Seismic hazard in the Queenstown Lakes district

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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, known as '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 focused attention on 'blind' faults with no surface expression, particularly smaller faults close to urban areas. The 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 quantify the local seismic risks.

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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, as seen in the network of shear structures (Quigley *et al*., 2012).

Fault rupture does not always manifest at the surface as a discrete 'fault line', and the deformation can be distributed across a zone tens or hundreds of metres 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.

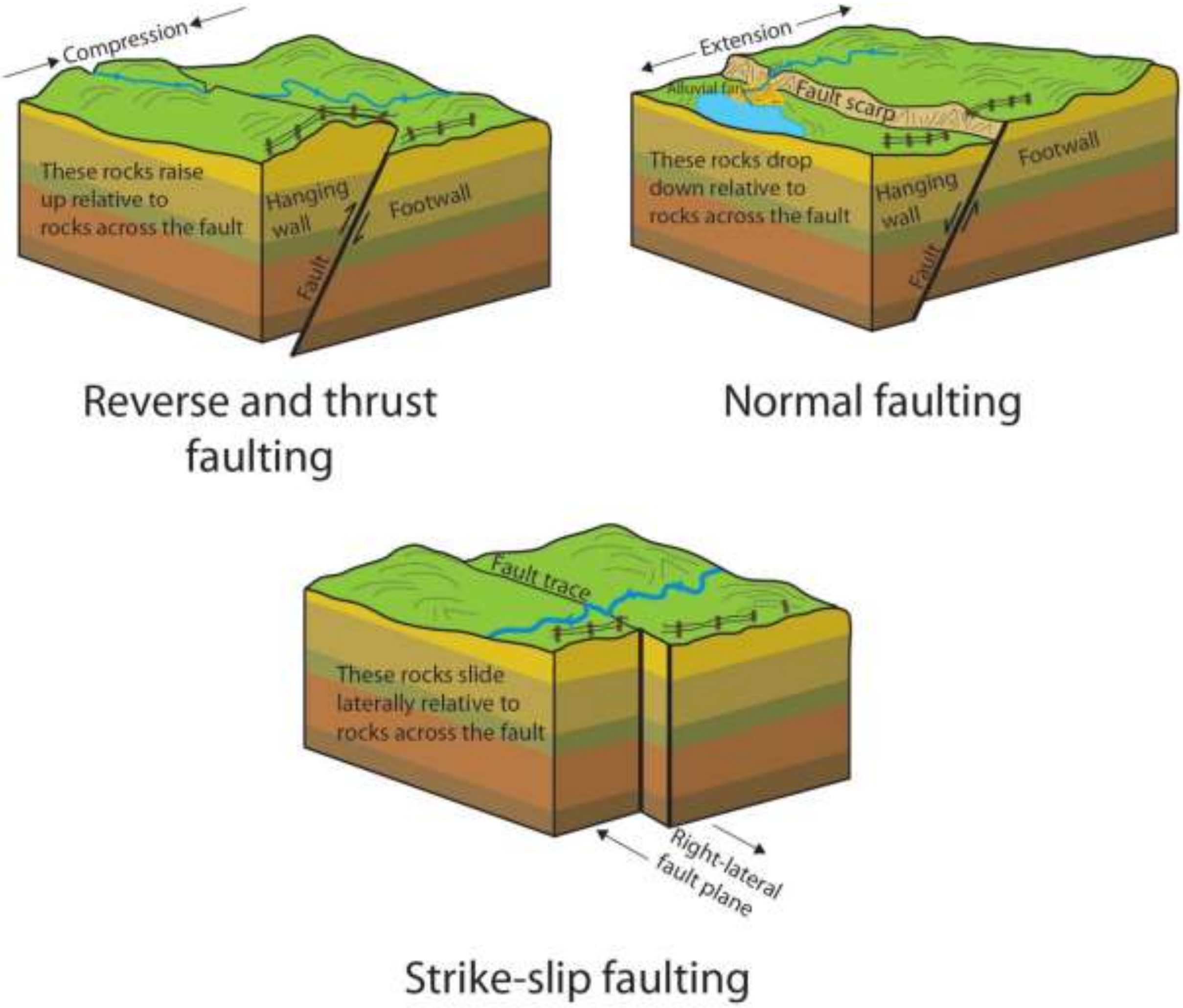

Figure 2. The main styles of faulting. Faults in western Otago are primarily reverse faults, reflecting the regional compression, whereas the Alpine Fault is a predominantly a strike-slip fault (from USDA National Park Service).

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 that 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 moment 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.

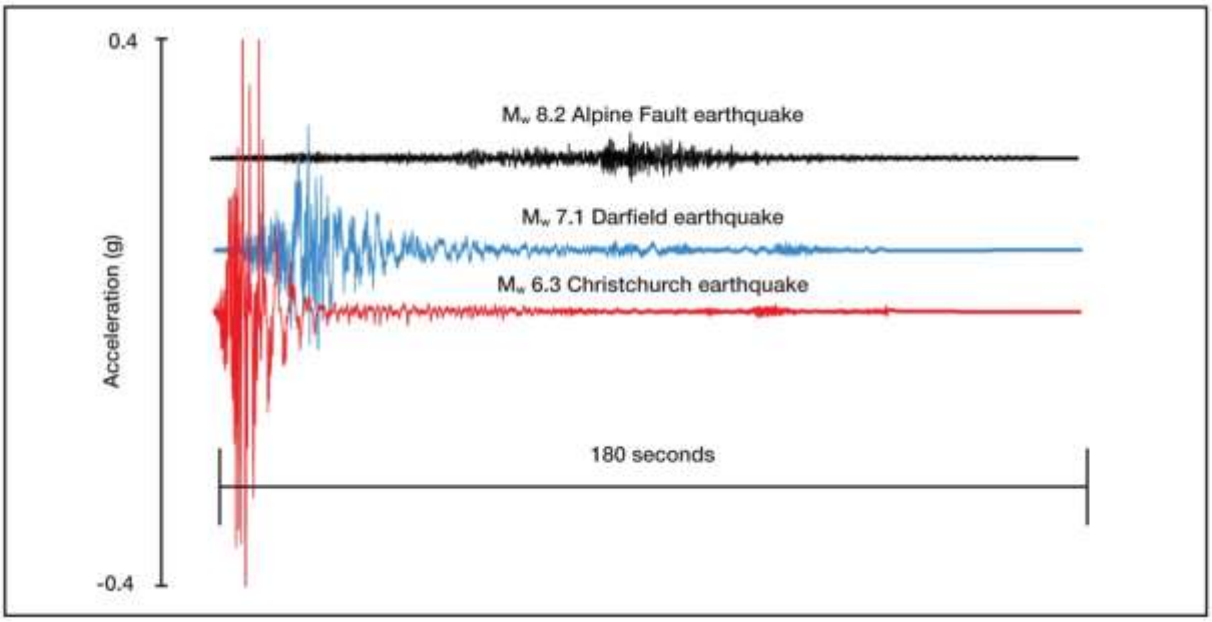

Figure 3. Seismographs from two Canterbury earthquakes as recorded in Christchurch in Sept. 2010 (blue line) and Feb. 2011 (red line). The black line is a synthetic seismograph predicting the level and duration of shaking recorded in Christchurch during a hypothetical Alpine Fault earthquake. The more 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’s surface.

Sites on shallow soils (<30 m) near the basin's 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 that the offset is primarily vertical, as opposed to the 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. 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 that 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 that 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 it 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.

