Seismic Hazard in Queenstown Lakes District

August 2015
Overview

The Otago Regional Council is assessing the seismic hazard across parts of Otago, with a focus on the more densely populated urban areas of Wanaka, Queenstown, Alexandra, and Dunedin. This review focuses on the seismic hazard facing the Queenstown Lakes district, encompassing the Upper Clutha region around Wanaka, and the Wakatipu basin area surrounding Queenstown. Previous assessments of the seismic hazard in the broader Otago region were provided by Johnston and Heenan (1995) and Murashev and Davey (2005).

The first section of the report outlines the primary hazards associated with earthquakes, notably fault rupture, ground shaking, and tectonic deformation. Ground shaking during earthquakes has a range of subsequent effects, termed secondary hazards. Section 2 describes secondary hazards associated with earthquakes, which include liquefaction, landslides and rockfall, lake tsunami and seiching, and channel aggradation. Some of these secondary effects are not unique to earthquakes, but seismic shaking is commonly a significant factor in their occurrence.

Sections 3 and 4 respectively assess the seismic hazards in the Upper Clutha and Wakatipu areas. Although geographically close, the two areas have contrasting geography, patterns of development, and are exposed to different seismic sources. In combination, these factors determine that each area has contrasting vulnerabilities to earthquakes.

The primary seismic hazard facing the Queenstown Lakes district is an Alpine Fault earthquake, which has a 30% probability of rupture in the next 50 years. An $M_W$ 8.1 Alpine Fault earthquake is predicted to cause low frequency shaking for 1–2 minutes in Wanaka and Queenstown, at a shaking intensity of MMVII (Modified Mercalli scale).

Other known active faults in the region, such as the Nevis-Cardrona Fault Zone, the Grandview Fault and Pisa Fault are smaller and rupture much less frequently than the Alpine Fault, but they are closer to Wanaka and Queenstown, and are capable of generating high intensity ground shaking.

The Nevis-Cardrona Fault System crosses both the Wakatipu and Upper Clutha areas. An earthquake on the Nevis-Cardrona Fault System will potentially cause ground deformation along the length of the rupture. This may incorporate surface cracking, tilting, warping or folding. Ground deformation can impact on the functionality of buildings, infrastructure and natural or engineered drainage systems along or near the fault.

In addition to known fault structures, the 2010–2011 Canterbury earthquake sequence has focussed attention on ‘blind’ faults with no surface expression, particularly smaller faults close to urban areas. The 2010–2011 Canterbury earthquake sequence occurred on faults with low recurrence intervals that had not been identified prior to their rupture. Beyond shaking, the Christchurch earthquakes emphasise the hazard posed by secondary effects of earthquakes, notably liquefaction, lateral spreading, and rockfall.

Property owners and infrastructure managers in the Upper Clutha and Wakatipu areas need to be aware of the hazard posed by earthquakes. The effects of an earthquake do not end once the shaking stops. Post-event functionality of structures and assets should be considered, with particular attention given to the landscape response to an earthquake, and
how this will impact the built environment. Earthquake-induced hazards and landscape changes with potential to affect the Queenstown Lakes district include rapid channel aggradation and increased susceptibility to debris flows, transient changes in groundwater level, extensive landsliding and rockfall in the surrounding mountains, liquefaction-induced instability along some river banks and lake margins, and impaired drainage from the outlets of Lakes Wanaka and Wakatipu. Regional transport corridors, particularly the Haast Highway, Crown Range Road, Kawarau Gorge, and major bridges would need to be able to withstand the effects of earthquake shaking and related effects to remain functional after an event.

Finally, section 5 assesses the seismic hazards in the context of what additional information will help reduce the seismic hazard to the Queenstown Lakes district. In particular, increased understanding relating to the susceptibility of lake silts to liquefy, local exposure to rockfall, and the hazard posed by the Nevis Cardrona Fault System will help to better quantify the local seismic risks.
Contents

Overview iii

1. Primary Seismic Hazards........................................................................................................................................1
   1.1. Surface Rupture .............................................................................................................................................1
   1.2. Ground Motion .............................................................................................................................................2
      1.2.1. Topographic amplification of seismic waves ..................................................................................3
   1.3. Tectonic Movement ....................................................................................................................................4

2. Secondary Seismic Hazards ....................................................................................................................................5
   2.1. Liquefaction and Lateral Spreading ..............................................................................................................5
   2.2. Landslides and Mass Movement ..................................................................................................................7
      2.2.1. Lake Edge and River Bank Collapse .................................................................................................7
      2.2.2. Rockfall ................................................................................................................................................8
      2.2.3. Rock Avalanches .................................................................................................................................9
      2.2.4. Deep Seated Schist Landslides ...........................................................................................................9
   2.3. Lake Tsunami .............................................................................................................................................10
   2.4. Seismic effect on aquifers .......................................................................................................................11

2.5. Medium-Term Geomorphic Impact .............................................................................................................12
      2.5.1. Channel aggradation and debris flows ...............................................................................................12
      2.5.2. Landslide Dams ..................................................................................................................................12

3. Seismic Hazard in the Upper Clutha Area .......................................................................................................13
   3.1. Regional Setting and Glacial History .......................................................................................................13
      3.1.1. Geology ..............................................................................................................................................13
      3.1.2. Glacial History .....................................................................................................................................16
      3.1.3. Active Faulting ..................................................................................................................................19
   3.2. Upper Clutha Area Seismic History ........................................................................................................22
   3.3. Primary Seismic Hazards in the Upper Clutha Area ................................................................................25
      3.3.1. Ground Motion ....................................................................................................................................25
      3.3.2. Active Faults in Wanaka Area ...........................................................................................................26
      3.3.3. NW Cardrona Fault ...........................................................................................................................27
      3.3.3.1. Effect of Cardrona Fault Rupture .................................................................................................29
      3.3.4. Grandview Fault ................................................................................................................................30
      3.3.4.1. Effect of Grandview Fault Rupture ...............................................................................................30
      3.3.5. Other Local Active Faults ..................................................................................................................31
      3.3.6. ‘Blind’ Faults .......................................................................................................................................31
      3.3.7. Alpine Fault Earthquake ....................................................................................................................32
      3.3.8. Active Faults beyond the Upper Clutha Area ....................................................................................32
      3.3.9. Tectonic Movement at Lake Wanaka Outlet .....................................................................................33
   3.4. Secondary Seismic Hazards in Wanaka ....................................................................................................33
      3.4.1. Liquefaction risk in the Upper Clutha area ..........................................................................................33
      3.4.2. Landslides and Mass Movement .......................................................................................................36
      3.4.2.1. Lake Edge and River Bank Collapse ............................................................................................36
      3.4.2.2. Rockfall .........................................................................................................................................38
      3.4.2.3. Rock Avalanches ...........................................................................................................................39
3.4.2.4. Deep Seated Schist Landslides ................................................................. 40
3.4.3. Lake Tsunami ................................................................................................. 41

3.5. Medium-Term Geomorphic Impact ................................................................. 42
3.5.1. Channel aggradation and debris flows ....................................................... 42
3.5.2. Landslide Dams ............................................................................................... 43

4. Seismic Hazard in the Wakatipu Basin ............................................................... 45
4.1. Regional Setting and Glacial History ............................................................... 47
4.1.1. Geologic history ............................................................................................. 47
4.1.2. Active Faulting ............................................................................................... 48
4.1.3. Glacial History ............................................................................................... 49
4.1.4. Seismic History ............................................................................................. 51

4.2. Primary Seismic Hazards ............................................................................... 53
4.2.1. Surface Rupture ............................................................................................. 53
4.2.1.1. Nevis Cardrona Fault Rupture ................................................................. 53
4.2.1.1. Effect of Nevis-Cardrona Fault Rupture .................................................. 54
4.2.2. Other Local Active Faults ............................................................................ 55
4.2.3. 'Blind' Faults .................................................................................................. 55
4.2.4. Ground Motion ............................................................................................... 55
4.2.4.1. Alpine Fault Earthquake ......................................................................... 56
4.2.4.2. Regional Faults .......................................................................................... 57
4.2.5. Topographic amplification of seismic waves ............................................... 57
4.2.6. Tectonic Movement ...................................................................................... 57

4.3. Secondary Seismic Hazards ........................................................................... 58
4.3.1. Liquefaction risk in Wakatipu Area .............................................................. 58
4.3.2. Landslides and Mass Movement ................................................................. 60
4.3.2.1. Lake Edge and River Bank Collapse ...................................................... 60
4.3.2.2. Rockfall ..................................................................................................... 61
4.3.2.3. Rock Avalanches ...................................................................................... 63
4.3.2.4. Deep Seated Schist Landslides ................................................................ 64
4.3.3. Lake Tsunami ................................................................................................ 64

4.4. Medium-Term Geomorphic Impact ................................................................ 65
4.4.1. Channel aggradation and debris flows ....................................................... 65
4.4.2. Growth of Shotover Delta ........................................................................... 66
4.4.3. Landslide Dams ............................................................................................. 67

5. Summary and future work .................................................................................. 69
5.1. Liquefaction ...................................................................................................... 69
5.1.2. Site-Specific Seismic Response .................................................................... 70
5.1.3. Nevis-Cardrona Fault System ..................................................................... 70
5.1.4. Earthquake Induced Tsunami ..................................................................... 70
5.1.5. Rockfall Hazard Zonation ........................................................................... 71
5.1.6. Benchmarks to detect tectonic change ....................................................... 71

6. Acknowledgements ............................................................................................. 72
7. References ........................................................................................................... 73
Appendix A – Measuring Earthquake Size and Shaking Intensity
Probabilistic Seismic Hazard Analysis
Appendix B – Geologic History
Appendix C – Upper Clutha Glacial History
Appendix D – Geologic Time Scale
Appendix E – Modified Mercalli Scale

List of figures
Figure 1. The surface trace of the Greendale Fault rupture cut across paddocks in the Canterbury Plains in September 2010. (Photo courtesy M. Quigley). The ground moved up to 5.3 m laterally, but was expressed at the surface as a zone of distributed deformation up to 300 m wide, seen in the network of shear structures (Quigley et al., 2012).

Figure 2. The main styles of faulting. Faults in western Otago are primarily Reverse Faults, reflecting the regional compression, whereas the Alpine Fault is a predominantly a strike-slip fault (From USDA National Park Service).

Figure 3. Seismographs from two Canterbury Earthquakes as recorded in Christchurch in Sept 2010 (blue line) and Feb 2011 (red line). The Black line is a synthetic seismograph predicting the level and duration of shaking recorded in Christchurch during a hypothetical Alpine Fault earthquake. The more distant but larger Alpine Fault event has less intense ground shaking, but continues for a much longer duration (Canterbury Earthquakes Royal Commission).

Figure 4. Avulsion of the Hororata River following fault movement during the September 2010 Darfield Earthquake (Photo courtesy D. Barrell, GNS Science).

Figure 5. Effects of liquefaction (from IPENZ Factsheet).

Figure 6. Liquefaction following the Christchurch 2011 Earthquake (Photo courtesy A. King, GNS Science).

Figure 7. Lake edge failure along Lake Te Anau during the 2003 Fiordland earthquake (Hancox et al. 2003). This failure incorporated liquefaction and lateral spreading of the lake beach area.

Figure 8. Rockfall damage to dwelling at Rapaki, Christchurch, during Feb 22nd 2011 earthquake. The gouge in the foreground is an impact divot from a boulder, which then impacted the house (Photo courtesy D. Barrell, GNS Science).

Figure 9. The 2003 Fiordland earthquake caused a 200,000 m³ rockslide into Charles Sound. The landslide caused a small tsunami which ran 4-5 m up the other side of the sound, approximately 800 m away. (Hancox et al., 2003).

Figure 10. Upper Clutha study area and principal geographic features. The report focuses on the populated areas below the outlets of Lakes Wanaka and Hawea.

Figure 11. Geology of the Upper Clutha area. The pale blues and purples are varying metamorphic grades of schist bedrock. Glacial deposits (undifferentiated) and alluvial deposits occupy most of the valleys and lower hillslopes. Stippled areas represent glacial moraines. Remnants of Quaternary gravels persist in the Cardrona Valley, and isolated outcrops of the Tertiary Manuherikia sediments can be found southeast of Wanaka. Modified from QMAP (Turnbull, 2000).

Figure 12: Active faults in west Otago and surrounding regions (From QMAP and GNS Active Fault Database). Otago region is outlined.

Figure 13. Depositional glacial landforms in the Upper Clutha area, and location of major active faults. Each glacial advance has a moraine (stippled) and an associated outwash plain (unstippled). Older
glacial periods (e.g., Lindis, Lowburn) had larger glaciers which extended further down the Clutha Valley, and are preserved higher on the valley walls, beyond the extent of the more recent glacial advances. For age of glacial advance, \( ka = \text{thousand years}. \) Modified from QMAP (Turnbull, 2000).

Figure 14. Major faults and structures near Wanaka. Map from Officers (1984), overlaid on elevation model. Cross section A-A’ is shown in Figure 15 below.

Figure 15. NW-SE oriented cross-section through the Cardrona Valley and Cromwell Basin (marked on Figure 14) showing the orientation of major fault structures (Officers, 1984). Tertiary sediments remain preserved along the valley floors, but have been removed by erosion at higher elevations.

Figure 16. Seismograph record of vertical accelerations recorded at the Wanaka National Park headquarters during the May 4th 2015 earthquake (Figure 17). This event caused some stock to fall from shop shelves in Wanaka, with a peak acceleration of 0.054 g (image from GNS Science).

Figure 17. Historic seismicity in the west Otago area, with earthquakes larger than Mw 3.0 from 1942 – July 2015. Two earthquakes larger than Mw 5.5 have been recorded over that period. The highest concentration of earthquakes occurs towards the Alpine Fault in the northwest of the mapped area. Data from GeoNet (accessed July 2015).

Figure 18. Map of Otago region showing MM Intensity expected to be exceeded once in 100 years (Murashiev and Davey, 2005).

Figure 19. Probabilistic seismic hazard map for New Zealand (Stirling et al. 2012). This map shows the maximum expected peak ground acceleration (relative to gravity) expected over a 475 year period. The zone of red down the west of the South Island follows the Alpine Fault.

Figure 20. Active and inactive mapped faults near Wanaka. Active faults are mapped as either accurate (e.g., where there is a clear surface trace), or approximate. FZ = Fault Zone. From QMAP (Turnbull, 2000).

Figure 21. Diagram of a trench wall cut through active section of a splay of the Northern Cardrona Fault, just south of MacDonalds Creek (6 km north of Cardrona village). The ~18,000 year old alluvial terrace deposit (terrace alluvium layer) has been offset by 4 m vertically, by at least three recognised earthquakes (from Beanland and Barrow-Hurlbert, 1988).

Figure 22. View towards the west across the Cardrona Valley. The Cardrona Skifield access road runs lower right to upper left across the ridge. A visible, active trace of the NW Cardrona Fault is highlighted between the two arrows (Photo April 2015).

Figure 23. Road cut along Mt Pisa Road showing faulted alluvium and glacial till units along the Pisa Fault Zone. The gravels, assessed as outwash deposits, are associated with the Lindis glacial advance (~430,000 years old).

Figure 24. Map of liquefaction risk in the Wanaka area assessed by Tonkin & Taylor Ltd (2012) for the Queenstown Lakes District Council. The most susceptible layers are river courses and some lake margin areas. The mapping is intended to guide the appropriate level of site investigation at the development stage, rather than assess the likelihood of liquefaction at a site.

Figure 25. Mapped areas subject to mass-movement hazards in the Upper Clutha area (ORC Natural Hazard Database). Inset shows area around Wanaka Township.

Figure 26. View of the east side of Mt Iron. Steep to subvertical schist cliffs on the eastern and southern sides of the hill provide source areas for rockfall boulders to roll downslope (July 2015).

Figure 27. Rock avalanche deposit south of Wanaka township (Photo courtesy of G. Halliday). Approximate extent of rock avalanche outlined in black.

Figure 28. Oblique view towards the north, with downtown Wanaka visible in top right of image.
Seated schist landslide south of Wanaka is outlined in black. Ridgeline relaxation can be seen at the top of the landslide.

Figure 29. Oblique view towards south of Stoney Creek and Waterfall Creek Catchments, and their associated alluvial fans in southern Wanaka (Modified from Woods, 2011).

Figure 30. View down Pipson Creek near Makarora (May 2015). The eroding cliffs in the foreground (and other cliffs upstream) contribute rock and sediment to the channel, which can mobilise into debris flows during high rainfall. Earthquake shaking is liable to cause extensive rockfall and landsliding into the creek.

Figure 31. View of the Young River Landslide Dam. A landslide in August 2007 dammed the Young River to a height of 70m, and formed a ~1.5 km long lake. (May 2015).

Figure 32. Wakatipu region study area and prominent geographic features. The report focuses on the populated areas surrounding Queenstown and Arrowtown, Bobs Cove, and the Kawarau Gorge down to the Gibbston Basin.

Figure 33. Geology of the Wakatipu area. The pale blues and purples are varying metamorphic grades of schist bedrock. Glacial deposits (undifferentiated) and alluvial deposits occupy most of the valleys and lower hillslopes. Lake silts were deposited during a higher lake level. Isolated outcrops of the Tertiary Manuherikia sediments can be found east of the Nevis Cardrona Fault zone. Modified from QMAP (Turnbull, 2000).

Figure 34. Topographic map of Wakatipu Area showing active and inactive faults. Modified from QMAP (Turnbull 2000).

Figure 35. Glacial deposits in the Wakatipu area. ‘Q’ denotes glacial age based on Oxygen isotope stage (See Appendix C). Modified from QMAP (Turnbull, 2000).

