Otago Regional Council

Seismic Risk in the Otago Region

Study Report

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Contents

List of Appendices

ABSTRACT

A study of the earthquake hazards in the Otago Region has been undertaken by Opus International Consultants Limited (Opus) to meet the wishes of the Otago Regional Council to provide high level information to assist Local Territorial Authorities to perform lifeline projects.

Maps have been compiled in a geographical information system spatial database, and present:

(a) Recorded earthquakes affecting the region, and their magnitudes

(b) Recorded potentially damaging past earthquakes affecting the region

(c) Damage distribution in the 1974 Dunedin Earthquake

(d) MM Intensity for recurrence intervals of 100 years and 2,500 years

(e) MM Intensity for fault rupture on the Alpine, Akatore and Dunstan Faults

(f) Ground class, indicating the potential for enhanced ground shaking

(g) Liquefaction and settlement hazards

(h) Earthquake induced mass movement hazards

(i) Potential susceptibility to land movement and drainage reorganisation

(j) Known tsunami hazards

In addition, the potential for seiche hazard is discussed.

A review of the recorded earthquakes indicates that on average there have been about three potentially damaging earthquakes of magnitude 5.5 or greater affecting the region in each decade. However, all of these did not cause damage as much of the region is sparsely populated. The records also indicate that most earthquakes have epicentres outside to the northwest of the region. The major Alpine Fault and the subduction zone are located to the west and northwest of the region and contribute to much of the earthquake hazard.

Research into the 1974 Dunedin Earthquake indicated that the damage was concentrated in South Dunedin, and is likely to be due to the enhanced shaking due to the poorer ground conditions (alluvium), higher density and poorer construction, and proximity to earthquake source.

Also a higher incidence of things falling off shelves on the western edge of South Dunedin may reflect basin edge effects and amplification of some frequencies in earthquake shaking.

The assessment of the Modified Mercalli intensities of earthquake shaking indicate that the region has a low to moderate hazard in the east and moderate to high hazard in the west of the region, as indicated in the table below.

Area of Region	Modified Mercalli Intensity on firm to stiff ground	
	ARI 100 years	ARI 2,500 years
Dunedin and Oamaru	V to VI	VII
Queenstown, Wanaka	VII	IX

The ground class indicates that there is the potential for amplification of ground shaking in the built up areas such as Dunedin and Queenstown. It would be prudent to refine these further so that this would enable an assessment of the enhanced shaking likely.

There are significant areas with a susceptibility to liquefaction and settlement in the developed urban areas such as Dunedin, Queenstown and Wanaka. It would be prudent to undertake detailed assessments of liquefaction in Dunedin to confirm the liquefaction hazard and its severity given that the likely earthquake shaking is low, and also in Queenstown where there is a significant risk from liquefaction due to the high susceptibility and also moderate to high ground shaking potential.

The earthquake induced mass movement or slope failure susceptibility assessed indicates that the hazard is low in the eastern part of the region, except in some gorges, bluffs and coastal areas, and the hazard is high in the western part of the region, in particular areas such as Queenstown. Therefore, a more detailed slope hazard study for the Queenstown area is recommended.

It should also be noted that the slope failure hazard along lifeline corridors is usually high due to slope modification such as through road cuttings and should be assessed in detail along the corridors.

Areas of potential land movement and drainage reorganisation are identified subjectively and should be further considered where it poses a significant risk to the community or lifelines.

The eastern coastal areas are vulnerable to tsunamis, and areas vulnerable are presented based on general past studies. The Tsunami hazard should be assessed in detail for the coastal areas, in particular for urban areas such as Dunedin and Oamaru.

There are significant large water bodies such as the Central Otago lakes and the Dunedin harbour, which may be prone to seiche hazard. The seiche hazards needs to be considered for significant urban areas such as Dunedin, Queenstown and Wanaka.

The earthquake hazards have been mapped by Opus in digital GIS format, and this lends itself to use by the local authorities to assess the risk to lifelines, infrastructure and the community, by overlaying the infrastructure and assessing the risk. The GIS format would also enable ease of modifying and updating the hazards in the future.

However, the GIS format could also be misused to print or consider the hazards at a larger scale than at which it has been mapped, and giving a misleading level of accuracy. The hazards are identified and mapped to a regional scale and this limitation should be taken into consideration when assessing individual areas or specific sites. The hazard maps do not provide an alternative to site specific studies or investigations.

1 Introduction

Otago Regional Council wishes to carry out a study to assess the hazards and associated risks arising from seismic events in the Region. The purpose of the study is to provide high-level information on the recurrence interval and magnitude of damaging earthquakes in Otago, designed to assist Local Territorial Authorities perform future 'lifelines' projects.

Opus International Consultants Limited (Opus) has been engaged by the Otago Regional Council to undertake the study on the seismicity in the Otago Region, potential impact of the seismicity on the physical environment including the hazards and associated risks arising from seismic events in the Region. This study further advances the previous seismic studies undertaken for the Otago Region.

The study will contribute towards fulfilling Otago Regional Council's statutory responsibilities under the Resource Management Act 1991 and the Building Act 1991 to undertake research into natural hazards affecting the Otago Region. The Council is also required to understand the effects of major natural hazard events that may occur in the region, under its civil defence functions. The Civil Defence Emergency Management Act 2002 also requires various local authorities and lifeline utility operators to assess and manage the risks to the community and their services in hazard events.

The results of this study provides earthquake hazard information, which will :

- Assist Local Authorities and other utility operators to perform lifelines projects, to identify, assess and manage the risk to utilities, which are lifelines for the community in major hazard events,
- Enable Local Authorities to undertake long-term land use planning, and ensure that future development or redevelopment takes the earthquake hazards into consideration,
- Enable an understanding of the hazard events, for emergency response planning purposes.

This study comprised collection and review of information from various sources, compilation and assessment of the earthquake hazards in the Region including the seismcity and its impact on the physical environment. Earthquake hazard maps have been prepared based on this information. This report presents the outcomes of the study and the methodology used to derive the hazard maps.

2 The Study Area

Otago is the second largest region in New Zealand in terms of land area, see Map 1. It occupies approximately 32,000 square kilometres. The coastal marine area forming part of the Otago region extends out to sea 22.2 km (12 nautical miles).

There are four districts and one city in the Otago Region: Queenstown Lakes District, Central Otago District, Clutha District, Waitaki District and Dunedin City. Waitaki District falls partly within the Otago Region and partly within the Canterbury Region.

Otago's resident population is approximately 190,600. Of the region's population 60%lives in the Dunedin urban area.

The study area is shown on Map 1.

3 Previous Studies

Data was collected from various sources to provide the base information for this study. A literature search was carried out by Opus to obtain information relevant to this study.

A number of studies of the seismicity and seismic hazards in the Otago Region have been completed in the past. The Hazards Register Part II studies (Opus International Consultants, 2002) identified the earthquake hazards in the Queenstown-Lakes District of the Otago Region. The earthquake hazards in Dunedin including seismicity, ground shaking, liquefaction and slope stability hazards, potential for ground damage and impact on lifelines were studied by McCahon et. al. (1993).

An earthquake hazard study was carried out by Royds Consulting (1995) with inputs from the Institute of Geological and Nuclear Sciences and resulted in a broad overview of the seismicity of the region and the generic risks to the infrastructure. The Royds Consulting study concluded that the Otago Region has a sufficiently high earthquake hazard risk to require mitigation measures to be implemented through the planning process and recommended that geohazard maps for the Otago Region be periodically reviewed and updated.

Information on previous studies and other relevant publications have been collected and used in this study. Relevant publications and references in this report are listed in the bibliography.

4 Geology

4.1 Geological Maps

The geology of the Otago Region has been compiled from published geological maps. No new geological mapping has been carried out.

The following published maps have been utilised:

- QMAP 18 - Geology of the Wakatipu Area, developed by Turnbull (Institute of Geological and Nuclear Sciences, 2000).
- QMAP 19 - Geology of the Waitaki Area, developed by Forsyth (Institute of Geological and Nuclear Sciences, 2002).
- QMAP 21 - Geology of the Dunedin Area developed by Bishop and Turnbull (Institute of Geological and Nuclear Sciences, 1996).
- QMAP 20 - Geology of the Mirihiku Area developed by Turnbull (Institute of Geological and Nuclear Sciences, 2003). Only GIS data for QMAP 20 supplied by IGNS has been used, as the map had not been published at the time of this study.
- Geological Map of New Zealand, 1:250,000, Sheet 19 Haast developed by Mutch and McKellar (Department of Scientific and Industrial Research, 1964).
- Geological Map of New Zealand, 1:250,000, Sheet 20 Mt Cook developed by Gair (Department of Scientific and Industrial Research , 1967).
- Geology of the Otago Schist and Adjacent Rock, Scale 1:150,000, Geological Map 7 developed by Mortimer (Institute of Geological and Nuclear Sciences, 1993).

These maps cover different parts of the study area. The first four maps (QMAPs) were available in digital form. However, as the available QMAPs maps do not cover all of the Otago Region, the geology of the remaining area had to be digitised from older DSIR maps (Department of Scientific and Industrial Research, 1964; Department of Scientific and Industrial Research, 1967).

In addition to the above maps, for some parts of the region, more detailed geological maps presented in reports and papers have also been used. These reports and papers are listed in the bibliography.

4.2 Geotechnical Information

The following information has been utilised:

- Geotechnical information presented in reports and papers on various geological and geotechnical issues in the Region. These papers and reports reviewed as part of this study are listed in the bibliography.
- 62 borehole logs (supplied by Otago Regional Council) for larger urban areas in the Region including Dunedin, Queenstown, Oamaru, Wanaka and Alexandra, as well as for a number of sites located in the areas distant from these population centres.
- Geotechnical information from previous projects undertaken by Opus.
- Local knowledge and experience. In particular, our engineering geologist David Stewart worked for a number of years in the Otago Region, and his local knowledge and experience have been utilised to develop the hazard maps.

4.3 Geology of the Otago Region

The Otago Region occupies the southeast part of the South Island and extends from the Pacific Coast to the main divide in the vicinity of Mount Aspiring. The geology of the area is complex with a range of metamorphic, sedimentary and igneous rocks, and recent marine, estuarine and alluvial sediments.

The geology of the Otago Region is discussed separately for Quaternary Deposits, Tertiary Rocks and Basement Rocks, as follows.

Quaternary Deposits

Quaternary deposits are sediments that are less than 1.8 million years old and in the Otago Region typically comprise moraine deposits (till), lake deposits (sand, silt, mud), beach deposits (sand, silt, clay, mud), outwash gravels, alluvial terrace and floodplain deposits (gravels with sand and silt, peat), windblown deposits (sand dunes, loess), landslide deposits and colluvium, and manmade fills. These materials are typically unconsolidated, poorly sorted and have lower strength compared to older (Tertiary) rocks.

Tertiary Rocks

The age of these rocks vary from 1.8 million years to 100 million years. The tertiary rocks in the Otago Region include sedimentary and igneous rocks. The sedimentary rocks include some slightly older (Upper Cretaceous) rocks.

The sedimentary rocks comprise a sequence that varies considerably in composition, age and thickness. In coastal Otago, the sequence typically consists of a basal breccia and/ or coal measures overlain by a variety of marine sediments including mudstone and sandstone. Inland, the sequence is thin, and is dominated by conglomerates and coal measures. The igneous rocks are dominated by basalts and other mafic rocks and locally include volcanic breccias and tuff layers. These Tertiary materials are typically stronger than the quaternary deposits but generally not as strong as basement rocks.

Basement Rocks

The age of these rocks is taken as more than 100 million years (older than the Upper Cretaceous rocks). Metamorphic rocks of the Otago Schist dominate the basement rocks in the Region. The Otago Schist has been derived from largely sedimentary rocks of late Palaeozoic to early Mesozoic age forming two contrasting terrains: quartzofeldspathic Torlesse terrain in the northeast, and the volcanogenic Caples terrain in the southwest. The contact between the two terrains trends northwest-southwest but is largely obliterated by the metamorphism that formed the Otago Schist. The Otago Schist is characterised by having foliation or layering defined by metamorphic materials such as quartz and mica, varying from slightly foliated to well foliated and thickly segregated schist. On the margins of the schist to the south and northeast of the region, rocks are only weakly metamorphosed and the original sedimentary layering is preserved.

In the west and particularly the south of the Region there small areas of mafic and ultramafic rocks overlain by sedimentary rocks of early to late Paleozoic age (approximately 250 to 500 million years). In the southeast, Triassic sedimentary rocks outcrop in the south of the Clutha District.

5 Surface Fault Rupture Hazard

Surface fault rupture hazard is associated with the potential for surface displacement along active faults, and surface displacement has the potential to cause severe damage to infrastructure and surface development. An active fault is a fault that has ruptured repeatedly in the past, and whose history indicates that it is likely to rupture again. New Zealand geological maps use a distinctive colour for the faults that have moved in the last 120,000 years. In accordance with the New Zealand Ministry for the Environment interim guidelines "Planning for Development of Land Close to Active Faults" (Institute of Geological and Nuclear Sciences, 2002a), this is "generally regarded as the upper limit for a fault to be classified as active". The faults mapped as active on the New Zealand Geological maps including QMAPs were marked as active for the purposes of this study. Active fault data was compiled from Stirling et al (2000) with additional data collected from Van Dissen et al (2003) and Norris & Nicolls (2004).

A number of faults were not classified as active faults in this study, based on the classification in previous studies and maps.

Fault Rupture recurrence intervals and characteristics of the active faults in the region are presented in Table 1, based on published information.

Additional information about active faults can be obtained from the Active Faults Database held by the Institute of Geological and Nuclear Sciences, through the IGNS website (www.gns.cri.nz). The relative confidence level with respect to the return periods for a few of the Otago faults is given in the Ministry for the Environment guidelines (Institute of Geological and Nuclear Sciences, 2002a). The relative confidence level will improve as more paleoseismic studies are undertaken and more detailed information on the Otago faults becomes available.

It should be noted that there is no universally accepted definition for an active fault. For example, the Fault Activity Guidelines developed by the California Division of Safety of Dams (Fraser, 2001) define an "active fault" as having ruptured within the last 35,000 years. The Fault Activity Guidelines also define a "conditionally active fault" as having ruptured in the Quaternary (period last 1.8 million years), but its displacement history in the last 35,000 years is unknown. This or any other fault activity criterion is somewhat arbitrary by its nature. There is no physical reason why a fault that has not moved during last 35,000 years (or last 120,000 years) cannot move again.

The active fault criteria adopted by various studies and guidelines essentially define an acceptable risk level for a specific application. Therefore, the surface fault rupture hazard should be considered based on both the fault recurrence intervals and the specifics of a particular application. For example, the faults with a recurrence interval of more than 20,000 years are still classified as active in accordance with the Ministry for the Environment Guidelines, but it is acceptable to locate buildings with high importance category (such as structures with special post disaster functions) in the fault avoidance zone of such faults (Institute of Geological and Nuclear Sciences, 2002a).

While Otago is normally considered to have a low seismic risk compared to other parts of New Zealand, there are a number of active faults near the boundaries of the Region and within the Otago Region itself.

The Alpine Fault is approximately 20 kilometres west of the northwest boundary of the Otago Region. While it makes a significant contribution to the seismicity of the Otago Region, it does not itself pose a surface fault rupture hazard, as it is outside the region.

There are also a number of other active and potentially active faults in the Otago Region. Faults with definite evidence of Holocene activity (last 10, 000 years) include the Cardrona, Dunstan, Rough Ridge, Hyde, Taieri Ridge, Waihemo and Akatore faults. Most of the other faults have evidence for Quaternary movement and some may have Holocene movement. The Pisa and Titri faults have evidence indicating no Holocene movement (Norris, 2004).

Active faults are sources of earthquake and of intense ground displacement and deformation. The surface fault rupture hazards have been mapped using the latest active fault maps and the recently published QMAP series geology maps for the Otago Region. The active faults in the Otago Region are shown on Map 2.

Further studies to better map and define active faults are being carried out offshore as well as on land in the Otago Region. Therefore, it would be prudent to review the active fault information presented in this report, as new information becomes available.

Most of the active faults in the Otago Region are outside the urban areas and thus rupture of the faults does not pose a significant risk, except for key roads or other lifelines crossing the area. An exception would be the Cardrona Fault which runs close to Wanaka and Albert Town, see Map 2.

Table 1 - Active Fault Characteristics

Fault	Recurrence Interval (yrs)	Fault Rupture Displacement (m)	Estimated Magnitude
Alpine Fault	300 < 2,000 *	8.0	8.1
Fault 16	633	-	7.3
Fault 15	711	-	7.4
Highland Fault	Not established *	-	-
Cardrona Fault (North and South)	7,500 5,000 – 10,000 *	2.0	North 7.0 South 7.1
Nevis Fault	3677 5,000 – 10,000 *	-	6.8
Wrights Fault	3677 5,000 – 10,000 *	-	6.8
Grandview Fault	30,000 Not established *	3.0	7.0
Timaru Creek Fault	Not established *	-	-
Pisa Fault	30,000 >10,000 *	3.0 1 – 5 *	7.1
Longslip/Lindis Pass Fault	3,500 – 5,000 *	-	-
Blue Lake Fault	5,000 3,500 – 5,000 *	3.0	7.0
Dunstan Fault (North and South)	8,000 5,000 –10,000 *	4.0	North 7.2 South 6.9
Fault 13	3,597	-	7.3
Blackstone/Raggedy Range Fault	8,000 2,000 – 3,500 *	3.0	7.0
Rough Ridge North	8,000 3,500 – 5,000 *	3.0 1 – 5 *	7.0
Ranfurly Fault	8,000 2,000 – 3,500 *	3.0	7.0
Waipiata Fault	2,000 – 3,500 *	-	-
Long Valley Fault	2,000 – 3,500 *	-	-
Spylaw Fault	1,300 5,000 – 10,000 *	-	6.3
Blue Mountain No 1 Fault	800 >8,000	-	6.4
Hyde Fault	15,000 > 4,000 – 5,000 *	3.0 1 – 5*	7.0
Clifton Fault	5,000 – 10,000 *	-	-
Settlement Fault	Not established *	-	-
Akatore Fault	2,987 2,000 – 3,000 *	- 0.8 – 2.3 *	7.1
Taieri Ridge Fault*	-	-	-
North Taieri Fault*	-	-	-
Titri Fault*	70,000 – 80,000*	0.8 – 2.3 *	-
Waihemo Fault	3,176	-	7.1

Active fault data was complied from Stirling et al (2000b) with additional data indicated by * collected from Van Dissen et al (2003), Norris & Nicolls (2004) and Norris (2004).

6 Ground Class

6.1 Class Definition

Seismic ground shaking can vary considerably depending on ground conditions. Areas underlain by soft or deep sediments would experience higher seismic shaking levels compared to those experienced by rocks. Also ground shaking may be attenuated in areas underlain by very soft deposits compared to stiff or deep soil sites. It is therefore important to characterise areas of different 'ground classes'. See Table 2

A five-step scale of ground class (Class A to Class E) is proposed in the draft **Australia/ New Zealand Loadings Standard AS/NZS 1170.4 (Standards New Zealand, 2003).** 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 50 MPa or greater). Average shear wave velocities over the upper 30 m of greater than 1500 m/s.
B	Rock	Sites with weaker rock (ie material with a compressive strength between 1 MPa and 50 MPa). Average shear wave velocities over the upper 30 m of greater than 360 m/s. A surface layer of soil with a thickness not exceeding 3 m overlying rock may be present.
C	Shallow Soil	Sites with soil depths less than the limits defined in Table 3.
D	Deep or Soft Soil	Soil sites with the low-amplitude natural period 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 of 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 Class criteria of the draft Loadings Standard may change before the standard is finalised.

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)***	
Very soft	<12.5	0
Soft	12.5-25	20
Firm	25-50	25
Stiff	50-100	40
Very stiff or hard	100-200	60
Cohesionless soil	***Representative SPT (N) values***	
Very loose	<6	0
Loose	6-10	40
Medium dense	10-30	45
Dense	30-50	55
Very dense	>50	60
Gravels	>30	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.

6.2 Evaluation of Ground Class

The ground classification presented above was used for assigning ground class to the mapped geological units of the Otago Region using maps listed in Section 4.1 of this report.

The evaluation of ground class was carried out in three steps:

1) Assessment of the properties of the mapped geological units based on material nature, descriptions and age.
2) Assignment of ground class to the geological units as shown in Table 4, based on the above assessment.
3) Use of geotechnical properties obtained from available research reports, publications and borehole logs supplied by the ORC as well as experience from previous Opus projects and local material knowledge to review and modify the assignment of ground class as appropriate.

The geological units having the same ground class have been combined and mapped. The ground class for the Region is presented in Map 3. The ground classes for the Dunedin and Queenstown areas are shown to a larger scale in Map 4 and Map 5 respectively.

Table 4 - Simplified Geological Units and Assignment of Ground Class

Material Type	Geological Age	Rock / Soil Type	Assessed Ground Class
Quaternary Deposits	Less than 1.8 million years	Peat, Mud, Swamp	E
		Loose/Soft: Lake Deposits, Alluvium with Mud or Peat	E
		Tailings, Reclamation, Fill	D
		Loose/Soft: Scree, Alluvium, Alluvial Fans, Beach Gravels & Sands, Sand Dunes, Till	D
		Dense: Alluvium, Fans, Till, Outwash, Old Lake Beaches, Moraine Remnants, Marine Terraces	C
Tertiary Rocks	From 1.8 million years to 100 million years	Conglomerate	B
		Sandstone	B
		Mudstone, Siltstone, Claystone, Diatomite	B
		Limestone, Greensand	B
		Basalt, Dolerate, Phonolite, Trachyte, Lamprophyre	B
		Breccia, Tuff	B
		Lignite, Quartzite	B
Basement Rocks	More than 100 million years	Mudstone, Siltstone, Argillite	B
		Conglomerate	B
		Sandstone	B
		Schist	B
		Marbel, Serpentine	B
		Breccia	B
		Spilite, Keratophyre	B
		Limestone	B

7 Historical Earthquakes

7.1 Records of Past Earthquakes

Maps 6 to 10 show earthquake epicentre locations for the earthquakes selected from the GeoNet Data Centre database of earthquake hypocentre locations using the following criteria:

- Post 1994 earthquakes with Magnitude 4.0 and greater (Map 6)
- All recorded historical earthquakes with Magnitude 4.0 to 5.0 and shallow (0 to 45 km) earthquake epicentre locations (Map 7)
- All recorded historical earthquakes with Magnitude 5.0 and greater with shallow (0 to 45 km) earthquake epicentre locations (Map 8)
- All recorded historical earthquakes with Magnitude 4.0 and greater with shallow (0 to 45 km) earthquake epicentre locations (Map 9)
- All recorded historical earthquakes with Magnitude 4.0 and greater with deep (45 to 140 km) earthquake epicentre locations (Map 10)

We acknowledge the New Zealand GeoNet project that allows to maintain the database of earthquake epicentre locations and its sponsors Earthquake Commission, Institute of Geological & Nuclear Sciences, and Foundation for Research, Science & Technology for providing data used in this study.

7.2 Distribution of Damaging Earthquakes

Map 11 shows the distribution of historic earthquakes that have produced potentially damaging earthquake intensities within the Otago region.

Earthquakes were considered likely to be damaging if they would have resulted in MMI intensity greater than 6 on firm to stiff soil sites at any location within the Otago region. The damaging earthquakes were extracted from the Geonet Data Centre Earthquake Hypocentre Location Database using an averaged version of the Dowricks attenuation relationship. When applying this attenuation relationship the published earthquake magnitude in the database that, for example, may have been the Richter magnitude was assumed to be approximately equal to the Moment Magnitude, Mw.

The set of earthquakes that resulted from this filtering process was checked to see that it included all of the earthquakes that have resulted in actual recorded MMI intensities greater than 6. These actual recorded intensities were obtained from the Atlas of Isoseismal Maps of New Zealand (Downes, 1995). Most of the potentially damaging earthquakes shown in Map 11 have no mapped felt intensities which is not surprising as many of the earthquakes would have only produced potentially damaging intensities in localised and remote or lightly settled areas.

It can be seen that very few potentially damaging earthquakes have been centred within the Otago regional boundaries and only two of these earthquakes have had a magnitude greater than 5, the most notable being the Oamaru earthquake cluster in 1876. It can also been seen that most of the potentially damaging earthquakes have been clustered around the regional boundary at the north-western part of the region.

