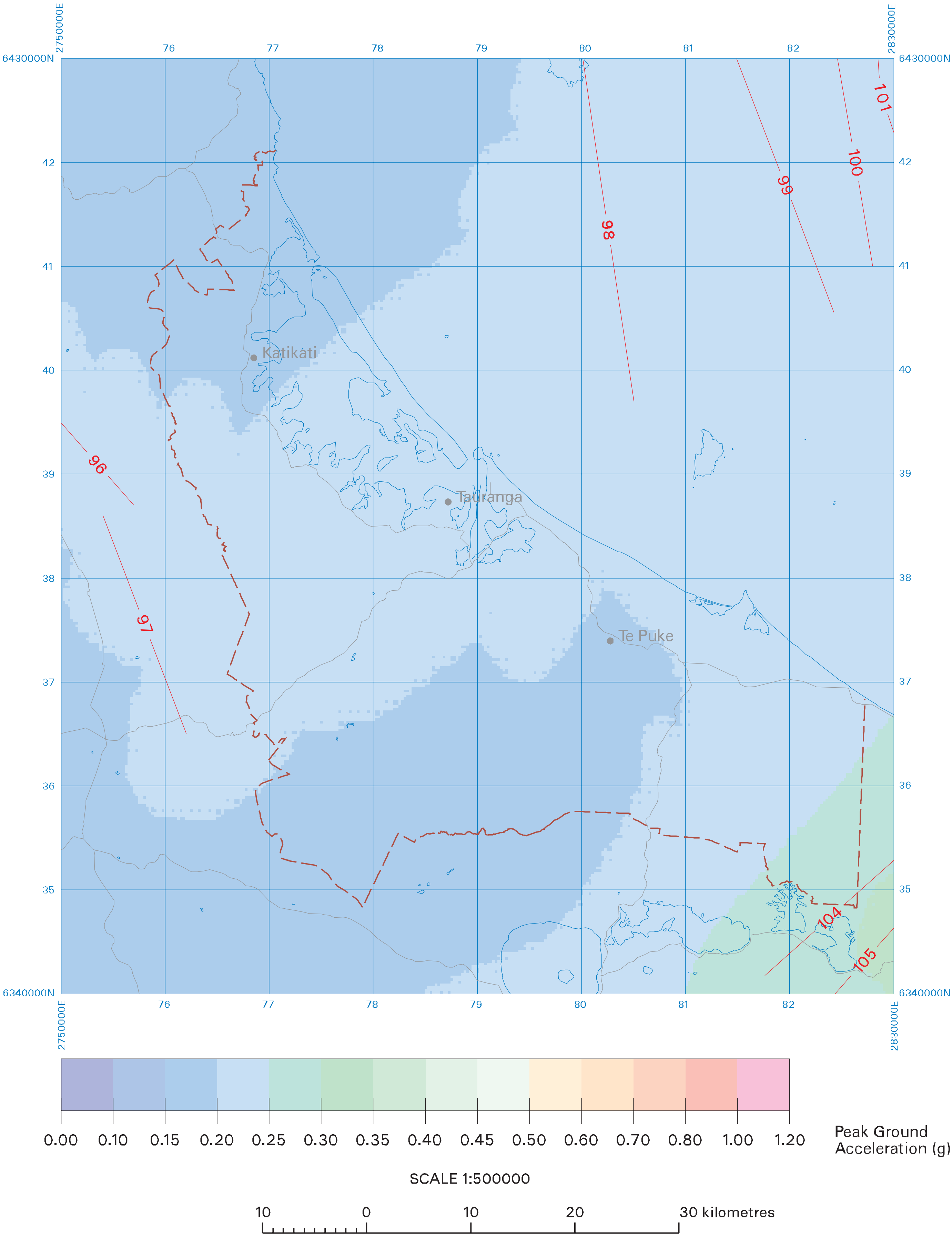


Figure B12(b) Magnitude Weighted peak ground accelerations, 10% probability of exceedance in 50 years, site class D/E.