Figure 36. Historic seismicity in the Wakatipu area, with earthquakes larger than Mw 3.0 from 1942 – July 2015. Two earthquakes larger than Mw 5.5 have been recorded over that period (labeled). The highest concentration of earthquakes occurs towards the Alpine Fault in the northwest of the mapped area, 80 km from downtown Queenstown. Data from GeoNet (accessed July 2015).

Figure 37. Oblique view of the upper Kawarau Gorge towards the Northwest. The Nevis Cardrona Fault (red) runs across the gorge and continues along the Cardrona Valley. The trench in Figure 38 is across the upstream-most strand (Kawarau Trace). The Fault runs through a large landslide complex on the north side of the valley. The Crown Range Road can be seen climbing up from the Crown Terrace and crossing the fault near the summit (Google Earth).

Figure 38. Cross section through the Kawarau Trace of the Nevis Fault on terrace above the Kawarau River. Evidence for three earthquakes can be seen in the deposits, which date to up to 23,000 years old (Beanland and Barrow Hurlbert, 1998).

Figure 39. Map of Otago region showing MM Intensity expected to be Exceeded once in 2500 years (Murashev and Davey, 2005). See also Figure 18 for 100 year exceedence map.

Figure 40. Map of liquefaction risk in the Wakatipu Region assessed by Tonkin & Taylor Ltd (2012) for the Queenstown Lakes District Council. The most susceptible layers are river courses and lake margin areas, particularly areas underlain by lake silts. Inset shows downtown Queenstown area. The mapping is intended to guide the appropriate level of site investigation, rather than assess the likelihood of liquefaction at a site.

Figure 41. Mapped areas subject to mass movement hazards in the Wakatipu Area (ORC Natural Hazards Database).

Figure 42. Oblique view towards the foothills of the southern Remarkables Range. SH6 runs across the lower view, with Lake Wakatipu lower right. Large boulders, likely from a rockfall, can be seen on the
slopes below the rocky cliffs in the middle of the view (white dots). Active alluvial fans drain the catchments (view from Google Earth). .................................................................................................................. 63

Figure 43. Oblique view showing outline of the Coronet Peak landslide, a large deep-seated schist landslide. The Shotover River runs along the left side of the image. (Google Earth) ...................................................................................... 64

Figure 44. Active alluvial fan and debris deposition in February 1994 as seen from SH6 looking towards the Remarkables. Gravel was deposited across SH6. These fans have potential to become more active if the headwaters are inundated with sediment following an earthquake. Photo from Cunningham (1994). ........................................................................................................................................ 66

Figure 45. View of the Shotover River confluence with the Kawarau River. The Shotover River (in flood) meets the Kawarau River 4 km downstream of Lake Wakatipu. The training line on the left of photo is intended to focus the Shotover flow to the right (2013). ........................................................................................................ 67

Figure 46. View down the Kawarau Gorge from Chard Farm Winery. The deep narrow gorge along this section of the river, which drains the Wakatipu Basin, has the potential to be blocked by a large landslide from the side slopes. (May 2015) ........................................................................................................ 68

Figure 47. Major faults form a series of tilted blocks across the Otago region. The NW Cardrona Fault and Pisa fault are the western-most faults. (From Litchfield and Norris, 2000). ........................................................................ 80

Figure 48. Glacial advances in the Upper Clutha area. Each advance has a moraine (stippled) and an associated outwash plain. Modified from QMAP (Turnbull, 2000). ............................................................................. 82

List of tables
Table 3.1 Major known active faults in and surrounding the Upper Clutha. SED = Single event displacement, Wanaka Dist = closest point of fault to Wanaka. Slip Sense: RV = reverse, SS = Strike Slip, RS = reverse slip. Cardrona North and Cardrona South are two segments of the NW Cardrona Fault (From Stirling et al., 2012). ................................................................. 19

Table 4.1 Major active faults near the Wakatipu basin. SED = Single event displacement, Dist = closest point of fault to Queenstown. Slip Sense: RV = reverse, SS = Strike Slip, RS = reverse slip. (Stirling et al., 2012). Note the recurrance intervals are estimates. .................................................................................................. 49

Table 7.1 Recognised glacial advances in Upper Clutha Valley (as updated by Turnbull, 2000). Age correlation of the older units is tentative. ........................................................................................................ 81

Table of Contents
1. Primary Seismic Hazards

The primary hazards presented by earthquakes are rupture or deformation of the ground surface along the trace of a fault, and the shaking caused by seismic waves generated by movement along a fault during an earthquake.

1.1. Surface Rupture

A fault rupture at the ground surface is one of the most dramatic signs of an earthquake (Figure 1). The ground can be displaced laterally on a strike slip fault, or vertically on a thrust or normal fault (Figure 2).

Figure 1. The surface trace of the Greendale Fault rupture cut across paddocks in the Canterbury Plains in September 2010. (Photo courtesy M. Quigley). The ground moved up to 5.3 m laterally, but was expressed at the surface as a zone of distributed deformation up to 300 m wide, seen in the network of shear structures (Quigley et al., 2012).

Fault rupture does not always manifest at the surface as a discrete ‘faultline’, and the deformation can be distributed across a zone tens or hundreds of meters wide. Surface
deformation caused by faulting can include tears in the ground surface, rents, cracks, tilting and folds. Commonly faults can ‘splinter’ near the surface, with multiple traces connecting at depth to the master fault.

Figure 2. The main styles of faulting. Faults in western Otago are primarily Reverse Faults, reflecting the regional compression, whereas the Alpine Fault is a predominantly a strike-slip fault (From USDA National Park Service).

Surface deformation can cause permanent damage to structures along the fault trace. Damage can include tearing structures in half where they straddle the fault trace, distributed shearing across the building footprint, or tilting of foundations.

1.2. Ground Motion

Beyond rupturing and deforming the ground surface, fault movement during an earthquake radiates seismic waves which propagate out from the earthquake focus. The seismic waves propagate through the ground causing a point on the surface to move or shake in response
to the passing waves, the familiar shaking experienced during an earthquake. The strength and period of shaking at a given site depends on distance and direction to the fault, the size of the earthquake, and the local ground conditions. Shaking intensity generally declines with increasing distance from the earthquake source. Further from the earthquake source, the waves pass through a larger volume of rock, and energy is absorbed along the transmission path. The strength of shaking at a point is characterised by shaking intensity, which is governed by the amplitude, velocity and acceleration of the passing seismic waves.

Earthquake size is measured in terms of magnitude ($M_W$). Ground shaking intensity is qualitatively measured using the Modified Mercalli (MM) scale, and shaking intensity can be quantified in units of Peak Ground Acceleration (PGA) and the frequency content of the shaking. Methods used to measure shaking intensity and quantify the size of earthquakes are outlined in Appendix A.

![Seismographs from two Canterbury Earthquakes](image)

Figure 3. Seismographs from two Canterbury Earthquakes as recorded in Christchurch in Sept 2010 (blue line) and Feb 2011 (red line). The Black line is a synthetic seismograph predicting the level and duration of shaking recorded in Christchurch during a hypothetical Alpine Fault earthquake. The more distant but larger Alpine Fault event has less intense ground shaking, but continues for a much longer duration (Webb et al., 2011).

### 1.2.1. Topographic amplification of seismic waves

As seismic waves pass through the Earth’s surface they interact with both topography and the materials they travel through. Differing ground conditions can change the shaking intensity experienced between nearby locations. A primary example is topographic amplification of seismic waves on ridgelines and cliff tops, where ridge tops can shake more than flat ground. Seismic waves can also become trapped within sedimentary basins, reflecting off bedrock and increasing the intensity of shaking at the basin surface.
Sites on shallow soils (<30 m) near basin margins are liable to have more intense shaking (e.g., Bradley, 2012). Shallow soils over bedrock amplify high frequency waves, the frequency most damaging to low buildings such as residential dwellings.

1.3. Tectonic Movement

In addition to causing strong ground motion, fault movement can permanently deform the ground surface. Faults in Otago generally have a reverse mechanism, meaning the offset is primarily vertical, as opposed to sideways movement typical of a strike-slip fault (Figure 2). Earthquakes on reverse faults can cause vertical uplift or deformation of large areas of the land surface, and are a primary process in mountain building.

Localised ground deformation can damage structures and infrastructure along the fault, as described in Section 1.1 above. Subtle tilting, uplifting or subsidence may be less spectacular than the visible offset on a fault, but tectonic movement can affect large areas of the landscape. Tectonic movement can particularly influence natural processes or engineered systems which involve gravity drainage, or are susceptible to small changes of elevation or slope.

Figure 4. Avulsion of the Hororata River following fault movement during the September 2010 Darfield Earthquake (Photo courtesy D. Barrell, GNS Science).

Subsidence in low-lying areas can increase local vulnerability to flooding by changing the base-level for natural and man-made drainage networks. Fault movement across a stream can impound flow and generate flooding upstream of the fault or cause river avulsion (Duffy
et al., 2012). Tectonic deformation can similarly cause problems for gravity drainage networks such as sewers and storm water. Tectonic uplift in the 2011 Christchurch earthquake impeded the flow of the Heathcoate River in southern Christchurch and increased local susceptibility to flooding (e.g., Hughes et al. 2015).

2. Secondary Seismic Hazards

Besides direct damage caused from fault rupture and ground shaking, many hazards from earthquakes are secondary effects. Modern engineered structures are intended to perform well under seismic shaking, so the suite of secondary earthquake effects can pose the greatest and most widespread hazard to life and property.

2.1. Liquefaction and Lateral Spreading

During seismic shaking, cyclic shearing of loose, fine grained (sand and silts) saturated sediment can cause the soils to compact, with excess pore pressure leading to liquefaction of the soil. During liquefaction, the soil can lose bearing capacity (the ability to support a load), meaning any structures founded in or above a liquefiable layer can subside or settle differentially. After liquefaction, ground settlement can occur due to the expulsion of soil from underground.

Buried structures or services, which are lighter than liquefied soil, can become buoyant and be lifted out of the ground. This can affect septic systems, pipes, cellars, and buried fuel tanks.

Liquefaction is rarely a direct risk to life, but can cause extensive damage to structures and civil infrastructure (flood banks, buried services). If sewerage networks are compromised liquefaction ejecta can be contaminated. When liquefaction silt dries out on the surface it can present a dust hazard.
Liquefaction and its Effects

Before the Earthquake
Areas of flat, low lying land with groundwater only a few metres below the surface, can support buildings and roads, buried pipes, cables and tanks under normal conditions.

During and after the Earthquake
During the earthquake fine sand, silt and water moves up under pressure through cracks and flows out onto the surface. Heavy objects like cars can sink into these cracks. Sand, silt and water cover the surface.

Sand Boils (Sand Volcanoes)
Sand, silt and water erupts upward under pressure through cracks and flows out onto the surface. Heavy objects like cars can sink into these cracks. Sand, silt and water cover the surface.

Power poles are pulled over by their wires as they can’t be supported in the liquefied ground. Underground cables are pulled apart.

Lateral Spreading
River banks move toward each other. Cracks open along the banks. Cracking can extend back into properties, damaging houses.

Tanks, pipes and manholes float up in the liquefied ground and break through the surface. Pipes break, water and sewage leaks into the

Figure 5. Effects of liquefaction (from IPENZ Factsheet)

Figure 6. Liquefaction following the Christchurch 2011 Earthquake (Photo courtesy A. King, GNS Science)
In the presence of a suitable free face, such as a river bank, ditch, or lake edge, sections of land can move laterally during liquefaction, a process known as lateral spreading. The upper crust of land can also stretch towards the free face through a series of cracks. The net result is any structures on laterally spreading land can move sideways, and have the ground crack and stretch beneath them.

Lateral spreading can cause extensive damage to any structures or services (pipes, cables, poles) in the zone of spreading. Structures and infrastructure near the free face are particularly vulnerable to lateral spreading, and include roads, slope retention systems, or bridge abutments.

2.2. Landslides and Mass Movement

Landslides have a range of triggers, such as storms or river undercutting, or alternatively can occur with no apparent external factor. In seismically active areas earthquakes are a primary cause of landslides, as earthquake ground accelerations can lead to slope instability. Many landslides can be triggered across a wide area by an individual earthquake.

A range of landslide types could be triggered or reactivated by earthquakes in the Queenstown Lakes district, from small slips in riverbank and road cuttings, through to rapidly moving rock avalanches incorporating millions of cubic meters of rock.

2.2.1. Lake Edge and River Bank Collapse

River or lake banks composed of unconsolidated deposits are particularly susceptible to mass movement during an earthquake. The river or lake edge can effectively act as an unbuttressed free-face, allowing movement of the bank towards the water. The affected area is usually localised to the areas of movement and deposition adjacent to the bank, and the hazard can be recognised in advance of an earthquake. Increasing the risk, river banks and lake-margin sites are commonly desirable real estate, or used as routes for roads or bridges.

Lake edge collapse was observed on the margins of Lake Te Anau during the 2003 MW 7.0 Fiordland earthquake (Figure 7). These failures occurred in undeveloped shorelines, but people with assets on lakeshores in Queenstown or Wanaka should be prepared for this process occurring during an earthquake.
2.2.2. Rockfall

Rockfall is the process by which clasts of rock detach from steep terrain, and roll, slide or bounce downslope. On steep slopes or slopes with few obstructions (such as vegetation) rocks can attain significant speed and momentum, and cause serious impact damage to structures. Rocks can be dislodged by a number of causes (storms, root wedging, animals, residual weathering), but earthquake shaking is a primary factor in seismically active areas.

Rocks are particularly susceptible to being detached and mobilised during strong local earthquakes. Research following the 2010–2011 Christchurch earthquakes showed that strong local earthquakes were more likely to cause rockfall than larger more distant earthquakes, as can be generated from active faults in the Canterbury foothills and Southern Alps (Mackey and Quigley, 2014). Seismic sources close to the Wanaka and Queenstown urban areas, such as the NW Cardrona Fault, should be considered especially liable to generate coseismic rockfall. If the experience from the Canterbury earthquakes is applied to the Upper Clutha and Wakatipu areas, small local faults may be a higher rockfall generating hazard than the residual threat posed by the Alpine Fault, despite the vast difference in earthquake magnitude and recurrence intervals.
2.2.3. Rock Avalanches

Rock avalanches are a devastating type of landslide involving the rapid, flow-like motion of rock fragments. They can initiate from rock slides or rock falls, and travel significant distances (> several km) from the source area. A seismic trigger is commonly the cause of rock avalanches.

2.2.4. Deep Seated Schist Landslides

Regional landslide mapping in central and west Otago has highlighted the abundance of large schist landslides, which are an important geomorphic process operating across Otago’s schist terrain (e.g., McSaveney et al., 1991). Approximately half the mountainous terrain in the Queenstown Lake district is affected by large schist landslides, variably known as sackung, or deep-seated gravitational instability features (Turnbull, 2000).

Some deep-seated schist landslides are large, and can incorporate whole mountain sides. Instability can extend for kilometres from valley floors up to and through ridgelines. The depth of the slides is likely to range from tens to hundreds of meters. The landslides are ultimately driven by changes in base level, such as channel incision at the toe, and tectonic uplift. Long-term changes in climate may also regulate movement via changing hillslope hydrology. Movement rates are usually <20 mm/yr, but can reach several m/yr (McSaveney et al., 1991).
Large schist landslides were studied intensively during assessment of the Clyde Dam reservoir (Lake Dunstan), and remain some of the best studied landslides globally. These slides have long term creep rates up to 10 mm/yr (MacFarlane, 2009). Research and field observations indicate the slides are unlikely to move significantly during seismic shaking, although the landslides have yet to be observed during a large earthquake. Small landslide movements, in the order of hundreds of mm, are predicted during seismic shaking, but catastrophic failure is considered unlikely. Such movement of deep seated schist landslides is unlikely to pose a risk to life safety, but has potential to adversely affect any structures constructed on the landslides.

In the Upper Clutha area the large landslide-prone slopes have to date seen little residential development, so few of these landslides pose a risk to property. Development has occurred on some deep-seated schist landslides in the Wakatipu area. In both regions, population pressure may see these slopes deemed viable for development in the future, which can increase the risk of any landslide movement.

2.3. Lake Tsunami

The rapid displacement of a large volume of water can generate tsunami waves or lake seiching, which can inundate near shore areas. Tsunami can be caused by landslides falling into lakes, or by rupture of faults on the lake bed. Movement of a mass of sediment underwater, as can occur when river deltas collapse or landslides occur underwater, can also generate tsunami waves. Tsunami waves can inundate shorelines, and overtop lake outlets and send flood waves downstream.
2.4. Seismic effect on aquifers

Earthquakes have a well-recognised effect on groundwater (e.g., Cooper et al., 1965). Earthquake shaking can effectively squeeze aquifers, leading to increased groundwater levels, spring flow, and river discharge. These effects were observed during the Canterbury earthquake sequence (Cox et al., 2012).

Temporarily increased groundwater levels following an earthquake can increase the hazard posed by liquefaction in subsequent earthquakes or aftershocks, as an elevated groundwater level saturates sediment to a shallower level.

Additionally, earthquakes can affect the hydrology of large landslides. Earthquakes in the 2010-2011 Christchurch sequence were shown to affect the groundwater in the large schist debris landslides along the Cromwell Gorge, although these changes in hydrology as a consequence of those distant earthquakes were not considered to affect landslide stability (O’Brien, 2014).
2.5. Medium-Term Geomorphic Impact

2.5.1. Channel aggradation and debris flows

The secondary effects of a large earthquake in the steep, rapidly eroding mountains of New Zealand’s South Island will be felt for decades (e.g., Robinson and Davies, 2013). Regional seismic shaking will liberate abundant hillslope material into streams through landslides, slips and rockfall, a process which has been documented following other large earthquakes (Xu et al., 2012). The increased sediment will overwhelm the transport capacity of many rivers, leading to debris flows, channel aggradation, avulsion, and increased flood risk.