7.3 Periodicity of Damaging Earthquakes in Otago Region

Figure 1 shows the same potentially damaging historic earthquakes shown geographically in Map 11, re-plotted on a time-line.

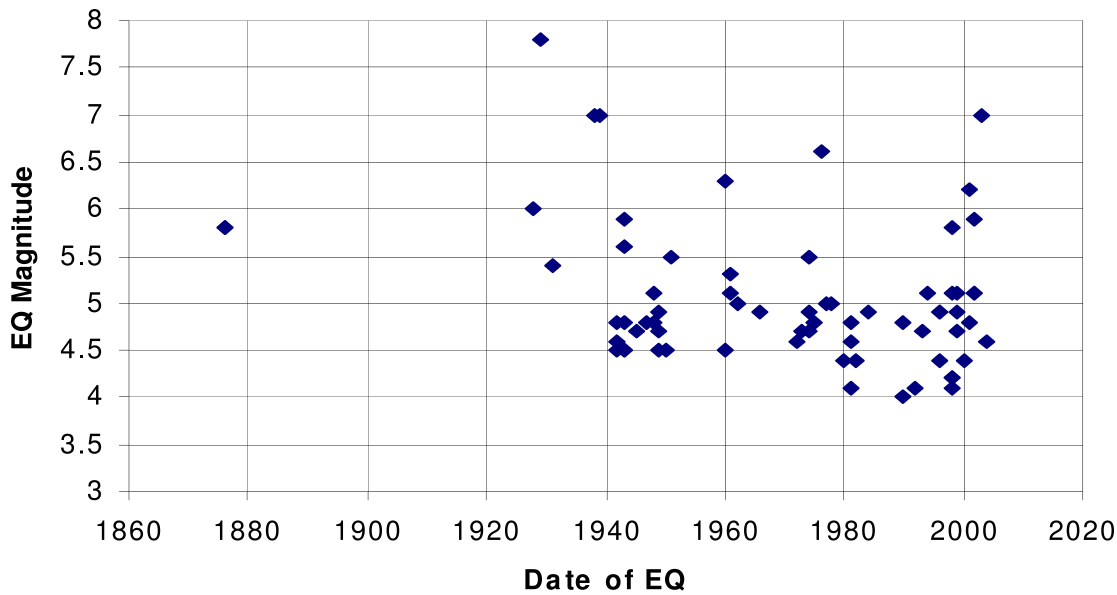

Figure 1: Potentially Damaging Historic Earthquakes in the Otago Region

The time-line plot indicates that, for earthquakes less than about Magnitude 5.5, the historic record is incomplete prior to about 1940 and is probably incomplete for larger earthquakes prior to about 1920. The time-line indicates that 2 or 3 earthquakes of magnitude 5.5 or greater, that can produce damaging felt intensities somewhere in the Otago region, can be expected every decade. Approximately 8 additional smaller earthquakes producing damaging intensities, usually over a smaller area, can also be expected every decade.

7.4 Earthquake History

Documented historic damage from earthquakes has been recorded in the Otago Region in only a few instances. The main documented damage from earthquakes was from the 1974 Dunedin earthquake, which is discussed in Section 9. Other damage has been reported for the 2003 Fiordland earthquake (Hancox et al, 2003).

8 Earthquake Ground Shaking Hazard

8.1 Estimated Modified Mercalli Recurrence Intervals

The earthquake ground shaking hazard in the Otago Region has been assessed in terms of the Modified Mercalli Intensity (MMI) scale. This scale measures the intensity of shaking at a location by the effect it has on people and the natural and built environment. A description of the MMI scale is presented in Appendix A.

Our estimates of average recurrence intervals of MM intensities on firm to stiff soil sites at three locations in the region are shown in Table 5.

Table 5 - Average Recurrence Intervals of MM Intensities on Firm to Stiff Soil Sites

≥ MMI* Intensity	Dunedin (yrs)	Oamaru (yrs)	Queenstown (yrs)
5.0	29	25	5
6.0	110	97	16
7.0	536	460	60
8.0	3,135	2,530	219
9.0	-	-	1,239

* MMI in this table relates to isoseismals, e.g. MMI 7 in the table corresponds to the transition from MMI VI intensity zone to MMI VII intensity zone.

Recurrence intervals for MM 9 or greater have not been estimated for Dunedin and Oamaru because the expected intervals are very large and beyond the range that the available hazard models can reliably estimate. The shorter recurrence intervals in Queenstown compared to Dunedin and Oamaru are due to Queenstown's much closer proximity to active faults and to the Alpine Fault in particular.

Map 12 and Map 13 show the spatial distribution of MM intensities (boundaries between the zones with different MM are isoseismals) on firm to stiff soil sites having average recurrence intervals of (a) 100 years and (b) 2500 years respectively.

While interpreting Maps 12 and 13, it should be noted that, for example, in MMI 7 region shown on the Maps, most of the reported intensities on "firm to stiff soil" would be reported after the scenario event as 7 (or VII) on the stepped MMI scale given in Appendix A.

8.2 Method Used to Derive Modified Mercalli Intensity Recurrence Intervals

The MM intensities in Table 5, Map 12 and Map 13 have been empirically derived from the most current published seismic hazard data for the region as presented in the draft revision to the New Zealand Loadings Code AS/NZS 1170.4 (Standards New Zealand, 2003), which in turn is derived from the results of a probabilistic seismic hazard model developed by the Institute of Geological and Nuclear Sciences (Stirling et al, 2000a). The method adopted is intended to provide regional assessments of shaking hazard. It does not delineate locally higher hazard zones in the near vicinity of active faults.

The draft code and the GNS model quantify the hazard in terms of spectral accelerations and peak ground accelerations (PGA) rather than MMI. We have used the following equation to convert the draft code peak ground accelerations to MMI:

$$MMI = 1.48\ Ln(PGA) + 10.0 \qquad \text{(Equation. 1)}$$

where PGA = peak ground acceleration (g).

Equation 1 was derived by matching the spectral acceleration/PGA attenuation relationship used in the GNS hazard model (McVerry et al, 2000) and the MMI attenuation relationship developed by Dowrick (Dowrick and Rhoades, 1999), with adjustments made to allow for the different soil classes assumed by McVerry and Dowrick.

Stirling et al (1999) has used Equation 2 to convert PGA to MMI, which gives similar results to Equation 1.

$$Log(PGA) = -0.384 + 0.347(MMI) \qquad \text{(Equation. 2)}$$

where PGA = peak ground acceleration (cm/sec^2)

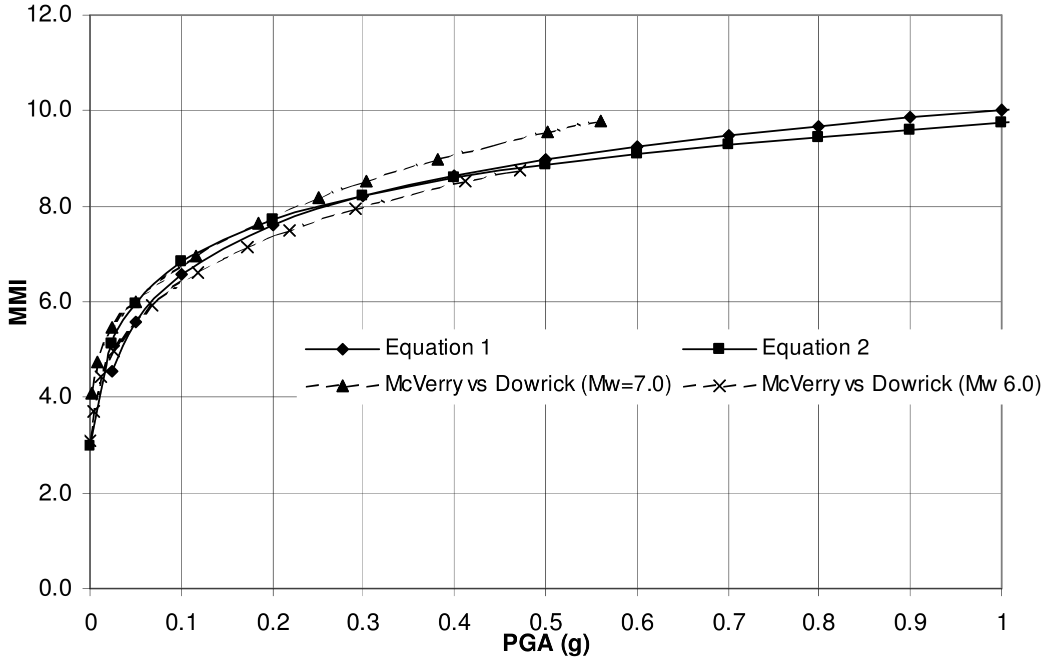

Figure 2: PGA versus MMI Relationships

Equations 1 and 2 are plotted in Figure 2 along with a plot of the PGA and MMI calculated at equal distances from the epicentre using the McVerry and Dowrick attenuation relationships respectively for earthquake magnitude M_w = 7.0 and 6.0.

The MMI recurrence intervals estimated in this study are compared with the results from other studies (Davenport et al, 2002; Dowrick & Cousins, 2003) in Table 6.

Table 6 - Comparison of MMI recurrence interval estimates with other studies

≥ MMI* Intensity	Dunedin (yrs)	Oamaru (yrs)	Queenstown (yrs)
5	29 *28*(2)	25 *27.5*(2)	5 *3.9*(2)
6	110 *103*(1)		16 *18*(2)
7	536 *547*(1)		
8	3135 *2800* (1)		

(1)*Davenport et al, 2002*
(2)*Dowrick and Cousins, 2003*
* MMI in this table relates to isoseismals, e.g. MMI 7 in the table corresponds to the transition from MMI VI zone to MMI VII intensity zone.

There is good correlation indicating that the method adopted in this study to estimate MM intensity gives results that are consistent with those produced by other researchers. It should be noted however, that there are considerable uncertainties associated with these estimates of MMI recurrence intervals as the models from which they are derived are based on a relatively short history of earthquake records and limited geological evidence.

It should also be pointed out that the Stirling et al. model used for the probabilistic seismic hazard assessment on which this study is based (Stirling et al, 2000) assumes that the probability of an earthquake is essentially random in time. This is reasonable for smaller events, but for rupture of major faults such as the Alpine Fault, the longer the time since the last break, the greater the probability is likely to be. Conditional probability models can be used to reflect this. If a conditional probability model is used (Rhoades and Van Dissen, 2000), the effect of this would be to increase the hazard particularly in the west of the Otago region, close to the Alpine Fault. This is because the Alpine Fault has not moved for nearly 300 years.

8.3 Site Soil Effects

There is evidence from historic earthquake effects, that the MM intensity at a site is influenced by the response of soils that overlie the bedrock. Soft or deep soils will generally amplify the ground motion, except that high intensity shaking (i.e. >MM9) can be attenuated by non-linear response of soft soils. While the effects are complex, for the purposes of hazard assessment it is common practice to approximate the effects by increasing the firm soil MMI to allow for the amplified soil response on soft or deep soil sites, and reducing it for rock sites.

Adjustments to the firm ground MMI shown in Map 12 and Map 13 for other ground classes are given in Table 7. The ground classes are described in Section 6 of this report, and maps showing ground classes assessed for the Region are presented in Map 3.

Table 7 - Modifications to Map MMI to Account for Site Ground Class

Map MMI	Ground Class		
	A/B	C	D/E
V	V	V	VI
VI	V	VI	VII
VII	VI	VII	VIII
VIII	VII	VIII	IX
IX	VIII	IX	IX

8.4 Earthquake Scenarios

The MMI isoseismals expected for scenario earthquakes occurring on the Akatore, Alpine, Dunstan North and Dunstan South faults are shown in Map 14, Map 15, Map 16 and Map 17 respectively.

The fault parameters used in the analysis and characteristic magnitudes of these scenario earthquakes are shown in Table 8. The modelled magnitudes given in Table 8 are those required by the Otago Regional Council for the scenario earthquakes, and these are similar to the characteristic magnitudes presented by Stirling et al. (2000). The return periods are presented in Table 1.

The isoseismals for the scenario earthquakes were plotted using the MMI attenuation relationship developed by Dowrick (Dowrick and Rhoades, 1999). Fault parameters required for the Dowrick attenuation relationship: depth to the centroid of the rupture surface, fault focal mechanism and dip angle and direction were assumed to be the characteristic values for the fault provided by Stirling (1999) and these are given in Table The fault rupture lengths were also obtained from Stirling or by scaling the faults on geological maps.

The isoseismals obtained using the Dowrick attenuation relationship were also adjusted as suggested by Smith (2002). Smith has observed that large earthquakes that produce MMI intensities greater than MMI 9.2 at the epicentre, generate an MMI intensity at the ends of the surface trace of the fault rupture of approximately MMI 9.2. This "fault break-out intensity" of MMI 9.2 is independent of the magnitude of the earthquake. Smith provides a procedure for adjusting the Dowrick isoseimals so that they conform to this observation.

Table 8 - Parameters of the Scenario Earthquakes

Parameter	Fault Name			
	Akatore	Alpine	Dunstan North	Dunstan South
Moment Magnitude of EQ (Mw)	7	8	7	7
Length of surface fault rupture (km)	42.4	430	38	16
Depth to top of fault rupture plane (km)	0	0	0	0
Depth to centroid of rupture (km)	10	6	7.5	7.5
Reverse Focal Mechanism Factor	1	0	1	1
Strike-Slip Focal Mechanism Factor	0	1	0	0
Central Volcanic Region Event Factor	0	0	0	0
Interface Event Factor	0	0	0	0
Dip angle - degrees to horizontal	45	60	60	60
Dip bearing - from North to downwards dip direction	132.6	145	320	320

Where the fault rupture plane is not vertical, so that it dips at an angle to the horizontal, the origin of the isoseismals has been positioned at the epicentre of the earthquake (i.e. above the centroid of the rupture area) rather than at the centre of the surface trace of the fault.

Map 16 shows a small MMIX zone for the Dunstan North Scenario earthquake that is inside the MMI10 isosiesmal. Using the Dowrick attenuation relationship this zone remains fixed in size but can be positioned anywhere along the fault between two limiting points . The limiting positions of the MMIX zone are shown dotted.

The similar small MMIX zone shown on Map 15 for the Alpine fault has an equal probability of being located anywhere along the section of the Alpine fault line shown.

The MMI shown on Map 14, Map 15, Map 16 and Map 17 should be modified in accordance with Table 7 to account for site ground classes. The ground classes are described in Section 6 of this report, and ground class maps for the region are presented in Map 3.

There is substantial uncertainty associated with the recurrence intervals of many faults in the Otago Region. The nature of the uncertainty is discussed in Section 15 of this report. As the active fault parameters were used in the National Probabilistic Seismic Hazard Model (Stirling et al., 2000b), which provided data for the assessment of the earthquake ground shaking hazard, there is also significant uncertainty associated with the earthquake ground shaking presented in this report.

9 Dunedin Earthquake 1974

9.1 Distribution and Nature of Damage

The 1974 earthquake is the only earthquake that has caused damage to Dunedin since it's founding (McCahon et al, 1993). The details from a number of sources that described the distribution and nature of the damage are summarised in Appendix B.

The Earthquake and War Damages Commission received approximately 3000 claims following the earthquake indicating that damage was widespread. The claims were analysed by Bishop (1974). Both the Earthquake Commission and the Dunedin City Council were approached, but no additional information was available from the 1974 Dunedin Earthquake.

Map 18 shows the density of claims plotted as number of claims per sq km. The density of claims is superimposed on a section of the Ground Class map developed as part of the current study. The Map indicates that the claims were concentrated in the area of deep alluvium in South Dunedin. It appears that the higher density of housing and older age of houses in this area would have tended to concentrate damage in this area in addition to the major influence of site ground conditions. Closer proximity to the earthquake epicentre would also have been a factor in concentrating the damage in this area.

Of the 3000 claims received by the Earthquake and War Damages Commission, "at least half … involved damage to chimneys" (Bishop, 1974). Successively less important categories of damage were: interior plaster cracks, external masonry cracks, plumbing damage, breakage of household contents and tile roof damage.

Chimney pot displacement and chimney plaster cracks damage occurred to chimneys throughout the city. In the "inner zone" indicated in Map 18, bricks were dislodged and there were a "few instances of a substantial part of the chimney collapsing" (Bishop, 1974). However, in many of these instances the brick/mortar bond was poor.

Adams & Kean (1974) report that chimney damage was "consistent and widespread" in the "southern suburbs on the alluvium between Otago Peninsula and St Clair". Chimney damage occurred over most of the rest of the city but was less dense. In the hill suburbs the damage was usually more superficial (i.e. only fall of pots and plaster damage).

Bishop also reports the results of a survey of fallen items in grocery stores. The survey results indicate a high concentration of fallen items on the west side of the South Dunedin alluvium filled basin. This may be a basin edge amplification effect although it is also the area with deepest alluvium and the rock/alluvium interface dips steeply here. However, the general Earthquake and War Damages Commission claims data does not reflect a similar concentration of damage in this zone suggesting only a narrow range of frequencies in the earthquake motion may have been amplified by the basin edge effect.

There were no instances of landsliding reported and only one case of subsidence (a house in St Clair).

9.2 Modelling of the 1974 Dunedin Earthquake

The Atlas of Isoseismal Maps of New Zealand Earthquake (Downes, 1995) gives the details of the 1974 Dunedin Earthquake. The magnitude of the earthquake is given as M_L 4.9, the position of the epicentre is given as 45.97°S 170.52°E and the depth is given as 12 km. Isoseismals plots are also provided and these are the same as those originally produced by Adams & Kean (1974).

Map 19 shows a comparison between the theoretical isoseismals calculated using the Dowrick attenuation model (Dowrick, 1999) and the observed MMI damage intensities evaluated by Adams & Kean (1974).

The theoretical plot was obtained assuming the moment magnitude of the earthquake (M_w) was equal to the reported local magnitude M_L 4.9 and that the focal depth was 12 km.

A formula given by Stirling (Stirling et al, 2000) was then used to calculate the likely fault rupture area (1.5 x 1.5 km in plan) assuming a fault displacement of 0.5 m during the earthquake. This indicates that the length of the fault rupture was only about 1.5 km. A reverse slip mechanism and the same strike orientation as expected for a major Akatore Fault movement (fault rupture area 40 x 20 km in plan) were also assumed for the theoretical plot.

The theoretical plot is for damage expected on “firm to stiff soil” sites applicable for the Dowrick attenuation relationship. This model predicts a maximum intensity at the epicentre of the earthquake of MMI 6.7 and about MMI 6.3 in South Dunedin. Based on the damage observed in South Dunedin, Adams & Kean have placed South Dunedin in the MMI VII region on the stepped MMI scale. The MMI VII region corresponds to MMI values between 7 and 8 on the continuous MMI scale used in this study. This indicates that the observed MM intensity was about one MMI increment higher in South Dunedin compared with the expected theoretical MMI for “firm to stiff soil” sites. The difference can be explained by the adverse soil conditions (deep alluvium) in the South Dunedin area. This difference is consistent with observations made on soft soil sites in other earthquakes at this intensity of shaking, and to the changes in MMI due to Ground Class proposed in Table 7.

Elsewhere there is good agreement between the observed and expected damage.

10 Liquefaction and Settlement

10.1 Mechanisms of Liquefaction and Settlement

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*".

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 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. Even if loose sands and silty sands do not reach the state of initial liquefaction, they may settle as a result of seismic shaking.

Also, loose granular materials such as sands and gravels on sites with deep groundwater levels will not liquefy but may settle due to densification caused by seismic shaking.

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.

10.2 Historical Evidence of Liquefaction

Some liquefaction effects, including sand boils and small scale lateral spreading were observed in many places after the 22 August 2003 Fiordland earthquake, particularly in areas with fine sandy materials at the southwest and northern ends of Lake Te Anau, and on Hillside Road east of Manapouri, within 70-80 km from the epicentre (IGNS, 2003). The liquefied areas are beyond the Otago Region boundary, while having similar geology to the adjacent areas of the Otago Region.

- Fairless (1984) compiled case histories of liquefaction throughout New Zealand. There are also reasonably detailed records for the 1974 Dunedin earthquake (McCahon, 1993) that had a magnitude of 4.9 and a maximum intensity of MMVII. However, no instances of liquefaction were reported for this earthquake and no detailed historical evidence of liquefaction elsewhere in the Otago Region was reported by Fairless (1984) or Adams and Kean (1974). This could be attributed to the lack of strong earthquake shaking in the Otago Region 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 1848 Marlborough, 1885 Wairarapa, 1931 Napier, 1968 Inangahua, 1987 Edgecumbe earthquakes etc. Generally, liquefaction in New Zealand has been reported for earthquakes of Magnitude 6.3 or greater.

10.3 Liquefaction and Settlement Susceptibility

Map 20 presents the susceptibility to liquefaction and settlement in the Otago Region. The susceptibility of the Dunedin, Queenstown and Wanaka areas to liquefaction and settlement is shown to a larger scale on Map 21, Map 22 and Map 23 respectively. These aeras are shown to a larger scale because of their intensity of development and susceptibility to liquefaction.

The liquefaction susceptibility has been mapped into three susceptibility classes depending on the nature and density of the soils. The classes are presented in Table 9.

Table 9 - Liquefaction and Settlement Susceptibility Classes

Class	Susceptibility to Liquefaction	Description	Material Description
A	Not Susceptible	Liquefaction is unlikely in any scenario, but some strength loss may occur in surficial materials in a large earthquake.	*Very Dense/Hard*: Alluvium, Moraine Remnants, Marine Terraces. Tertiary & Basement Rocks
B	Low Susceptibility	Liquefaction and settlement are unlikely, but localised areas may liquefy in a large earthquake.	*Dense/Firm*: Alluvium, Fans, Till, Outwash, Old Lake Beaches, Moraine Remnants, Marine Terraces
C	Possibly Susceptible	Very loose to medium dense sediments, liquefaction and settlement are possible with seismic shaking of sufficient intensity.	Peat, Mud, Swamp, Tailings, Reclamation, Fill, and *Loose/Soft to Medium Dense:* Alluvium, Lake Deposits, Beach Gravels and Sands, Scree, Alluvial Fans, Sand Dunes, Till, Alluvium.

10.4 Liquefaction and Settlement Hazard

The liquefaction and settlement hazard is presented in Table 10 based on the susceptibility to liquefaction and the general likelihood of liquefaction, for various intensities of ground shaking from MM VI to MM IX that the expected in the region. No significant liquefaction is expected in earthquake shaking felt intensities below MM VI.

Table 10 - Liquefaction and Settlement Hazard

Susceptibility Class	Modified Mercalli Intensity of Shaking			
	MM6	MM7	MM8	MM9
Possibly Susceptible	Liquefaction and settlement are unlikely, no ground damage expected	Liquefaction and settlement of limited layers may occur resulting in minor ground damage	Liquefaction and settlement of some areas resulting in moderate ground damage	Liquefaction and settlement resulting in significant ground damage are possible
Low Susceptibility	Liquefaction and settlement are unlikely, no ground damage expected	Liquefaction and settlement are unlikely, no ground damage expected	Liquefaction and settlement of limited layers may occur resulting in minor ground damage	Liquefaction and settlement of some areas resulting in moderate ground damage
Not Susceptible	Liquefaction and settlement are unlikely, no ground damage expected	Liquefaction and settlement are unlikely, no ground damage expected	Liquefaction and settlement are unlikely, no ground damage expected	Liquefaction and settlement are unlikely, no ground damage expected

The table covers the expected MM Intensities of earthquake ground shaking for 100 year and 2,500-year recurrence intervals (shown in Map 12 and Map 13), and associated with the four fault rupture earthquake scenarios considered (shown on Map 14, Map 15, Map 16 and Map 17).

The liquefaction and settlement hazard (Table 10) is also presented in the liquefaction and settlement susceptibility presented in Map 20, Map 21, Map 22 and Map 23.

The liquefaction and settlement hazard for a particular area of the Otago Region for different recurrence intervals of shaking or earthquake scenarios can be determined by looking-up the expected felt intensities from Maps 12 to 17, and then from the table and plan given in the liquefaction and settlement hazard maps (Maps 20 to 23).

10.5 Assessment Approach

Given the absence of historical records of liquefaction and settlement in the area, the assessment has been based on consideration of the geology and ground conditions and estimated ground shaking hazards.