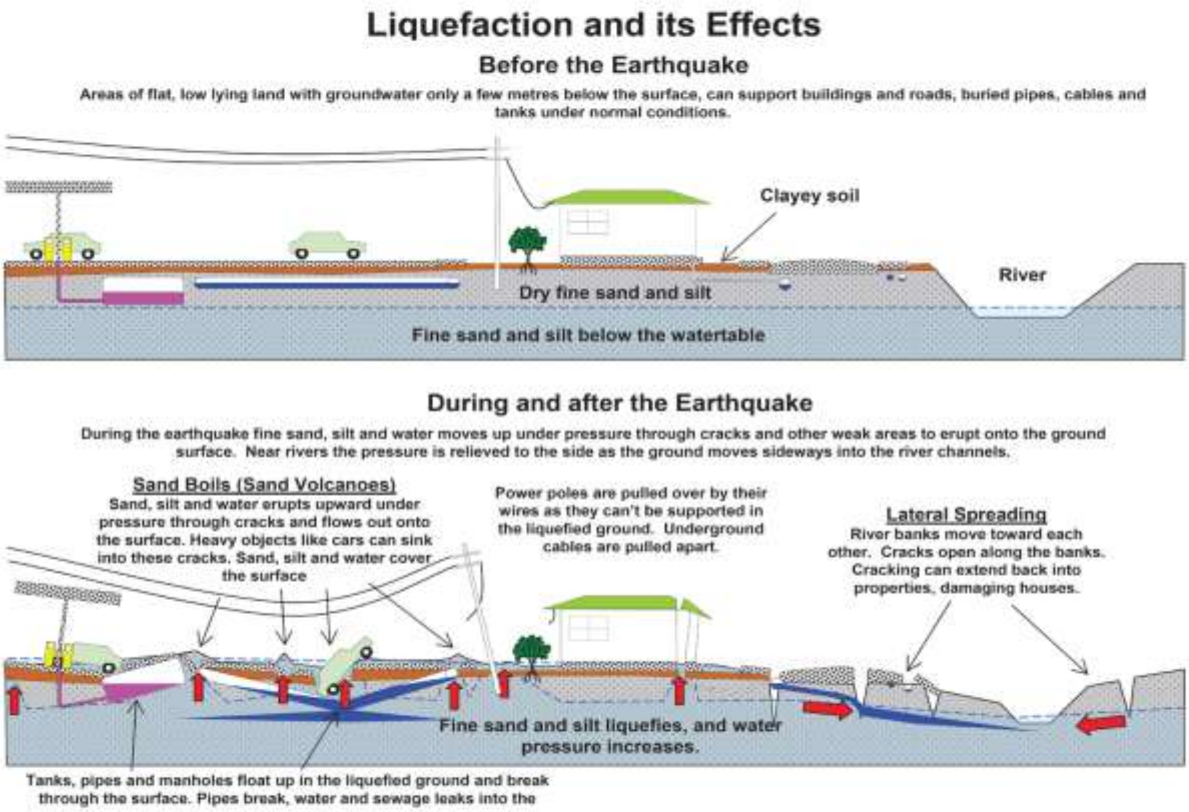

Figure 5. Effects of liquefaction (from IPENZ factsheet)

Figure 6. Liquefaction in Avonside following the February 21 Christchurch 2011 earthquake (photo by Martin Luff, Wikipedia Commons).

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 that 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 they 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 metres 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 un-buttressed 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 M_W 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.

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.

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 these strong, local earthquakes were more likely to cause rockfall than larger, more distant earthquakes, such as those 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.

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).

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 metres. 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 that the slides are unlikely to move significantly during seismic shaking, although the landslides have yet to be observed during intense earthquake shaking. Small landslide movements, in the order of hundreds of millimetres, 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 it does have the 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.

Figure 9. The 2003 Fiordland earthquake caused a 200,000 m^3 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).

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.

Furthermore, 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 that 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 that 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 focuses on seismic hazards in the Upper Clutha, which is 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 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 five 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.

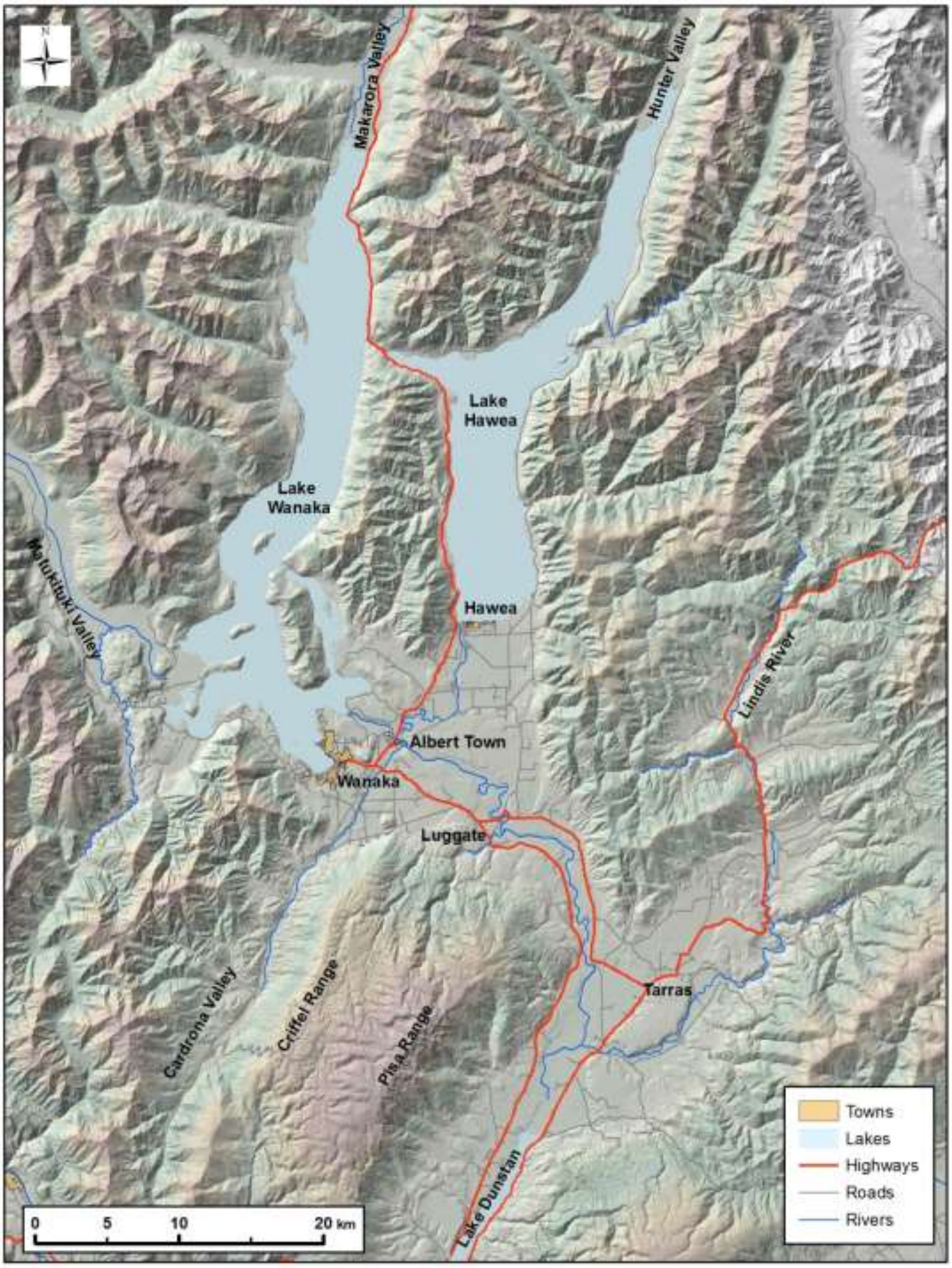

Figure 10. Upper Clutha study area and principal geographic features. The report focuses on the populated areas below the outlets of lakes Wanaka and Hawea.