2.5.2. Landslide Dams

Landslides which deposit debris in valley floors can form landslide dams, particularly in narrow, steep-sided valleys. The impoundment of water behind the landslide dam presents a hazard by inundating the valley upstream (potentially to an elevation equal to the dam crest), and the dam has the potential to fail catastrophically and flood areas downstream. Failure of landslide dams is common (Costa and Schusta, 1988), due to their weak geotechnical composition. Breach of a landslide dam typically occurs during lake filling, or dam failure can occur when the water level overtops the crest and scours the downstream face of the landslide. Numerous landslide dams would be expected to form following a large earthquake in the Southern Alps and mountains of west and Central Otago, contributing to the rapid sediment influx to mountain streams and rivers.
3. Seismic Hazard in the Upper Clutha Area

This section focusses on seismic hazards in the ‘Upper Clutha’, broadly defined as the towns of Wanaka and Hawea, the Cardrona Valley, and the Upper Clutha Valley extending down towards Tarras (Figure 10). The review is intended to collate and assess known information about the seismic hazards within the Upper Clutha region, and describe the possible consequences of various earthquake scenarios on the area, both on the landscape, and the implications for the built environment, primarily buildings and civil infrastructure. Section 5 identifies aspects of seismic hazard where the risks could be minimised through future work.

The seismic hazard profile for the Upper Clutha is dominated by the Alpine Fault. Several other active regional faults, such as the NW Cardrona, Grandview, Pisa, Ostler, and Dunstan Faults, are capable of generating large earthquakes with Magnitude ($M_w$) 7.0–7.4.

3.1. Regional Setting and Glacial History

3.1.1. Geology

The Upper Clutha area is a fault-controlled, structural depression that has been extensively modified by a sequence of Quaternary glaciations. The area is underlain by schist bedrock, which comprises foliated Mesozoic metasedimentary rocks (Figure 11). The schist basement rock is being actively folded, faulted and eroded in response to regional compression and strain distributed across the mid to lower South Island. Much of the fault activity and uplift in the area has occurred over the past 5 million years. The geology of the Upper Clutha area is comprehensively detailed in the Wakatipu QMAP compiled by Turnbull (2000), and a summary is provided in Appendix B.
Figure 10. Upper Clutha study area and principal geographic features. The report focuses on the populated areas below the outlets of Lakes Wanaka and Hawea.
Figure 11. Geology of the Upper Clutha area. The pale blues and purples are varying metamorphic grades of schist bedrock. Glacial deposits (undifferentiated) and alluvial deposits occupy most of the valleys and lower hillslopes. Stippled areas represent glacial moraines. Remnants of Quaternary gravels persist in the Cardrona Valley, and isolated outcrops of the Tertiary Manuherikia sediments can be found southeast of Wanaka. Modified from QMAP (Turnbull, 2000).
3.1.2. Glacial History

The Upper Clutha area has an extensive glacial history (e.g., McKellar, 1960) which is shown in Figure 13 and outlined in Appendix C. Much of the developed landscape around the Upper Clutha is a result of erosion or deposition by various glacial processes over the past million years. The urban areas of Wanaka and Hawea are built upon glacial deposits dating from ~23,000 years ago. The importance of this glacial history for seismic hazard assessment in the Upper Clutha area is two-fold: a) glacial deposits provide important age control on fault activity, and b) different glacial lithologies respond differently under seismic shaking.

a) Glacially related features (moraines, outwash plains, lake sediments) of known ages provide an important means to assess fault activity and rates of deformation. This is crucial in establishing long term fault movement rates, assessing fault behaviour, and understanding how frequently a fault is likely to rupture. For example, if a fault trace deforms a glacial outwash plain, it is known to have ruptured at least once since the outwash plain was active. In other cases glacial processes can destroy or bury evidence for faulting, and limit the preservation of surficial fault activity to the previous
glaciation. This is an issue in west Otago where many of the faults have recurrence intervals of tens of thousands of years, which commonly exceed the time since the last period of glaciation (Hawea advance, ~18,000 years ago) shaped much of the landscape in valley floor regions. There is no surface evidence for rupture of the NW Cardrona Fault, for example, where it is projected through Hawea outwash deposits, but it is thought to be active, as described in Section 3.3.3 below.

b) The second aspect of glacial history which influences seismic hazard is that glacial lithologies can behave differently during seismic shaking. Glacial moraines, outwash alluvial deposits, valley wall fans, and glacial lake sediments all have different geotechnical characteristics. The behaviour of different glacial landforms under seismic shaking needs to be considered during development. Glacial tills are generally strong and make good building platforms, whereas silt-dominated lake sediment can be loose and prone to liquefaction. The varying strength and properties of the glacial deposits can affect the seismic risk to buildings and infrastructure.
Figure 13. Depositional glacial landforms in the Upper Clutha area, and location of major active faults. Each glacial advance has a moraine (stippled) and an associated outwash plain (unstippled). Older glacial periods (e.g., Lindis, Lowburn) had larger glaciers which extended further down the Clutha Valley, and are preserved higher on the valley walls, beyond the extent of the more recent glacial advances. For age of glacial advance, ka = thousand years. Modified from QMAP (Turnbull, 2000).
3.1.3. Active Faulting

Many faults have been recognised across the Upper Clutha area, although only a few can be deemed active (Figure 12). There are a range of definitions for what constitutes an active fault. A recent compilation of active New Zealand faults defined ‘active’ as a rupture in the past 125,000 years (Litchfield et al., 2014). Confirming fault displacement over this timeframe in the New Zealand environment can be difficult, due to the rapidly evolving environment and shortage of datable landscape features. The default approach in New Zealand is to assess a fault as active where it has offset or deformed the ground surface or near surface deposits (e.g., Barrell, 2015). In the Upper Clutha area, extensive glacial and fluvial deposits provide a valuable reference surface for assessing fault activity. There are potentially un-mapped active faults in the Upper Clutha region, particularly buried beneath glacial lakes and deposits, and in the rapidly eroding landscape towards the Alpine Fault (Beanland and Barrow-Hurlbert, 1989, Cox et al., 2012). Major active faults within and surrounding the Upper Clutha area are listed in Table 3.1. The earthquake recurrence interval and related data are from a seismic hazard model based on strain accumulation across New Zealand, and can have significant uncertainties.

<table>
<thead>
<tr>
<th>Fault Name</th>
<th>Fault Length (km)</th>
<th>Slip Sense</th>
<th>Slip Rate (mm/yr)</th>
<th>Moment Magnitude (Mw)</th>
<th>SE D (m)</th>
<th>Rec. Interval (yrs)</th>
<th>Wanaka dist. (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpine</td>
<td>411</td>
<td>SS</td>
<td>27</td>
<td>8.1</td>
<td>9.2</td>
<td>340</td>
<td>75</td>
</tr>
<tr>
<td>Cardrona (north)</td>
<td>34</td>
<td>RS</td>
<td>0.38</td>
<td>7.0</td>
<td>2.4</td>
<td>6200</td>
<td>2.5</td>
</tr>
<tr>
<td>Cardrona (south)</td>
<td>28</td>
<td>RS</td>
<td>0.38</td>
<td>6.7</td>
<td>2</td>
<td>5100</td>
<td>15</td>
</tr>
<tr>
<td>Grandview</td>
<td>32</td>
<td>RV</td>
<td>0.1</td>
<td>7.0</td>
<td>2.2</td>
<td>22000</td>
<td>12</td>
</tr>
<tr>
<td>Pisa</td>
<td>47</td>
<td>RV</td>
<td>0.1</td>
<td>7.2</td>
<td>3.3</td>
<td>31000</td>
<td>22</td>
</tr>
<tr>
<td>Nevis</td>
<td>69</td>
<td>RV</td>
<td>0.4</td>
<td>7.5</td>
<td>4.8</td>
<td>12000</td>
<td>42</td>
</tr>
<tr>
<td>Dunstan</td>
<td>63</td>
<td>RV</td>
<td>0.63</td>
<td>7.4</td>
<td>4.4</td>
<td>7000</td>
<td>48</td>
</tr>
<tr>
<td>Ostler</td>
<td>68</td>
<td>RV</td>
<td>1.43</td>
<td>7.4</td>
<td>4.7</td>
<td>3310</td>
<td>58</td>
</tr>
</tbody>
</table>

Table 3.1 Major known active faults in and surrounding the Upper Clutha. SED = Single event displacement, Wanaka Dist = closest point of fault to Wanaka. Slip Sense: RV = reverse, SS = Strike Slip, RS = reverse slip. Cardrona North and Cardrona South are two segments of the NW Cardrona Fault (From Stirling et al., 2012).

The long term rates of displacement on the Otago reverse faults are generally low, on the order of ~1 mm/yr (e.g., Litchfield et al., 2014). Although seemingly slow, over 2 million years, faults moving at this rate have been displaced sub-vertically ~2000 m and transformed a low-relief surface into the mountainous landscape recognised today (Beanland and Berryman, 1989). This low slip rate means the faults have long recurrence intervals; thousands of years are required to build sufficient strain on the fault from one earthquake to the next, a time known as the inter-seismic period. Despite their slow slip rates and long recurrence intervals, the faults forming the Otago ‘basin and range’ topography are capable of generating large earthquakes as described in Section 1.1 above.
The behaviour and characteristics of the Otago faults contrast starkly with the Alpine Fault, which lies 75 km to the northwest of Wanaka township. The Alpine Fault is a globally significant structure, and marks the plate boundary between the Australian and Pacific tectonic plates. The Alpine Fault has a slip rate approaching 30 mm/yr, including a component of compression, which has resulted in the rise of the Southern Alps. The southern segment of the Alpine Fault has a recurrence interval of several centuries, and is thought capable of earthquakes up to $M_W$ 8.1.
Figure 14. Major faults and structures near Wanaka. Map from Officers (1984), overlain on elevation model. Cross section A-A’ is shown in Figure 15 below.
3.2. Upper Clutha Area Seismic History

There have been no reported surface ruptures of faults in the Upper Clutha area in historic times (mid-19th Century to present). Since 1940, the Upper Clutha has experienced two earthquakes greater than $M_W$ 5.5: May 1943 and May 2015 (Figure 17).

Historically, most shaking felt in the region has been from distant fault sources, such as the $M_W$ 7.2 Fiordland earthquake of 22 August, 2003 which occurred near Secretary Island. This earthquake generated horizontal ground motions of 0.05 g at the Wanaka National Park Headquarters (Reyners et al., 2003).

The largest recent earthquake within the study area was a $M_W$ 5.8 earthquake which occurred in the afternoon of 4th May 2015, ~30 km NW of Wanaka Township. This earthquake was shallow (~5 km deep) and was widely felt across the lower South Island. Minor damage was reported in Wanaka, where peak horizontal ground accelerations of 0.057 g were recorded at the National Park headquarters (Figure 16). As of 24th July 2015 EQC had received 351 claims for this event.
Figure 16. Seismograph record of vertical accelerations recorded at the Wanaka National Park headquarters during the May 4th 2015 earthquake (Figure 17). This event caused some stock to fall from shop shelves in Wanaka, with a peak acceleration of 0.054 g (image from GNS Science.)
Figure 17. Historic seismicity in the west Otago area, with earthquakes larger than $M_W$ 3.0 from 1942 – July 2015. Two earthquakes larger than $M_W$ 5.5 have been recorded over that period. The highest concentration of earthquakes occurs towards the Alpine Fault in the northwest of the mapped area. Data from GeoNet (accessed July 2015).
3.3. **Primary Seismic Hazards in the Upper Clutha Area**

This section describes the potential for surface rupture on faults in the Upper Clutha, and the more widespread risk from ground motion or shaking which can be caused by distant seismic sources, such as the Alpine Fault. Potential earthquake magnitudes and related data are taken from the New Zealand National Seismic Hazard Model (Stirling et al., 2012).

3.3.1. **Ground Motion**

The predicted ground shaking intensity in Wanaka over 100 years is MMVII (Figure 18), and over 2500 years is MMIX (Murashev and Davey, 2005).

![Figure 18. Map of Otago region showing MM Intensity expected to be exceeded once in 100 years (Murashev and Davey, 2005).](image)

Based on the 2010 NZ National Seismic Hazard Model (Stirling et al., 2012), Wanaka shallow soil sites have an expected max PGA of 0.4 g over a 475 year period, and 0.75 g over a 2500 year period.
3.3.2. Active Faults in Wanaka Area

The Upper Clutha is crossed by two major mapped active faults, the NW Cardrona and Grandview Faults (Figure 12, Figure 20). The Pisa Fault is a range bounding fault that cuts across the south-eastern extent of the study area and splits into the Grandview Fault and
Lindis Peak Fault. Like most faults in the Otago region, the faults have a thrust or reverse mechanism, and they are the western margin of a series of compressional structures which extend east across Otago to the east coast (Figure 12, Appendix B).

![Figure 20. Active and inactive mapped faults near Wanaka. Active faults are mapped as either accurate (e.g., where there is a clear surface trace), or approximate. FZ = Fault Zone. From QMAP (Turnbull, 2000).](image)

**3.3.3. NW Cardrona Fault**

The NW Cardrona Fault system trends NNE along the north-western side of the Cardrona Valley, out across the Wanaka Basin, and is projected to continue north beneath Lake Hawea (Figure 20). Land to the west of the fault is uplifting relative to land on the east of the fault, with the fault plane dipping to the northwest. Along the Cardrona Valley the NW Cardrona Fault is distinct from the SE Cardrona Fault. The SE Cardrona Fault runs along the SE side of Cardrona Valley, on the margin of the Criffel Range (Figure 15, Figure 20), and is not known to be active.

The northern and southern sections of the NW Cardrona Fault together comprise the northern segment of the larger NNE-trending Nevis-Cardrona Fault System, a major regional structure in Otago. South of the Kawarau Valley, the structure is termed the Nevis Fault, which dog-legs east of the Remarkables Range and continues south down the Nevis Valley (Figure 12).
For seismic hazard assessment, the NW Cardrona Fault is broken into northern and southern sections. The Northern NW Cardrona Fault extends south from Lake Hawea to Cardrona village, while the Southern NW Cardrona Fault extends from Cardrona village south across the Crown Range to the Kawarau Valley. The northern NW Cardrona Fault has potential to generate a $M_W$ 7.0 earthquake, a rupture displacement of 2.4 m, and has a recurrence interval of approximately 6200 years. This fault is the primary local seismic hazard in the Wanaka Basin. The southern NW Cardrona Fault is estimated to generate a $M_W$ 6.9 earthquake, with a displacement of 2 m, and has a recurrence interval of 5130 years (Stirling et al., 2012).

Paleoseismic studies show evidence of surface rupture of the NW Cardrona Fault in the Cardrona Valley (Figure 21, Figure 22). This section of the fault has been assigned a recurrence interval of 4000–9000 years based on paleoseismic investigations (Beanland and Barrow-Hurlbert, 1988), which involved excavating a trench across a section of the fault scarp (Figure 21).

The NW Cardrona Fault is located near several population centres. The fault runs 300 m northwest of the township of Cardrona, and is within 2.5 km of the Cardrona Valley Road along the length of the valley. The fault crosses the Crown Range Road just south of the summit, and runs within 100 m of the road for a 3 km stretch just south of the Cardrona village.

Closer to Wanaka, the trace of the NW Cardrona fault is inferred to be located just east of Mt Iron, and is mapped to be approximately beneath Albert Town (Figure 20). The projected fault trace is 2.4 km southeast of downtown Wanaka, and closer still to the rapidly developing area between Wanaka and the Cardrona River. The fault is mapped to cross through the western part of Hawea township (Turnbull, 2000), approximately 800 m east of the Lake.
Hawea control gates, although there is no obvious surface expression of the trace in this area.

There is no recognised surface rupture where the projected fault trace crosses the Mt Iron and Hawea glacial till or outwash surfaces, suggesting this northern section of the fault has not ruptured in the past 17,000–23,000 years, the time when the glacial-derived deposits were deposited. In comparison, three ruptures on the fault are recorded along the Cardrona Fault in the Cardrona Valley in this period (Figure 21).

![Figure 22. View towards the west across the Cardrona Valley. The Cardrona Skifield access road runs lower right to upper left across the ridge. A visible, active trace of the NW Cardrona Fault is highlighted between the two arrows (Photo April 2015).](image)

3.3.3.1. Effect of Cardrona Fault Rupture

Rupture of the NW Cardrona Fault would cause direct damage to land and assets on and near the trace. The most active section of the fault is in the Cardrona Valley south of Wanaka. The Cardrona Valley is comparatively sparsely populated, but attracts many tourists and is the route of a major road linking Wanaka and the Wakatipu Basin. The Crown Range Road would likely be impassable due to fault ruptures through the road surface, and earthquake induced landslides and rockfall onto or incorporating the road.
Were a rupture to occur on the northern section of the NW Cardrona Fault, ground rupture could directly affect more populated areas. This includes Albert Town, which is inferred to sit atop the fault trace, and the western section of Hawea township.

Owners of assets in close proximity to the fault (subparallel to the lower Cardrona and Hawea Rivers), need to consider potential effects of fault rupture. The effects include severe shaking during an event, and permanent deformation of the ground after an earthquake. Ground deformation could necessitate replacement or re-levelling of dwellings, and impair the functionality of gravity drainage systems.

Affected infrastructure will include buildings, roads, bridges, sewer and water networks, and hydropower structures. Assessment of seismic risks to assets should encompass physical damage to the asset (such as damaged structures), and the consequences of asset failure (e.g., dam, sewage networks).