The liquefaction and settlement susceptibility of the study area was considered using the geology and geotechnical information described in Section 4.

The approach used for the assessment and mapping of the liquefaction and settlement hazard is similar to that used for the Dunedin Earthquake Study (McCahon, 1993), and the Queenstown-Lakes District Hazards Register Part II (Opus International Consultants, 2002).

This approach, tailored to suit this study, comprised the following:

- Identification of areas susceptible to liquefaction and settlement based on the geology,
- Review of available borehole information to confirm susceptibility,
- Mapping the liquefaction hazard using the geology maps.

Areas of fine-grained soils (silts) are present within the materials mapped as being susceptible to liquefaction and settlement. While the fine-grained soils are generally considered to be resistant to liquefaction, the ground damage observations in Wellington during the 1855 Wairarapa Earthquake and new research data indicate that fine grained soils can liquefy (Brabhaharan et al, 1994; Youd & Idris, 1997). Even when liquefaction of very soft fine grained soils does not occur, these soft soils can undergo severe loss of strength during ground shaking, may experience some settlement and can give rise to ground strains and lateral spreading similar to ground damage experienced due to classic liquefaction. Therefore, where fine-grained soils were encountered within the potentially susceptible geological units, these were considered to be susceptible to liquefaction and settlement.

Information on a number of site investigation locations was chosen from the large ORC database of ground investigation information (borehole logs), reviewed and used in the assignment of susceptibility of various geological areas to liquefaction susceptibility.

10.6 Liquefaction Induced Ground Damage

The extent of damage from liquefaction id dependent on the type of structures or development as well as the type and extent of ground damage due to liquefaction.

Liquefaction can lead to ground damage in the form of :

- settlement or subsidence
- failure of sloping ground
- flow failure

- lateral spreading of ground towards natural banks and
- lateral spreading of 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 and liquefaction of overlying denser layers.

11 Earthquake Induced Mass Movement

11.1 Definition

Mass movement refers to failure of slopes and consequent movement of land due to earthquakes. Mass movement affecting sloping ground has been considered and assessed under mass movement. Although mass movement could also occur due to liquefaction and lateral spreading, this has been assessed as liquefaction and settlement hazard in Section 10, and hence is not included under mass movement in this section.

11.2 Earthquake Induced Mass Movement Susceptibility

The mapped earthquake-induced mass movement susceptibility for the Otago region, on a low, moderate, and high susceptibility classification, is presented on Map 24. Given the significant earthquake induced mass movement susceptibility, and the intensity of current and future development, the susceptibility for Queenstown area is shown to a larger scale on Map 25.

11.3 Earthquake Induced Mass Movement Hazard

The indicative earthquake-induced mass movement hazard is presented in Table 11, for the mapped mass movement susceptibility classess and for Modified Mercalli Intensities of earthquake ground shaking from MM VI to MM IX expected in the Otago Region.

Table 11 - Earthquake Induced Mass Movement Hazard

<table>
<tr><th rowspan="2">Susceptibility Category</th><th colspan="5">Modified Mercalli Intensity</th></tr>
<tr><th>≤MM VI</th><th>MM VI</th><th>MM VII</th><th>MM VIII</th><th>MM IX</th></tr>
<tr><td>Low</td><td>Landslides and rockfalls are unlikely</td><td colspan="2">Landslides and rockfalls are unlikely except for very small rock and soil falls</td><td colspan="2">Localised small rock and soil falls on the most susceptible natural slopes, modified slopes and fill embankments</td></tr>
<tr><td>Moderate</td><td>Landslides and rockfalls are unlikely</td><td>Landslides and rockfalls are unlikely except for very small rock and soil falls</td><td colspan="2">Small landslides, soil and rockfalls may occur on more susceptible slopes</td><td>Small to moderate landslides and rockfalls</td></tr>
<tr><td>High</td><td>Landslides and rockfalls are unlikely</td><td>Small rock and soil falls</td><td colspan="2">Significant small to moderate landslides and rockfalls</td><td>Widespread landslide and rockfalls</td></tr>
</table>

The earthquake induced mass movement hazard (Table 11) is also presented on the earthquake induced mass movement susceptibility presented in Map 24 and Map 25.

The earthquake induced mass movement hazard for a particular area of the Otago Region for different recurrence intervals of shaking or earthquake scenarios can be determined by looking-up the expected felt intensities from Maps 12 to 17, and then from the table and plan given in the earthquake induced mass movement hazard maps (Map 24 and Map 25).

11.4 Assessment Approach

The following data was compiled to facilitate the assessment and mapping of earthquake induced slope failure (mass movement) hazard for this study:

- Geology, based on the geological maps listed in Section 4
- Topography of the area as digital terrain models and hardcopy 1:50 000 topographic maps
- Information on geotechnical material properties obtained from available research reports, publications and borehole logs supplied by the ORC as well as from experience on previous Opus projects and local knowledge

Previous studies on earthquake-induced landsliding by Hancox et. al. (2002), Hancox et. al.(2003), Works Consultancy Services (1994) and McCahon (1993) were also reviewed.

The above information was used to broadly classify the terrain in the Region into the following earthquake-induced mass movement susceptibility categories:

- Low
- Moderate
- High

The above earthquake-induced land movement susceptibility categories have been mapped based on consideration of slope angles, geology and local experience. The susceptibility categories are based primarily on slope angle for various rock and soil types (Table 12). These categories are generally consistent with those of Hancox et al. (2002).

It should be noted that there are a large number of past landslides in the Otago Region. However, previous studies indicate that these large landslides behave in a "ductile" manner, and would not be significantly vulnerable to mass movement in earthquakes, and may undergo only a small movement during large earthquake events. Therefore these landslides have not been included in the earthquake induced mass movement susceptibility and hazard mapped as part of this study.

Such landslides would be more vulnerable to movement in prolonged rainfall events and storms. Therefore, in consideration of the hazards to existing or future development or lifelines, the pre-existing landslides as well as the potential for rainfall-induced landslides should be considered in addition to the earthquake induced landslides. The risk associated with pre-existing landslides is presented for the Queenstown-Lakes District by Opus International Consultants, 2002).

Table 12 - Earthquake Induced Mass Movement Susceptibility

Rock / Soil Type	Slope Angle (degrees)		
	15-30	30-40	40 or steeper
Quaternary Deposits			
Fill, Peat, Tailings, Sand Dunes, Mud, Swamp	High	High	High
Loose: Scree, Alluvium, Lake Deposits, Alluvial Fans, Beach Gravels & Sands	Moderate	High	High
Dense: Alluvium, Fans, Till, Outwash, Old Lake Beaches, Moraine Remnants	Moderate	Moderate	High
Tertiary Rocks			
Conglomerarate	Moderate	Moderate	High
Sandstone	Moderate	Moderate	High
Mudstone, Siltstone, Claystone, Diatomite	Moderate	High	High
Limestone, Greensand	Moderate	Moderate	High
Basalt, Dolerate, Phonolite, Trachyte, Lamprophyre	Low	Moderate	High
Breccia, Tuff	Low	Moderate	High
Lignite	Moderate	High	High
Quartzite	Low	Moderate	High
Basement Rocks			
Mudstone, Siltstone, Argillite	Low	Moderate	High
Conglomerate	Low	Moderate	High
Sandstone	Low	Moderate	High
Schist			
Slightly Folitaed Schist	Low	Moderate	High
Well Foliated Schist	Low	Moderate	High
Well Foliated and Segregated Schist	Moderate	High	High
Greenschist	Moderate	High	High
Marbel, Serpentine	Low	Moderate	High
Breccia	Low	Moderate	High
Spilite, Keratophyre	Low	Moderate	High
Limestone	Low	Moderate	High

12 Land Movement and Drainage Reorganisation

12.1 Definition and Scope

Land movement and drainage reorganisation can occur due to:

- Fault movement,
- Large landslides.
- Earthquakes are caused by energy released during dislocation along a discontinuity or defect in the earth's crust. At times these dislocations propagate to the ground surface and relative displacements occur at the surface. In most cases the displacements occur along the existing active faults. Single event displacement of the order of hundreds of millimetres to few meters horizontally and vertically can be expected along the active faults in the Otago Region. Where the active faults cross narrow valleys and watercourses, the active fault rupture and associated horizontal and vertical movements can potentially cause some blockages and drainage reorganisation. Also, large earthquake-induced landslides in narrow mountain valleys often create landslide–dammed lakes. The sudden collapse of landslide dams may cause a serious flooding hazard downstream.

12.2 Susceptibility to Land Movement and Drainage Reorganisation

The areas susceptible to land movement and consequent drainage reorganisation are shown on Map 26.

12.3 Assessment Approach

The potential for land movement and drainage reorganisation for this study has been assessed based on the following:

- Mapped locations of the active faults and potential for fault rupture,
- Mapped earthquake-induced mass movement susceptibility and assessed earthquake-induced mass movement hazard
- Topographical information for the Region
- Geology of the area and local knowledge

The areas susceptible to land movement and consequent drainage reorganisation have been subjectively mapped based on a desk study using the above maps and local knowledge by our engineering geologist who has a good working knowledge of the Otago Region.

13 Tsunami and Seiching

13.1 Tsunami

Definition and Scope

Tsunamis are tidal waves caused by a sudden displacement of the sea by undersea earthquake fault rupture, landslide or volcanic eruption (undersea or flow into sea). Earthquake induced tsunamis can be caused by an undersea fault rupture or consequent landslide. Tsunamis can be locally generated by such events or could be generated at a distance with tidal waves travelling many hundreds or thousands of kilometres to affect coastal areas. The tidal wave magnitude could be amplified by the local seabed profile.

On Sunday 26 December 2004: at 0100 GMT, an 9 magnitude earthquake occurred on the seafloor near Aceh in northern Indonesia. This earthquake generated a huge tsunami wave, hitting the coasts of Indonesia, Malaysia, Thailand, Myanmar, India, Sri Lanka, Maldives and even Somalia. The tsunami wave caused extensive damage in the affected areas and resulted in substantial (more than 150,000 people) loss of life. The 26 December 2004 tsunami reaffirmed the importance of the tsunami warning systems, and of the plans, methods, procedures and actions that would be required to be taken by the government officials and the general public for the purpose of minimising potential risk and mitigating the effects of future tsunamis. In particular, the appropriate preparedness for a warning of impending danger from a tsunami requires knowledge of areas that could be flooded (tsunami inundation maps) and knowledge of the warning system to know when and how to circulate information and evacuate and when it is safe to return.

The tsunami hazard is localised in the coastal area of the Otago Region. Most tsunami reports for New Zealand have been associated with distantly generated tsunamis, and these can reach the Otago coastline. There is no evidence of a near field tsunami affecting the Otago coast since 1840. However, it is possible that local tsunamis could be generated by local offshore faults such as the Akatore Fault, which extends offshore.

No specific tsunami study was undertaken for this project. Information from existing studies was used to map the tsunami hazard for the Otago Region.

Historical Tsunamis

The major tsunami threat to Otago is from a large earthquake on the South American coast. Four such tsunamis have been experienced since 1840. The largest 1868 tsunami had a an assessed maximum water level of 2.4 m above the predicted tidal level at Oamaru. Inside the Otago Harbour, river mouths and estuaries, the recorded tsunami magnitudes from these past events have been generally less than on the open coast. The assessed return period for a similar sized tsunami to that of 1868 is considered to be approximately 118 years.

Tsunami Susceptibility

An indicative Tsunami Susceptibility map is presented in Map 27. This shows lengths of the coastline, estuaries and river mouths susceptible to Tsunamis from a previous study by Tonkin & Taylor (1997).

The likely tsunami wave height of a near field tsunami generated from fault movements on the Eastern Otago continental shelf is assessed to be about 2 m. Due to a lesser wave height and longer return periods for a near field tsunami, it is considered that the level of risk from this type of tsunami is less than from a far-field tsunami. The best available estimate of the return period for a near field tsunami generated from fault movements on the Eastern Otago continental shelf is in the order of 1,500 to 2,000 years (Tonkin & Taylor, 1997).

Based on a simplistic approach, Tonkin & Taylor (1997) proposed a maximum credible scenario for the water level in a far-field tsunami of 3.9 m above MSL for stretches of the Otago open coast oriented to the south, 2.8 m above MSL for the open coast oriented to the north, and 1.7 m above MSL at Dunedin. According to Tonkin & Taylor (1997), the estimated return period for such event is in the order of 350 years. Assuming this maximum credible tsunami scenario, indicative lengths of Otago coastline, estuaries and river mouths that are likely to suffer from direct inundation were mapped by Tonkin & Taylor. For the purposes of this study, these lengths of the coastline, estuaries and river mouths have been captured in GIS.

13.2 Seiching

Definition and Scope

A similar phenomenon, seiches, can occur on inland bodies of water. Seiches are described as standing wave in a closed body of water such as a lake or bay. A seiche can be characterized as the sloshing of water in the enclosing basin. Large earthquakes and the permanent tilting of lake basins caused by nearby fault motions may generate long period movements of water (seismic seiches). Tsunamis waves may also force oscillations within semi-enclosed basins such as estuaries, harbours and the lower reaches of to produce seiches.

For generation of significant seiche waves by ground shaking, the frequency of earthquake ground motion must be close to the natural frequency of the lake. There are historical records of seiches comprising up to 3.7 m high waves in lakes caused by MM6 seismic shaking and of higher waves for higher seismic shaking intensities. Analysis of the natural frequencies of the lakes in the Otago Region is beyond the scope of this study. In the worst scenario, seiches caused by strong (MM7 or higher) seismic shaking could comprise waves up to 4m or higher that would travel across the lakes and flood low lying land on the lakes' edges and cause torrents down the rivers.

Seiche Susceptibility

Seiching hazard exists for the Otago Harbour and the Central Otago lakes. Areas where large bodies of water are present may be susceptible to seiching if they experience MM6 or higher level of seismic shaking. It should be noted, however, that even strong seismic shaking may generate only minor seiching if the frequency of the earthquake ground motion and the frequency of a lake/harbour are substantially different.

Given the presence of large lakes and inland waterways, there is a significant potential for seiche in the Otago Region, and could affect areas such as Queenstown and Wanaka. It is recommended that further studies be undertaken to better assess the likelihood and consequence of seiche hazards.

14 Mapping

Earthquake Hazard maps have been prepared for this study using the ArcView Geographical information System (GIS) software.

Published geology maps (QMap) at 1 : 250,000 scale and associated digital datasets have been used to facilitate mapping the hazards, in particular the ground class and liquefaction and settlement. As the available QMaps do not cover all of the Otago Region, the geology of the remaining area was digitised from older DSIR maps.

The hazard information is generally held as shape files in GIS with the attribute information in the associated database. The hazard maps developed in this study have been supplied to the Otago Regional Council in GIS format.

Indicative maps are presented in this report to illustrate the hazards, and these are presented at a scale of 1 in a million. Selected developed areas with significant hazards are shown at a larger scale of 1 : 100,000.

15 Uncertainty

The information on the rupture history of the Otago faults is limited. Most of the return periods given in the Probabilistic Seismic Hazard Assessment of New Zealand (Stirling et al., 2000) are best estimates based on the available (sometimes very little) information. Because of the uncertainty, where only insufficient or poor information is available on the faults, there is a discrepancy between the return periods of rupture assessed by different authors. The assessed return periods are likely to be refined as more data on individual faults becomes available.

The uncertainty with respect to the fault rupture hazard has an effect on the assessment of the earthquake ground shaking hazard. As the information on the active faults was used to assess the earthquake ground shaking hazard, there is significant uncertainty associated with the assessed earthquake ground shaking hazard.

More information on the faults would become available with time as the faults are studied by scientists. The GeoNet programme of monitoring would also provide valuable information on the seismicity of New Zealand including the Otago Region. The seismic hazard in the Otago Region should be reassessed as understanding of the seismicity and the active faults improves over time.

16 Use and Limitations

This report and maps have been prepared to meet Otago Regional Council's objective to provide high-level information on the earthquake hazards in the Otago Region, to assist Local Territorial Authorities perform future lifeline projects.

The assessment of the seismic hazards for this study has been carried out as a regional hazard assessment based on the available information and within the available time and resources. Because of the level of the study, it provides a high-level indication of the susceptibility to earthquake hazards.

The results of this study could be used by the local authorities to :

- assist with identification of the risk to utilities, which are lifelines for the community in major hazard events as part of lifelines projects,
- assist with long-term land use planning, and ensure that future development or redevelopment takes the earthquake hazards into consideration,
- enable civil defence emergency response planning.

Once the broad risks are identified, it may be prudent to assess the earthquake hazards in greater detail to enable more detailed risk assessment and for deciding on risk management measures necessary. Further assessment would also be required to enable detailed land use planning under district planning or for issue of hazard information as part of Land Information Memoranda.

Recommendations are made in this report to assess the hazards in greater detail for the developed areas where the risk from different earthquakes hazards are significant. This would then assist with risk assessments and land use planning.

The results of this study should not be considered as a substitute for site-specific site investigations and geotechnical engineering assessment of seismic hazards for any project in the Region.

The boundaries between different hazard zones are only indicative at a regional level, rather than provide specific hazard differentiation at a local level.

17 Recommendations

The earthquake hazards have been mapped at a regional level to provide high-level information for local authorities to assist with lifelines projects.

Considering the outcomes of this high level assessment, and the potentials risks tom, lifelines and the community, it may be prudent to consider further studies targeting specific areas and specific hazards. We have considered possible future studies on the basis of the significance of the hazard and the consequence to the community and lifeline utilities. The risk is a combination of the hazard level and probability and the consequences.

The following recommendations are made on the basis of the risk to the community:

- Assessment of the earthquake ground shaking and mapping of peak ground accelerations for the Dunedin and Queenstown areas, where the risk is significant due to a combination of the level of the hazard (Queenstown) and the consequences (Dunedin and Queenstown). Peak ground acceleration provides a better basis for engineering assessment of the impact on lifelines.
- Study of the liquefaction and ground damage hazard and ground class for the Dunedin and Queenstown Urban areas, to a greater detail, involving collection of good quality borehole information and a geotechnical engineering analysis of the liquefaction and consequent ground damage.
- Study of the earthquake induced slope failure (mass movement) hazard to the greater Queenstown area with significant hazards and also current and future new development. This will involve a greater level of assessment and some limited field reconnaissance.
- Study of the tsunami hazard to the Otago coastline and in particular to Dunedin and Oamaru.
- Study of the sieche hazard in Dunedin, Queenstown and Wanaka, where there are significant bodies of water that may be susceptible to seiche and consequent impact to the community.
- Study to assess the risk to the community, infrastructure and lifelines from earthquakes in the urban areas of the district, perhaps, Dunedin, Oamaru and Queenstown.

It is also recommended that the earthquake hazards be periodically updated, particularly as more information becomes available. This is particularly important if the ongoing studies show the Active Faults in the Otago Region to have a greater probability of rupture (or smaller recurrence interval) than understood to date.

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Appendix A - MMI Information

Modified Mercalli Intensity Scale

MM1

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

MM2

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

MM3

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

MM4

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

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

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

MM5

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

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

Structures
Some windows Type I cracked.
A few earthenware toilet fixtures cracked.

MM6

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

Fittings
Objects fall from shelves.
Pictures fall from walls.
Some furniture moved on smooth floors, some free-standing unsecured fireplaces moved.
Glassware and crockery broken.
Very unstable furniture overturned.
Small church and school bells ring.
Appliances move on bench and table tops.
Filing cabinets or 'easy glide' drawers may open [or shut].

Structures
Slight damage to Buildings Type I.
Some stucco or cement plaster falls.
Windows Type I broken.
Damage to a few weak domestic chimneys, some may fall.

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

MM7

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

Fittings
Large bells ring.
Furniture moves on smooth floors, may move on carpeted floors.
Substantial damage to fragile contents of buildings.

Structures
Unreinforced stone and brick walls cracked.
Buildings Type I cracked with some minor masonry falls.
A few instances of damage to Buildings Type II.
Unbraced parapets, unbraced brick gables, and architectural ornaments fall.
Roofing tiles, especially ridge tiles may be dislodged.

Many unreinforced domestic chimneys damaged, often falling from the roof-line.
Water tanks Type I burst.
A few instances of damage to brick veneers and plaster or cement-based linings. Unrestrained water cylinders [Water Tanks Type II] may move and leak.
Some windows Type II cracked.
Suspended ceilings damaged.

Environment
Water made turbid by stirred up mud.
Small slides such as falls of sand and gravel banks, and small rock-falls from steep slopes and cuttings.
Instances of settlement of unconsolidated or wet, or weak soils.
Some fine cracks appear in sloping ground. A few instances of liquefaction [i.e. small water and sand ejections].

MM8

People
Alarm may approach panic.
Steering of motor cars greatly affected.

Structures
Building Type I, heavily damaged, some collapse.
Buildings Type II damaged, some with partial collapse.
Buildings Type III damaged in some cases.
A few instances of damage to Structures Type IV.
Monuments and pre-1976 elevated tanks and factory stacks twisted or brought down.
Some pre-1965 infill masonry panels damaged.
A few post-1980 brick veneers damaged.
Decayed timber piles of houses damaged.
Houses not secured to foundations may move.
Most unreinforced domestic chimneys damaged, some below roof-line, many brought down.

Environment
Cracks appear on steep slopes and in wet ground
Small to moderate slides in roadside cuttings and unsupported excavations
Small water and sand ejections and localised lateral spreading adjacent to streams, canals, lakes etc.

MM9

Structures
Many Buildings Type I destroyed
Buildings Type II heavily damaged, some collapse
Buildings Type III damaged, some with partial collapse
Structures Type IV damaged in some cases. Some with flexible frames seriously damaged.
Damage or permanent distortion to some Structures Type V.
Houses not secured to foundations shifted off
Brick veneers fall and expose frames

Environment
Cracking of ground conspicuous
Landsliding general on steep slopes
Liquefaction effects intensified and more widespread, with large lateral spreading and flow sliding adjacent to streams, canals, lakes etc.

MM10

Structures
Most Buildings Type I destroyed
Many Buildings Type II destroyed
Buildings Type III heavily damaged, some collapse
Structures Type IV damaged, some with partial collapse.
Structures Type V moderately damaged, but with few partial collapses
A few instances of damage to Structures Type VI
Some well-built timber buildings moderately damaged [excluding damage from falling chimneys]

Environment
Landsliding very widespread in susceptible terrain, with very large rock masses displaced on steep slopes
Landslide dams may be formed
Liquefaction effects widespread and severe

MM11

Structures
Most Buildings Type II destroyed
Many Buildings Type III destroyed
Structures Type IV heavily damaged, some collapse
Structures Type V damaged, some with partial collapse
Structures Type VI suffer minor damage, a few moderately damaged

MM12

Structures
Most Buildings Type III destroyed
Many Structures Type IV destroyed
Structure Type V heavily damaged, some with partial collapse
Structures Type VI moderately damaged.

Notes on Construction Types

Buildings Type I [Masonry D in NZ 1965 MM Scale]

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

Buildings Type II [Masonry C in the NZ 1966 MM Scale]

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

Buildings Type III [Masonry B in the NZ 1966 MM Scale]

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

Structures Type IV [Masonry A in the NZ 1966 MM Scale]

Buildings and bridges designed and built to resist earthquakes to normal use standards, i.e. no special collapse or damage limiting measures taken [mid-1930s to c1970 for concrete and to c1980 for other materials].

Structures Type V

Buildings and bridges, designed and built to normal use standards, i.e. no special damage limiting measures taken, other than code requirements, dating from since c1970 for concrete and c1980 for other materials.

Structure Type VI

Structures dating from c1980, with well-defined foundation behaviour, which have been specially designed for minimal damage, e.g. seismically isolated emergency facilities, some structures with dangerous or high contents, or new generation low damage structures.

Windows

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

Water Tanks

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

Other Comments

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

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

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

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

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

Correlations with EMS Scale

Correlations between EMS building Classes and MM building/structure Types are approximately A:I, B:II, C:III, D and E:IV, F:V, no EMS equivalent to MM Type VI.

The damage levels in the two scales are harder to compare but EMS grade 5 » destroyed, 4 » heavily damaged,

2-3 » moderate to light damage.

References

Dowrick D J, 1996, The Modified Mercalli Intensity Scale - Revisions arising from Recent studies of New Zealand Earthquakes, Bulletin of the New Zealand National Society for Earthquake Engineering, 29[2], 92-106.