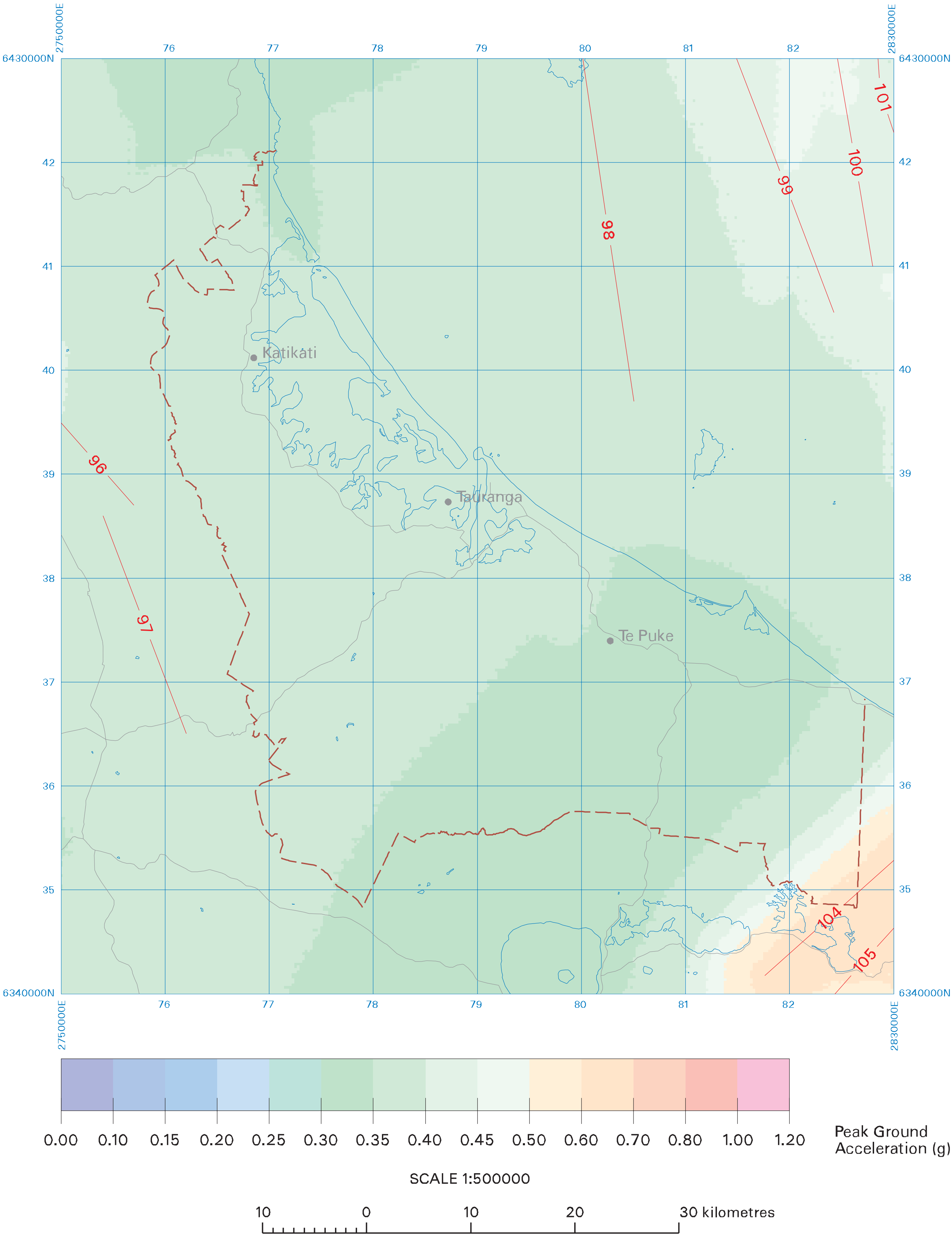


Figure B13(a) Magnitude Weighted peak ground accelerations, 2% probability of exceedance in 50 years, site class C.