It is not known how a rupture of the NW Cardrona Fault will manifest at the surface where it crosses glacial till and outwash deposits. Fault rupture may not propagate to the surface, and cause the characteristic rent or tear in the ground. Failure of faults to extend to the ground surface is commonly observed where faults rupture beneath thick sequences of gravel or sediment; the gravel and lake silt layers are flexible and can absorb or accommodate the displacement propagated from the bedrock below (Beanland and Berryman, 1989). If the fault does not propagate to the ground surface, movement on the fault can cause warping or folding of moraine or gravel outwash surfaces for a width of many tens to hundreds of meters perpendicular to the fault, along the length of fault rupture.

3.3.4. Grandview Fault

The Grandview Fault runs along the eastern edge of the Upper Clutha area at the foot of the Grandview Mountain range (Figure 20). Land to the east of the fault is uplifting relative to land west of the fault. It connects with the Pisa Fault zone to the south, but the location of the fault under Lake Hawea is not well constrained (Figure 12). The estimated recurrence interval is 22,000 years, with an estimated magnitude of $M_W$ 7.0, resulting in a fault displacement of 2.2 m (Stirling et al., 2012).

Activity on the Grandview Fault has been established on the basis of deformed subsurface glacial lake sediments encountered by drillholes and geophysical surveys (Officers, 1984; Beanland and Berryman, 1989). The deformed lake sediments range in age from 300,000 to 70,000 years, and have been folded into a monocline with approximately 100 m vertical offset. The surficial Albert Town, Mt Iron and Hawea outwash alluvium is not deformed across the fault, suggesting the Grandview Fault has not been active in at least the past 70,000 years.

3.3.4.1. Effect of Grandview Fault Rupture

The projected trace of the Grandview Fault does not intersect any urban areas, so any future ground rupture or disturbance will primarily affect rural properties. The Upper Clutha area is experiencing significant growth, so future developments in this location should be aware of
the hazard posed by the Grandview Fault. Due to the long interval since the fault’s last surface rupture, and subsequent glacial advances, the location of the fault trace is not well constrained. With a predicted earthquake magnitude of $M_W$ 7.0, rupture of the Grandview Fault has the potential to cause severe shaking across the region.

### 3.3.5. Other Local Active Faults

Near Queensberry, the Grandview Fault merges with the Pisa Fault, which is a range-bounding reverse fault zone on the eastern side of the Pisa Range (Figure 14). The Pisa Fault deforms glacial sediments on the western side of the Clutha Valley (Figure 23). Like the Grandview Fault, the Pisa Fault has no evidence for activity over the past 35,000 years (Beanland and Berryman, 1989). An earthquake on the Pisa Fault is estimated to have a potential magnitude of $M_W$ 7.2, with displacement of 3.3 m, and a recurrence interval of approximately 30,000 years (Stirling et al., 2012).

The short Highland Fault trace has been identified near Glendhu Bay. There is no known data on recurrence interval, or the time of last rupture.

### 3.3.6. ‘Blind’ Faults

Blind faults are faults where the fault plane may not propagate to the surface, or faults whose surface traces have been buried by sediment from rivers or glaciers. As there is no surface evidence for the fault, they can be very difficult to detect.

The Christchurch earthquakes illustrated how smaller blind faults can cause extensive damage if located near urban areas. The $M_W$ 6.2 February 22nd 2011 Christchurch earthquake had no recognisable surface expression prior to the earthquake as it was buried beneath the Holocene age marine and fluvial sediments underlying Christchurch city. Movement of the Port Hills fault did cause some relative uplift of the ground surface (Hughes et al., 2014), but the fault rupture terminated below ground and did not reach the surface. Even immediately after the earthquake, mapping the location of the fault on the ground would have been nearly impossible without information from seismographs, and remote sensing data from LiDAR and Satellites.

The thick sequence of glacial, alluvial, and lake deposits across Wanaka basin are more susceptible to deform or fold than propagate fault ruptures to the surface (Beanland and Berryman, 1989), impeding recognition of faults at the surface. Statistics of earthquakes and faults suggest that there are many unmapped faults in New Zealand, and that only one third of $M_W$ 6.0 earthquakes rupture the ground surface (Nichol et al., 2012).

The hazard posed by unrecognised faults near Wanaka was illustrated by the $M_W$ 5.8 earthquake which occurred in the afternoon of 4th May 2015 ~30 km NW of Wanaka township (Figure 17, Figure 16). This fault, in the lower section of the Matukituki Valley, had a strike-slip focal mechanism, in an area where the major structures are reverse faults. No surface trace was located. Events of this nature could potentially occur anywhere across the western Otago region.
3.3.7. Alpine Fault Earthquake

Although some 75 km to the northwest of Wanaka at its closest point, the ~600 km long Alpine Fault presents the major seismic risk to the area. The southern section of the Alpine Fault is predicted to rupture generating a $M_W$ 8.1 earthquake, resulting in 9.2 m of lateral displacement. Adding to the hazard is the frequency of rupture, with four documented Alpine Fault earthquakes in the past 900 years with an average recurrence interval of 340 years. The most recent Alpine Fault earthquake was in 1717 AD, and the likelihood of a major Alpine Fault rupture has been assessed at 30% in the next 50 years (Berryman et al., 2012).

Rupture of the Alpine Fault has a predicted shaking intensity of MMVIII across the Wanaka area (Murashev and Davey, 2005). The earthquake would generate sustained low frequency shaking over the Wanaka region, potentially for a period of 1−2 minutes.

Given the historical frequency of Alpine Fault events (average interval ~340 years), an argument can be made that the landscape may be ‘well-conditioned’ to the type of ground shaking generated by Alpine Fault earthquakes. The effects of an Alpine Fault earthquake on the Upper Clutha landscape may not be as severe as would be predicted for a seldom shaken region, as the Upper Clutha has likely experienced over 50 Alpine Fault earthquakes since the last glacial advance (18,000 years ago). Loose rocks may have already fallen off cliffs, liquefaction prone soils may have liquefied repeatedly, and large, slow-moving landslides attained a relatively stable configuration. The counter to this is that effects are most likely to be felt where people have changed the landscape, such as de-vegetated hillsides, raised lake levels, and cut roads through the mountains.

Although the landscape may be attuned to Alpine Fault earthquake, the effects are less well constrained on the built environment, such as buildings, roads, and bridges. Modern New Zealand infrastructure has not been tested by an earthquake of this magnitude, with the expected characteristics of prolonged low frequency shaking.

3.3.8. Active Faults beyond the Upper Clutha Area

In addition to the Alpine Fault, and the two local structures (Cardrona and Grandview), the central Otago region has several other active faults capable of generating large earthquakes. Foremost amongst these include the Pisa Fault, discussed in section 3.3.4 on the south-eastern side of the Pisa Range in the Cromwell Valley. Others include the Dunstan Fault on the south-eastern side of the Dunstan Mountains, the Nevis Fault - a southern extension of the NW Cardrona Fault, and the Ostler Fault in the McKenzie Basin which links into the Pisa Fault structure (Figure 12). The estimated recurrence intervals for these faults vary widely, from 3300 years on the Oster Fault, 7000 years on the Dunstan Fault, 12,000 years on the Nevis Fault, and 30,000 years on the Pisa Fault (Table 3.1).

The episodic nature of fault activity across Otago requires an integrated assessment of many sources, as few individual faults show time-predictable or characteristic earthquake behaviour (i.e., regular recurrence interval) (Norris and Nicolls, 2004). It has been shown that faults can be inactive for tens of thousands of years, but then experience several
earthquakes over a period of a few thousand years (Litchfield and Norris, 2000). Such aperiodicity makes predicting fault activity on individual faults difficult.

Figure 23. Road cut along Mt Pisa Road showing faulted alluvium and glacial till units along the Pisa Fault Zone. The gravels, assessed as outwash deposits, are associated with the Lindis glacial advance (~430,000 years old).

3.3.9. Tectonic Movement at Lake Wanaka Outlet

The projected trace of the NW Cardrona Fault cuts across the Clutha River approximately 3 km downstream from the lake outlet. Rupture of the reverse fault will see relative uplift of the upstream side of the fault, on the order of 1−2 meters. Uplift on the hanging wall of a reverse fault is greatest at the fault, and decays exponentially with distance from the fault. The outlet of the lake or a section of the river bed could effectively be raised in elevation with respect to the rest of the lakeshore. This will increase the flood risk to parts of Lake Wanaka west of the outlet, at least until the river channel eroded to its pre-earthquake level. Conversely, low lying parts of Albert Town, such as the lagoon area, could be affected by localised subsidence which can occur in the footwall adjacent to the fault.

3.4. Secondary Seismic Hazards in Wanaka

3.4.1. Liquefaction risk in the Upper Clutha area

The liquefaction risk across the Upper Clutha has been broadly assessed in two reports: a regional study by OPUS in 2005 (Murashev and Davey, 2005), and a study focussed on the
Queenstown Lakes urban areas by Tonkin & Taylor (2012) (Figure 24). The OPUS report used existing geologic mapping and local knowledge to assess areas at risk of liquefaction, whereas the T&T study drew upon subsequent knowledge of subsurface conditions.

The risk of liquefaction is primarily governed by three factors:

- The presence of loose, fine-grained, uncohesive soils, and
- Saturation, usually through a high water table, and
- Cyclic shearing caused by earthquake shaking.

The risk of seismic shaking is present across the Wanaka area, meaning that any location with susceptible soils and a sufficiently high water table is vulnerable to liquefaction.

Liquefaction-prone soils are typically young (<10,000 years old) and unconsolidated. These conditions are typical of the following depositional environments in the Wanaka area:

- Fine grained sediments deposited by glacial lakes impounded behind terminal moraines. Lake silts are extensive across the Wanaka Basin, but commonly buried beneath outwash or moraine gravels.
- Lagoon area in Albert Town
- Creek and river deltas entering lakes
- Any hollows or depressions across moraines (such as kettle lakes) which have been infilled with fine grained sediment or slope wash.
- Lake margin areas

Moraine deposits, glacial outwash fans, and beach gravels are the most common surficial deposits in the Upper Clutha area and generally have low susceptibility to liquefaction. However some of these deposits overly glacial lake silt deposits which can liquefy at depth, even if there is no surface expression of liquefaction (e.g., sand boils). The overlying non-liquefiable layers can provide a ‘crust’ and offer some protection if layers below liquefy.
Figure 24. Map of liquefaction risk in the Wanaka area assessed by Tonkin & Taylor Ltd (2012) for the Queenstown Lakes District Council. The most susceptible layers are river courses and some lake margin areas. The mapping is intended to guide the appropriate level of site investigation at the development stage, rather than assess the likelihood of liquefaction at a site.

The downtown Wanaka area has locally high groundwater levels due to connection with the Cardrona aquifer, which can be seen in the form of springs feeding Bullock Creek. Lake margin areas, such as downtown Wanaka can also have lake silts at shallow depth, deposited following the last glaciation prior to lake lowering. The combination of high groundwater levels and lake silts make downtown Wanaka and similar lake-shore locations potentially susceptible to liquefaction.

Better information about liquefaction risk should be used to inform decisions on appropriate future development. As more geotechnical information is collected across the Upper Clutha
area, identifying the areas prone to liquefaction can be done with greater certainty. Development pressure in the form of lifestyle blocks, and growth of satellite towns such as Luggate, increase the need for better subsurface information for liquefaction assessment.

3.4.2. Landslides and Mass Movement

Landslides are commonly triggered in response to seismic shaking, where ground accelerations can lead to slope instability. A range of landslide types could be triggered or reactivated by earthquakes in the Upper Clutha area, from small slips in riverbank and road cuttings, through to rapidly moving rock avalanches incorporating millions of cubic meters of rock. Figure 25 illustrates that much of the mountainous schist terrain surrounding the Upper Clutha has been affected by landslide movement, and certain places in the glacial deposits are also vulnerable.

3.4.2.1. Lake Edge and River Bank Collapse

Due to the glacial history of the Upper Clutha area, many areas are underlain by fine-grained lake sediments, which can be particularly unstable during earthquake shaking. The effect is that a layer of lake silts, even if buried under a thickness of outwash gravel, can fail by sliding laterally and cause bank collapse. This process can involve liquefaction of the silt deposits, or sliding on weak horizons within the silt. The affected areas can extend some distance (tens of meters) back from the edge of the affected bank. Planning approaches such as setback distances can be used to avoid development adjacent to slopes or banks prone to failure.

Areas vulnerable to bank collapse in the Upper Clutha area include the banks of the Clutha River, particularly at and down-stream of Albert Town where lake sediments underlie a cap of outwash gravel. Sections of river bank along this section of river have failed in the past. In 2004 an 80m length of riverbank collapsed into the Clutha River just upstream of the SH6 Bridge, and in 2014 a slip occurred just west of this location.
Figure 25. Mapped areas subject to mass-movement hazards in the Upper Clutha area (ORC Natural Hazard Database). Inset shows area around Wanaka Township.
3.4.2.2. Rockfall

Most of the densely populated areas urban areas of the Upper Clutha area are largely flat or gently sloping, and not at risk of rockfall. However some locations near steeper terrain are vulnerable.

Mt Iron is a large glacially sculptured roche moutonnée, with steep cliffs on the eastern and southern faces. Urban development has occurred near the base of these slopes (Figure 26), and although building has occurred largely on flat land, there is potential for rockfall boulders to run-out into these areas. Glacial plucking generally leaves the cliffs of roche moutonnées plucked clean of loose rock. However ice last overtopped Mt Iron ~70,000 years ago, a suitably long period for weathering to have loosened rock on the cliff faces, and expansion cracks can be seen in parts of the cliff face from the Mt Iron walkway. Paleo-rockfall boulders can be seen on the lower eastern and southern slopes of Mt Iron, indicating rockfall activity over the past 23,000 years.

![Figure 26. View of the east side of Mt Iron. Steep to subvertical schist cliffs on the eastern and southern sides of the hill provide source areas for rockfall boulders to roll downslope (July 2015).](image)

New subdivisions have pushed into the foothills of the Wanaka Basin, including parts of the Criffel Range, the northern end of the Pisa Range, and the lower slopes of the Roys Peak
area. In these locations, upslope schist outcrops, including cliffs and tors are potential sources of rockfall boulders, and there is the potential for earthquake shaking to remobilise boulders resting on ridges or talus slopes (e.g., Khajavi et al., 2012).

Rockfall can also affect locations at the base of steep terraces. Pre-historic river erosion has cut sub-vertical banks in glacial moraines and outwash alluvium, leaving steep terrace risers. Although a localised hazard, development at the base of these banks needs to take into consideration the risk of bank failure, and of rocks falling out of the cliff. Outwash alluvium and especially moraine deposits can incorporate large individual boulders.

### 3.4.2.3. Rock Avalanches

Rock avalanches are comparatively rare and unpredictable, but cause total destruction to anything in the run-out path. Occupants living at the base of slopes should be aware of the risk from rock avalanches. There are essentially no methods to mitigate the hazard of rock avalanches, but increased development along the lower slopes of mountains increases the risk.

Examples of rock avalanches in the Upper Clutha region include a small avalanche above the Haast Pass Highway near Sheepskin Creek in 2002 (Halliday, 2008), and the major rock avalanche which dammed the Young River in 2007. Neither of these events had a seismic trigger - earthquake shaking is just one of a range of triggers of rock avalanches – but they indicate the potential for these events to occur in the Upper Clutha area.

Closer to Wanaka, the Wanaka Rock Avalanche\(^1\) deposit has been identified just three kilometres south of the town centre (Figure 27), and efforts are ongoing to determine the timing of the landslide. Shaking from the nearby (<1 km) Cardrona Fault is a possible candidate for co-seismic triggering of this rock avalanche.

\(^1\) Graeme Halliday (Personal communication - Work in prep.)
3.4.2.4. Deep Seated Schist Landslides

Large schist landslides are common in the mountains surrounding Wanaka (Figure 25), including on the slopes to the west of the township (Figure 28). The activity state or rate of movement of these large landslides in the Upper Clutha area is not well known, and many may be inactive. As described above, research indicates these large slope failures are unlikely to fail catastrophically, but future developments on the slopes should consider the potential for ongoing creep, or minor displacement during large earthquakes.
3.4.3. Lake Tsunami

Mapped fault traces project under both Lakes Wanaka and Hawea, although only the northern NW Cardrona Fault and Grandview Fault, which run under Lake Hawea, are considered active. Reverse faults, such as the NW Cardrona Fault, are liable to uplift a section of lake floor. This fault motion, as opposed to strike slip movement, has greater potential to generate a tsunami than strike-slip fault movement.

Large, fat moving landslides or rock avalanches which run out into either Lake Wanaka or Lake Hawea will displace a large volume of water and generate waves. The effects of a landslide entering the lake will depend strongly on the size and speed of the landslide, the direction of impact, and where it occurs in the lake. A landslide into an isolated arm of Lake Wanaka, for example, will have less impact on Wanaka township than a slide into the main Lake body.

Like rock avalanches, lake derived-tsunamis are rare and unpredictable, and can have catastrophic effects. Specific investigations may reveal the potential magnitude of tsunamis, and the impact on lakeshore communities. One consideration may be whether there is sufficient warning time of an impending tsunami to warrant evacuation planning.
3.5. Medium-Term Geomorphic Impact

3.5.1. Channel aggradation and debris flows

Regional seismic shaking will liberate abundant hillslope material into streams through landslides, slips and rockfall. The increased sediment will overwhelm the transport capacity of many rivers, leading to channel aggradation, avulsion, and increased flood risk. The Clutha and Hawea Rivers are lake-fed and unlikely to be directly affected by this process, but streams and rivers draining mountainous terrain, such as the Cardrona, Matukituki, and Makarora Rivers, will potentially be inundated with sediment.