Appendix B – Information on 1974 Dunedin Earthquake

Dunedin Earthquake, 9th April 1974

A number of sources of information on the 1974 Dunedin EQ were located and information relating the nature and distribution of damage contained in each reference is given below:

Adams & Kean 1974

- Earthquake was magnitude, ML 5.0 and probably 20 km deep.
- Total damage was $250,000 in1974 $
- Damage was "almost entirely confined to the Dunedin area"
- A plot of the assessed damage on Modified Mercalli Intensity (MMI) given (refer to isoseismal map of ?? in body of report).
- MMVII intensity assessed in "southern suburbs on the alluvium between Otago Peninsula and St Clair". Here chimney damage was "consistent and widespread"
- Chimney damage was less dense over most of the rest of city but in hill suburbs was usually more superficial (i.e. only fall of pots and plaster damage).
- EQC received 3000 claims "at least half of which involved damage to chimneys"

Bishop 1974

- 0.27g Peak Ground Acceleration (PGA) recorded at the St Clair Telephone Exchange in region classified as MMVII.
- 0.12 g PGA recorded Dunedin Central Post office in region classified as MMV1.
- Epicentre reported to be about 10km south of city.
- Masonry damage, particularly chimney damage, widespread in St Clair, St Kilda and Caversham areas.
- Power supplies to Corstorphine were interrupted for 45 minutes (high tension switches tripped in the foreshore substation).
- No instances of land sliding reported.
- Only one case of subsidence. A house in St Clair (subsidence appeared 2 days after EQ?)
- Surveyed the distribution of items that fell in grocery stores and the distribution of EQC claims – see body of report.
- Chimney pot displacement and chimney plaster cracks damage occurred to chimneys throughout city. Bricks dislodged and a "few instances of a substantial part of the chimney collaps[ing]" reported in inner zone only – in many instances the brick/mortar bond was poor.
- Successively less important categories of damage were: chimneys, interior plaster cracks, external masonry cracks, plumbing damage, breakage of household contents and tile roof damage.

McCahon et al 1993

- Reports magnitude of 1974 EQ as M 4.9 with epicentre on the Akatore Fault "7km offshore to the South of St Kilda".
- Notes that this is the only EQ since the founding of Dunedin to cause damage.

Otago Daily Times 10th April 1974

- Day after EQ was headlined as “Dunedin People Shaken by ‘Minor’ Earthquake”. “Cracks appeared in numerous buildings and several windows were broken and many houses – especially in the South Dunedin area - were littered with broken crockery, ornaments and spilt bookshelves”. Damage reported to police “was minor, involving cracked chimneys and broken windows and slight damage to some buildings”

Otago Daily Times 11th April 1974

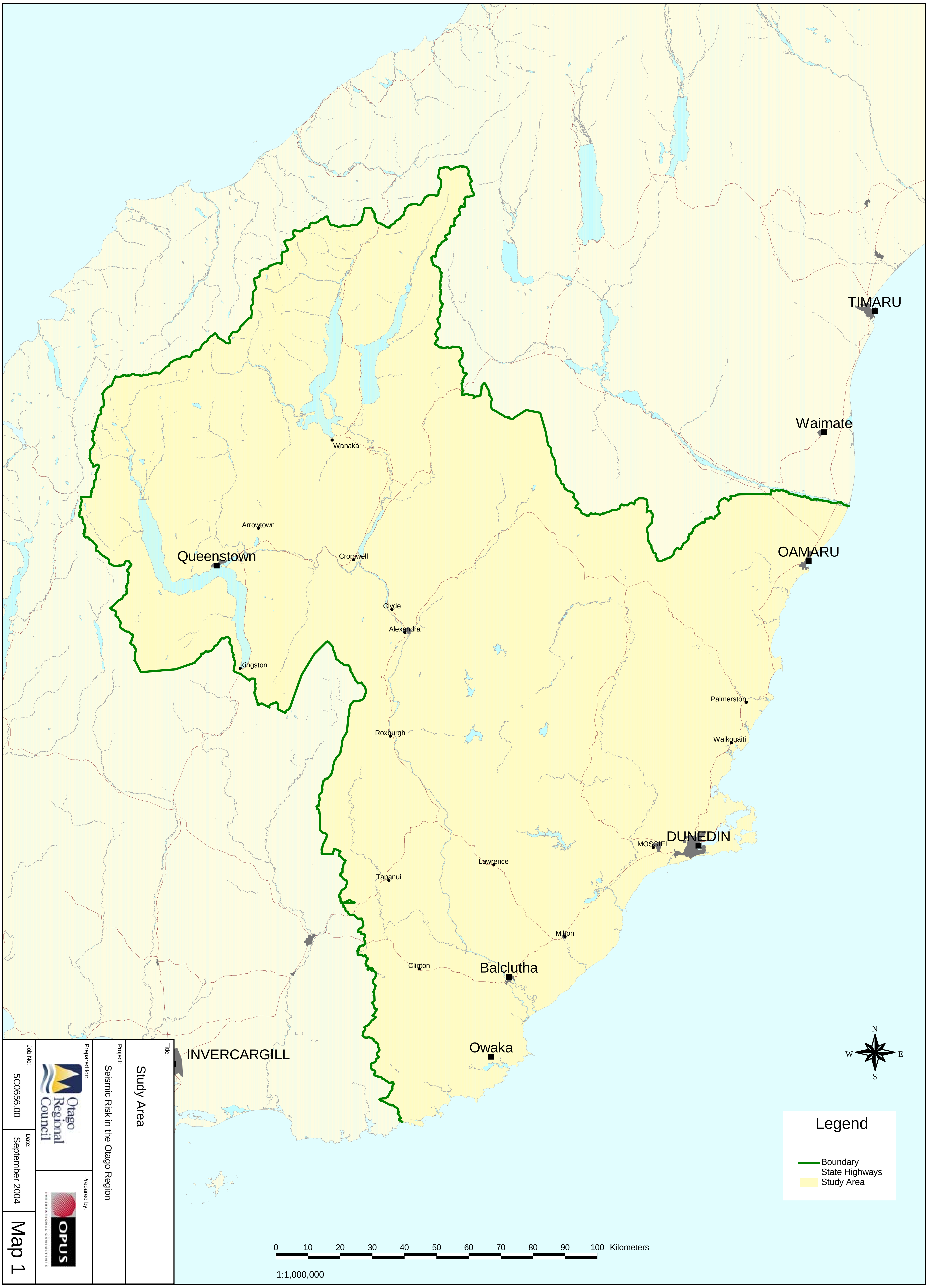
- A city roofing firm had 25 inquires for repairs – all in the St Clair – Kew area.
- Virtually all residents in Ings Av. St Clair had some house damage – “some substantially” damaged.
- The Salvation Armies Eventide Home (45 Beach St – St Clair) “received substantial damage” with “one wall moving about 4 inches revealing roof trusses”
- Most of the damage was reported as being in the “Kew - St Clair - St Kilda area.

No other reports were found in the Otago Daily Times.

References

Adams R D, and Kean R J (1974) “The Dunedin EQ ,9 April 1974. Part 1: Seismological Studies” Bulletin of NZNSEE Vol 7, No.3

Bishop DG (1974) “The Dunedin EQ, 9 April 1974. Part 2: Local Effects” Bulletin of NZNSEE Vol 7, No.3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Roxburgh
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DUNEDIN
MOSGIEL
Lawrence
Tapanui
Milton
Clinton
Balclutha
Owaka
INVERCARGILL
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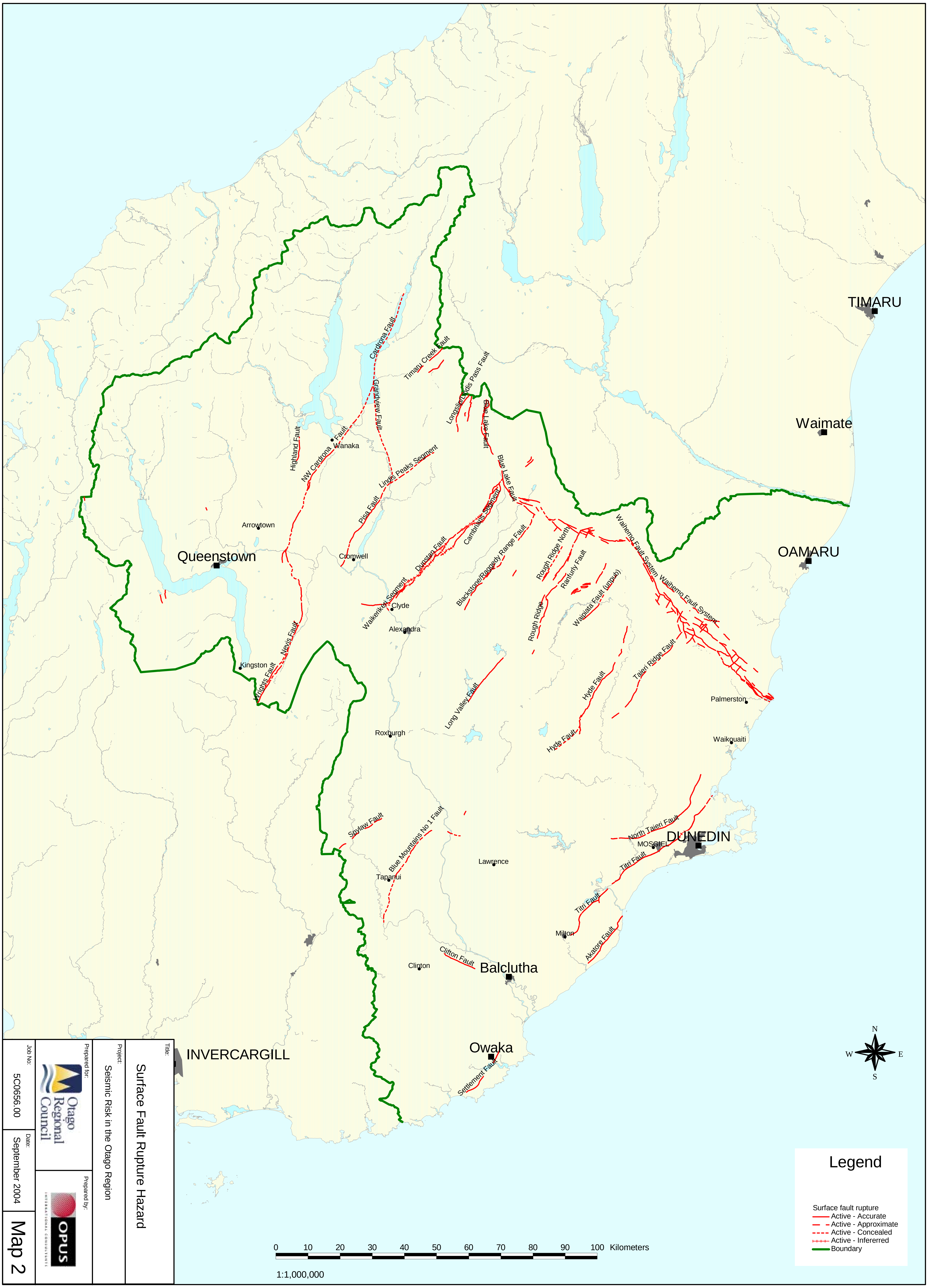
Legend
Boundary
State Highways
Study Area
0 10 20 30 40 50 60 70 80 90 100 Kilometers
1:1,000,000
Title:
Study Area
Project:
Seismic Risk in the Otago Region
Prepared for:
Otago Regional Council
Prepared by:
OPUS
Job No:
5C0656.00
Date:
September 2004
Map 1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Clinton
Balclutha
Owaka
INVERCARGILL
Cardrona Fault
Grandview Fault
Timaru Creek Fault
Lindis Pass Fault
Longslip Fault
Blue Lake Fault
Highland Fault
NW Cardrona Fault
Lindis Peaks Segment
Pisa Fault
Cambrians Segment
Dunstan Fault
Waihemo Fault System
Rough Ridge North
Ranfurly Fault
Blackstone/Raggedy Range Fault
Waipiata Fault (unpub)
Rough Ridge
Waitaki Segment
Nevis Fault
Wrights Fault
Taieri Ridge Fault
Hyde Fault
Long Valley Fault
Spylaw Fault
Blue Mountains No 1 Fault
North Taieri Fault
Titri Fault
Akatore Fault
Clifton Fault
Settlement Fault
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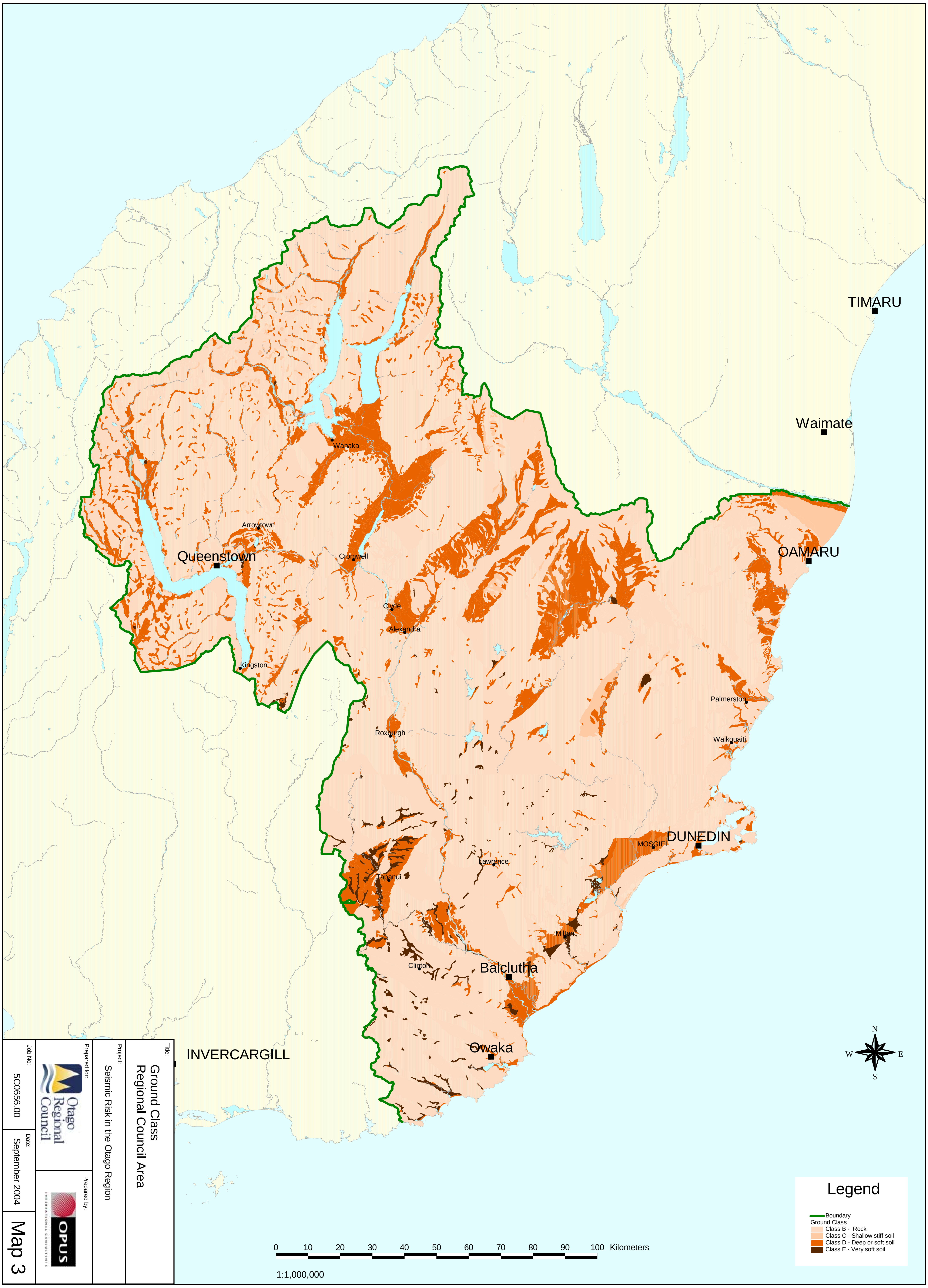
Kilometers
1:1,000,000
Legend
Surface fault rupture
Active - Accurate
Active - Approximate
Active - Concealed
Active - Inferrered
Boundary
Title:
Surface Fault Rupture Hazard
Project:
Seismic Risk in the Otago Region
Prepared for:
Otago Regional Council
Prepared by:
OPUS
Job No:
5C0656.00
Date:
September 2004
Map 2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DUNEDIN
Lawrence
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Clinton
Balclutha
Owaka
INVERCARGILL
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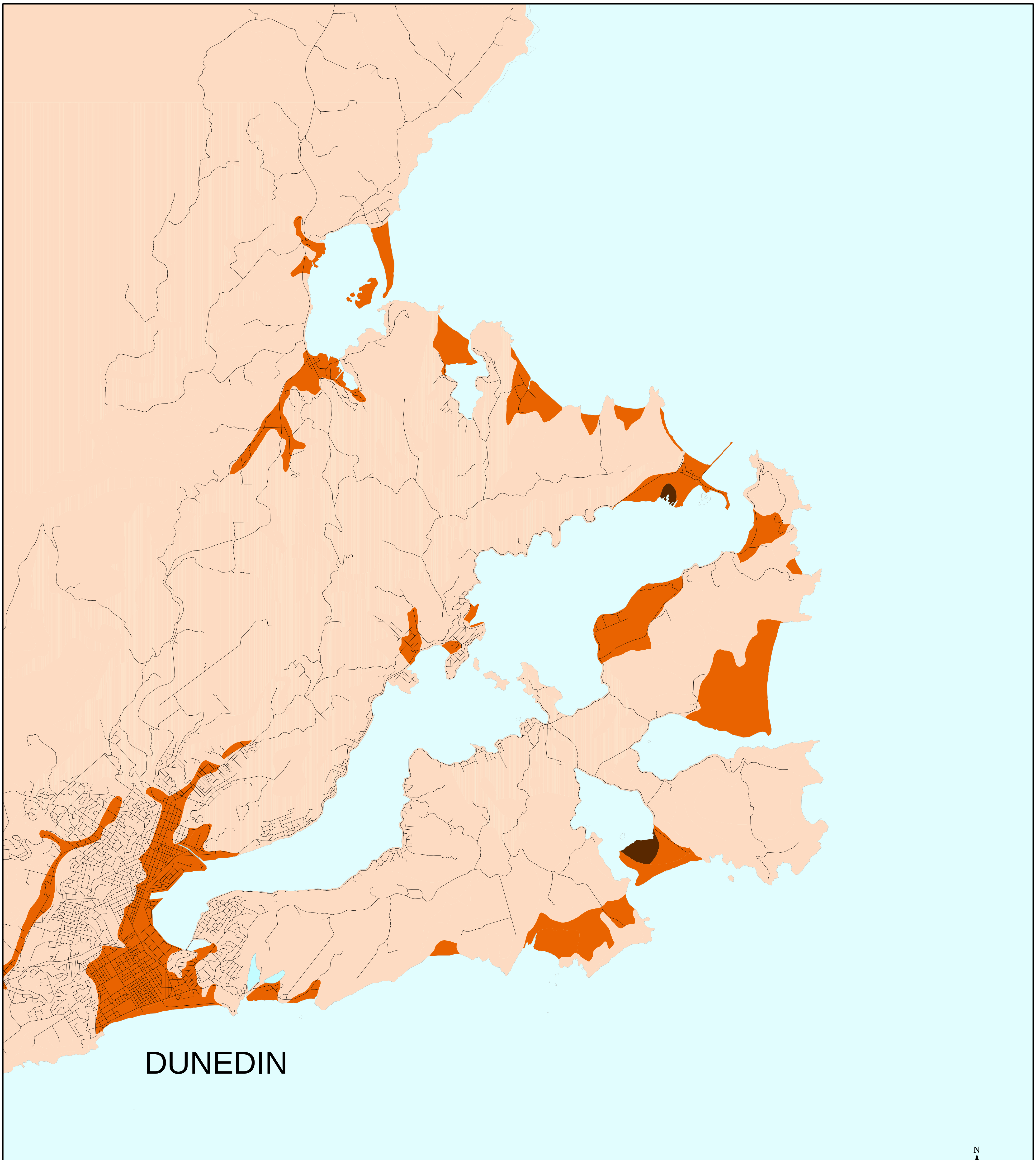
Legend
Boundary
Ground Class
Class B - Rock
Class C - Shallow stiff soil
Class D - Deep or soft soil
Class E - Very soft soil
0 10 20 30 40 50 60 70 80 90 100 Kilometers
1:1,000,000
Title:
Ground Class
Regional Council Area
Project:
Seismic Risk in the Otago Region
Prepared for:
Otago Regional Council
Prepared by:
OPUS
Job No:
5C0656.00
Date:
September 2004
Map 3