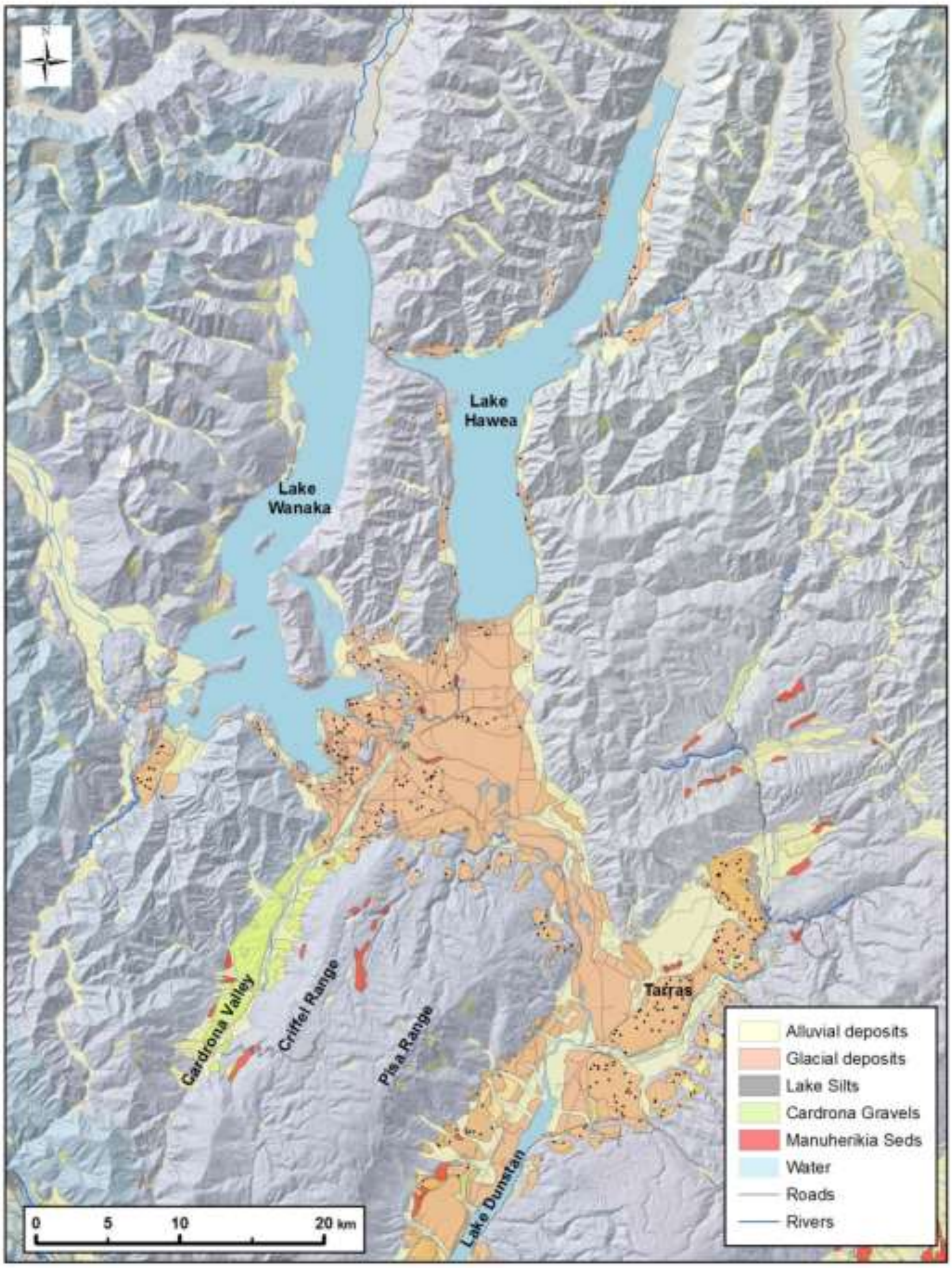

Figure 11. Geology of the Upper Clutha area. The pale blues and purples are varying metamorphic grades of schist bedrock. Glacial deposits (undifferentiated) and alluvial deposits occupy most of the valleys and lower hillslopes. Stippled areas represent glacial moraines. Remnants of Quaternary gravels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

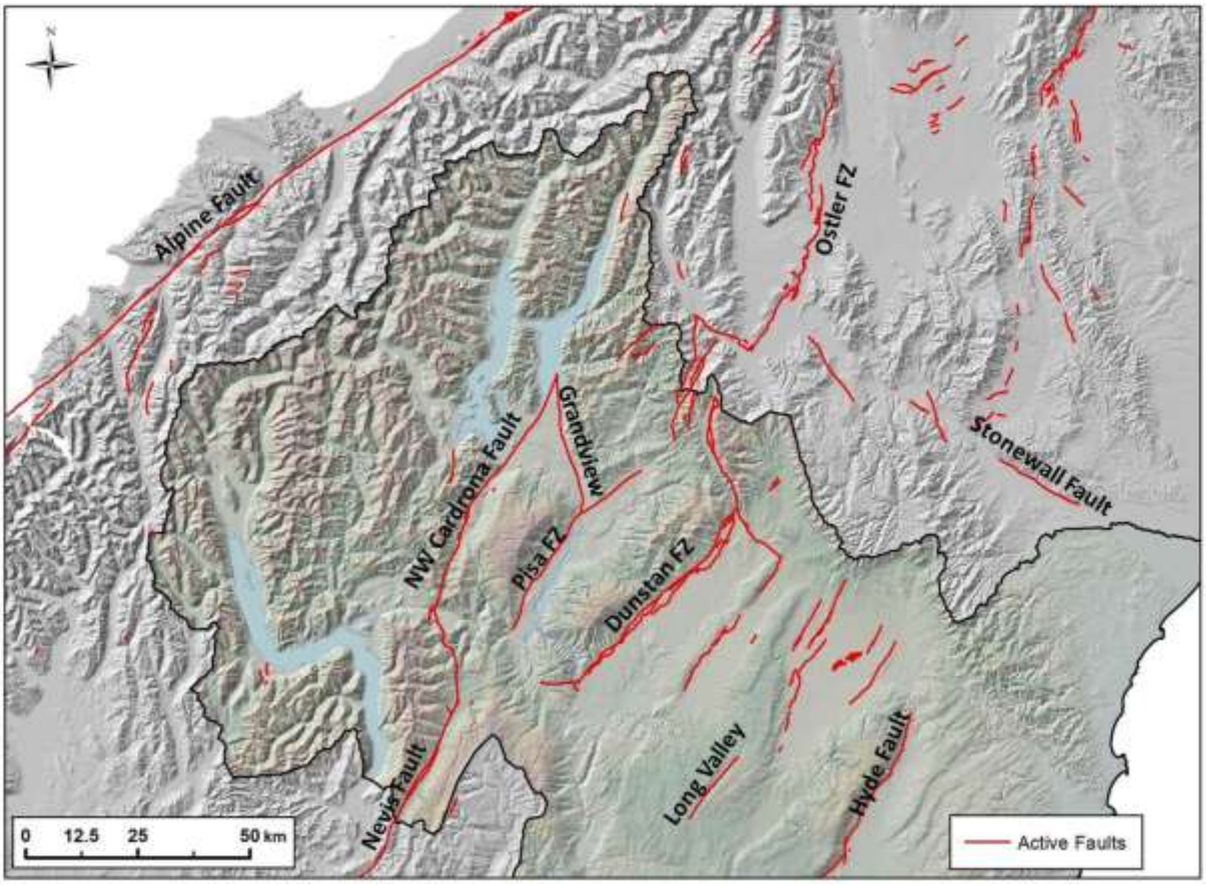

Figure 12. Active faults in West Otago and surrounding regions (from QMAP and GNS New Zealand Active Faults Database). Otago region is outlined.