Debris flow and alluvial fans are a hazard in the absence of earthquakes, but earthquake shaking is predicted to increase the hazard. The influx of sediment to steep channels will increase the risk of debris flows and channel avulsion, increasing the risk to properties on alluvial fans. Prominent alluvial fans include Stony Creek and Waterfall Creek in southern Wanaka (Figure 29), and Pipson Creek, near Makarora (Figure 30).

Figure 29. Oblique view towards south of Stoney Creek and Waterfall Creek Catchments, and their associated alluvial fans in southern Wanaka (Modified from Woods, 2011)
3.5.2. Landslide Dams

In general the populated areas of the Upper Clutha region lack suitable narrow valleys where hazardous landslide dams could form and pose a threat to urban populations. Steep glacial valleys in the headwaters of Lakes Hawea and Wanaka do have potential to form landslide dams. Although not triggered by a seismic event, a large rock avalanche blocked the Young River in 2007 (Figure 31). The formation of landslide dams in these remote areas presents a low risk to populated centres, as the landslides and associated lakes will typically affect only wilderness areas. Further, any outburst flood will attenuate as it travels down local catchments and spreads out across major river valleys such as the Makarora or Hunter River. Lakes Wanaka and Hawea will further buffer downstream settlements from an outburst flood in the headwaters.
There is potential for smaller landslide dams to form in other parts of the Upper Clutha area, such as the Cardrona or Lindis Valley. The valley geometries indicate that any dam will be a much smaller scale than that in the Young River.

Figure 31. View of the Young River Landslide Dam. A landslide in August 2007 dammed the Young River to a height of 70m, and formed a ~1.5 km long lake. (May 2015)
4. Seismic Hazard in the Wakatipu Basin

This assessment focusses on the ‘Wakatipu Basin’, encompassing Queenstown, the low relief area surrounding Lake Hayes including Arrowtown and Arthurs Point, and the populated areas of Bobs Cove, the Kelvin Peninsula, and the Gibbston Basin down to Nevis Bluff. The section is intended to collate and assess known information about the seismic risk facing the Wakatipu area, describe the possible consequences of various earthquake scenarios, and identify aspects of seismic hazard where knowledge and preparedness could be improved with future work.

The seismic hazard profile for the Queenstown Lakes district is dominated by the Alpine Fault. Several other major regional faults, such as the Nevis, Cardrona, Pisa, Ostler, and Dunstan Faults, are capable of generating large earthquakes on the order of Magnitude (Mw) 7.0–7.4.

This section looks at the consequences of an earthquake for the Wakatipu region, both on the landscape, and the implications for the built environment, primarily buildings and civil infrastructure. The regional geologic and glacial history are outlined, both of which have an important influence on the area’s seismic hazard.

In addition to ground motion, the primary seismic hazards comprise ground rupture and deformation, primarily along the Nevis Cardrona Fault which cuts across the Kawarau Gorge. Secondary seismic hazards are those generated by ground motion, and arguably pose the largest hazard to the Wakatipu area. These secondary hazards include liquefaction, landslides, rockfall, lake tsunami, landslide dams, and channel aggradation. Finally, the report identifies specific areas where increased knowledge will help to reduce to the seismic risk facing Queenstown and surrounding towns.
Figure 32. Wakatipu region study area and prominent geographic features. The report focuses on the populated areas surrounding Queenstown and Arrowtown, Bobs Cove, and the Kawarau Gorge down to the Gibbston Basin.
4.1. Regional Setting and Glacial History

4.1.1. Geologic history

The Wakatipu Basin is a glacially carved valley set amidst the uplifting ranges of the Otago mountains. The area is underlain by schist bedrock, which comprises foliated Mesozoic metasedimentary rocks (Figure 33). The schist basement rock is actively being folded, faulted and eroded in response to regional compression and strain distributed across the mid to lower South Island. Much of the fault activity and uplift in the area has occurred over the past 5 million years, which is reflected in the ruggedness of the local mountain ranges. The geology of the Wakatipu area is comprehensively detailed in the Wakatipu QMAP compiled by Turnbull (2000), and summarised in Appendix B.

![Figure 33. Geology of the Wakatipu area. The pale blues and purples are varying metamorphic grades of schist bedrock. Glacial deposits (undifferentiated) and alluvial deposits occupy most of the valleys and lower hillslopes. Lake silts were deposited during a higher lake level. Isolated outcrops of the Tertiary Manuherikia sediments can be found east of the Nevis Cardrona Fault zone. Modified from QMAP (Turnbull, 2000).](image-url)
4.1.2. Active Faulting

The primary active fault in the Wakatipu Basin area is the Nevis-Cardrona Fault System, which transects the Kawarau Gorge in the western Gibbston Basin (Figure 34). The Moonlight Fault is a large fault structure to the west of Queenstown, but does not have evidence for postglacial deformation.

Figure 34. Topographic map of Wakatipu Area showing active and inactive faults. Modified from QMAP (Turnbull 2000).

The Nevis-Cardrona Fault System trends NNE along the Nevis Valley, to the east of the Remarkables Range. The section of the Nevis-Cardrona fault system north of the Kawarau River is the NW Cardrona Fault. The fault system crosses the Kawarau River just downstream of the Kawarau suspension bridge, cuts through the Crown Range and runs along the Cardrona Valley. The NW Cardrona fault continues out across the Wanaka Basin, and north beneath Lake Hawea as described in section 3.3.3 above.
The Moonlight Fault Zone is a major fault structure which strikes NW-SE across the middle of Lake Wakatipu. The fault is considered inactive (Turnbull, 2000), although there are short mapped active traces on the southern side of Lake Wakatipu (Figure 34). An assessment of stranded lake shorelines along Lake Wakatipu do not show any offset across the fault, indicating there has been minimal activity on the Moonlight Fault Zone in the past 18,000 years (Stahl, 2014). Geodetic and hazard models attribute shortening of 1 mm/yr across the Moonlight Fault (Stirling et al., 2012; Litchfield et al., 2014), although much of this may be accommodated by large-scale folding and distributed deformation. North of the lake the western side of the Moonlight Fault is uplifting, whereas south of the lake the eastern side of the fault is uplifting, termed a scissor movement.

The 88 km long northern section of the Moonlight Fault runs north from the southern shore of Lake Wakatipu, across the lake through Bobs Cove, and north subparallel with Moonlight Creek into the headwaters of the Matukituki Valley. For hazard purposes, the fault is ascribed a slip rate of 1 mm/yr, a maximum earthquake of $M_W$ 7.6, a recurrence interval of 6000 years, and a single event displacement of 6.1 m. The 100 km long southern section heads south down the Oreti Valley towards the Waiau River south of Manapori. The southern section of the Moonlight Fault also given a shortening rate of 1 mm/yr, with a maximum earthquake of $M_W$ 7.6, a single event displacement of 7 m, and a recurrence interval of 7000 years.

### Table 4.1 Major active faults near the Wakatipu basin. SED = Single event displacement, Dist = closest point of fault to Queenstown. Slip Sense: RV = reverse, SS = Strike Slip, RS = reverse slip. (Stirling et al., 2012). Note the recurrence intervals are estimates.

<table>
<thead>
<tr>
<th>Fault Name</th>
<th>Fault Length (km)</th>
<th>Slip Sense</th>
<th>Slip Rate (mm/yr)</th>
<th>Moment Magnitude ($M_W$)</th>
<th>SED (m)</th>
<th>Recurrence Interval (yrs)</th>
<th>Q-town dist (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpine</td>
<td>411</td>
<td>SS</td>
<td>27</td>
<td>8.1</td>
<td>9.2</td>
<td>340</td>
<td>85</td>
</tr>
<tr>
<td>Cardrona (north)</td>
<td>34</td>
<td>RS</td>
<td>0.38</td>
<td>7.0</td>
<td>2.4</td>
<td>6200</td>
<td>40</td>
</tr>
<tr>
<td>Cardrona (south)</td>
<td>28</td>
<td>RS</td>
<td>0.38</td>
<td>6.7</td>
<td>2</td>
<td>5100</td>
<td>21</td>
</tr>
<tr>
<td>Grandview</td>
<td>32</td>
<td>RV</td>
<td>0.1</td>
<td>7.0</td>
<td>2.2</td>
<td>22000</td>
<td>60</td>
</tr>
<tr>
<td>Pisa</td>
<td>47</td>
<td>RV</td>
<td>0.1</td>
<td>7.2</td>
<td>3.3</td>
<td>31000</td>
<td>38</td>
</tr>
<tr>
<td>Nevis</td>
<td>69</td>
<td>RV</td>
<td>0.4</td>
<td>7.5</td>
<td>4.8</td>
<td>12000</td>
<td>22</td>
</tr>
<tr>
<td>Dunstan</td>
<td>63</td>
<td>RV</td>
<td>0.63</td>
<td>7.4</td>
<td>4.4</td>
<td>7000</td>
<td>55</td>
</tr>
<tr>
<td>Ostler</td>
<td>68</td>
<td>RV</td>
<td>1.43</td>
<td>7.4</td>
<td>4.7</td>
<td>3310</td>
<td>110</td>
</tr>
<tr>
<td>Moonlight North</td>
<td>88</td>
<td>RV</td>
<td>1</td>
<td>7.6</td>
<td>6.1</td>
<td>6100</td>
<td>8</td>
</tr>
<tr>
<td>Moonlight South</td>
<td>100</td>
<td>RV</td>
<td>1</td>
<td>7.6</td>
<td>7</td>
<td>7000</td>
<td>37</td>
</tr>
</tbody>
</table>

4.1.3. Glacial History

The Wakatipu Basin area has been extensively modified by glacial processes. Glaciers throughout the Quaternary flowed down the Wakatipu Valley and carved out the Lake Wakatipu depression.
Similar to the Upper Clutha glacial sequence (Appendix C), late Quaternary glaciations have systematically reduced in extent and earlier glaciations were more extensive. The glacial evolution of the Wakatipu Basin is described in some detail here due to the influence of glacial lake deposits on the area’s seismic hazard.

Early ice advances covered the Crown Terrace, and advanced down the Kawarau Gorge, and Mataura Valley. Ice from the larger Wakatipu glaciers backed up into the Arrow and Shotover catchments, and spilled into the Motatapu and Von Catchments (Barrell et al., 1994).

The most recent glacial period occurred approximately 18,000 years ago. The primary terminus was located at Kingston, and a secondary ice lobe advanced towards Arrowtown, reaching Dalefield, Lake Hayes and Morven Hill (Thomson, 1996).

Moraines from successive glaciations are preserved on the margins of Lake Wakatipu, on hillslopes, and across the low relief areas surrounding Lake Hayes (Figure 35). The former extent of mid-Pleistocene glaciations is illustrated by the presence of till across the top of Queenstown Hill, approximately 500 m above current lake level.

Figure 35. Glacial deposits in the Wakatipu area. ‘Q’ denotes glacial age based on Oxygen isotope stage (See Appendix C). Modified from QMAP (Turnbull, 2000)

At approximately 17,000 years ago the ice retreated, leaving a large lake at a level of ~351 m, which drained through the outlet near Kingston and down the Mataura Valley. A prominent
shoreline was cut at this level, and is visible around the margins of Lake Wakatipu. The postglacial history of the lake has been summarised by Thomson (1985, 1996), and Stahl (2014).

At approximately 13,000 years ago the lake’s drainage was captured by the Kawarau River, forcing abandonment of the Kingston outlet. The lake gradually lowered to a level of 327 m approximately 2000 years ago, likely controlled by incision of the Kawarau River into the Shotover delta. From 2000 years ago the lake level fell rapidly to 305 m (below current lake level), with shorelines preserved underwater in Frankton Bay. The present lake height is 310 m (±2 m), the recent increase in lake level most likely caused by a landslide or blockage of the Kawarau River, impounding the lake (Thomson 1996).

The legacy of this postglacial lake history is that much of the land surrounding modern Lake Wakatipu was underwater as recently as 2000 years ago. Lake sediments and lake marginal deltas are widespread across the margins of Lake Wakatipu, especially adjacent to rivers that formerly drained into the lake. This is particularly the case for the area around the Shotover River, which formed a large delta into paleo-Lake Wakatipu extending from Lake Hayes in the east to Frankton in the west. The high sediment load of this river also resulted in the deposition of extensive lake silt deposits, which can be seen today on the southern and eastern shores of Lake Hayes, the along the Kawarau River just downstream of the SH6 bridge near Frankton, and in the lowlands between Jacks Point and the Remarkables.

These areas which have a surficial sequence of subaqueous sediments (delta deposits, lake silt) are also the primary areas for growth of new residential and industrial developments. Lake silts are susceptible to liquefaction during earthquakes, so understanding the distribution of silts around the Wanaka Basin is important for better managing the liquefaction hazard.

4.1.4. Seismic History

There have been no reported surface ruptures of faults in the Wakatipu area in historic times (mid-19th Century to present). The Wakatipu area has experienced two earthquakes greater than Mw 5.5: March 1966 and May 2015 (Figure 36).

Historically, most shaking felt in the region has been from distant fault sources, such as the Mw 7.2 Fiordland earthquake of 22 August, 2003 which occurred near Secretary Island. This earthquake generated horizontal ground motions of 0.1 g at the Queenstown Police Station, 122 km from the source (Reyners et al., 2003).

The largest recent earthquake within the study area was a Mw 5.8 earthquake which occurred in the afternoon of 4th May 2015, ~30 km NW of Wanaka township. This earthquake was shallow (~5 km deep) and was widely felt across the lower South Island. Peak horizontal ground accelerations of 0.047 g were recorded at the Queenstown Police Station (GeoNet).
Figure 36. Historic seismicity in the Wakatipu area, with earthquakes larger than $M_W$ 3.0 from 1942 – July 2015. Two earthquakes larger than $M_W$ 5.5 have been recorded over that period (labeled). The highest concentration of earthquakes occurs towards the Alpine Fault in the northwest of the mapped area, 80 km from downtown Queenstown. Data from GeoNet (accessed July 2015).
4.2. Primary Seismic Hazards

The primary hazards presented by earthquakes are rupture or deformation of the ground surface along the trace of a fault, and the shaking caused by seismic waves generated by movement along a fault during an earthquake. This section describes the potential for surface rupture on faults near the Wakatipu basin, and the more widespread risk from ground motion or shaking which can be caused by distant seismic sources, such as the Alpine Fault. Potential earthquake magnitudes and related data are taken from the New Zealand National Seismic Hazard Model (Stirling et al., 2012).

4.2.1. Surface Rupture

The Wakatipu Basin is crossed by one major fault with documented Holocene movement, the Nevis-Cardrona Fault System (Beanland and Barrow-Hurlbert, 1989). Another major regional structure, the Moonlight Fault system cuts through Lake Wakatipu near Bob’s Cove, but has no documented postglacial movement, and it is not recognised as active (Turnbull, 2000). There are short active fault traces mapped in the vicinity of the Moonlight Fault system (Figure 34).

4.2.1.1. Nevis Cardrona Fault Rupture

Figure 37. Oblique view of the upper Kawarau Gorge towards the Northwest. The Nevis Cardrona Fault (red) runs across the gorge and continues along the Cardrona Valley. The trench in Figure 38 is across the upstream-most strand (Kawarau Trace). The Fault runs through a large landslide complex on the north side of the valley. The Crown Range Road can be seen climbing up from the Crown Terrace and crossing the fault near the summit (Google Earth).
Due to the rugged and remote terrain the Nevis Fault transects in the Nevis Valley, there are few structures or dwellings likely to be affected directly by rupture of the Nevis section of the NCFS. The Nevis Valley is sparsely populated, and the main structures are station buildings, historic mine buildings, and power generation assets.

The Nevis Cardrona Fault system is exposed in the bank of the Kawarau River as a broad zone of crushed rock. A future surface rupture could potentially occur anywhere near the three mapped traces which cross the Kawarau Valley. An active trace of the Nevis Cardrona Fault System deforms the terrace on the right (southern) bank above the Kawarau River, 700 m downstream of the suspension bridge. Trenching of this fault segment (Figure 38) has revealed it has ruptured three times in the past 23,000 years, with an average offset of 1.1 m per event (Beanland and Barrow-Hurlbert, 1988).

4.2.1.1. Effect of Nevis-Cardrona Fault Rupture

Rupture of the Nevis Fault would have greatest direct effect in the Kawarau Valley. Three traces are of the fault zone area recognised to cross the valley downstream of the Kawarau Suspension bridge used for bungy jumping.

![Figure 38. Cross section through the Kawarau Trace of the Nevis Fault on terrace above the Kawarau River. Evidence for three earthquakes can be seen in the deposits, which date to up to 23,000 years old (Beanland and Barrow-Hurlbert, 1998).](image)

Rupture of the Nevis-Cardrona Fault through the Kawarau Valley would cause direct damage to land and assets on and proximate to the trace. State Highway 6 which runs through the Kawarau Gorge would be ruptured with a ~1-2 m vertical offset, rendering it impassable until repairs could be undertaken. Operators of assets along this section of river, including tourism
activities, wineries and roading operators should be aware of the potential for ground displacement during an earthquake, assess the effect of that event on their operations.

4.2.2. Other Local Active Faults

Short (<3 km) segments along the Moonlight Fault Zone have been mapped as active (Figure 34). These include three mapped segments on the southern side of Lake Wakatipu below Mt Nicholas, and another short strand east of Mt Gilbert 16 km north of Queenstown. These active fault segments are located in remote areas, but surface rupture could possibly affect rural businesses and tourism operators.

4.2.3. ‘Blind’ Faults

Blind faults are faults where the fault plane may not propagate to the surface, or faults whose surface traces have been buried by sediment from rivers or glaciers. As there is no surface evidence for the fault, they can be very difficult to detect.

As described in Section 3.4.6 above for the Upper Clutha, the Wakatipu area should similarly be prepared for earthquakes on unknown faults. These could occur anywhere across the region, as occurred with the $M_w$ 5.8 earthquake of 4th May 2015 ~30 km NW of Wanaka township.