Title: Ground Class Dunedin Area

Project: Seismic Risk in the Otago Region

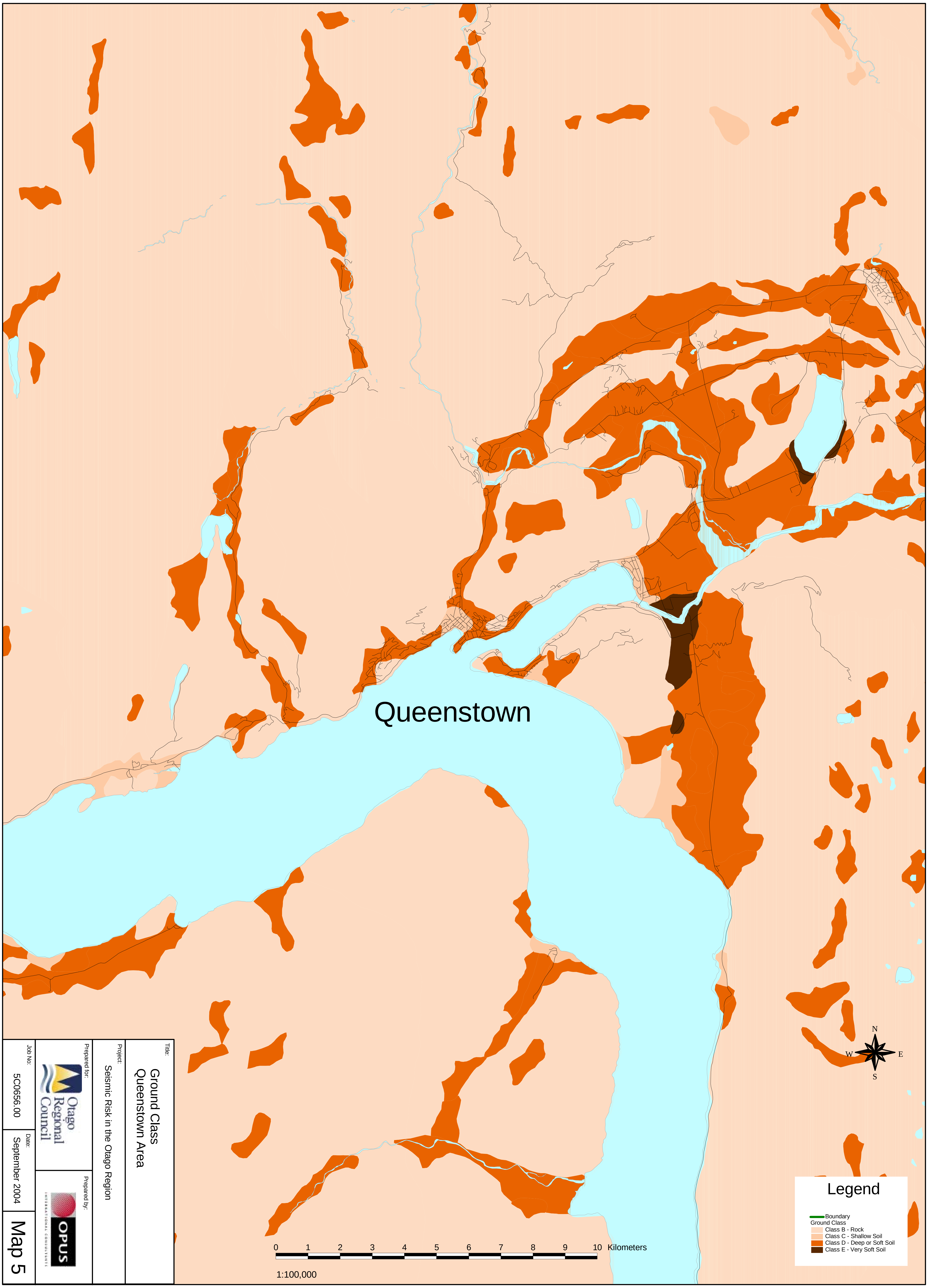
Prepared for: Otago Regional Council

Prepared by: OPUS International Consultants

Job No: 5C656.00

Date: September 2004

Map 4


Queenstown
Legend
Boundary
Ground Class
Class B - Rock
Class C - Shallow Soil
Class D - Deep or Soft Soil
Class E - Very Soft Soil
N
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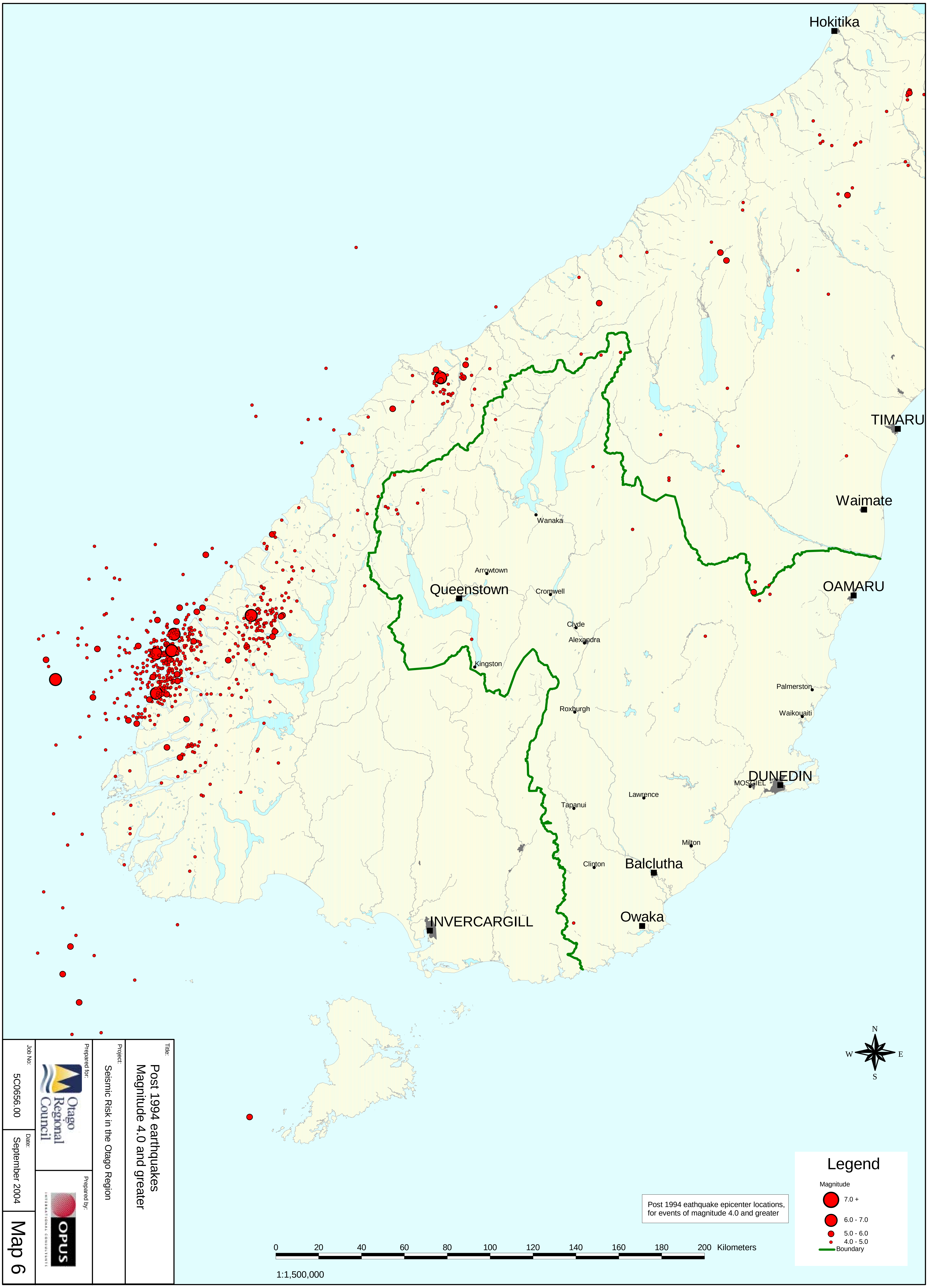
0 1 2 3 4 5 6 7 8 9 10 Kilometers
1:100,000
Title:
Ground Class
Queenstown Area
Project:
Seismic Risk in the Otago Region
Prepared for:
Otago Regional Council
Prepared by:
OPUS
INTERNATIONAL CONSULTANTS
Job No:
5C0656.00
Date:
September 2004
Map 5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INVERCARGILL
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Post 1994 eathquake epicenter locations, for events of magnitude 4.0 and greater
Legend
Magnitude
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6.0 - 7.0
5.0 - 6.0
4.0 - 5.0
Boundary
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20
40
60
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100
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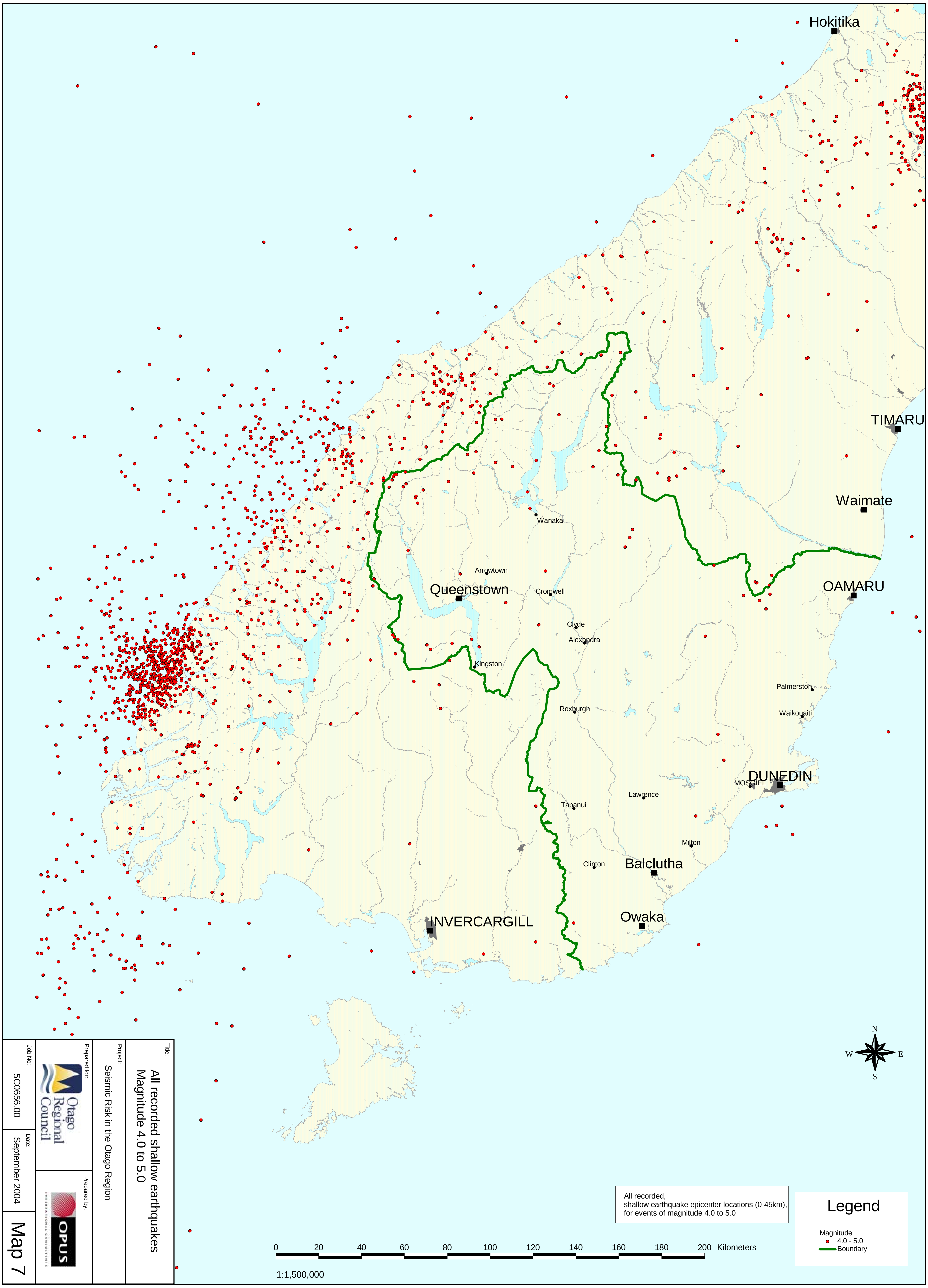
160
180
200
Kilometers
1:1,500,000
Title:
Post 1994 earthquakes
Magnitude 4.0 and greater
Project:
Seismic Risk in the Otago Region
Prepared for:
Otago Regional Council
Prepared by:
OPUS
Job No:
5C0656.00
Date:
September 2004
Map 6



Hokitika
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INVERCARGILL
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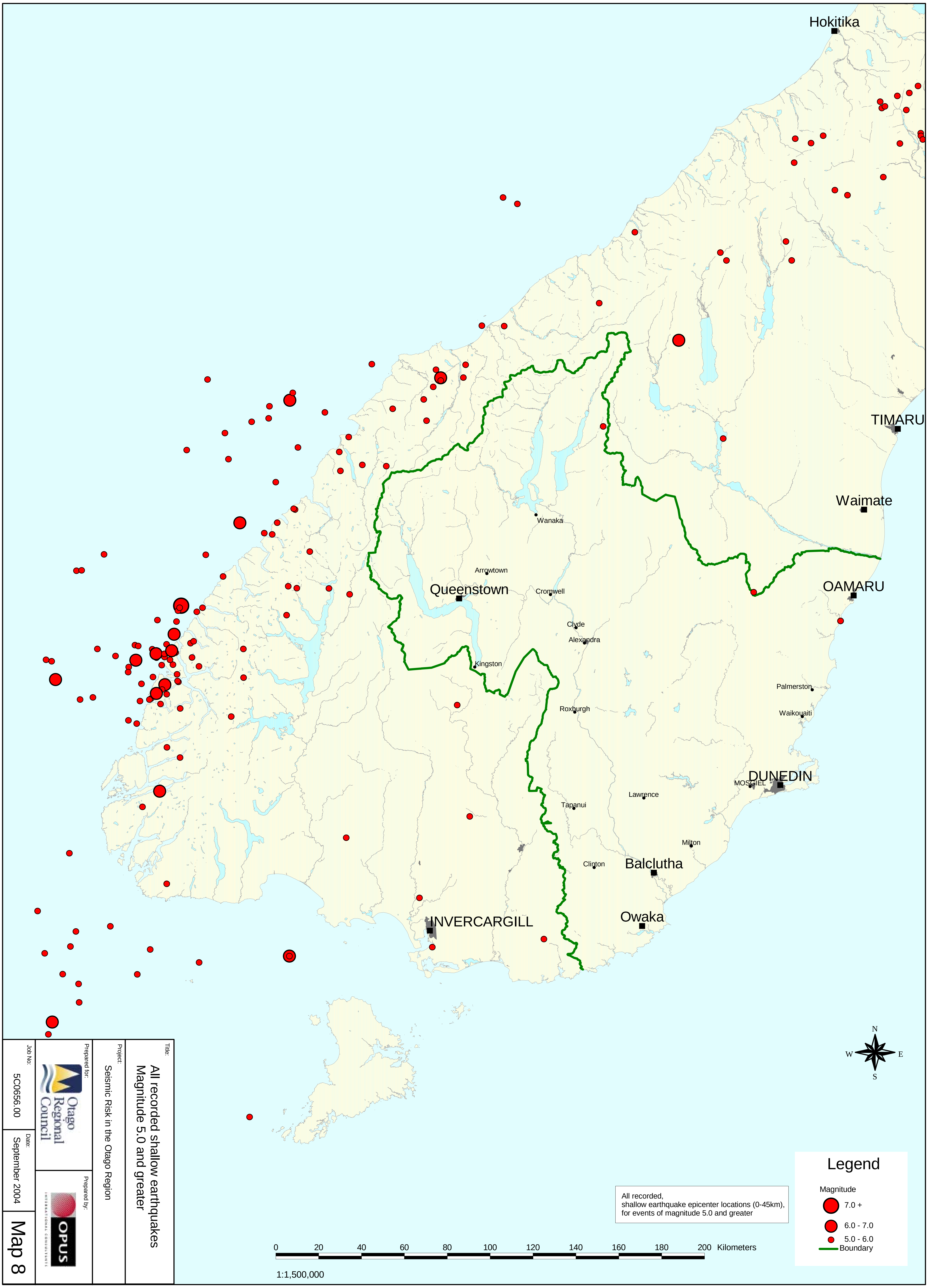
All recorded,
shallow earthquake epicenter locations (0-45km),
for events of magnitude 4.0 to 5.0
Legend
Magnitude
4.0 - 5.0
Boundary
0 20 40 60 80 100 120 140 160 180 200 Kilometers
1:1,500,000
Title:
All recorded shallow earthquakes
Magnitude 4.0 to 5.0
Project:
Seismic Risk in the Otago Region
Prepared for:
Otago Regional Council
Prepared by:
OPUS
Job No:
5C0656.00
Date:
September 2004
Map 7



Title:
All recorded shallow earthquakes
Magnitude 5.0 and greater

Project:
Seismic Risk in the Otago Region

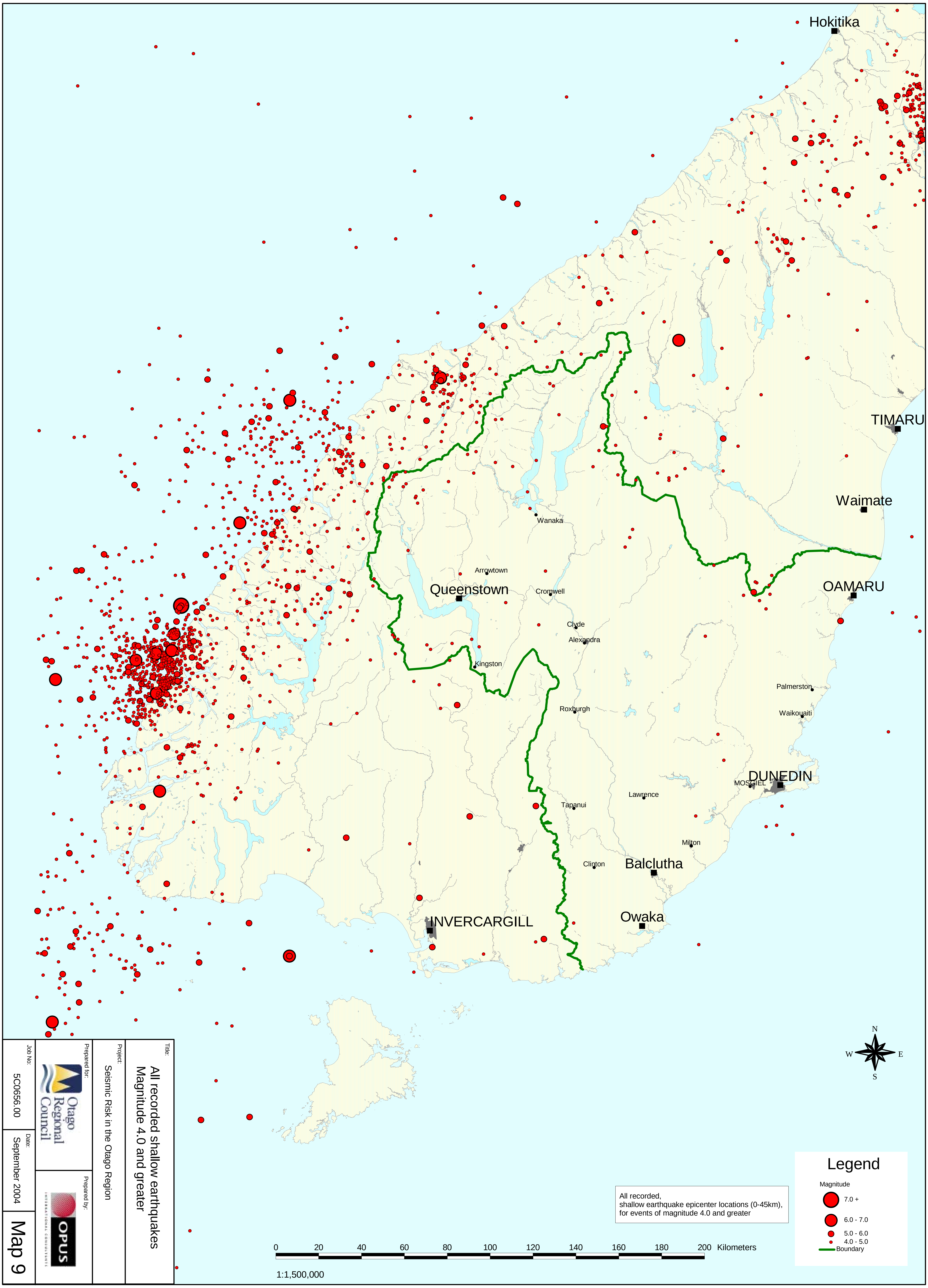
Prepared for:
Otago Regional Council

Prepared by:
OPUS
INTERNATIONAL CONSULTANTS

Job No:
5C0656.00

Date:
September 2004

Map 8



Title:
All recorded shallow earthquakes
Magnitude 4.0 and greater

Project:
Seismic Risk in the Otago Region

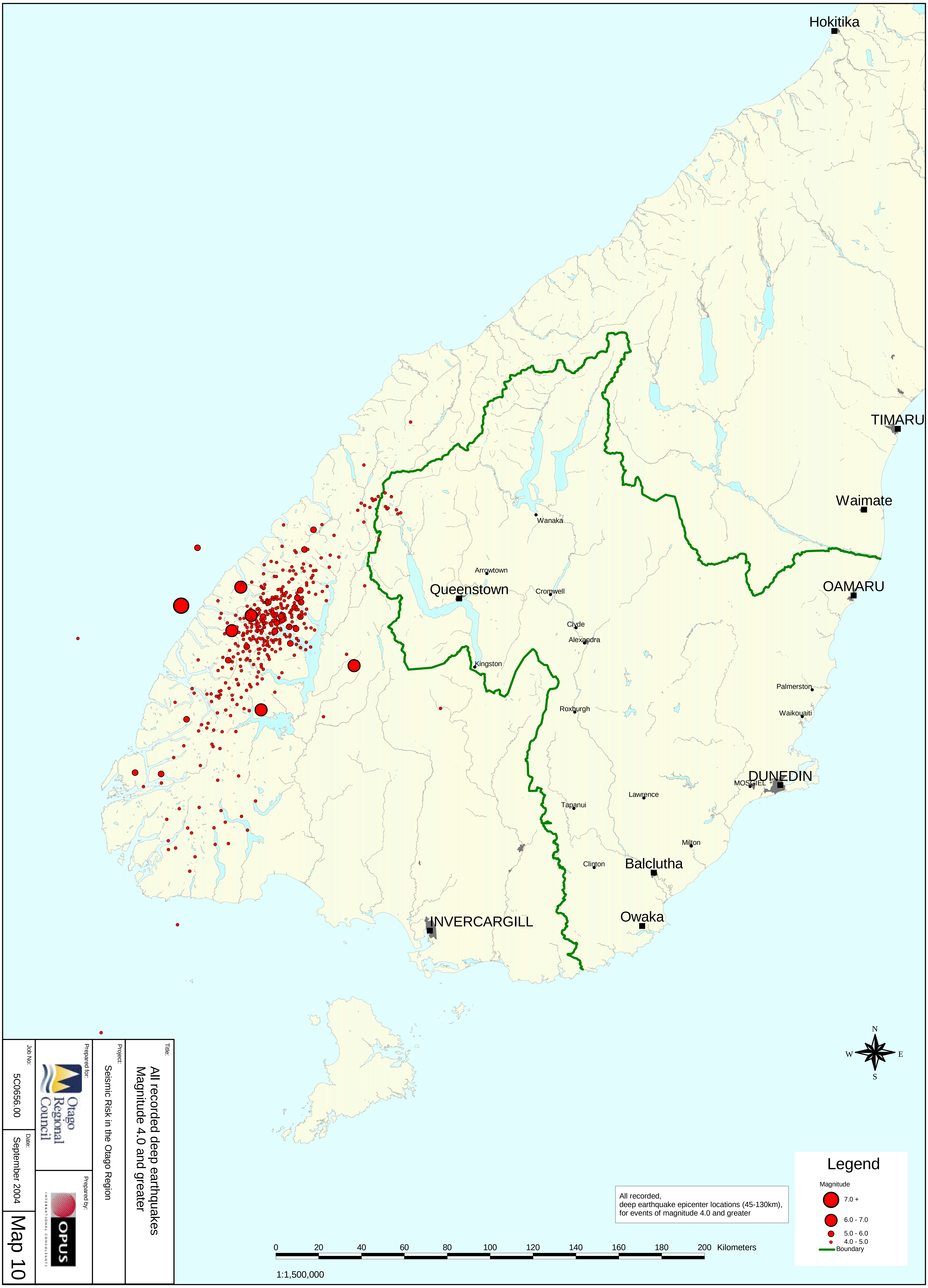
Prepared for:
Otago Regional Council

Prepared by:
OPUS

Job No:
5C0656.00

Date:
September 2004

Map 9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OAMARU
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DUNEDIN
Lawrence
Tapanui
Milton
Clinton
Balclutha
INVERCARGILL
Owaka
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All recorded,
deep earthquake epicenter locations (45-130km),
for events of magnitude 4.0 and greater
Legend
Magnitude
7.0 +
6.0 - 7.0
5.0 - 6.0
4.0 - 5.0
Boundary
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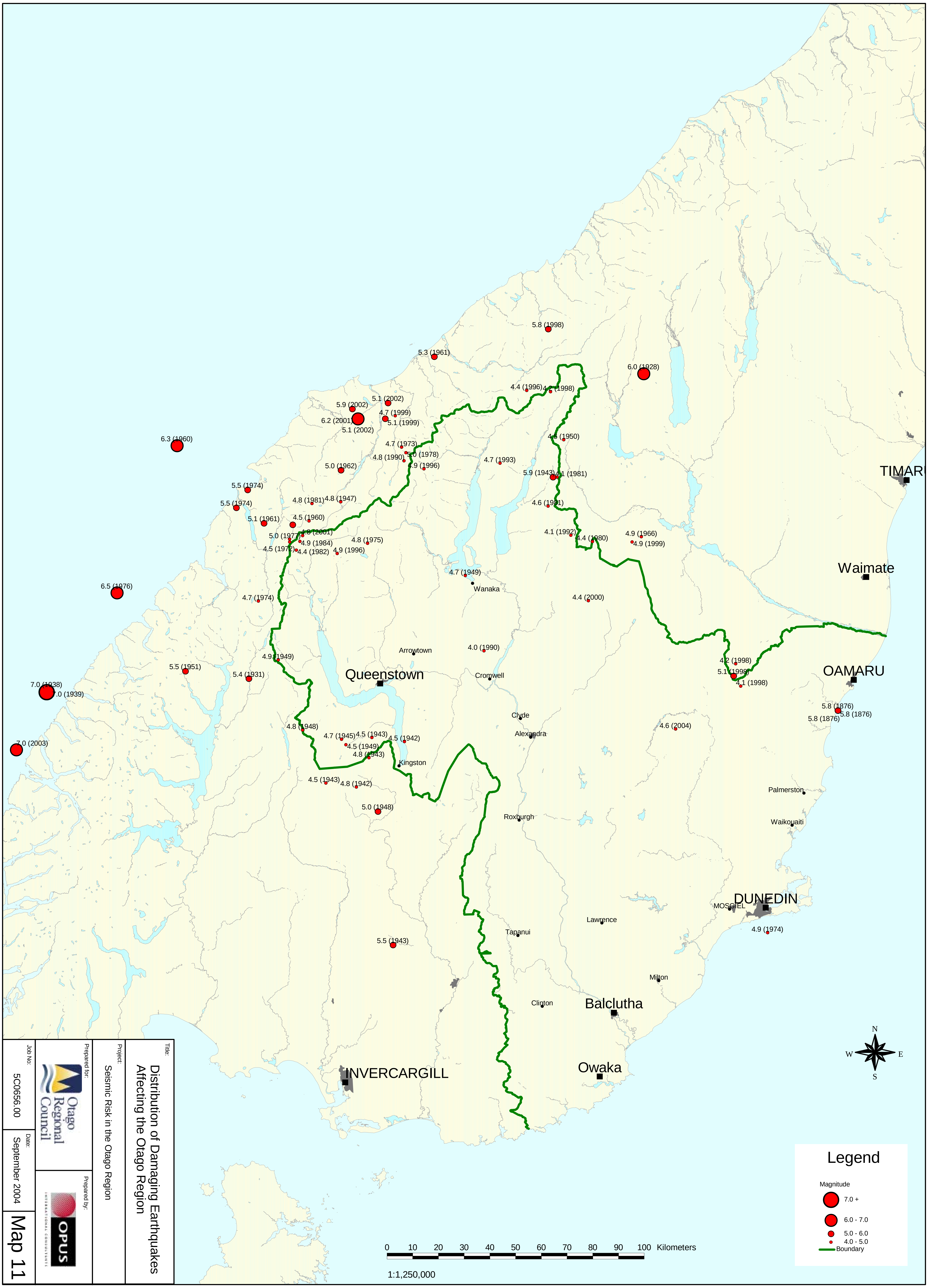
Kilometers
1:1,500,000
Title:
All recorded deep earthquakes
Magnitude 4.0 and greater
Project:
Seismic Risk in the Otago Region
Prepared for:
Otago Regional Council
Prepared by:
OPUS
Job No:
5C0656.00
Date:
September 2004
Map 10