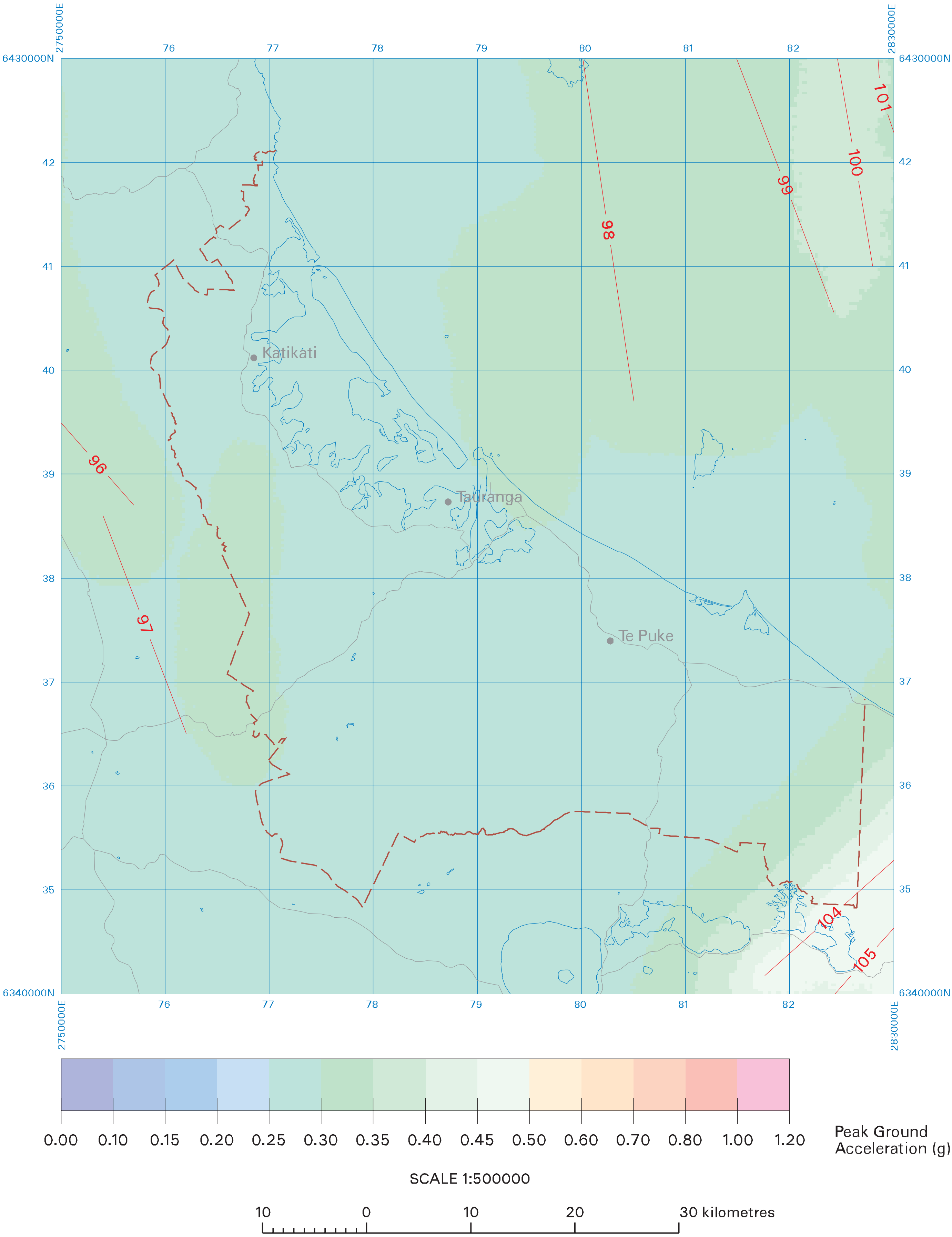


Figure B13(b) Magnitude Weighted peak ground accelerations, 2% probability of exceedance in 50 years, site class D/E.