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) Glacial history also influences seismic hazard as 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.

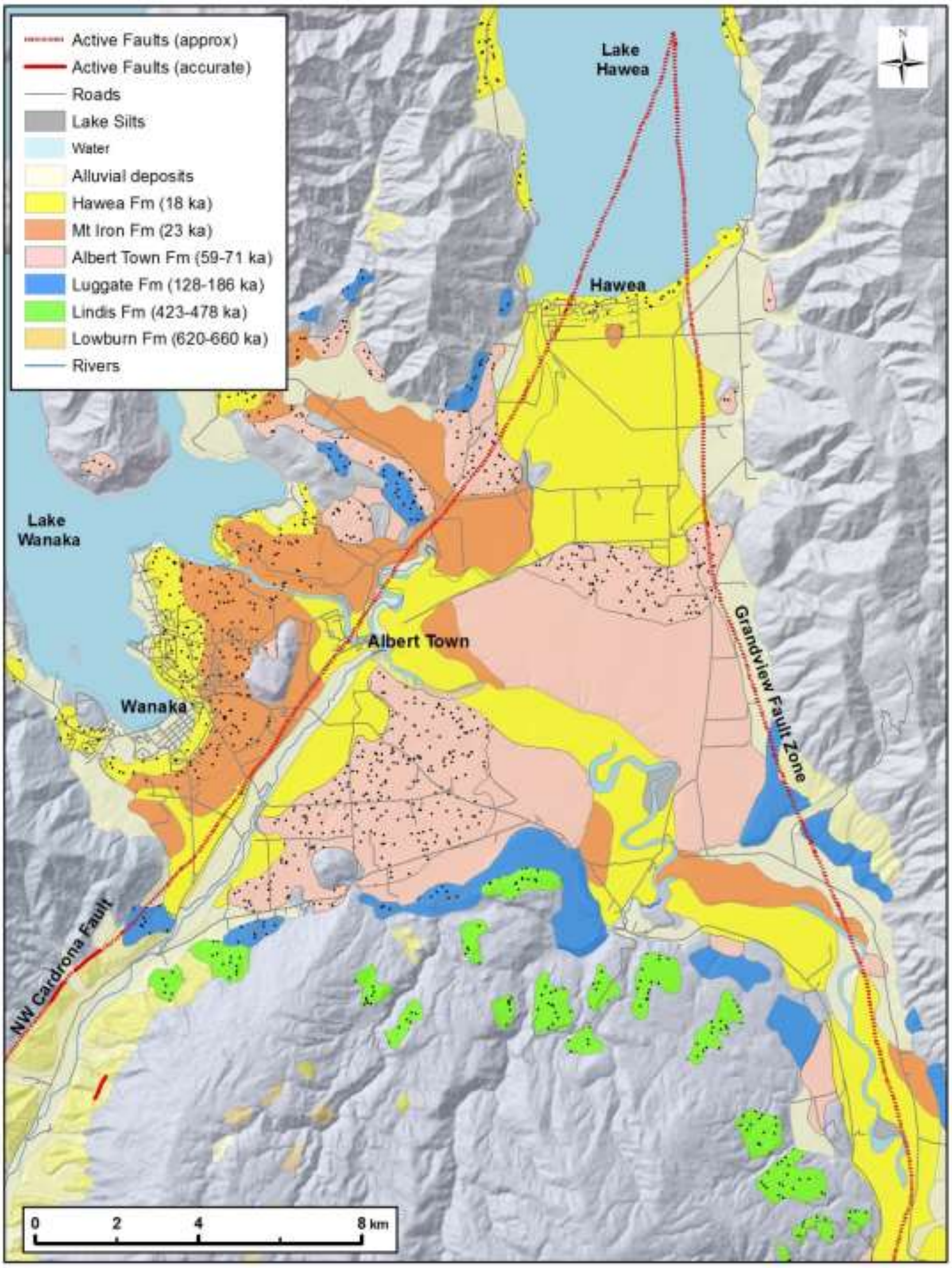

Figure 13. Depositional glacial landforms in the Upper Clutha area, and location of major active faults. Each glacial advance has a moraine (stippled) and an associated outwash plain (unstippled). Older glacial periods (e.g., Lindis, Lowburn) had larger glaciers that extended further down the Clutha Valley, and are preserved higher on the valley walls, beyond the extent of the more recent glacial advances. For age fo 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 unmapped 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.

Fault name	Fault length (km)	Slip sense	Slip rate (mm/yr)	Moment magnitude (M_W)	SED (m)	Rec. interval (yrs)	Wanaka dist. (km)
Alpine	411	SS	27	8.1	9.2	340	75
Cardrona (north)	34	RS	0.38	7.0	2.4	6200	2.5
Cardrona (south)	28	RS	0.38	6.7	2	5100	15
Grandview	32	RV	0.1	7.0	2.2	22000	12
Pisa	47	RV	0.1	7.2	3.3	31000	22
Nevis	69	RV	0.4	7.5	4.8	12000	42
Dunstan	63	RV	0.63	7.4	4.4	7000	48
Ostler	68	RV	1.43	7.4	4.7	3310	58

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, in the order of ~1 mm/yr (e.g., Litchfield *et al*., 2014). Although seemingly slow, over two 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 & Berryman, 1989). This low slip rate means that 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.