Title: Distribution of Damaging Earthquakes Affecting the Otago Region

Project: Seismic Risk in the Otago Region

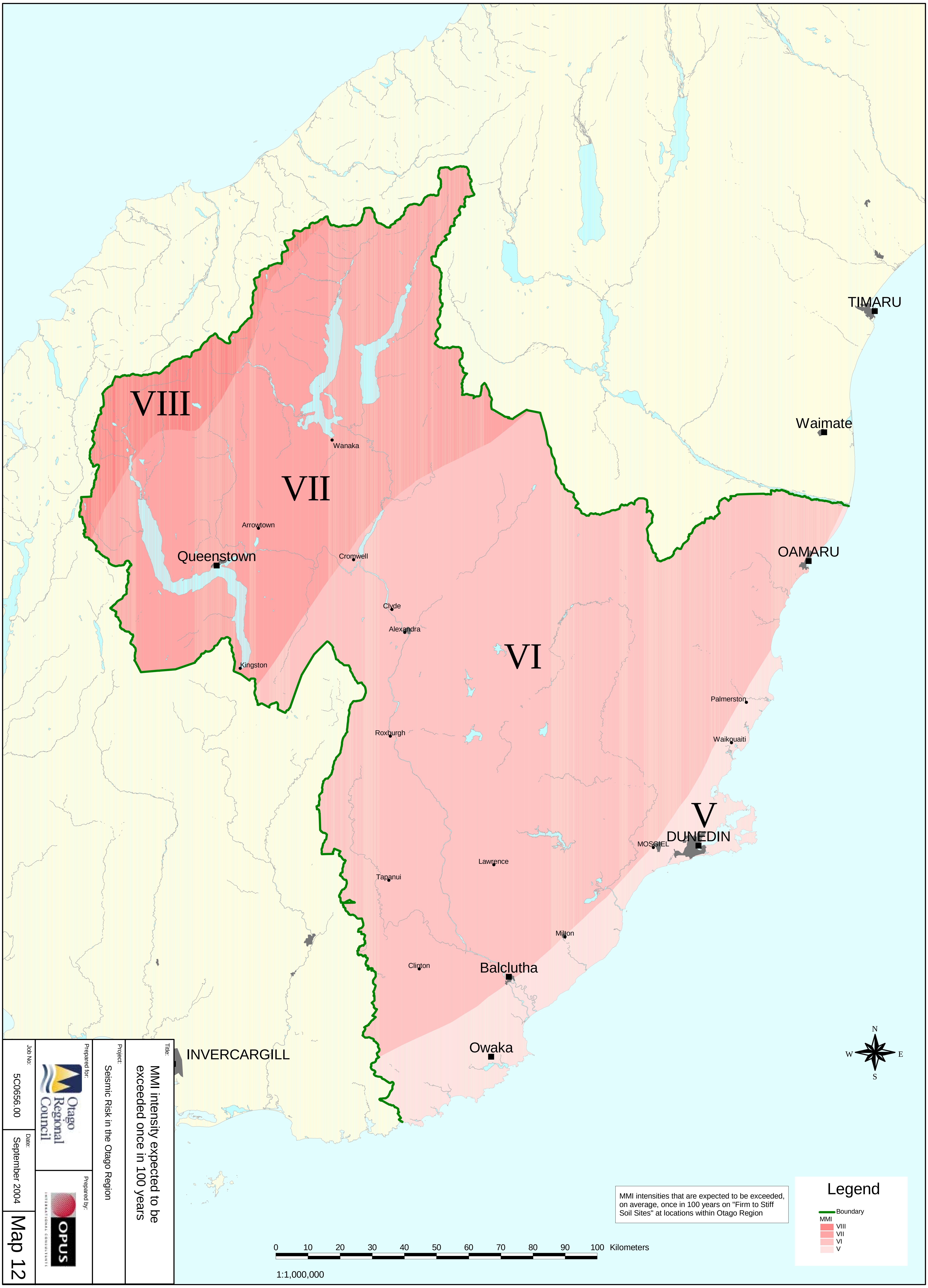
Prepared for: Otago Regional Council

Prepared by: OPUS

Job No: 5C0656.00

Date: September 2004

Map 11



Title: MMI intensity expected to be exceeded once in 100 years

Project: Seismic Risk in the Otago Region

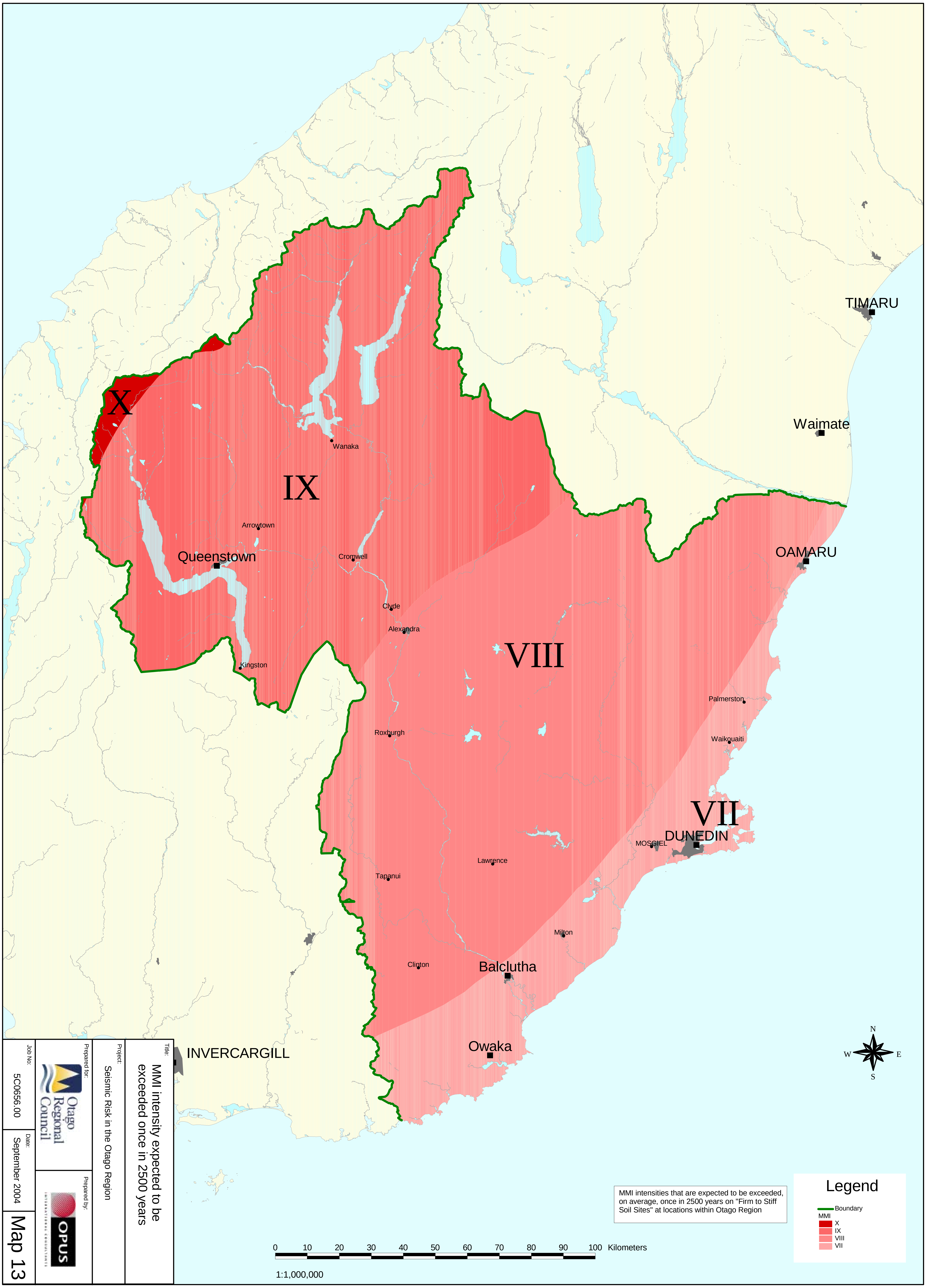
Prepared for: Otago Regional Council

Prepared by: OPUS

Job No: 5C0656.00

Date: September 2004

Map 12



Title: MMI intensity expected to be exceeded once in 2500 years

Project: Seismic Risk in the Otago Region

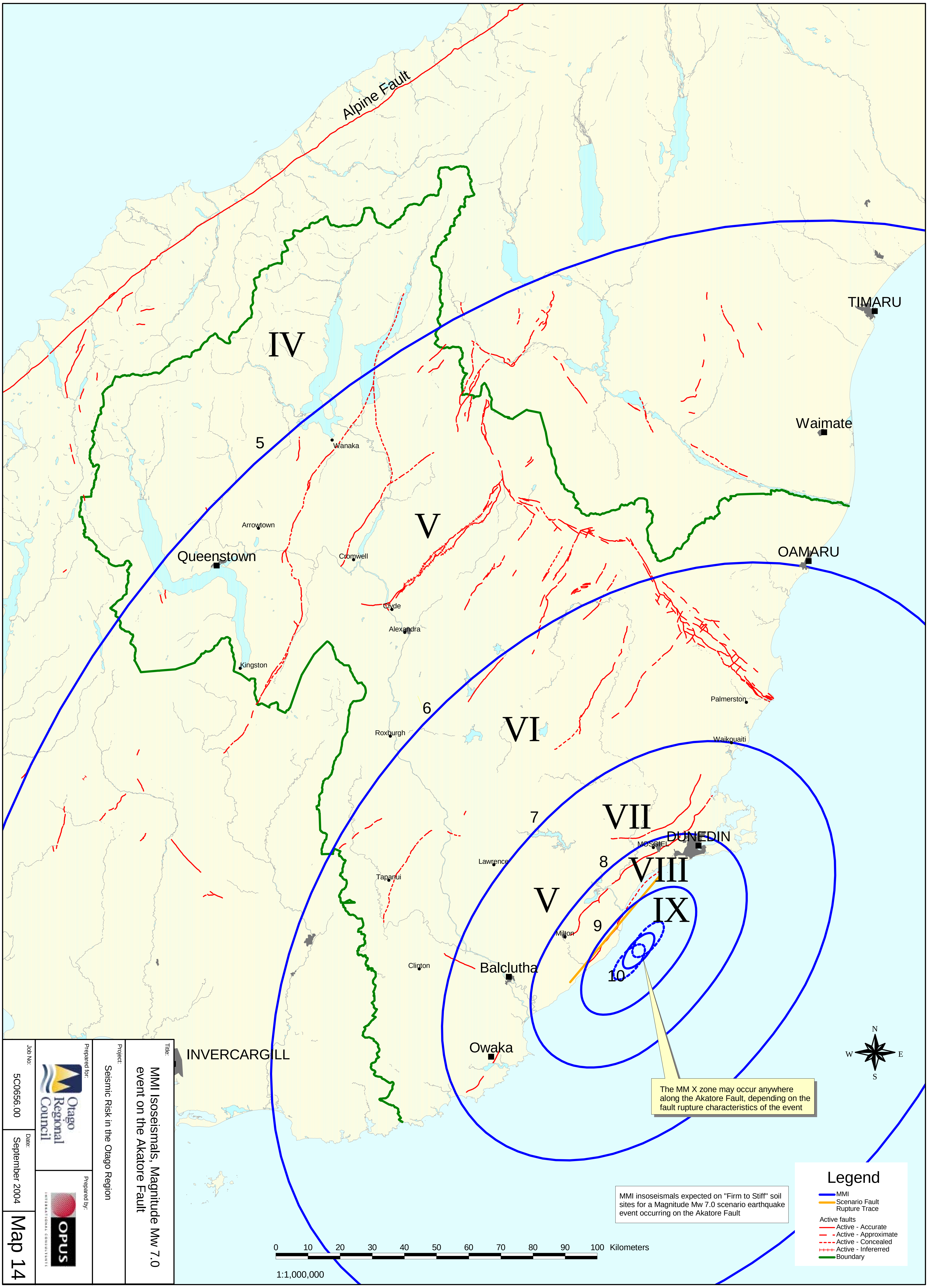
Prepared for: Otago Regional Council

Prepared by: OPUS

Job No: 5C0656.00

Date: September 2004

Map 13



Alpine Fault
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VI
VII
VIII
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TIMARU
Waimate
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Palmerston
Waikouaiti
DUNEDIN
MOSGIEL
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Clinton
Lawrence
Tapanui
Roxburgh
Alexandra
Clyde
Cromwell
Wanaka
Arrowtown
Queenstown
Kingston
INVERCARGILL
The MM X zone may occur anywhere along the Akatore Fault, depending on the fault rupture characteristics of the event
MMI insoseismals expected on "Firm to Stiff" soil sites for a Magnitude Mw 7.0 scenario earthquake event occurring on the Akatore Fault
Legend
MMI
Scenario Fault Rupture Trace
Active faults
Active - Accurate
Active - Approximate
Active - Concealed
Active - Inferrered
Boundary
N
S
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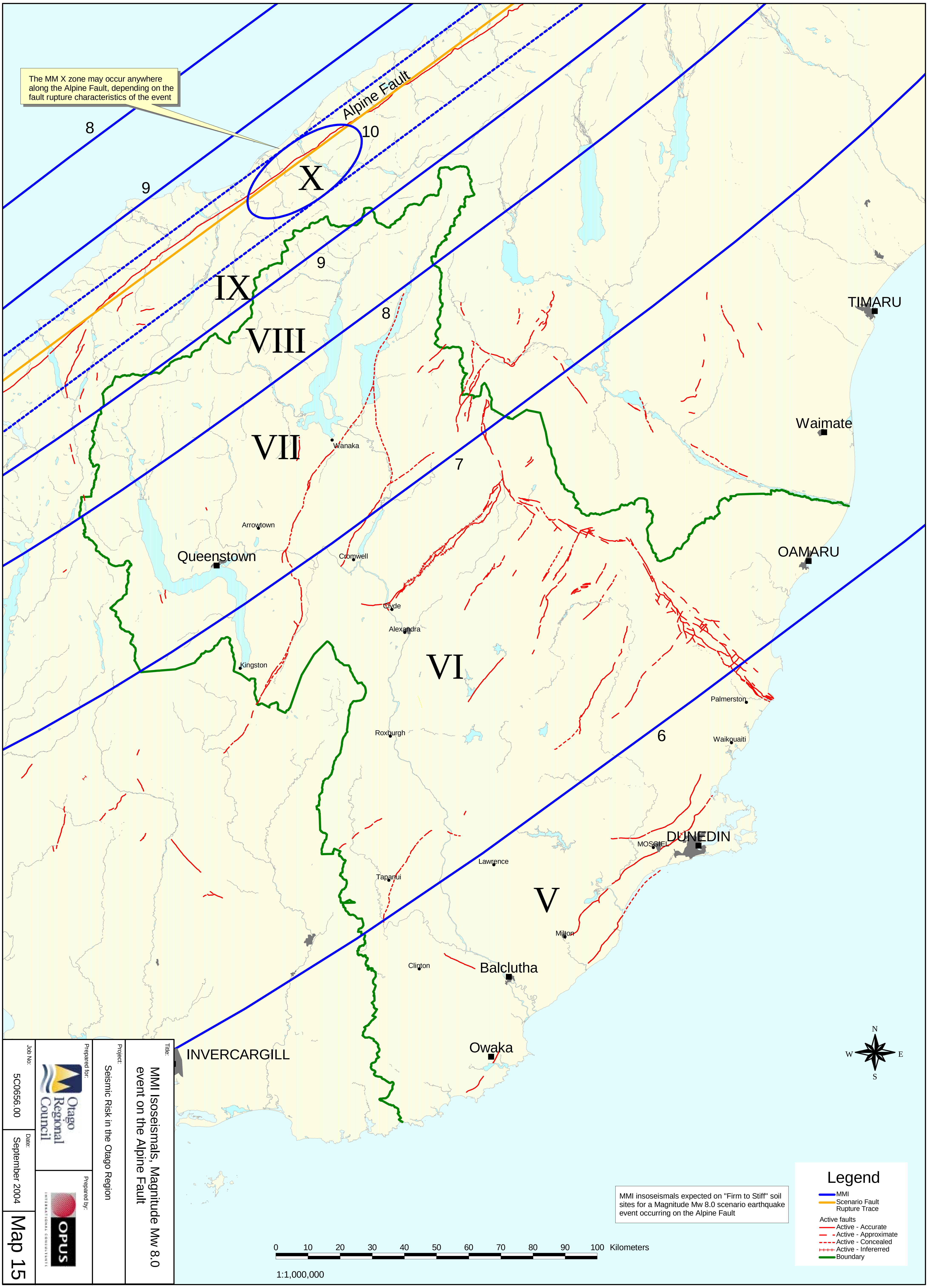
0 10 20 30 40 50 60 70 80 90 100 Kilometers
1:1,000,000
Title: MMI Isoseismals, Magnitude Mw 7.0 event on the Akatore Fault
Project: Seismic Risk in the Otago Region
Prepared for: Otago Regional Council
Prepared by: OPUS
Job No: 5C0656.00
Date: September 2004
Map 14



The MM X zone may occur anywhere along the Alpine Fault, depending on the fault rupture characteristics of the event
Alpine Fault
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TIMARU
Waimate
OAMARU
Palmerston
Waikouaiti
DUNEDIN
MOSGIEL
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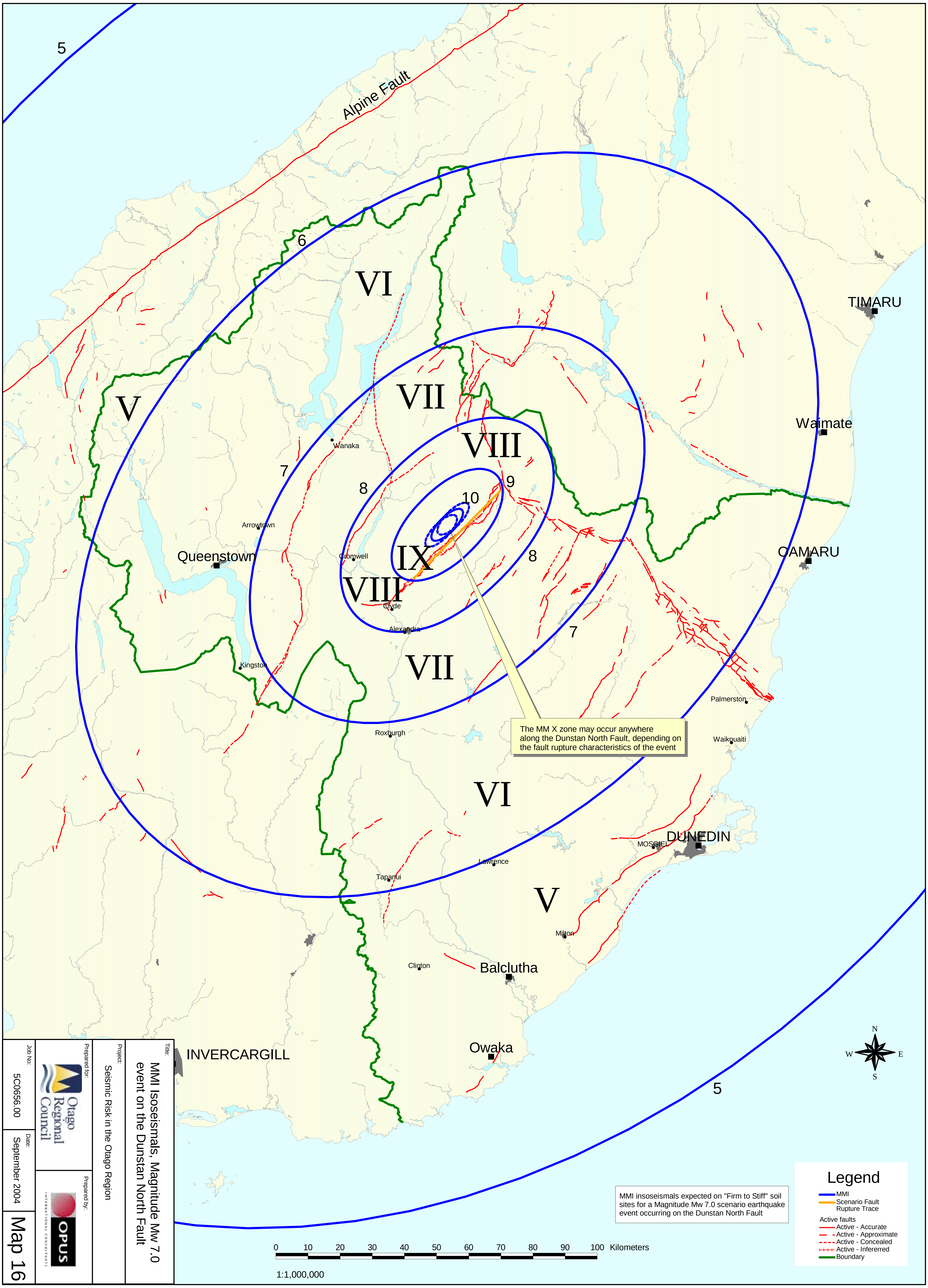
Owaka
INVERCARGILL
Tapanui
Roxburgh
Alexandra
Clyde
Cromwell
Wanaka
Arrowtown
Queenstown
Kingston
N
S
W
E
MMI insoseismals expected on "Firm to Stiff" soil sites for a Magnitude Mw 8.0 scenario earthquake event occurring on the Alpine Fault
Legend
MMI
Scenario Fault Rupture Trace
Active faults
Active - Accurate
Active - Approximate
Active - Concealed
Active - Inferrered
Boundary
0 10 20 30 40 50 60 70 80 90 100 Kilometers
1:1,000,000
Title:
MMI Isoseismals, Magnitude Mw 8.0 event on the Alpine Fault
Project:
Seismic Risk in the Otago Region
Prepared for:
Otago Regional Council
Prepared by:
OPUS
Job No:
5C0656.00
Date:
September 2004
Map 15