4.2.4. Ground Motion

The predicted ground shaking intensity in Queenstown over 100 years is MMVII, and over 2500 years is MMIX (Figure 39) (Murashev and Davey, 2005).

Based on the 2010 NZ National Seismic Hazard Model (Stirling et al., 2012), Queenstown shallow soil sites have an expected max PGA of 0.25 g over a 475 year period (Figure 19), and 0.6 g over a 2500 year period.
4.2.4.1. Alpine Fault Earthquake

Although some 75 km to the northwest of Queenstown, the 600 km long Alpine Fault presents the major seismic hazard to the area. The southern section of the Alpine Fault is predicted to rupture in a $M_w 8.1$ earthquake, resulting in up to 9.2 m of displacement along the fault.

Rupture of the Alpine Fault has a predicted shaking intensity of MMVIII across the Wakatipu area (Murashev and Davey, 2005). The earthquake would generate sustained low frequency shaking over the Wakatipu region, potentially for a period of 1−2 minutes.

Given the historical frequency of Alpine Fault events (every ~340 years), an argument can be made that the landscape may be ‘well-conditioned’ to the type of ground shaking generated by Alpine Fault earthquakes. The effects of an Alpine Fault earthquake on the Wakatipu landscape may not be as severe as would be predicted for a seldom shaken region, as Wakatipu has likely experienced ~50 Alpine Fault earthquakes since the last glacial maximum (18,000 years ago). Loose rocks may have already fallen off cliffs, liquefaction
prone soils may have liquefied repeatedly, and large slow-moving landslides attained a relatively stable configuration. The counter to this is that effects are most likely to be felt where people have changed the landscape, such as de-vegetated hillsides, raised lake levels, and cut roads through the mountains.

Although the landscape may be attuned to Alpine Fault earthquake, the effects are less well constrained on the built environment, such as buildings, excavations, roads, and bridges. Modern New Zealand infrastructure has not been tested by an earthquake of this magnitude, with the expected characteristics of prolonged low frequency shaking.

4.2.4.2. Regional Faults

Beyond the Alpine Fault, and the Nevis Cardrona Fault System, the central Otago region has several other large active faults capable of generating large earthquakes (Figure 12) outlined in Table 4.1.

The episodic nature of fault activity across Otago requires an integrated assessment of many sources, as few individual faults show time-predictable or characteristic earthquake behaviour (i.e., regular recurrence interval) (Norris and Nicolls, 2004).

4.2.5. Topographic amplification of seismic waves

Sites on ridgelines and on soft sediment may experience more severe shaking than flat bedrock locations. Ridgeline amplification of seismic waves on parts of the Port Hills was a notable feature of the 2010-2011 Canterbury earthquakes. Hillsides and ridges in parts of the Wakatipu basin are susceptible to topographic amplification, and structures located on ridges may need to incorporate an increased seismic risk in the design stage. Reconnaissance flights following the Mw 5.8 earthquake in May 2015 showed most landscape disturbance such as visible cracking and landslides to be focussed on ridgelines (Cox et al., 2015).

Seismic waves can also become trapped within sedimentary basins, reflecting of bedrock and increasing the intensity of shaking. The glacially scoured and infilled valleys around Wakatipu may be prone to basin amplification, particularly low frequency waves, such as those expected from an Alpine Fault earthquake.

Sites on shallow soils (<30 m) near the basin margins are also liable to have more intense shaking (e.g., Bradley, 2012). Shallow soils over bedrock amplify high frequency waves, the frequency most damaging to low buildings such as residential dwellings. Shallow soils are likely common among the scoured schist outcrops in the low-relief Wakatipu basin near Arrowtown and Lake Hayes.

4.2.6. Tectonic Movement

In addition causing strong ground motion, fault movement can permanently deform the ground surface. Faults in the Wakatipu area generally have a reverse mechanism, meaning
the offset is primarily vertical, as opposed to sideways movement typical of a strike-slip fault (Figure 2).

The primary fault in the Wakatipu area is the Nevis-Cardrona Fault System. Displacement on reverse faults is not wholly accommodated on the fault plane, and deformation decays exponentially away from the fault zone, the location of maximum displacement. Movement on the fault could uplift a large area of the hanging wall (west of the fault), including terrain tens of kilometres from the fault zone. Deformation fields from previous reverse fault ruptures indicate a point on the hanging wall 10 km back from the fault can experience uplift equivalent to 60% of the uplift at the fault (Stahl, 2014).

An earthquake on the Nevis Cardrona Fault with 1 m vertical displacement at the fault plane could result in relative uplift of 0.5 m at Kawarau Falls, 12 km perpendicular to the fault (Stahl, 2014). Uplift of the Kawarau River bed of 0.5m at the outlet of Lake Wakatipu would increase the flood risk for communities on the margins of Lake Wakatipu.

Rupture at the Nevis Fault has potential to generate a ~1-2 m scarp across the river, with potential to affect jet boat navigation along this section of the river.

4.3. Secondary Seismic Hazards

Besides direct damage caused from fault rupture and ground shaking, many hazards from earthquakes are secondary effects. Modern engineered structures are intended to perform well under seismic shaking, so the suite of secondary earthquake effects can pose the greatest and most widespread hazard to life and property.

4.3.1. Liquefaction risk in Wakatipu Area

The liquefaction risk across the Wakatipu Basin has been broadly assessed in two reports: a regional study by OPUS in 2005 (Murashev and Davey, 2005), and a study focussed on Queenstown Lakes urban areas by Tonkin & Taylor (2012) (Figure 40). The OPUS report used existing geologic mapping and local knowledge to assess areas at risk of liquefaction, whereas the T&T study drew upon prior work and recent knowledge of subsurface conditions.

The risk of liquefaction is primarily governed by three factors:

- The presence of loose, fine-grained, uncohesive soils, and
- Saturation, usually through a high water table, and
- Cyclic shearing caused by earthquake shaking.

The risk of seismic shaking is present across the Wakatipu area, meaning that any location with susceptible soils and a sufficiently high water table is vulnerable to liquefaction.
Figure 40. Map of liquefaction risk in the Wakatipu Region assessed by Tonkin & Taylor Ltd (2012) for the Queenstown Lakes District Council. The most susceptible layers are river courses and lake margin areas, particularly areas underlain by lake silts. Inset shows downtown Queenstown area. The mapping is intended to guide the appropriate level of site investigation, rather than assess the likelihood of liquefaction at a site.

Liquefaction-prone soils are typically young (<10,000 years old) and unconsolidated. These conditions are typical of the following depositional environments in the Wakatipu area:

- Fine grained sediments deposited by glacial lakes impounded behind terminal moraines and within the former extent of Lake Wakatipu. Such ground conditions are extensive across the Wakatipu Basin, due to the post-glacial lake high stands. Shallow lake silts are shown in Figure 33 and Appendix C, and are likely extensive across the basin. Extensive deposits of lake silts are buried beneath river-delta gravels and surficial deposits.

- Creek and river deltas entering lakes, which can contain fine-grained sands and silt. This includes modern deltas, but also deltas which formed during previous lake high stands and are now exposed around the lake margin. Downtown Queenstown is largely built upon a delta constructed by outflow from Home Ck into the formerly enlarged Lake Wakatipu.
• Hollows or depressions across moraines (such as kettle lakes) or outwash surfaces which have been infilled with fine grained sediment or slope wash. Localised parts of the undulating terrain in the low relief parts of the Arrowtown basin, including Dalefield, Lake Hayes and surrounds have these conditions.
• Modern river floodplains, such as the lower Shotover and Arrow Rivers.

From Figure 40 above, the only location assessed to have a possibly high risk of liquefaction is near the waterfront in downtown Queenstown. Drill cores in this location reveal up to 56 m of interbedded beach gravel, lake sediments, and till (Pocknall et al., 1989).

Better information about liquefaction risk should be used to inform decisions on appropriate future development. As more geotechnical information is collected across the Wakatipu area, identifying the areas prone to liquefaction can be done with greater certainty, and liquefaction susceptibility maps can be updated.

4.3.2. Landslides and Mass Movement

Landslides are commonly triggered in response to seismic shaking, where ground accelerations can lead to slope instability. A range of landslide types could be triggered or reactivated by earthquakes in the Wakatipu area, from small slips in riverbank and road cuttings, through to rapidly moving rock avalanches incorporating millions of cubic meters of rock. Figure 41 illustrates that much of the mountainous schist terrain surrounding the Wakatipu Basin has been affected by landslide movement. Many of the mapped landslides are likely to be prehistoric, with no movement for thousands of years.

4.3.2.1. Lake Edge and River Bank Collapse

Steep river or lake banks are particularly susceptible to mass movement during an earthquake as the river or lake edge effectively acts as an un-butressed free-face, allowing movement towards the water. The affected area is usually localised to the areas of erosion and deposition adjacent to the bank. However river banks and lake-margin sites are commonly desirable real estate, or used as routes for roads or bridges, or buried infrastructure.

The glacial history of the Wakatipu area means that many areas are underlain by weak, fine grained lake sediments, which can be particularly unstable during earthquake shaking. The effect is that a layer of lake silts, even if buried under a thickness of outwash or alluvial gravel, can fail by sliding laterally and cause bank collapse. This process can involve liquefaction of the silt deposits, or sliding on weak horizons within the silt. The affected areas can extend some distance (tens of meters) back from the edge of the affected bank.
4.3.2.2. Rockfall

Rockfall is the process by which clasts of rock detach from steep terrain, and roll, slide or bounce downslope. On steep slopes or slopes with few obstructions (such as vegetation) rocks can attain significant speed and momentum, and cause serious impact damage to structures. Rocks can be mobilised by a number of causes (storms, root wedging, animals, residual weathering), but earthquake shaking is a primary cause in seismically active areas.

Due to the expansion of urban development into steep areas, rockfall is arguably one of the greater hazards facing Queenstown during an earthquake. Areas in Queenstown that are located on or at the base of steep terrain are potentially exposed to rockfall. This includes much of the upper slopes of urban Queenstown, such as Fernhill and the Gondola area. Other populated areas where rockfall hazard exists include Glenorchy-Queenstown Road to Bobs Cove, Gorge Road, Arthurs Point, and the upper slopes along Frankton Arm. Sources of rockfall boulders are primarily schist bluffs and rocky outcrops, much of which are currently obscured by dense pine forest. Moraine deposits left high on the hillslopes from earlier ice advances can incorporate large boulders and also present a rockfall risk.
The potential removal of pines from hills behind Queenstown will likely increase the runout distance of rockfall boulders, as established trees do provide some protection from rockfall.

Future development in the Wakatipu area should consider the risk of rockfall, particularly on the slopes at the base of the mountains bordering the Wakatipu Basin. Paleo-rockfall boulders can be seen along the lower slopes of the Remarkables Range east of SH6 (Figure 42). Comparable locations where rockfall could be a hazard are the lower slopes of ‘The Coronet’, and along the Shotover River in the vicinity of Queenstown Hill. Local outcrops of schist in the Wakatipu basin such as Morven Hill and Peninsula Hill are also potential locations for rockfall runout.

Roads in the Wakatipu area are similarly likely to be affected by rockfall. The Nevis Bluff area in Kawarau Gorge is a well-known rockfall site, which has impacted SH6 in the past. The primary hazard is impact damage to passing vehicles, but due to their bench-like geometry, roads can also act as a trap for rockfall boulders, rendering the road impassable. Roads on and at the base of hillslopes slopes have potential to be affected by rockfall, and include the Kawarau Gorge, SH6 from Kawarau Falls to Kingston, the Crown Range, Gorge Road, and the Queenstown-Glenorchy Road.

Additional risk of rockfall can occur at the base of steep terraces. Pre-historic river erosion has cut sub-vertical banks in glacial moraines and outwash alluvium, leaving steep terrace risers. Although a localised hazard, development at the base of these banks needs to take into consideration the risk of bank failure, and of rocks falling out of the cliff. Outwash alluvium and especially moraine deposits can incorporate large individual boulders.

The predominant seismic hazard in the Wakatipu area is an Alpine Fault earthquake. However, rocks are particularly susceptible be detached and mobilised during strong local earthquakes, where they will experience more high frequency shaking than during distant earthquakes (see section 2.2.2).

There are no mapped active faults in the immediate vicinity of the major urban areas in the Wakatipu basin, although the active Nevis Fault is only 12 km east of Kawarau Falls, and the potentially active Moonlight Fault is 12 km west of downtown Queenstown. Other unmapped faults may also be present and cause intense local shaking.
4.3.2.3. Rock Avalanches

Rock avalanches are a devastating type of landslide involving the rapid, flow-like motion of rock fragments. They can initiate from rock slides or rock falls, and travel significant distances from the source area. A seismic trigger is commonly the cause of rock avalanches.

An example of a large pre-historic rock avalanche in the Wakatipu region is ‘The Hillocks’ at the head of Lake Wakatipu. This series of small hills was originally classified as a glacial moraine, but has been reassessed as a large rock avalanche deposit. The source was a landslide high on the Humboldt Mountains with a run out distance approaching 2 km across the valley floor (McColl and Davies, 2011).

Another rock avalanche deposit has been recognised in the Gibbston Basin, where the Resta Road Landslide deposit extends across 2.5 km² (Thomson, 1994). This landslide is thought to have been caused by glacial steepening and subsequent failure of the valley wall, over 500,000 years ago.

Rock avalanches are comparatively rare and unpredictable, but cause total destruction to anything in the run-out path. Occupants living at the base of slopes should be aware of the risk from rock avalanches. There are essentially no methods to mitigate the hazard of rock avalanches, but increased development along the lower slopes of mountains increases the risk.

Figure 42. Oblique view towards the foothills of the southern Remarkables Range. SH6 runs across the lower view, with Lake Wakatipu lower right. Large boulders, likely from a rockfall, can be seen on the slopes below the rocky cliffs in the middle of the view (white dots). Active alluvial fans drain the catchments (view from Google Earth).
4.3.2.4. Deep Seated Schist Landslides

Regional landslide mapping in the Wakatipu area has highlighted the abundance of large schist landslides (Figure 41), which are an important geomorphic process operating across Otago's schist terrain (e.g., McSaveney et al., 1991).

Examples of large schist landslides can be seen across the Wakatipu area. Notable large deep seated landslides are the Coronet Peak landslide (Cunningham, 1994), Arthurs Point Landslide (Willetts, 2006) and the Queenstown Hill landslide on the southern slope of Queenstown Hill (e.g., Stossel, 1999). The Coronet Peak Landslide (Figure 43) is one of the larger landslides in the Wakatipu Basin area, and is mapped to incorporate most of the southern slope of The Coronet between Arrowtown and Arthurs Point. Given the importance of slope hydrology in modulating movement of large landslides, the use of landslide headscarp grabens for water storage at the ski field should be managed carefully.

As described above large schist landslides are considered to have a low probability of failing catastrophically, but may move a small amount during seismic shaking which could cause some damage to any structures on the slide.

![Figure 43. Oblique view showing outline of the Coronet Peak landslide, a large deep-seated schist landslide. The Shotover River runs along the left side of the image. (Google Earth).](image)

4.3.3. Lake Tsunami

The rapid displacement of a large volume of water can generate tsunami waves or lake seiching, which can inundate near shore areas. Tsunami can be caused by landslides falling into lakes, or by rupture of faults on the lake bed. Movement of a mass of sediment underwater, such as can occur when river deltas collapse or landslides occur underwater, can also generate tsunami waves.

The Moonlight Fault trace is mapped to run beneath Lake Wanaka. Rupture of this or other faults on the lake floor could displace water and generate tsunami waves. As described in
section 4.1.2 above, the Moonlight Fault is not considered active, but it is assigned a presence in the National Seismic Hazard Model, and short sections within the broader fault zone adjacent to the lake have been mapped as active. Clark et al. (2011) describe rupture of the lake floor as the most hazardous tsunami generating scenario for the comparable Lakes Te Anau and Manapouri.

River-fed deltas have built up into Lake Wakatipu, particularly at the head of the lake near Glenorchy, and other major tributaries such as the Von and Greenstone Rivers. Collapse of loosely consolidated delta sediments, particularly during seismic shaking, is another recognised means of generating tsunami waves. An earthquake-generated slump from the Rees/Dart Delta at the head of Lake Wakatipu was reported in 1938 (Brodie and Irwin, 1970).

Large fast moving landslides or rock avalanches which fall into Lake Wakatipu will displace a large volume of water and generate waves. The consequence of a landslide entering the lake will depend strongly on the size and speed of landslide, the direction of impact, and where it occurs in the lake. A rock avalanche comparable to the event which created ‘The Hillocks’ on the Dart River (McColl and Davies, 2011) would be a major tsunami hazard if the landslide ran out into the lake body.

Lakes have a natural resonance, and seiche waves can be established if the frequency of seismic waves concides with the resonant frequency of the lake. Seiching of up to 1.8 m was observed in lakes in the south-eastern United States after the Mw 9.2 1964 Alaska earthquake, a distance of thousands of km from the earthquake source. The likelihood of an Alpine Fault earthquake generating seiche waves in Lake Wakatipu has not been assessed.

Like rock avalanches, lake tsunamis are rare and unpredictable, and can have catastrophic effects. Specific investigations may reveal the potential magnitude of tsunamis, and the impact on lakeshore communities. One consideration may be whether there is sufficient warning time of an impending tsunami to warrant evacuation planning.

4.4. Medium-Term Geomorphic Impact

4.4.1. Channel aggradation and debris flows

The secondary effects of a large earthquake in the dynamic landscape surrounding Wakatipu will be felt for decades. Regional seismic shaking has the potential to transfer abundant hillslope material into streams through landslides, bank collapse, slips and rockfall. The increased sediment will overwhelm the transport capacity of many rivers, leading to channel aggradation, avulsion, and increased flood risk. Streams and rivers draining mountainous terrain, such as the Shotover and Arrow Rivers will potentially be inundated with sediment, increasing the risk of downstream flooding.