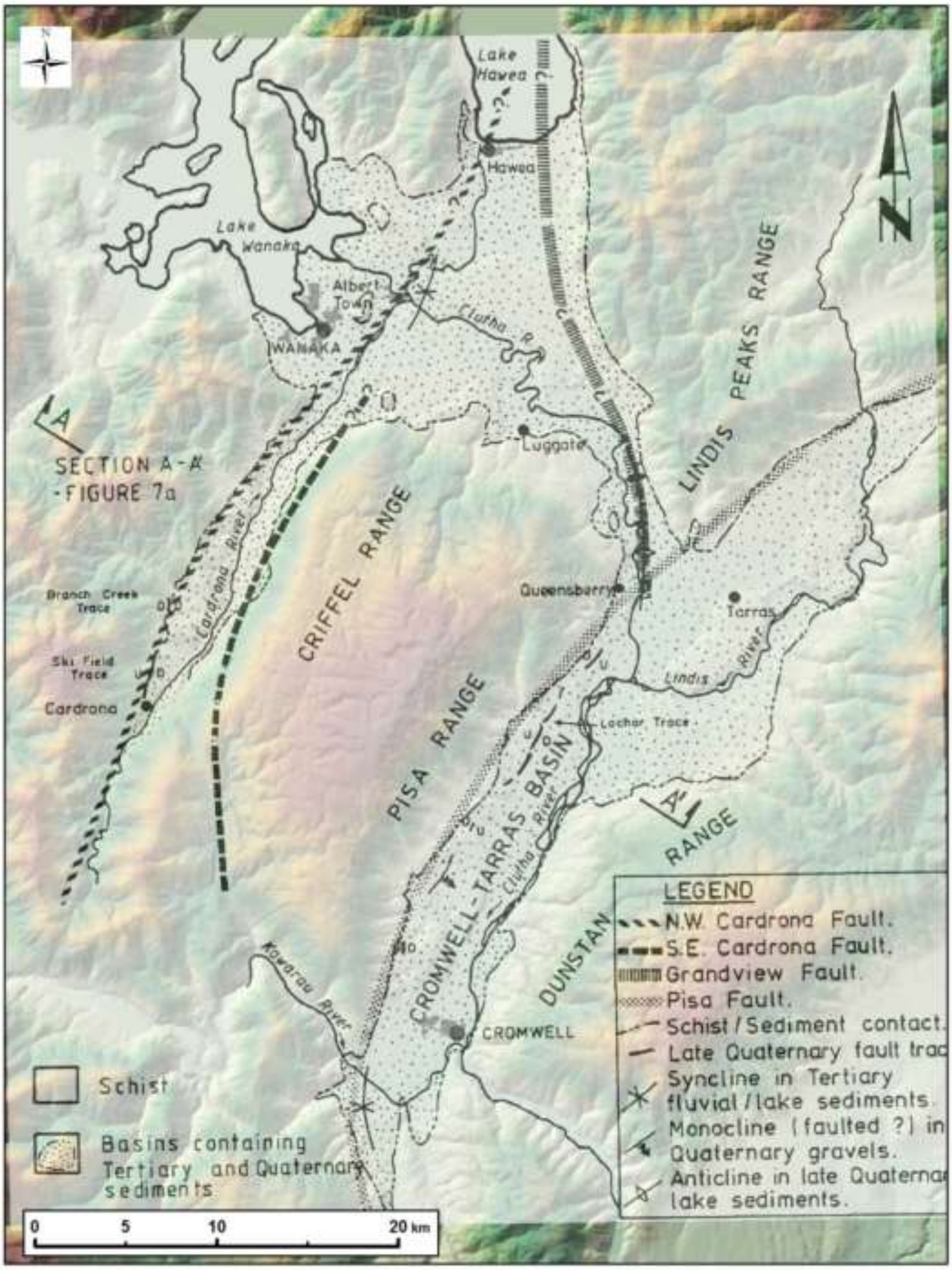

Figure 14. Major faults and structures near Wanaka. Map from Officers (1984), overlain on elevation model. Cross section A-A' is shown in Figure 15 below.

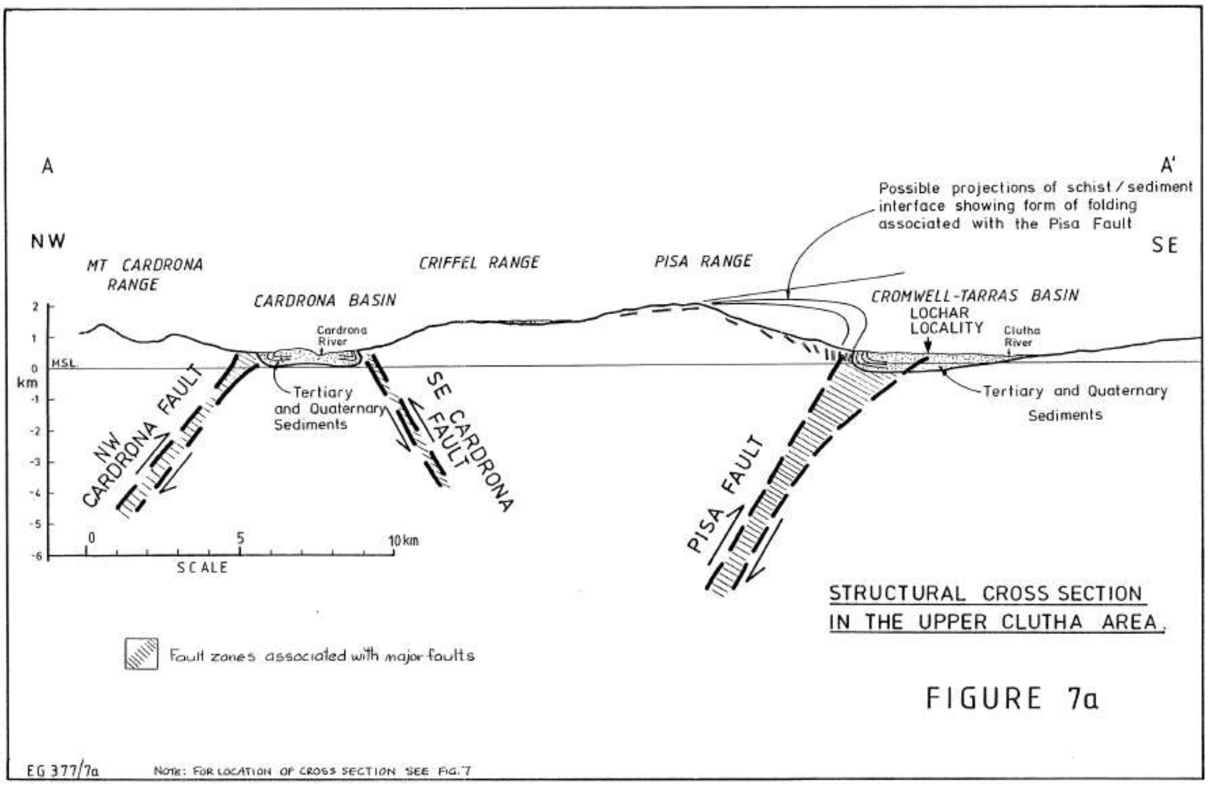

Figure 15. NW-SE oriented cross section through the Cardrona Valley and Cromwell Basin (marked on Figure 14) showing the orientation of major fault structures (Officers, 1984). Tertiary sediments remain preserved along the valley floors, but have been removed by erosion at higher elevations.

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 Mt Aspiring National Park Visitor Centre in Wanaka (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 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 Mt Aspiring National Park Visitor Centre (Figure 16). As of 24th July 2015, EQC had received 351 claims for this event.

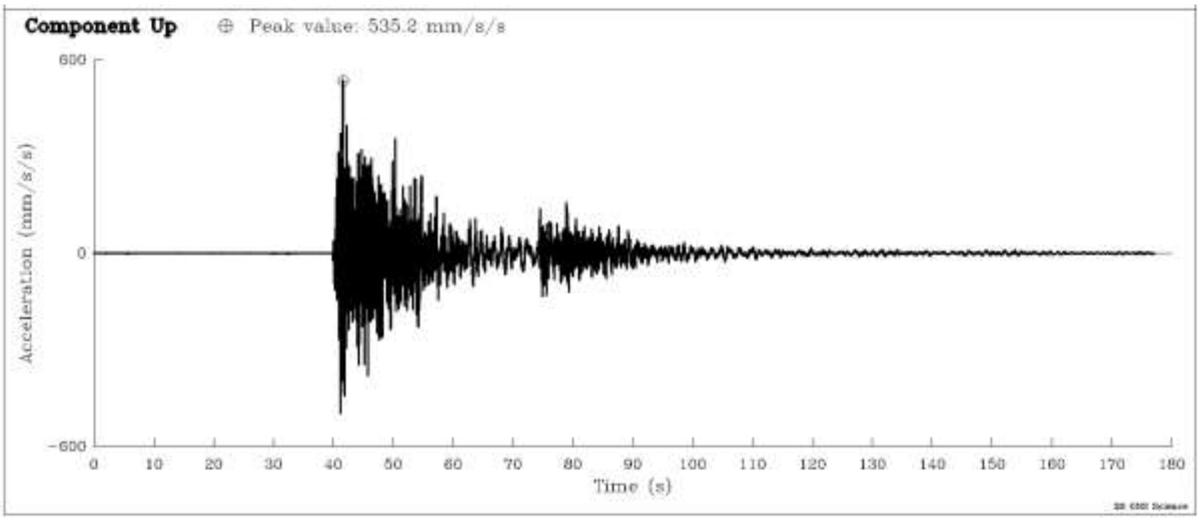

Figure 16. Seismograph record of vertical accelerations recorded at the Mt Aspiring National Park Visitor Centre during the May 4th 2015 earthquake (Figure 17). This event caused some stock to fall from shop shelves in Wanaka, with a peak acceleration of 0.054 g (image from GNS Science).