Alpine Fault
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TIMARU
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Roxburgh
Palmerston
Waikouaiti
DUNEDIN
MOSGIEL
Lawrence
Tapanui
Milton
Clinton
Balclutha
Owaka
INVERCARGILL
The MM X zone may occur anywhere along the Dunstan North Fault, depending on the fault rupture characteristics of the event
MMI insoseismals expected on "Firm to Stiff" soil sites for a Magnitude Mw 7.0 scenario earthquake event occurring on the Dunstan North Fault
Legend
MMI
Scenario Fault Rupture Trace
Active faults
Active - Accurate
Active - Approximate
Active - Concealed
Active - Inferrered
Boundary
N
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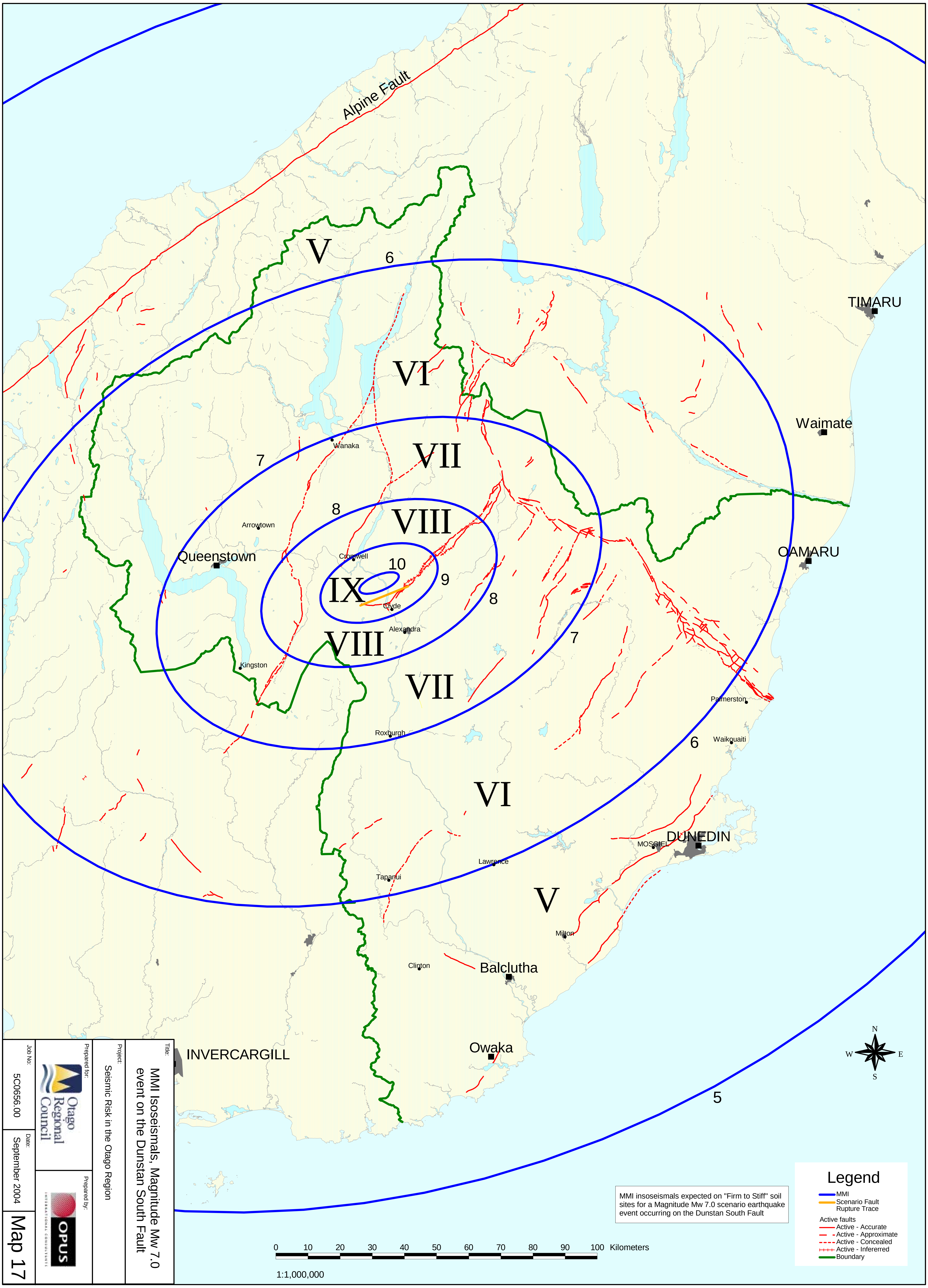
0 10 20 30 40 50 60 70 80 90 100 Kilometers
1:1,000,000
Title:
MMI Isoseismals, Magnitude Mw 7.0 event on the Dunstan North Fault
Project:
Seismic Risk in the Otago Region
Prepared for:
Otago Regional Council
Prepared by:
OPUS
Job No:
5C0656.00
Date:
September 2004
Map 16



Title: MMI Isoseismals, Magnitude Mw 7.0 event on the Dunstan South Fault

Project: Seismic Risk in the Otago Region

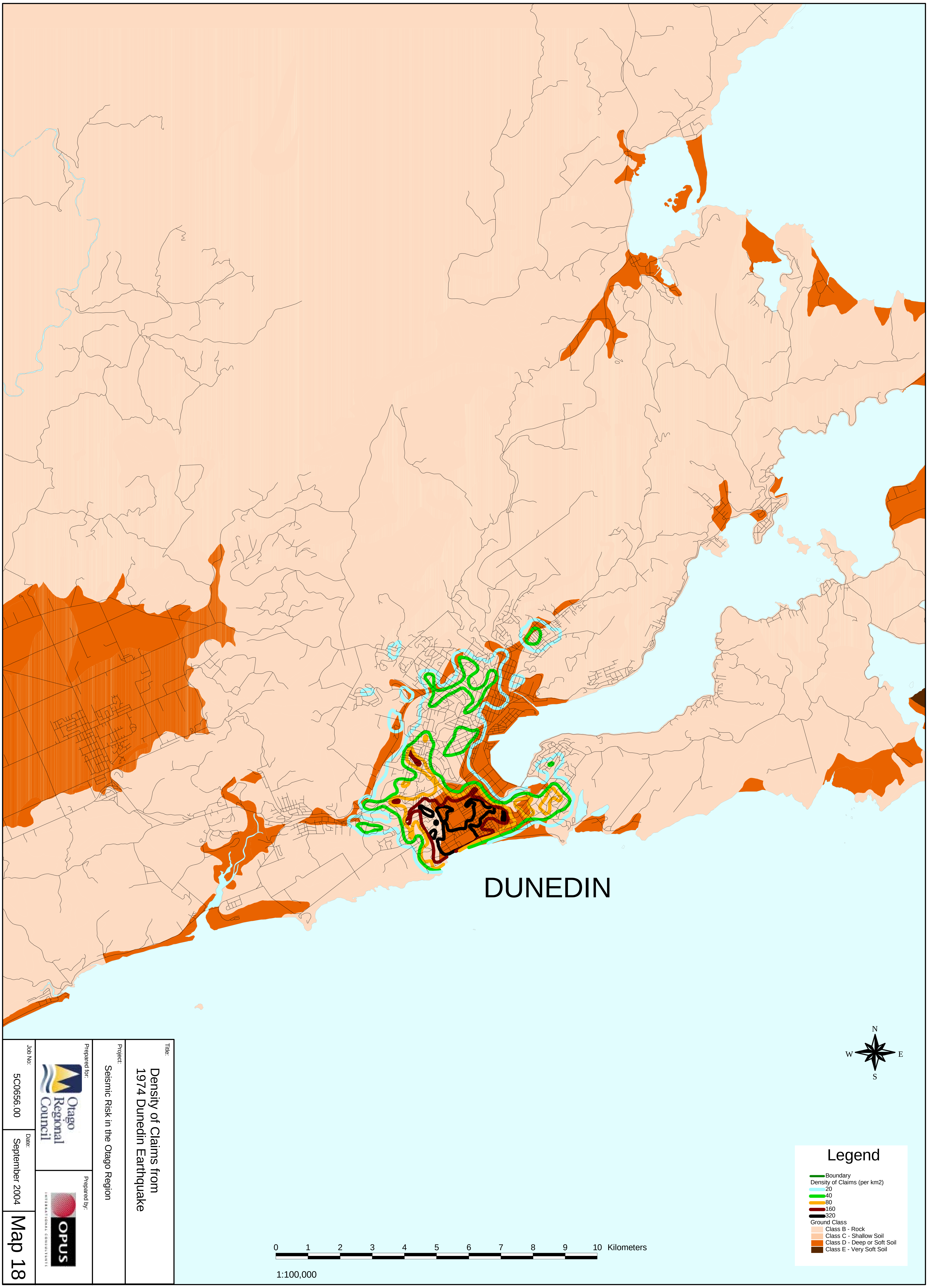
Prepared for: Otago Regional Council

Prepared by: OPUS

Job No: 5C0656.00

Date: September 2004

Map 17



Title: Density of Claims from 1974 Dunedin Earthquake

Project: Seismic Risk in the Otago Region

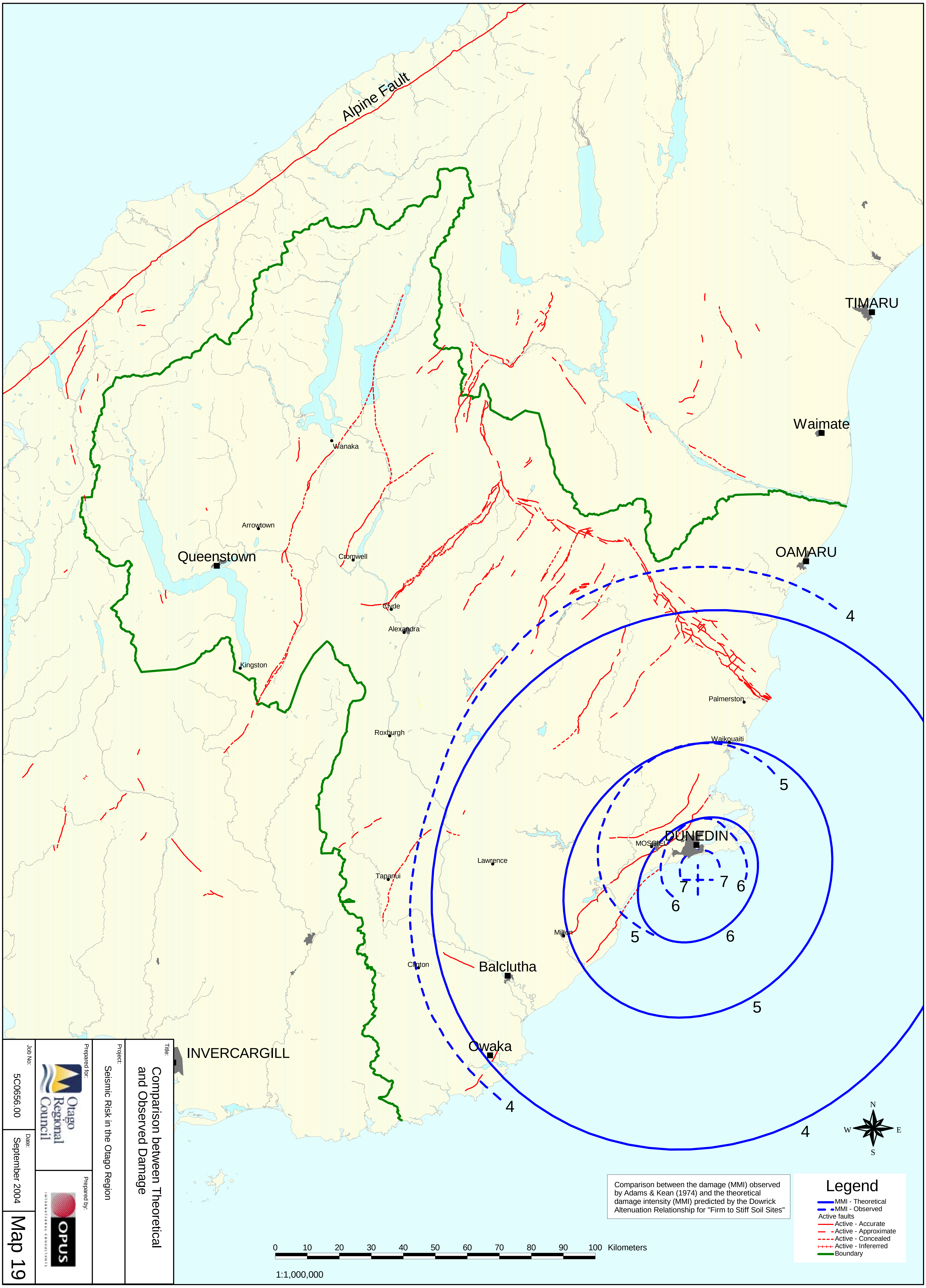
Prepared for: Otago Regional Council

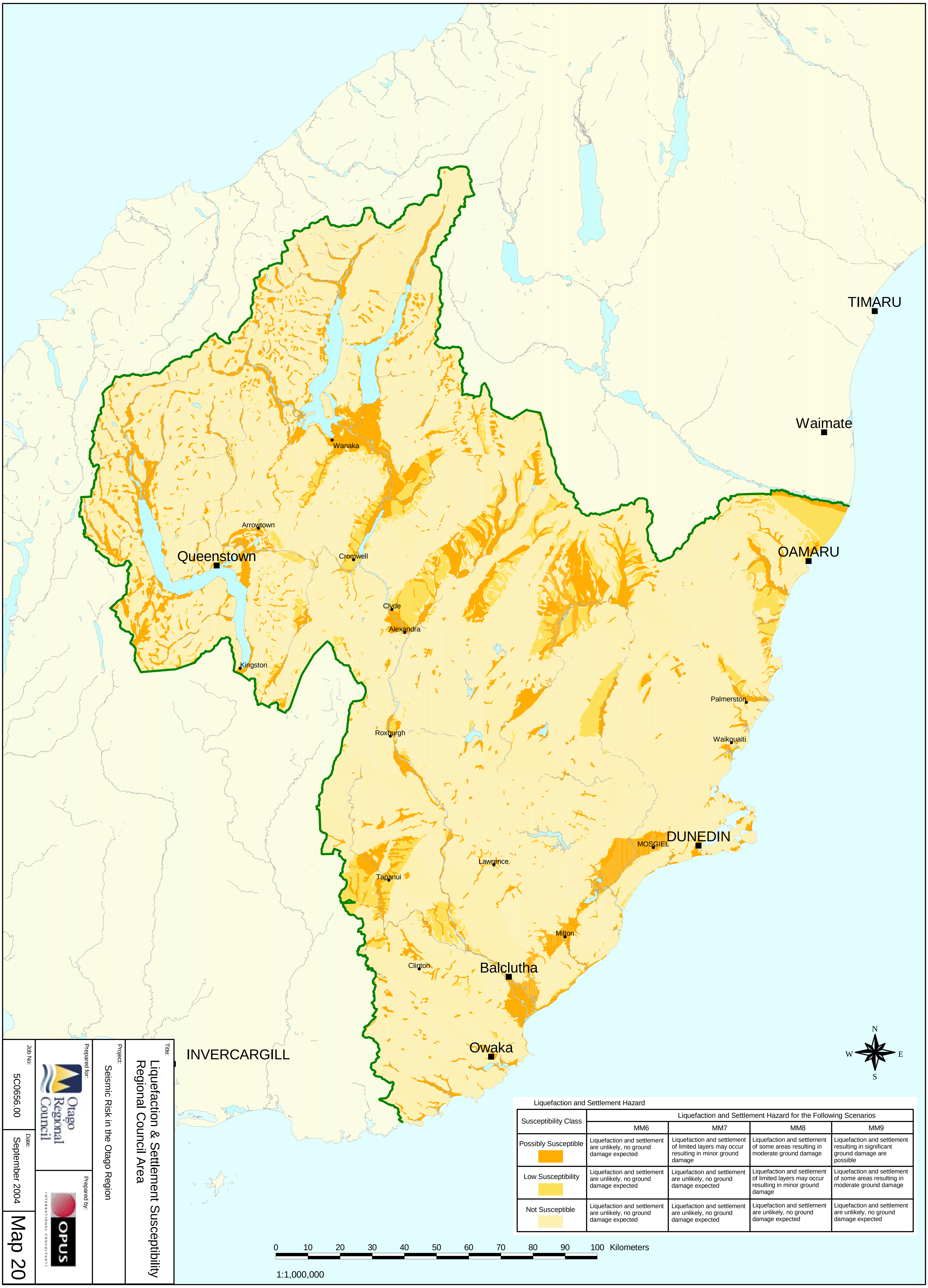
Prepared by: OPUS International Consultants

Job No: 5C656.00

Date: September 2004

Map 18


Alpine Fault
Wanaka
Arrowtown
Queenstown
Cromwell
Clyde
Alexandra
Kingston
Roxburgh
Tapanui
Lawrence
Clinton
Balclutha
Owaka
INVERCARGILL
Milton
MOSGIEL
DUNEDIN
Waikouaiti
Palmerston
OAMARU
Waimate
TIMARU
4
5
6
7
Comparison between the damage (MMI) observed by Adams & Kean (1974) and the theoretical damage intensity (MMI) predicted by the Dowrick Attenuation Relationship for "Firm to Stiff Soil Sites"
Legend
MMI - Theoretical
MMI - Observed
Active faults
Active - Accurate
Active - Approximate
Active - Concealed
Active - Inferrered
Boundary
0 10 20 30 40 50 60 70 80 90 100 Kilometers
1:1,000,000
N
S
E
W
Title:
Comparison between Theoretical and Observed Damage
Project:
Seismic Risk in the Otago Region
Prepared for:
Otago Regional Council
Prepared by:
OPUS
Job No:
5C0656.00
Date:
September 2004
Map 19



Liquefaction and Settlement Hazard

Susceptibility Class	Liquefaction and Settlement Hazard for the Following Scenarios			
	MM6	MM7	MM8	MM9
Possibly Susceptible	Liquefaction and settlement are unlikely, no ground damage expected	Liquefaction and settlement of limited layers may occur resulting in minor ground damage	Liquefaction and settlement of some areas resulting in moderate ground damage	Liquefaction and settlement resulting in significant ground damage are possible
Low Susceptibility	Liquefaction and settlement are unlikely, no ground damage expected	Liquefaction and settlement are unlikely, no ground damage expected	Liquefaction and settlement of limited layers may occur resulting in minor ground damage	Liquefaction and settlement of some areas resulting in moderate ground damage
Not Susceptible	Liquefaction and settlement are unlikely, no ground damage expected	Liquefaction and settlement are unlikely, no ground damage expected	Liquefaction and settlement are unlikely, no ground damage expected	Liquefaction and settlement are unlikely, no ground damage expected

Title: Liquefaction & Settlement Susceptibility Regional Council Area

Project: Seismic Risk in the Otago Region

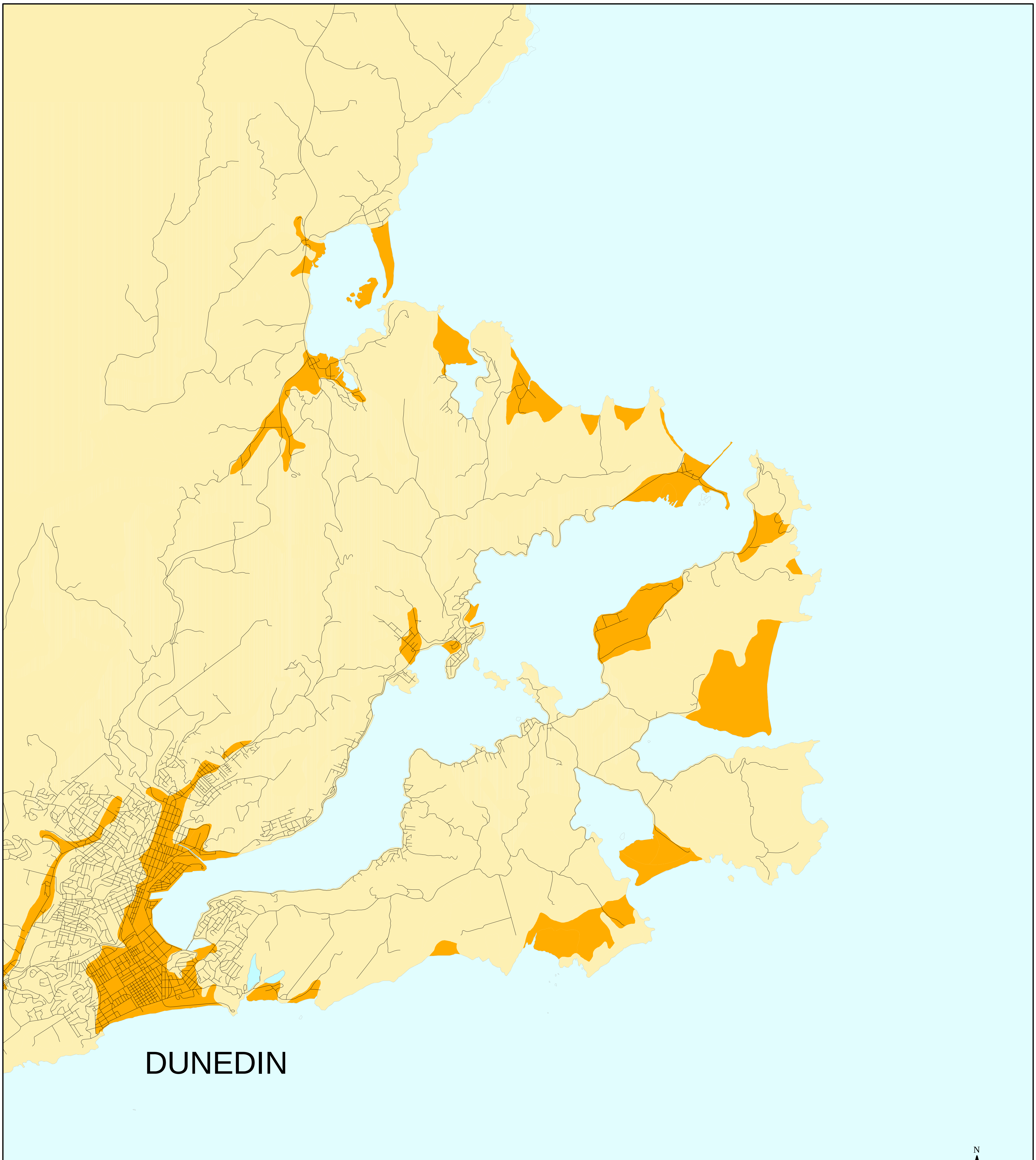
Prepared for: Otago Regional Council

Prepared by: OPUS International Consultants

Job No: 5C0656.00

Date: September 2004

Map 20



Liquefaction and Settlement Hazard

Susceptibility Class	Liquefaction and Settlement Hazard for the Following Scenarios			
	MM6	MM7	MM8	MM9
Possibly Susceptible	Liquefaction and settlement are unlikely, no ground damage expected	Liquefaction and settlement of limited layers may occur resulting in minor ground damage	Liquefaction and settlement of some areas resulting in moderate ground damage	Liquefaction and settlement resulting in significant ground damage are possible
Low Susceptibility	Liquefaction and settlement are unlikely, no ground damage expected	Liquefaction and settlement are unlikely, no ground damage expected	Liquefaction and settlement of limited layers may occur resulting in minor ground damage	Liquefaction and settlement of some areas resulting in moderate ground damage
Not Susceptible	Liquefaction and settlement are unlikely, no ground damage expected	Liquefaction and settlement are unlikely, no ground damage expected	Liquefaction and settlement are unlikely, no ground damage expected	Liquefaction and settlement are unlikely, no ground damage expected

0 1 2 3 4 5 6 7 8 9 10 Kilometers

1:100,000

Title:
Liquefaction & Settlement Susceptibility
Dunedin Area

Project:
Seismic Risk in the Otago Region

Prepared for:
Otago Regional Council

Prepared by:
OPUS
INTERNATIONAL CONSULTANTS

Job No:
5C0656.00

Date:
September 2004

Map 21

Liquefaction and Settlement Hazard

Susceptibility Class	Liquefaction and Settlement Hazard for the Following Scenarios			
	MM6	MM7	MM8	MM9
Possibly Susceptible	Liquefaction and settlement are unlikely, no ground damage expected	Liquefaction and settlement of limited layers may occur resulting in minor ground damage	Liquefaction and settlement of some areas resulting in moderate ground damage	Liquefaction and settlement resulting in significant ground damage are possible
Low Susceptibility	Liquefaction and settlement are unlikely, no ground damage expected	Liquefaction and settlement are unlikely, no ground damage expected	Liquefaction and settlement of limited layers may occur resulting in minor ground damage	Liquefaction and settlement of some areas resulting in moderate ground damage
Not Susceptible	Liquefaction and settlement are unlikely, no ground damage expected	Liquefaction and settlement are unlikely, no ground damage expected	Liquefaction and settlement are unlikely, no ground damage expected	Liquefaction and settlement are unlikely, no ground damage expected