The Wakatipu area has not experienced a large earthquake in historic times, during which period there have been major landscape changes, including changed vegetation, extensive mining, road construction, and slope modification. There is potential for these changes to have decreased the stability of hillslopes, which would increase the amount of sediment entering rivers in comparison to an equivalent pre-historic earthquake.
The influx of sediment to steep channels will increase the risk of debris flows and channel avulsion, increasing the risk to properties on alluvial fans. Prominent developed alluvial fans in the Wakatipu area include Brewery Creek and Reavers Lane catchment along Gorge Road in Queenstown, and Buckler Burn and Bible stream in Glenorchy (Woods, 2011). Numerous other less-intensively developed alluvial fans are present at the base of the neighbouring mountains (e.g., Figure 42) (Barrell et al., 2009).

Future development needs to consider the impact of alluvial fans and debris flows, especially given the likelihood that these systems will become more active following a large earthquake. Alluvial fans are present around the margin of most of the Wakatipu Basin, such as along the lower western slopes of the Remarkables.

Figure 44. Active alluvial fan and debris deposition in February 1994 as seen from SH6 looking towards the Remarkables. Gravel was deposited across SH6. These fans have potential to become more active if the headwaters are inundated with sediment following an earthquake. Photo from Cunningham (1994).

4.4.2. Growth of Shotover Delta

The Shotover River joins the Kawarau River 4 km from the outlet of Lake Wakatipu. The river elevation at this location is 308 m, compared with the elevation of Lake Wakatipu of 310 m. When in flood under current conditions, the Shotover can impede the flow of the Kawarau River, and cause water to back up and increase the level of Lake Wakatipu. This problem motivated the installation of a training line in the Shotover Delta to guide the Shotover to the eastern side of the confluence to minimise the potential for impedance of the Kawarau River flow (Figure 45).
A large earthquake affecting the Wakatipu area is expected to lead to aggradation of rivers draining steep areas, such as the Shotover River. The increased sediment in the river system has the potential to overwhelm the river's transport capacity, leading to build up of river bed level elevation and growth of the river delta at the confluence with the Kawarau River. Aggradation at the delta has the potential to partially block the flow of the Kawarau, and in turn cause elevated lake levels in Lake Wakatipu. This could exacerbate existing problems associated with floodwaters inundating lowland areas adjacent to Lake Wakatipu.

Increased sediment transport in rivers following a large earthquake is anticipated to take decades to work through the river system (e.g., Robinson and Davies, 2013), meaning that delta growth and channel aggradation at the Shotover/Kawarau confluence will be a long-term issue following a large earthquake.

### 4.4.3. Landslide Dams

The mountainous Wakatipu area has multiple catchments that could be impacted by a landslide dam. The greatest risk from a landslide impoundment is likely to be on either the Shotover or Kawarau Rivers, and this scenario has been assessed by Thomson (1996, 2009). Of particular concern, damming of the upper Kawarau River has the potential to cause
impoundment of Lake Wakatipu, and cause inundation of land around the margins of the lake.

The most likely dam scenario leading to inundation of Lake Wakatipu is a large landslide in the narrow Kawarau gorge downstream of the confluence with the Arrow River, in the vicinity of the suspension bridge (Figure 46). There is a large existing landslide on the north bank of the river in this location, which extends up to the Crown Range summit. This is also the location of the Nevis Fault, which is mapped to cut through the large landslide. Large-scale failure of this landslide, co-seismically or otherwise, could dam the river to a height of tens of meters along hundreds of meters of river length. If practical, it may take months to excavate a suitable channel through the landslide debris, during which time the Kawarau and its tributaries could back up to a height approaching 340 m before overtopping the landslide dam naturally.

Figure 46. View down the Kawarau Gorge from Chard Farm Winery. The deep narrow gorge along this section of the river, which drains the Wakatipu Basin, has the potential to be blocked by a large landslide from the side slopes. (May 2015)

A collection of large schist boulders on a terrace in the Victoria Basin of the lower Kawarau Gorge just downstream of Nevis Bluff have been assigned a possible pre-historic outburst flood origin (Turner, 1990). Future work would be required to confirm whether the boulders do have an outburst flood origin, and distinguish whether the outburst flood was from failure of a landslide dam or a glacial lake outburst.
5. Summary and future work

This review presents existing information known about the seismic risk facing the Upper Clutha and Wakatipu areas, and outlines scenarios for a range of earthquakes. It also highlights knowledge gaps, and identifies where additional information will help the local communities better understand earthquake hazards in the region.

Several major faults are located within or adjacent to the Queenstown Lake district and present a local seismic hazard. The Alpine Fault, 75 km to the northwest, poses a major risk. In historic times the Upper Clutha or Wakatipu areas have not experienced a large local or Alpine Fault earthquake, so questions remain about how the natural and built environment will respond.

This review of the information relating to the seismic hazard facing the Queenstown Lakes district, and discussions with local experts, has revealed a range of areas that would benefit from further assessment. This section identifies key areas where additional information will improve understanding of the seismic risk and the effects of earthquakes.

5.1.1. Liquefaction

Geotechnical tests and analyses using standard techniques suggest lake sediments in the Wanaka area should be highly prone to liquefaction. However there is little geologic evidence for widespread liquefaction, such as sites of prehistoric lateral spreading and collapse of river banks underlain by lake silts. This is despite the Queenstown Lakes district having experienced multiple Alpine Fault earthquakes.

The lake sediments in this area are primarily derived from the schist bedrock, which contains platy mica minerals. The platy structure of minerals in the silt may control the sediments propensity to liquefy\(^2\), and reduce liquefaction susceptibility in comparison with other silt or sand soils. A full geotechnical investigation of the silt behaviour under cyclic shearing would allow better assessment of liquefaction risk. The results of such a study could be incorporated into local standards, rather than relying on methodologies developed for other settings. Liquefaction assessments tailored for Christchurch may not be appropriate for the Wanaka (or Central Otago) schist-derived sediments. Liquefaction assessment using conventional methods and guidelines may overestimate the liquefaction risk in the lake silts.

Two studies have mapped liquefaction risk across parts of the Upper Clutha and Wakatipu areas (Murashev and Davey, 2005; T&T, 2012). As additional subsurface information becomes available the maps could readily be updated to show where ground conditions and liquefaction risk diverge from what is indicated by the mapping. Liquefaction maps can quickly become out of date as new subsurface information is acquired in the course of development, and should be updated regularly. Additionally, an up to date searchable database of subsurface geotechnical information will allow geotechnical professionals to efficiently assess the liquefaction risk in areas of future development.

\(^2\) G.Salt – personal communication
5.1.2. Site-Specific Seismic Response

The seismic event most likely to affect the Queenstown Lakes district comes from the Alpine Fault. The probable site response to an Alpine Fault earthquake could be investigated to assess where damage is likely to be concentrated. This could include aspects of basin amplification of seismic waves, ridgeline amplification, hanging wall effects, and the directionality and frequency component of incoming waves.

The town of Wanaka sits on the hanging wall of the NW Cardrona Fault. Experience from the Feb 2011 Christchurch earthquake, and other earthquakes on reverse faults, indicates that the hanging wall can experience shaking intensities 50% greater than predicted, due to focussing of seismic waves along the fault zone. Quantification of this ‘hanging wall effect’ around Wanaka could refine the local hazard from the NW Cardrona Fault.

5.1.3. Nevis-Cardrona Fault System

The Nevis-Cardrona Fault System is the major local seismic source in both the Upper Clutha and Wakatipu areas, and one of the more active faults in the Otago Region. Given its proximity to Wanaka, Cardrona and Hawea townships, it has potential to generate high frequency shaking to these areas which can cause different effects in comparison to a more distant earthquake, such as an event on the Alpine Fault. Several approaches could be used to improve understanding of this structure.

a) The NW Cardrona fault north of the confines of the Cardrona Valley cannot be accurately traced through the glacial outwash gravels or the Hawea moraine. Delineating this fault would improve prediction of the location of ground rupture during an earthquake along this fault, which could be used for fault avoidance zoning. Techniques to image the fault could include shallow seismic investigation to detect any deformation of the outwash deposits or underlying bedrock.

b) Scientific assessment of the Nevis and NW Cardrona fault was most recently conducted in the early 1980s. Since that time, understanding of fault behaviour, and paleoseismic techniques (geochronology, remote sensing, off-fault effects) have advanced greatly. A new paleo-seismic assessment of the Nevis-Cardrona Fault System could constrain the timing and extent of previous ruptures, and inform hazard modelling.

c) Previous studies (Murashev and Davey, 2005) have generated isoseismal’s (shaking intensity) for the Alpine Fault, and a number of Otago faults (e.g., Akotore, Dunstan). Extending this analysis to other major faults, especially the Nevis and NW Cardrona Faults would help constrain the shaking intensity from local earthquakes.

5.1.4. Earthquake Induced Tsunami

The consequence of an earthquake induced tsunami or seiche affecting the Lakes Wakatipu, Wanaka or Hawea has not been assessed. Such an investigation could involve assessing potential landslide source areas and the consequences if they entered the lake, or the effects
of fault rupture on the lake floor. Given the scale and speed at which landslide induced tsunami can occur, effective mitigation or response options for an event may be limited.

Studies have been undertaken for Southland and Canterbury lakes (Clark, 2011; Clark, 2015), and could provide a template for assessment of the potential for tsunami or seiching in the Queenstown Lakes district.

5.1.5. Rockfall Hazard Zonation

As towns in the Upper Clutha and Wakatipu areas expand, development is pushing into the surrounding hills, increasing the risk from rockfall. Parts of Queenstown, in particular, are exposed to rockfall hazard.

Rockfalls were a major secondary effect during the Canterbury earthquake sequence, and over 5000 mapped boulders fell in residential areas, with some run out distances exceeding 700 m. Following the earthquakes hundreds of residential properties were red zoned, or deemed uninhabitable due to rockfall hazard.

Sophisticated techniques have been developed to predict rockfall source areas, runout paths, and define hazard areas based on the risk of an annual individual fatality (e.g., Massey et al., 2014). Better zonation of rockfall hazard will help guide appropriate locations for development across the Upper Clutha and Wakatipu areas.

5.1.6. Benchmarks to detect tectonic change

Both the outlets of Lake Wakatipu and Lake Wanaka are on the hanging wall of reverse faults, with the potential for the river bed of the outlet to be uplifted during an earthquake. The outlet of Lake Wanaka especially is only several km from the projected trace of the NW Cardrona Fault, and it could be uplifted a comparable amount to the vertical offset on the fault. Uplift of the outlet of either lake could have major implications for flood hazard and inundation on the lake margin.

Establishment of a survey benchmark or similar system would enable quantification of any uplift following an earthquake on the Nevis or NW Cardrona Faults. In the absence of a strategy to measure the elevation of the lake outlets, any uplift may go un-detected until the next period of high lake levels. Rapid quantification of lake outlet elevation will enable post-event planning or response to occur quickly, potentially months ahead of high lake levels.
6. Acknowledgements

Discussions with numerous people during the course of this study improved the quality of this report. We thank Royden Thomson for valuable discussions and site visits relating to the geology and glaciology of the Upper Clutha and Wakatipu areas. Graeme Halliday, Graham Salt, Paul Faulkner, and Fraser Wilson of GeoSolve Ltd, and Brian Adams of Golder Associates Ltd are thanked for discussions relating to the hazards facing the Upper Clutha and Wakatipu Basin areas.
7. References


Mackey, B.H., Quigley, M.C., 2014. Strong proximal earthquakes revealed by cosmogenic $^3$He dating of prehistoric rockfalls, Christchurch, New Zealand: Geology v. 42, p. 975-978


Stahl, T., 2014. Active Tectonics and Geomorphology of the central South Island, New Zealand: Earthquake Hazards of Reverse Faults. PhD Thesis (Geology), University of Canterbury


Thomson, R., 1996. Landslide dam scenarios in the upper and lower reaches of the Kawarau and
Shotover Rivers respectively: Study prepared for the Otago Region Council.


Appendix A – Measuring Earthquake Size and Shaking Intensity

Earthquake shaking intensity is traditionally measured using the Modified Mercalli (MM) Scale (e.g., Dowrick et al. (1996), shown in Appendix E). The Modified Mercalli Scale qualitatively describes how strong shaking is at a given location, and ranges from barely felt (MMI) to destruction of buildings (MMXII). The Modified Mercalli scale measures shaking intensity at a point, not the size of the earthquake. The shaking intensity at a site a long way from a large magnitude earthquake can be different than the shaking intensity from a smaller earthquake closer to the site. This means that the nature of the ground motion at one location will vary for earthquakes with different sources.

Earthquake size is measured in Moment Magnitude ($M_W$), which describes the amount of energy released by an earthquake. Earthquake size is based on the area of fault plane that slips, the amount of slip (displacement), and the rigidity of the earth. The Moment Magnitude scale supersedes the Richter Scale, although the two scales are broadly similar.

Ground motion can be quantitatively characterised by the duration, intensity and frequency component of shaking. Earthquake rupture generates seismic waves that have a broad range of frequencies, with larger earthquakes generating a higher proportion of low frequency waves than smaller earthquakes. High frequency waves attenuate faster than low frequency waves, as they go through more wave cycles over a given distance, meaning that locations close to an earthquake source are exposed to high frequency waves. Faults that rupture infrequently are also thought to generate more high frequency seismic waves, as faults can partially heal or anneal between earthquakes.

Shaking intensity is the most important factor when assessing potential damage at a given location, and is generally quantified in units of Peak Ground Acceleration (PGA), but can also be quantified by Peak Ground Velocity (PGV – how fast the ground moves) and Peak Ground Displacement (PGD – how far the earth moves back and forth during shaking). Low frequency (long period) waves generate higher PGV’s and PGD’s, whereas higher frequency (short period) waves cause higher PGA’s.

The effect of earthquake shaking on a structure depends on the building’s resonant frequency. Structures have a natural frequency of vibration, a frequency of shaking at which the building will respond at greater amplitude (shake more) than other frequencies. Resonant frequency typically decreases with building height. This means that taller buildings are typically more susceptible to damage from lower frequency (long period) seismic waves, and therefore large magnitude earthquakes. Conversely, low rise buildings such as 1-2 story domestic houses have a higher resonant frequency, and shake most under high frequency seismic waves. Engineers incorporate this information when designing structures to be resistant to earthquake damage, as each building will have a resonance, or earthquake frequency, at which it is most susceptible to damage.

As an example, an Alpine Fault earthquake will have a different shaking intensity at Wanaka than an earthquake on a closer fault, such as the NW Cardrona Fault. Although a NW Cardrona Fault earthquake will have much smaller magnitude ($M_W$ 7.0 cf. $M_W$ 8.2), the Northern Cardrona Fault’s proximity to Wanaka means that the area will experience more high-frequency seismic waves (waves with a period less than 1-2 seconds). High frequency
Seismic waves generate the highest peak ground accelerations, and can be highly destructive. In Wanaka, an Alpine Fault earthquake, will be dominated by long sustained long period waves.

Beyond buildings, high frequency seismic waves can affect the natural landscape differently than low frequency waves. High PGA’s due to high frequency seismic waves are thought to have caused much of the rockfall in the 2011 Christchurch earthquakes, where the source faults were under and adjacent to the Port Hills. Similarly, high frequency shaking caused specific damage to houses, such as damaging tile roofs.

**Probabilistic Seismic Hazard Analysis**

When assessing the generic seismic hazard at a site, the probability of shaking of a given intensity is determined using probabilistic seismic hazard analysis. This process involves identifying all faults likely to affect an area, and characterises the seismicity of each source (magnitude and probability of rupture). Based on distance to an individual fault (seismic source), the shaking intensity at the site can be estimated based on how seismic waves attenuate as they travel through the earth. The probabilities for all potential seismic (known and predicted) sources are then integrated to derive the likelihood of the site experiencing a given shaking intensity over the period of interest. The most recent model for New Zealand is presented in Stirling et al. (2012).

Probabilistic seismic hazard analysis can assess the annual probability of shaking of a given intensity, or the maximum level of shaking expected over a certain period. These statistics are employed by engineers when designing structures to withstand earthquake shaking.
Appendix B – Geologic History

While schist supported landforms dominate the landscape surrounding the Upper Clutha and Wakatipu areas today, recent uplift and erosion has removed much of the evidence of the regions varied geologic history.

For much of the Tertiary, central and western Otago was a tectonically quiescent low-relief region of deeply weathered schist, known as the Waiponamu erosion surface or Otago Peneplain. Lake Manuherikia covered parts of the Otago region in the Miocene period, and a sequence of freshwater Tertiary sediments, the Manuherikia Group (Dunstan / Bannockburn Formations), were deposited in and around the Lake.

The last 5 million years was a period of deformation and mountain building, an episode known as the Kaikoura Orogeny. This initiated compression across Otago, which has transformed the low-relief erosion surface into Central Otago’s mountainous landscape seen today. In places remnants of the Waiponamu erosion surface survives, and can be used to model the amount of deformation and fault movement rates. Surviving erosion surfaces include the gently northwest-sloping surface spanning the Pisa and Criffel Ranges, the northwest side of the Dunstan Mountains in the Cromwell Valley, and the valley floor across much of the Upper Clutha Valley.

Studies estimate that Otago is shortening at a rate of 2–3 mm/yr along a NW–SE axis. This shortening is largely accommodated by faulting and folding of the schist bedrock perpendicular to the convergence (e.g., Denys et al. 2015). Major northeast-trending anticlinal folds and associated reverse faults across Otago have formed a series of ranges and basins, extending from the east coast to beyond the Pisa Range in the west (Figure 14). The Pisa Range southeast of Wanaka is an example of one such fault-bound range that has been uplifted relative to Wanaka and Cromwell.