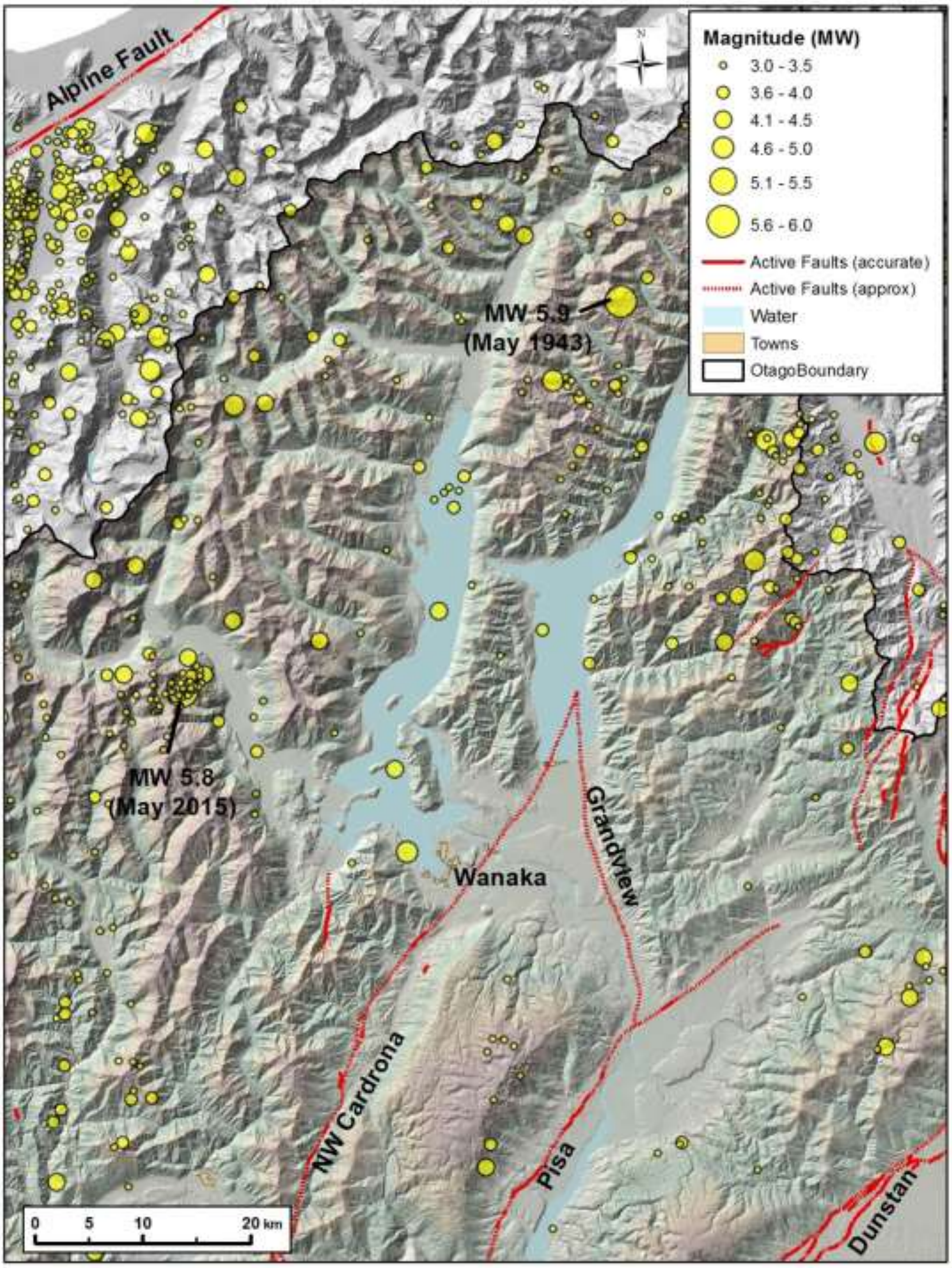

Figure 17. Historic seismicity in the West Otago area, with earthquakes larger than M_W 3.0 from 1942 – July 2015. Two earthquakes larger than M_W 5.5 have been recorded over that period. The highest concentration of earthquakes occurs towards the Alpine Fault in the northwest of the mapped area (data 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 that 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 2,500 years is MMIX (Murashev and Davey, 2005).

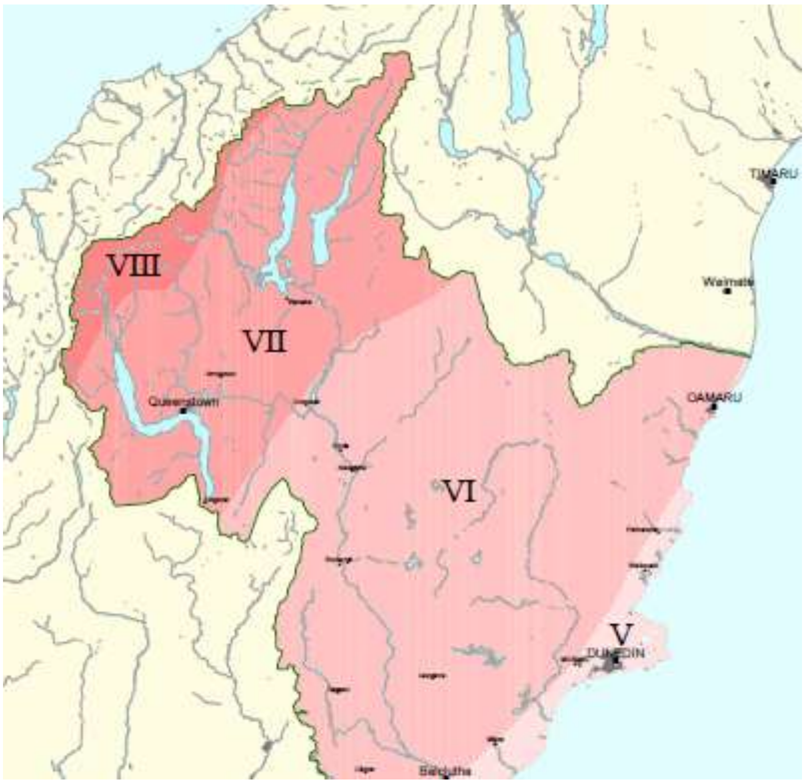

Figure 18. Map of the Otago region showing MM intensity expected to be exceeded once in 100 years (Murashev and Davey, 2005)

Based on the 2010 New Zealand National Seismic Hazard Model (Stirling *et al*., 2012), Wanaka shallow soil sites have an expected maximum PGA of 0.4 g over a 475-year period, and 0.75 g over a 2,500-year period.