Title:
Liquefaction & Settlement Susceptibility
Queenstown Area

Project:
Seismic Risk in the Otago Region

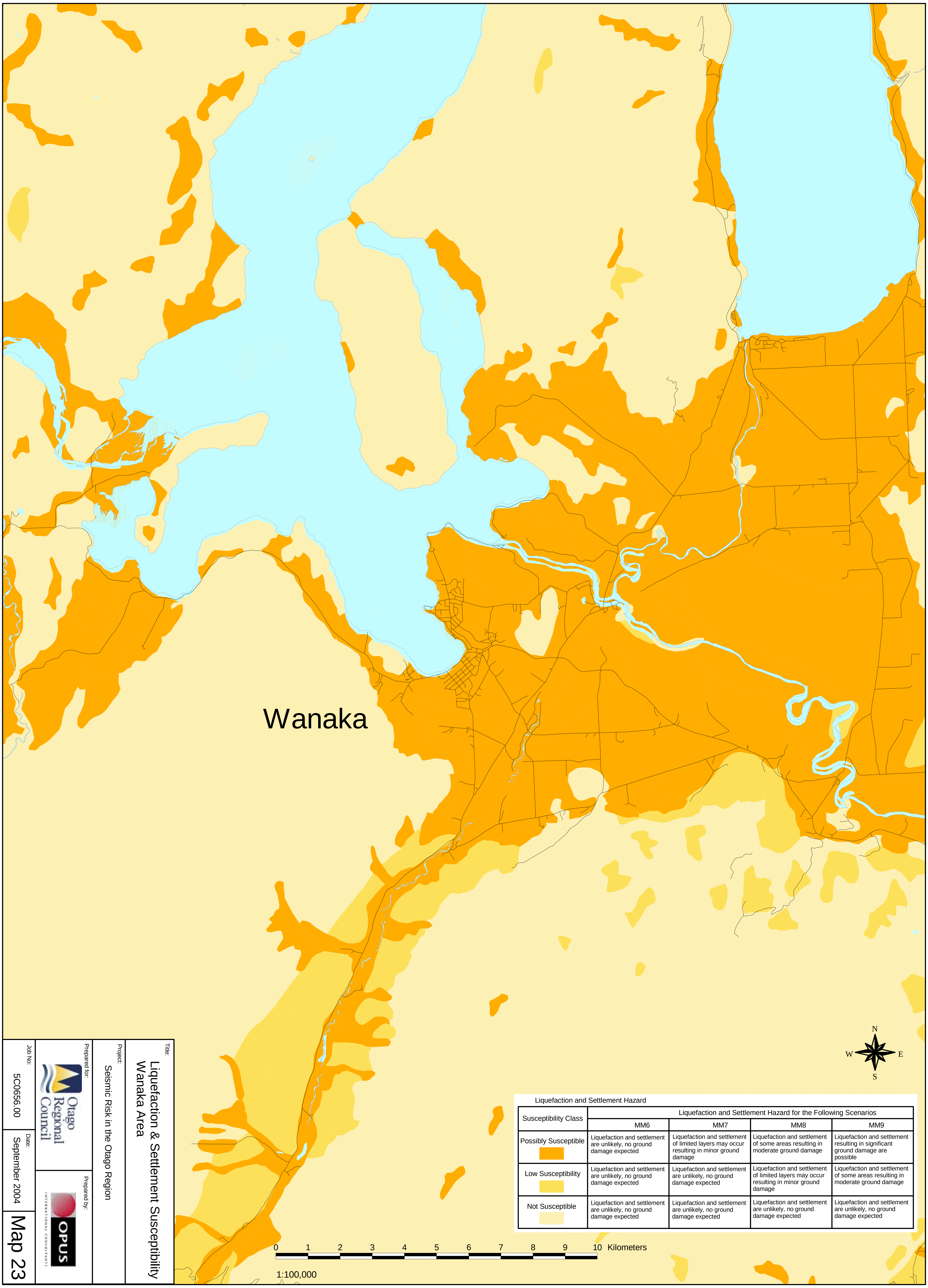
Prepared for:
Otago Regional Council

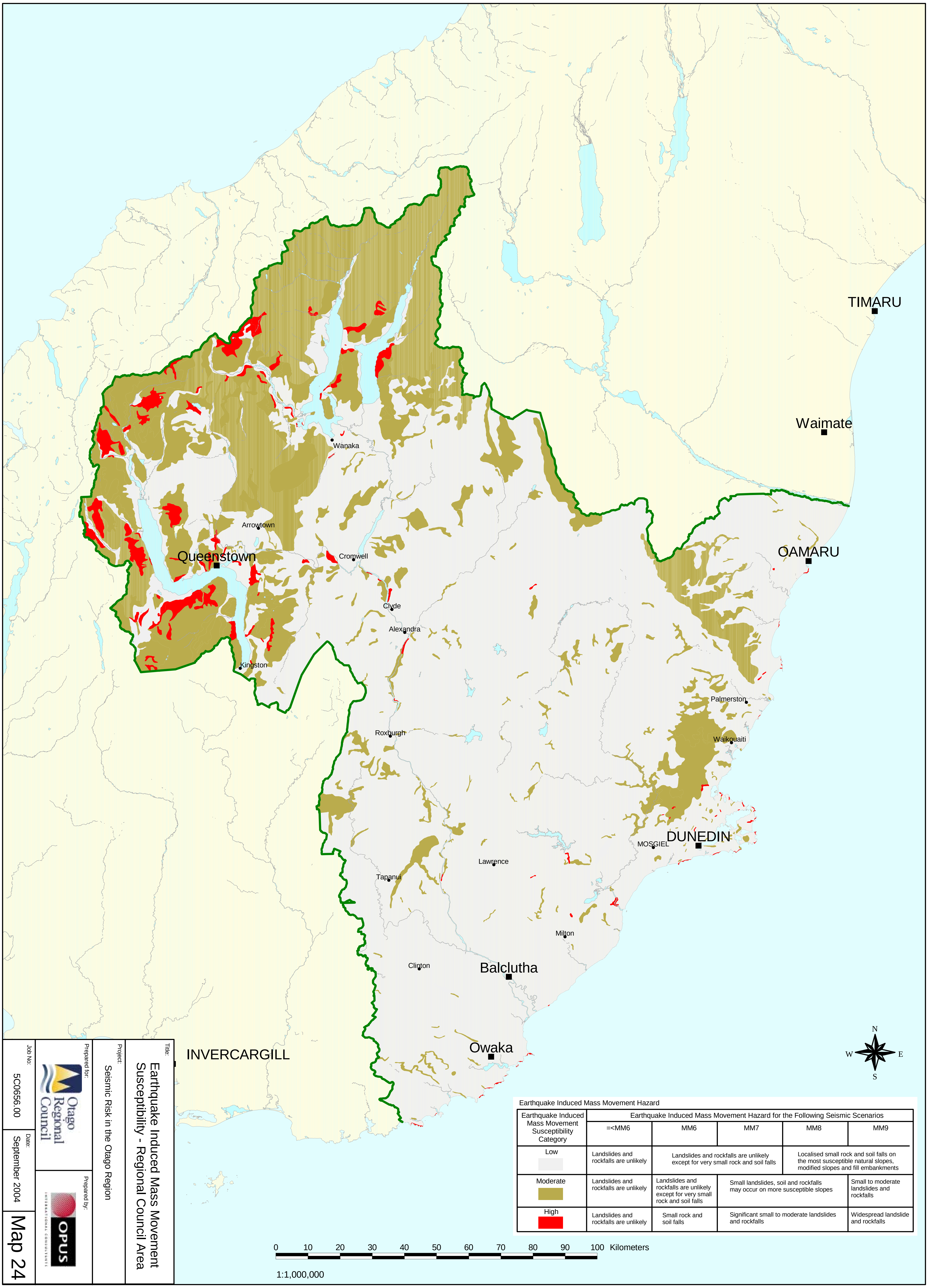
Prepared by:
OPUS

Job No:
5C0656.00

Date:
September 2004

Map 22


Wanaka
Liquefaction and Settlement Hazard
Susceptibility Class
Liquefaction and Settlement Hazard for the Following Scenarios
MM6
MM7
MM8
MM9
Possibly Susceptible
Liquefaction and settlement are unlikely, no ground damage expected
Liquefaction and settlement of limited layers may occur resulting in minor ground damage
Liquefaction and settlement of some areas resulting in moderate ground damage
Liquefaction and settlement resulting in significant ground damage are possible
Low Susceptibility
Liquefaction and settlement are unlikely, no ground damage expected
Liquefaction and settlement are unlikely, no ground damage expected
Liquefaction and settlement of limited layers may occur resulting in minor ground damage
Liquefaction and settlement of some areas resulting in moderate ground damage
Not Susceptible
Liquefaction and settlement are unlikely, no ground damage expected
Liquefaction and settlement are unlikely, no ground damage expected
Liquefaction and settlement are unlikely, no ground damage expected
Liquefaction and settlement are unlikely, no ground damage expected
N
W
E
S
0
1
2
3
4
5
6
7
8
9
10 Kilometers
1:100,000
Title:
Liquefaction & Settlement Susceptibility
Wanaka Area
Project:
Seismic Risk in the Otago Region
Prepared for:
Otago Regional Council
Prepared by:
OPUS
INTERNATIONAL CONSULTANTS
Job No:
5C0656.00
Date:
September 2004
Map 23



Earthquake Induced Mass Movement Hazard

Earthquake Induced Mass Movement Susceptibility Category	Earthquake Induced Mass Movement Hazard for the Following Seismic Scenarios				
	=<MM6	MM6	MM7	MM8	MM9
Low	Landslides and rockfalls are unlikely	Landslides and rockfalls are unlikely except for very small rock and soil falls		Localised small rock and soil falls on the most susceptible natural slopes, modified slopes and fill embankments	
Moderate	Landslides and rockfalls are unlikely	Landslides and rockfalls are unlikely except for very small rock and soil falls	Small landslides, soil and rockfalls may occur on more susceptible slopes		Small to moderate landslides and rockfalls
High	Landslides and rockfalls are unlikely	Small rock and soil falls	Significant small to moderate landslides and rockfalls		Widespread landslide and rockfalls

Title: Earthquake Induced Mass Movement Susceptibility - Regional Council Area

Project: Seismic Risk in the Otago Region

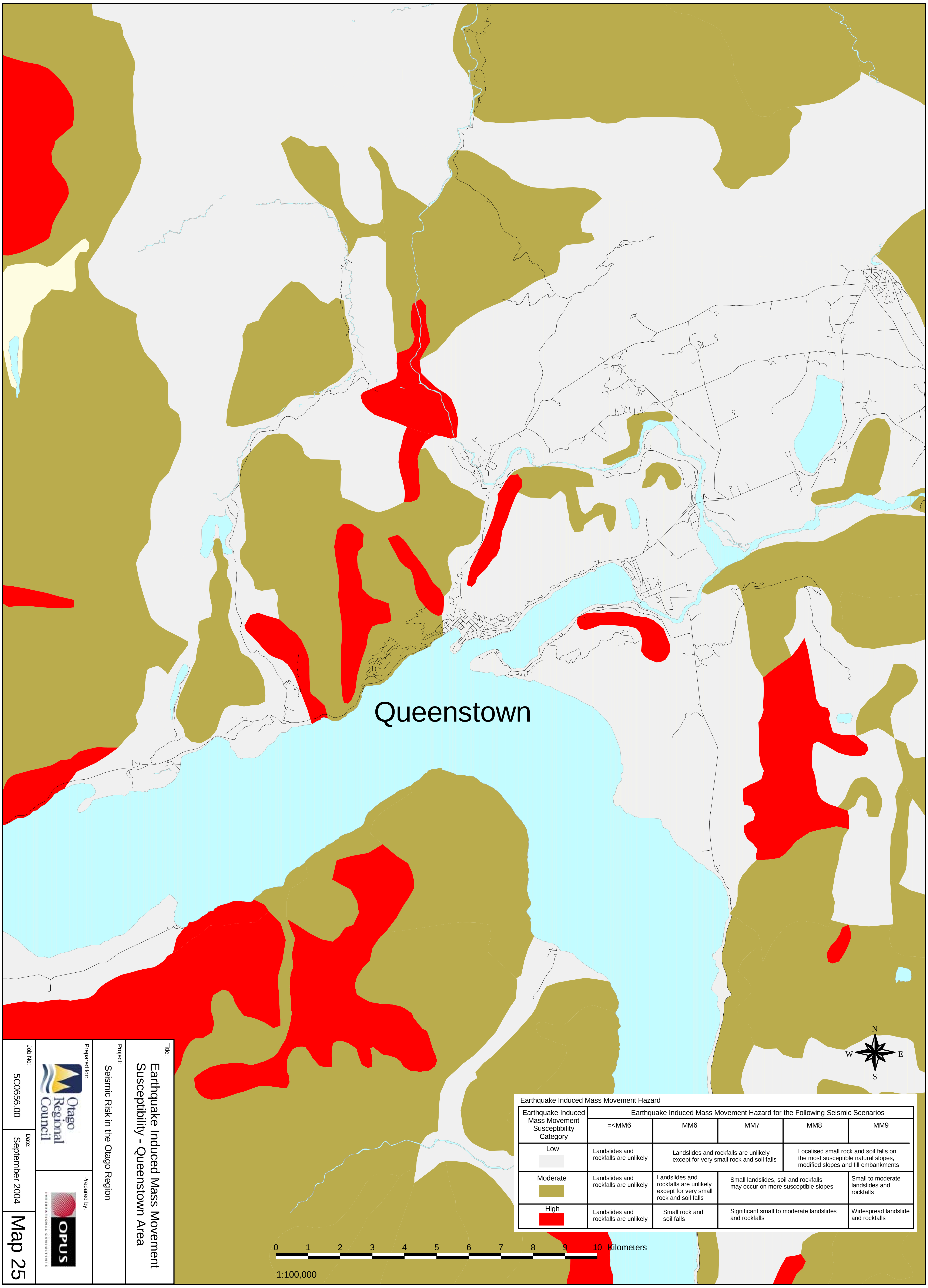
Prepared for: Otago Regional Council

Prepared by: OPUS INTERNATIONAL CONSULTANTS

Job No: 5C0656.00

Date: September 2004

Map 24



Earthquake Induced Mass Movement Hazard

Earthquake Induced Mass Movement Susceptibility Category	Earthquake Induced Mass Movement Hazard for the Following Seismic Scenarios				
	=<MM6	MM6	MM7	MM8	MM9
Low	Landslides and rockfalls are unlikely	Landslides and rockfalls are unlikely except for very small rock and soil falls		Localised small rock and soil falls on the most susceptible natural slopes, modified slopes and fill embankments	
Moderate	Landslides and rockfalls are unlikely	Landslides and rockfalls are unlikely except for very small rock and soil falls	Small landslides, soil and rockfalls may occur on more susceptible slopes		Small to moderate landslides and rockfalls
High	Landslides and rockfalls are unlikely	Small rock and soil falls	Significant small to moderate landslides and rockfalls		Widespread landslide and rockfalls

Title:
Earthquake Induced Mass Movement Susceptibility - Queenstown Area

Project:
Seismic Risk in the Otago Region

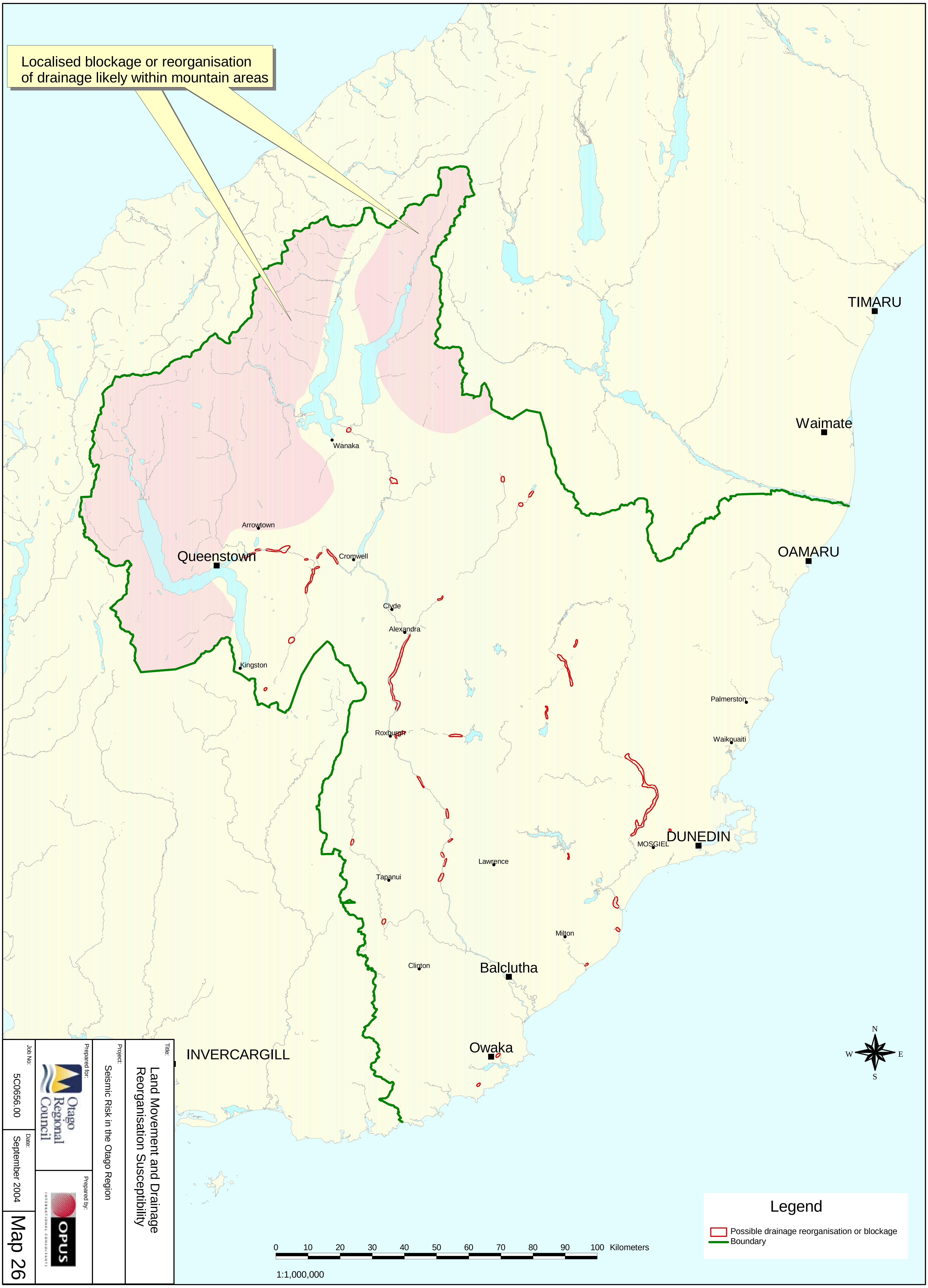
Prepared for:
Otago Regional Council

Prepared by:
OPUS International Consultants

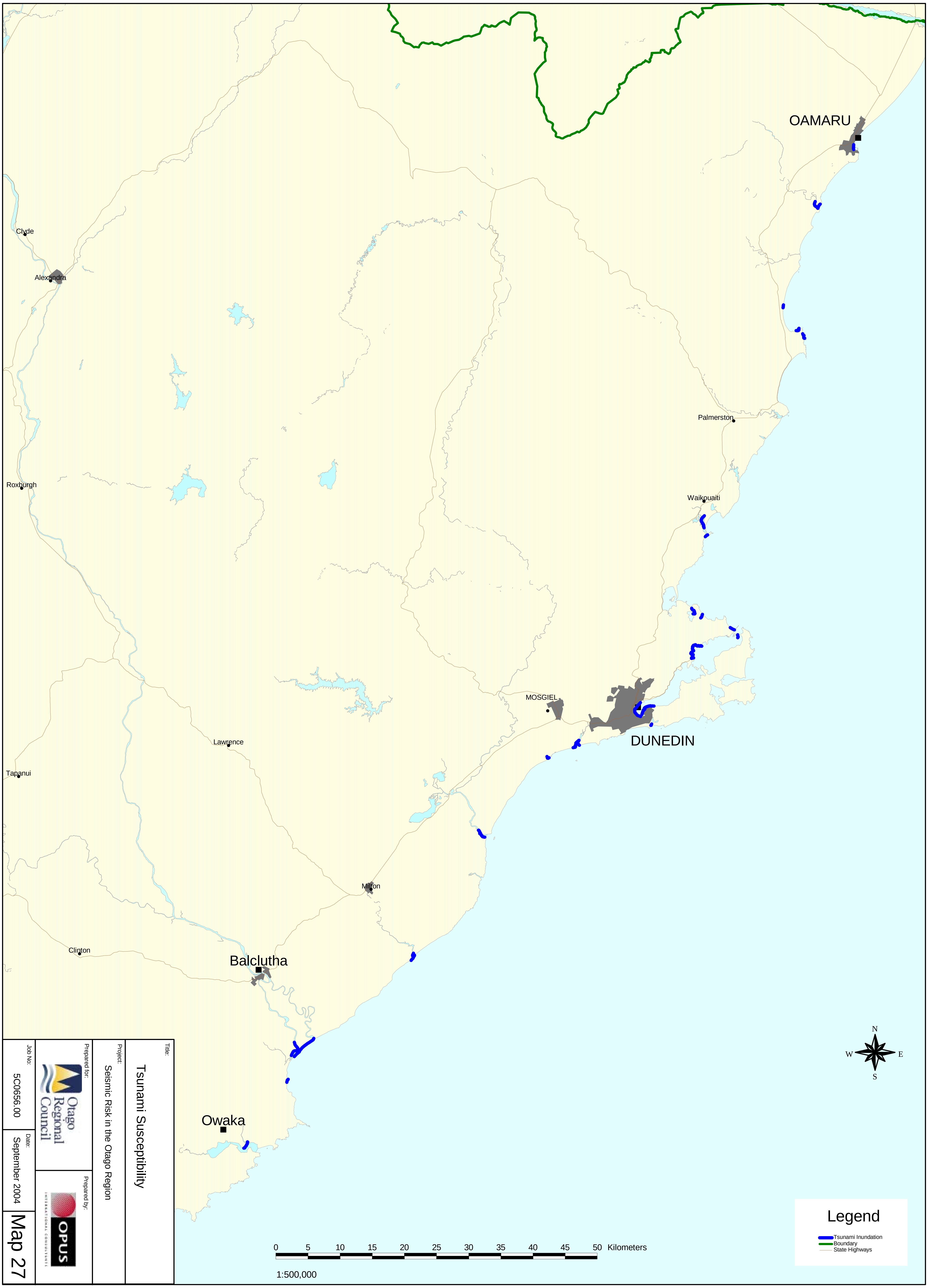
Job No:
5C0656.00

Date:
September 2004

Map 25



Localised blockage or reorganisation of drainage likely within mountain areas
TIMARU
Waimate
OAMARU
Wanaka
Arrowtown
Queenstown
Cromwell
Clyde
Alexandra
Kingston
Palmerston
Waikouaiti
Roxburgh
DUNEDIN
MOSGIEL
Lawrence
Tapanui
Milton
Clinton
Balclutha
Owaka
INVERCARGILL
N
W
E
S
Legend
Possible drainage reorganisation or blockage
Boundary
0 10 20 30 40 50 60 70 80 90 100 Kilometers
1:1,000,000
Title:
Land Movement and Drainage Reorganisation Susceptibility
Project:
Seismic Risk in the Otago Region
Prepared for:
Otago Regional Council
Prepared by:
OPUS
Job No:
5C0656.00
Date:
September 2004
Map 26


OAMARU
Clyde
Alexandra
Palmerston
Roxburgh
Waikouaiti
MOSGIEL
DUNEDIN
Lawrence
Tapanui
Milton
Clinton
Balclutha
Owaka
N
W
E
S
0 5 10 15 20 25 30 35 40 45 50 Kilometers
1:500,000
Legend
Tsunami Inundation
Boundary
State Highways
Title:
Tsunami Susceptibility
Project:
Seismic Risk in the Otago Region
Prepared for:
Otago Regional Council
Prepared by:
OPUS
INTERNATIONAL CONSULTANTS
Job No:
5C0656.00
Date:
September 2004
Map 27