In the Queenstown Lakes district, the Manuherikia (Tertiary aged) lake sediments primarily survive today where they are protected adjacent to and on the underside of faults, but can be seen locally across the area (Figure 11). Generally these cover rocks have been stripped off the schist basement rock by erosion as mountains have been uplifted during the Kaikoura Orogeny. The freshwater sedimentary rocks have been completely removed northwest of the Nevis-Cardrona Fault System, which has experienced greater uplift than areas east of the fault. The Cardrona, Nevis, Upper Clutha, and Cromwell Basin today contain remnants of these once-extensive Tertiary sediments (Figure 12, Figure 15). A sequence of late Quaternary alluvial and glacial sediment mantles the valley lowlands today, and obscures most evidence for these older rocks.

Parts of the Wakatipu region were formerly below sea level, indicated by Late Oligocene marine rocks preserved at Bob’s Cove.

The Cardrona Valley has a deposit of greywacke rich alluvium, thought to have been deposited when the ancestral Clutha River flowed southwest down the Cardrona Valley in the early Quaternary. The greywacke, unusual in the schist dominated region, is thought to

---

3 For chronology, see Geologic Time Scale – Appendix D
have been sourced from the north prior to recent uplift along the Southern Alps (Craw et al., 2012).

Figure 47. Major faults form a series of tilted blocks across the Otago region. The NW Cardrona Fault and Pisa fault are the western-most faults. (From Litchfield and Norris, 2000).
Appendix C – Upper Clutha Glacial History

Glaciers fed from the Lakes Wanaka and Hawea catchments advanced as far downstream as Cromwell in the Quaternary (past ~2.5 Million years), and deposits from a sequence of at least 7 glacial advances are recognised in the Upper Clutha Valley (Turnbull, 2000). The glacial history of the Wakatipu area is broadly similar, and described in section 4.1.3.

Over the past million years, successive glaciations have systematically reduced in extent, leaving a series of glacial landforms preserved along the Upper Clutha. The decreasing magnitude of glacial events has ensured partial preservation of older and more extensive glacial features, particularly their moraines and outwash surfaces which are either too high or too far downstream to have been removed by younger glacial advances. This sequence has left a complex series of moraines, truncated spurs, outwash plains, and lake sediments preserved across the Wanaka basin, traceable up the Clutha valley from Cromwell to the towns of Lakes Wanaka and Hawea.

Glacial advances are correlated with global oxygen isotope stages (a proxy for global temperature), and some glacial deposits have been dated (Turnbull 2000).

<table>
<thead>
<tr>
<th>Glacial Advance</th>
<th>Approximate Age (yrs)</th>
<th>Oxygen Isotope Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hawea</td>
<td>16 000 – 18 000</td>
<td>2</td>
</tr>
<tr>
<td>Mt Iron</td>
<td>23 000</td>
<td>2</td>
</tr>
<tr>
<td>Albert Town</td>
<td>59 000 – 71 000</td>
<td>4</td>
</tr>
<tr>
<td>Luggate</td>
<td>128 000 – 186 000</td>
<td>6</td>
</tr>
<tr>
<td>Lindis</td>
<td>423 000 – 478 000</td>
<td>12</td>
</tr>
<tr>
<td>Loburn</td>
<td>620 000 – 659 000</td>
<td>16</td>
</tr>
<tr>
<td>Northburn</td>
<td>~ 1Myr</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.1 Recognised glacial advances in Upper Clutha Valley (as updated by Turnbull, 2000). Age correlation of the older units is tentative.

On valley floors and hillsides the schist has been eroded by glaciers and rivers, and infilled with a variety of glacial and alluvial sediment. Glaciers emplace compacted lodgement till as they advance, which can be smeared across the floor and walls of the glacial valley. Beyond the glacier’s terminus, sediment-laden braided rivers formed broad glacial outwash plains which extend across the valley floor and tens of kilometres downstream. Marginal rivers flowed along the shoulder of the ice adjacent to hillslopes, leaving kame terraces high on the hillsides. Upon receding the ice melted and any rock carried on or within the ice was deposited across the landscape as a hummocky recessional moraine. Commonly glacial lakes formed behind terminal moraines in the space left by retreating ice, which allowed the deposition of fine-grained glacially derived sediment across the lake bed, and lake-marginal deltas formed along the lake edge.
Figure 48. Glacial advances in the Upper Clutha area. Each advance has a moraine (stippled) and an associated outwash plain. Modified from QMAP (Turnbull, 2000).
The approximate ages and extent of glaciations in the Wanaka Basin are presented in Table 7.1. The most important glaciations for the Wanaka urban area are the most recent advances (Albert Town, Hawea and Mt Iron), which formed the surficial deposits in the Wanaka, Albert Town and Hawea areas.

In addition to depositional landforms, resistant outcrops of rock, up to the scale of large hills such as Mount Iron, present gently sloping ice-scoured faces into the direction of ice flow, but steep blocky cliffs on the down-stream side, generally plucked clean of loose rock. Large schist bedrock landslides have developed on hillslopes as ice has retreated, extending from channels to ridgelines. The dip of the schist foliation controls landslide behaviour; foliation dipping parallel to the slope causes large landslides along planes of weakness, whereas foliation dipping out of the slope can topple leading to schist debris landslides and rock avalanches.
Appendix D – Geologic Time Scale

Geologic time scale (Jurassic-Present). From GNS Science.
Appendix E – Modified Mercalli Scale


<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
</table>
| **MM 1** | *People*  
Not felt except by a very few people under exceptionally favourable circumstances. |
| **MM 2** | *People*  
Felt by persons at rest, on upper floors or favourably placed. |
| **MM 3** | *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. |
| **MM 4** | *People*  
Generally noticed indoors but not outside. Light sleepers may be awakened. Vibration may be likened to the passing of heavy traffic, or to the jolt of a heavy object falling or striking the building.  
*Fittings*  
Doors and windows rattle. Glassware and crockery rattle. Liquids in open vessels may be slightly disturbed. Standing motorcars may rock.  
*Structures*  
Walls and frames of buildings, and partitions and suspended ceilings in commercial buildings, may be heard to creak. |
| **MM 5** | *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. |
<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
</table>
| **MM 6** | **People**<br>Felt by all. People and animals alarmed. Many run outside. Difficulty experienced in walking steadily.  
**Fittings**<br>Objects fall from shelves. Pictures fall from walls. Some furniture moved on smooth floors, some unsecured free-standing fireplaces moved. Glassware and crockery broken. Very unstable furniture overturned. Small church and school bells ring. Appliances move on bench or table tops. Filing cabinets or "easy glide" drawers may open (or shut).  
**Structures**<br>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**<br>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. |
| **MM 7** | **People**<br>General alarm. Difficulty experienced in standing. Noticed by motorcar drivers who may stop.  
**Fittings**<br>Large bells ring. Furniture moves on smooth floors, may move on carpeted floors. Substantial damage to fragile contents of buildings.  
**Structures**<br>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 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**<br>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). |
<p>| <strong>MM 8</strong> | <strong>People</strong>&lt;br&gt;Alarm may approach panic. Steering of motorcars greatly affected. |</p>
<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Structures</strong></td>
<td>Buildings 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.</td>
</tr>
<tr>
<td><strong>Environment</strong></td>
<td>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.</td>
</tr>
<tr>
<td><strong>MM 9</strong></td>
<td>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.</td>
</tr>
<tr>
<td><strong>Environment</strong></td>
<td>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.</td>
</tr>
<tr>
<td><strong>MM 10</strong></td>
<td>Most Buildings Type I destroyed. Many Buildings Type II destroyed. Buildings Type III heavily damaged, some collapse. Structures Type IV damaged, some with partial collapse. Structures Type V moderately damaged, but few partial collapses. A few instances of damage to Structures Type VI. Some well-built timber buildings moderately damaged (excluding damage from falling chimneys).</td>
</tr>
<tr>
<td><strong>Environment</strong></td>
<td>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.</td>
</tr>
<tr>
<td><strong>MM 11</strong></td>
<td>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.</td>
</tr>
<tr>
<td>Level</td>
<td>Description</td>
</tr>
<tr>
<td>-------</td>
<td>-------------</td>
</tr>
</tbody>
</table>
| MM 12 | **Structures**  
Most 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. |

**Construction types**

*Buildings Type I*

Buildings with low standard of workmanship, poor mortar, or constructed of weak materials like mud brick or rammed earth. Soft storey structures (e.g. shops) made of masonry, weak reinforced concrete or composite materials (e.g. some walls timber, some brick) not well tied together. Masonry buildings otherwise conforming to buildings Types I to 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*

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*

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

*Structures Type IV*

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 c. 1970 for concrete and to c. 1980 for other materials).

*Structures Type V*

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

*Structures Type VI*

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

**Windows**

*Type I*
Large display windows, especially shop windows.

*Type II*

Ordinary sash or casement windows.

**Water tanks**

*Type I*

External, stand mounted, corrugated iron 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" (MM 6) is variable depending upon mass behaviour, or conditioning by occurrence or absence of previous earthquakes, i.e. may occur at MM 5 or not until MM 7.

"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 foundation.

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

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

<table>
<thead>
<tr>
<th>Class</th>
<th>Geological description</th>
<th>Engineering description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Strong Rock</td>
<td>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.</td>
</tr>
<tr>
<td>B</td>
<td>Rock</td>
<td>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.</td>
</tr>
<tr>
<td>C</td>
<td>Shallow Soil</td>
<td>Sites with soil depths less than the limits defined in Table 3.</td>
</tr>
<tr>
<td>D</td>
<td>Deep or Soft Soil</td>
<td>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.</td>
</tr>
<tr>
<td>E</td>
<td>Very Soft Soil</td>
<td>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.</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Soil type and description</th>
<th>Depth of soil (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cohesive soil</strong></td>
<td></td>
</tr>
<tr>
<td>Very soft</td>
<td>&lt;12.5</td>
</tr>
<tr>
<td>Soft</td>
<td>12.5-25</td>
</tr>
<tr>
<td>Firm</td>
<td>25-50</td>
</tr>
<tr>
<td>Stiff</td>
<td>50-100</td>
</tr>
<tr>
<td>Very stiff or hard</td>
<td>100-200</td>
</tr>
<tr>
<td><strong>Cohesionless soil</strong></td>
<td></td>
</tr>
<tr>
<td>Very loose</td>
<td>&lt;6</td>
</tr>
<tr>
<td>Loose</td>
<td>6-10</td>
</tr>
<tr>
<td>Medium dense</td>
<td>10-30</td>
</tr>
<tr>
<td>Dense</td>
<td>30-50</td>
</tr>
<tr>
<td>Very dense</td>
<td>&gt;50</td>
</tr>
<tr>
<td>Gravels</td>
<td>&gt;30</td>
</tr>
</tbody>
</table>

- 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

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

![Image of a scatter plot showing earthquake magnitude and date]

**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

<table>
<thead>
<tr>
<th>&gt; MMI* Intensity</th>
<th>Dunedin (yrs)</th>
<th>Oamaru (yrs)</th>
<th>Queenstown (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>29</td>
<td>25</td>
<td>5</td>
</tr>
<tr>
<td>6.0</td>
<td>110</td>
<td>97</td>
<td>16</td>
</tr>
<tr>
<td>7.0</td>
<td>536</td>
<td>460</td>
<td>60</td>
</tr>
<tr>
<td>8.0</td>
<td>3,135</td>
<td>2,530</td>
<td>219</td>
</tr>
<tr>
<td>9.0</td>
<td>-</td>
<td>-</td>
<td>1,239</td>
</tr>
</tbody>
</table>

* 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:

\[ \text{MMI} = 1.48 \ln(\text{PGA}) + 10.0 \]  

(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.

\[ \log(\text{PGA}) = -0.384 + 0.347(\text{MMI}) \]  

(Equation 2)

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

![Figure 2: PGA versus MMI Relationships](image)
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**

<table>
<thead>
<tr>
<th>≥ MMI* Intensity</th>
<th>Dunedin (yrs)</th>
<th>Oamaru (yrs)</th>
<th>Queenstown (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>29 $^{(2)}$</td>
<td>25 $^{(2)}$</td>
<td>5 $^{(2)}$</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>27.5</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>110 $^{(1)}$</td>
<td>103 $^{(1)}$</td>
<td>16 $^{(2)}$</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>536 $^{(1)}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>547 $^{(1)}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>3135</td>
<td>2800 $^{(1)}$</td>
<td></td>
</tr>
</tbody>
</table>

($^{(1)}$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

<table>
<thead>
<tr>
<th>Map MMI</th>
<th>Ground Class</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A/B</td>
</tr>
<tr>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td>VI</td>
<td>V</td>
</tr>
<tr>
<td>VII</td>
<td>VI</td>
</tr>
<tr>
<td>VIII</td>
<td>VII</td>
</tr>
<tr>
<td>IX</td>
<td>VIII</td>
</tr>
</tbody>
</table>

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 isoseisms 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 8. 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

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

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 isoseismal. 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 (Brabaharan 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 (Mc Cahon, 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 areas 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

<table>
<thead>
<tr>
<th>Class</th>
<th>Susceptibility to Liquefaction</th>
<th>Description</th>
<th>Material Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Not Susceptible</td>
<td>Liquefaction is unlikely in any scenario, but some strength loss may occur in surficial materials in a large earthquake.</td>
<td>Very Dense/Hard: Alluvium, Moraine Remnants, Marine Terraces. Tertiary &amp; Basement Rocks</td>
</tr>
<tr>
<td>B</td>
<td>Low Susceptibility</td>
<td>Liquefaction and settlement are unlikely, but localised areas may liquefy in a large earthquake.</td>
<td>Dense/Firm: Alluvium, Fans, Till, Outwash, Old Lake Beaches, Moraine Remnants, Marine Terraces</td>
</tr>
<tr>
<td>C</td>
<td>Possibly Susceptible</td>
<td>Very loose to medium dense sediments, liquefaction and settlement are possible with seismic shaking of sufficient intensity.</td>
<td>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.</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Susceptibility Class</th>
<th>Modified Mercalli Intensity of Shaking</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MM6</td>
</tr>
<tr>
<td>Possibly Susceptible</td>
<td>Liquefaction and settlement are unlikely, no ground damage expected</td>
</tr>
<tr>
<td>Low Susceptibility</td>
<td>Liquefaction and settlement are unlikely, no ground damage expected</td>
</tr>
<tr>
<td>Not Susceptible</td>
<td>Liquefaction and settlement are unlikely, no ground damage expected</td>
</tr>
</tbody>
</table>

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 (sils) 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 (Brabaharan 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 classes and for Modified Mercalli Intensities of earthquake ground shaking from MM VI to MM IX expected in the Otago Region.

<table>
<thead>
<tr>
<th>Susceptibility Category</th>
<th>Modified Mercalli Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MM VI</td>
</tr>
<tr>
<td>Low</td>
<td>Landslides and rockfalls are unlikely</td>
</tr>
<tr>
<td>Moderate</td>
<td>Landslides and rockfalls are unlikely</td>
</tr>
<tr>
<td>High</td>
<td>Landslides and rockfalls are unlikely</td>
</tr>
</tbody>
</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

<table>
<thead>
<tr>
<th>Rock / Soil Type</th>
<th>Slope Angle (degrees)</th>
<th>15-30</th>
<th>30-40</th>
<th>40 or steeper</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Quaternary Deposits</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fill, Peat, Tailings, Sand Dunes, Mud, Swamp</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td><em>Loose</em>: Scree, Alluvium, Lake Deposits, Alluvial Fans, Beach Gravels &amp; Sands</td>
<td>Moderate</td>
<td>High</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td><em>Dense</em>: Alluvium, Fans, Till, Outwash, Old Lake Beaches, Moraine Remnants</td>
<td>Moderate</td>
<td>Moderate</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td><strong>Tertiary Rocks</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conglomerate</td>
<td>Moderate</td>
<td>Moderate</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Sandstone</td>
<td>Moderate</td>
<td>Moderate</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Mudstone, Siltstone, Claystone, Diatomite</td>
<td>Moderate</td>
<td>High</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Limestone, Greensand</td>
<td>Moderate</td>
<td>Moderate</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Basalt, Dolerite, Phonolite, Trachyte, Lamprophyre</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Breccia, Tuff</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Lignite</td>
<td>Moderate</td>
<td>High</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Quartzite</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td><strong>Basement Rocks</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mudstone, Siltstone, Argillite</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Conglomerate</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Sandstone</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Schist</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slightly Foliated Schist</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Well Foliated Schist</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Well Foliated and Segregated Schist</td>
<td>Moderate</td>
<td>High</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Greenschist</td>
<td>Moderate</td>
<td>High</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Marbel, Serpentine</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Breccia</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Spilite, Keratophyre</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Limestone</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
<td></td>
</tr>
</tbody>
</table>
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 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 potential risks to 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 sieche 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.
18 **Bibliography**


Benson, W.N (1968). *Dunedin district, 1: 50 000. New Zealand Geological Survey miscellaneous series map 1*. Wellington, Department of Scientific and Industrial Research. 1


Bishop, D.G 1979; *Sheet S135 -Ranfurly Geological map of New Zealand 1: 63 160*. Wellington, Department of Scientific and Industrial Research.


Department of Scientific and Industrial Research (1967). *Geological Map of New Zealand 1: 250 000, Sheet 20 Mt Cook.*


Seismic Risk in the Otago Region: Study Report


Institute of Geological & Nuclear Sciences (2003). *Geology of the Mirihiku area. 1: 250 000*. Geological Map 20. (In publication, only digital data was used)


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**

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 in 1974 $.
- 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.

McCaPon 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