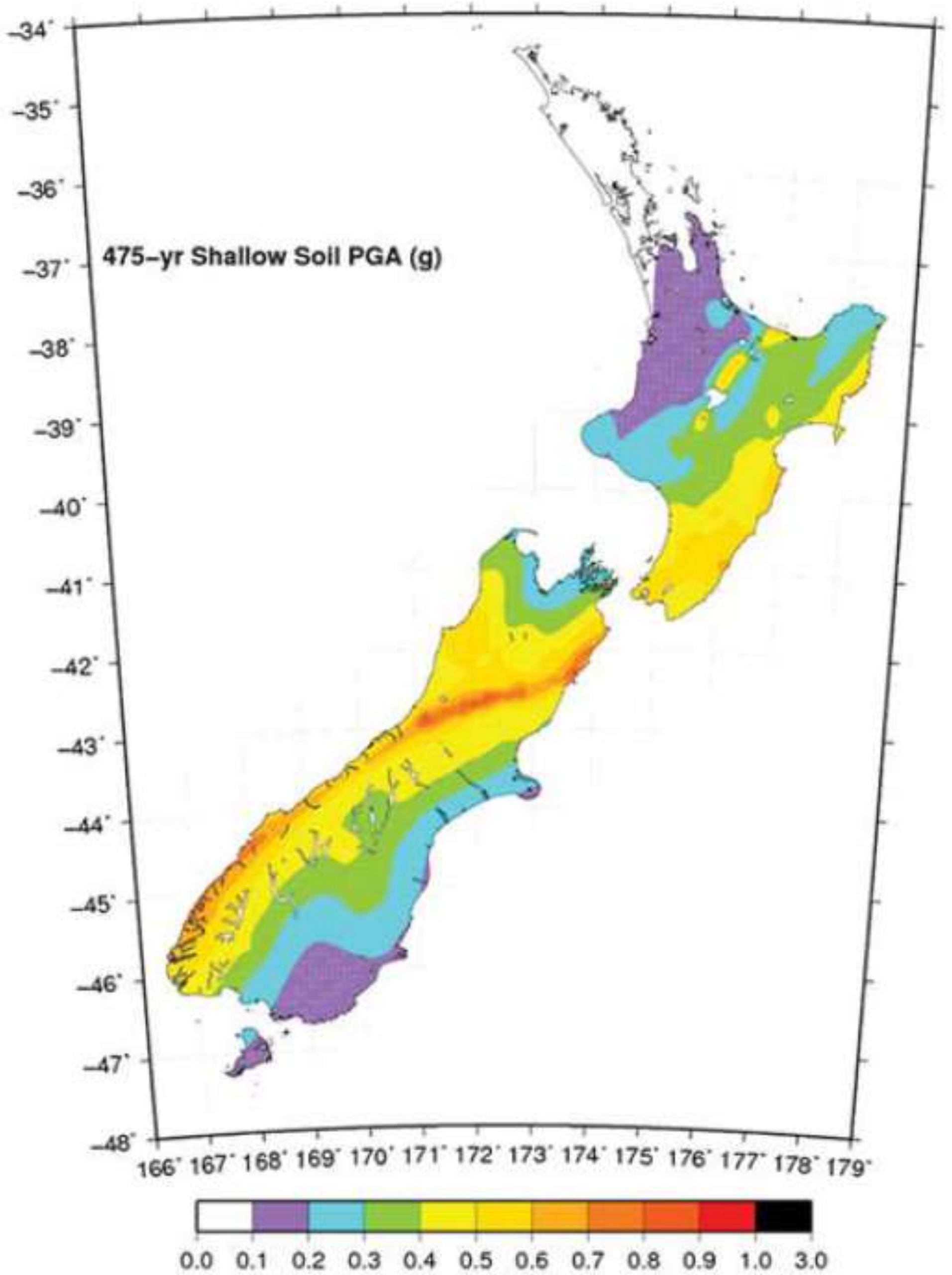

Figure 19. Probabilistic seismic hazard map for New Zealand (Stirling *et al.*, 2012). This map shows the maximum expected peak-ground acceleration (relative to gravity) expected over a 475-year period. The zone of red down the west of the South Island follows the Alpine Fault.

3.3.2. Active faults in the 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 that extend east across Otago to the East Coast (Figure 12, Appendix B).

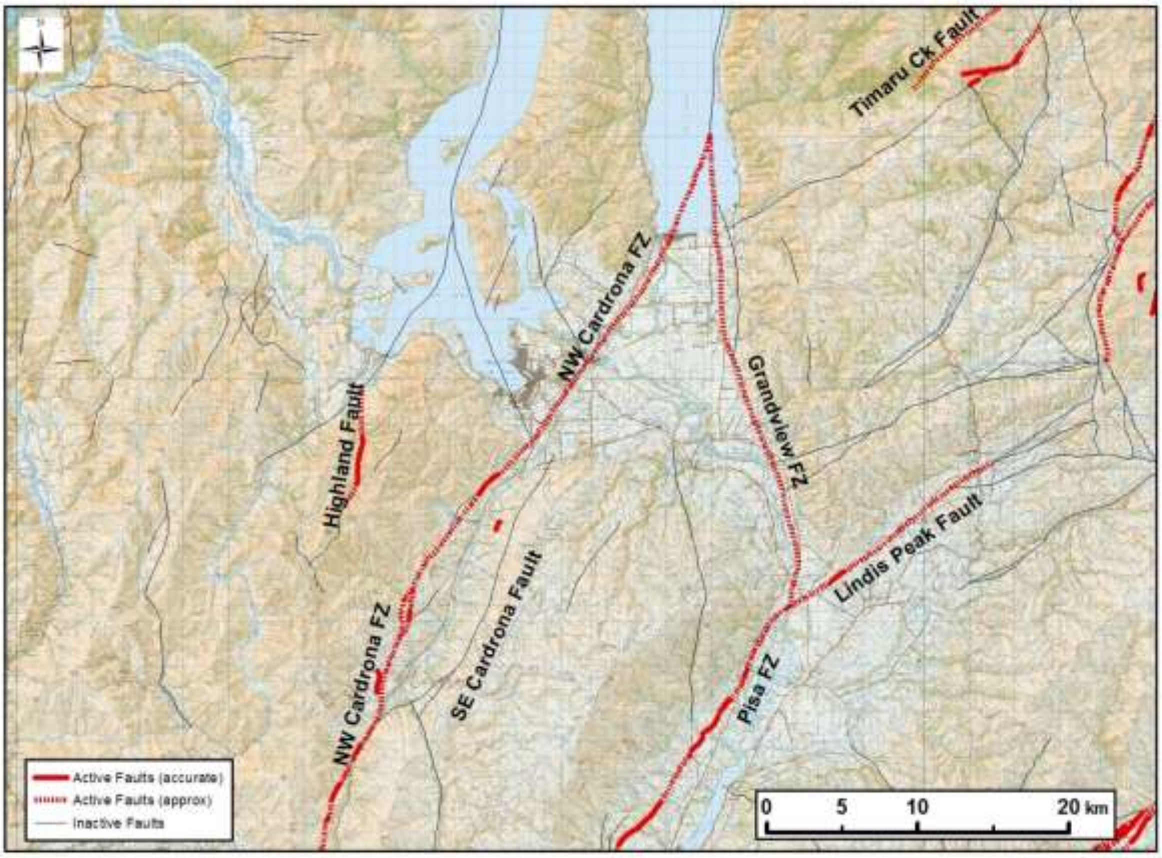

Figure 20. Active and inactive mapped faults near Wanaka. Active faults are mapped as either accurate (e.g., where there is a clear surface trace), or approximate. FZ = Fault zone (from QMAP (Turnbull, 2000)).

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 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).

To aid assessment of seismic hazard, the NW Cardrona Fault is broken into its 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 the 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 about 6,200 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 5,130 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 4,000−9,000 years, based on paleoseismic investigations (Beanland and Barrow-Hurlbert, 1988), which involved excavating a trench across a section of the fault scarp (Figure 21).

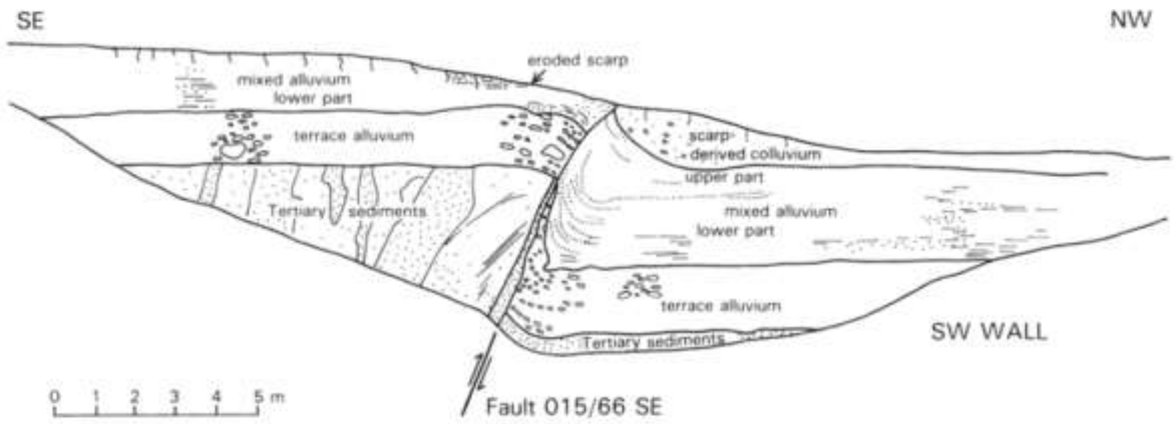

Figure 21. Diagram of a trench wall cut through active section of a splay of the northern Cardrona Fault, just south of MacDonalds Creek (6 km north of Cardrona village). The ~18,000 year old alluvial terrace deposit (terrace alluvium layer) has been offset by 4 m vertically, by at least three recognised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

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 thought 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), about 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 that 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 during 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).

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 considered 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 the 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 metres 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 drill holes 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 about 100 m vertical offset. The surficial Albert Town, Mt Iron and Hawea outwash alluvium is not deformed across the fault, suggesting that the Grandview Fault has not been active in at least the past 70,000 years.

3.3.4.1. Effect of Grandview Fault rupture

As the projected trace of the Grandview Fault does not intersect any urban areas, 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 before 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 the 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 that 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 part of the 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, occurring, on average, every 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 probably 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 surrounding area has several other active faults capable of generating large earthquakes. Foremost amongst these is 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 that links into the Pisa Fault structure (Figure 12). The estimated recurrence intervals for these faults vary widely, from 3,300 years for the Oster Fault, 7,000 years for the Dunstan Fault, 12,000 years for the Nevis Fault, and 30,000 years for 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 about 3 km downstream from the lake outlet. Rupture of the reverse fault will see relative uplift of the upstream side of the fault, in the order of 1−2 metres. 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 erodes 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 focused 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 Tonkin & Taylor’s 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
- saturation, usually through a high water table
- 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) that 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 overlie glacial-lake silt deposits that 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.

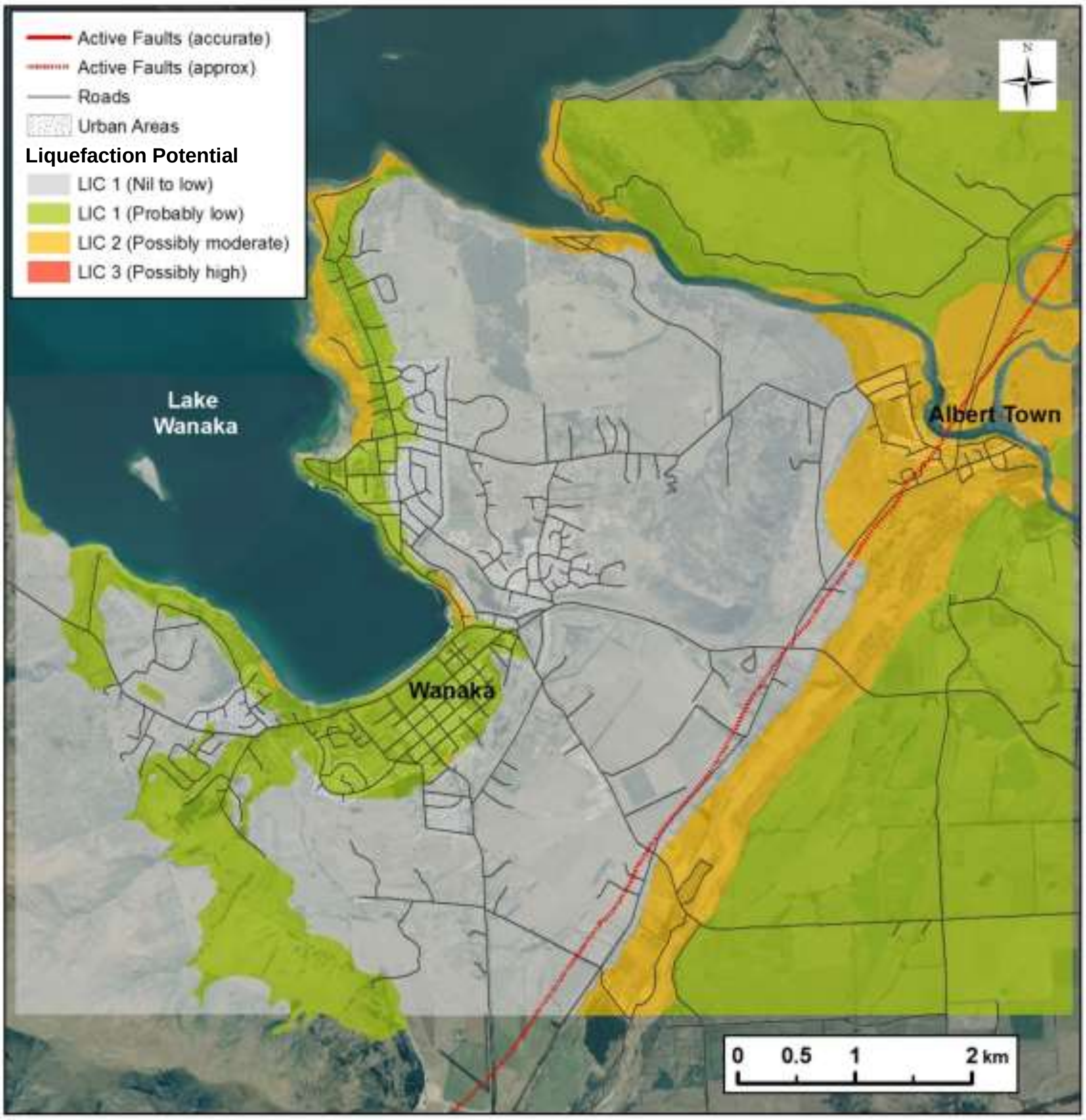

Figure 24. Map of liquefaction risk in the Wanaka area assessed by Tonkin & Taylor Ltd (2012) for the Queenstown Lakes District Council. The most susceptible layers are river courses and some lake-margin areas. The mapping is intended to guide the appropriate level of site investigation at the development 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 specific areas that are 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 metres 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 metres) back from the edge of the bank concerned. Planning approaches, such as set-back distances, can be used to avoid development next to slopes or banks prone to failure.

Banks vulnerable to collapse in the Upper Clutha area include those of the Clutha River, particularly at and downstream 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 80 m 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.

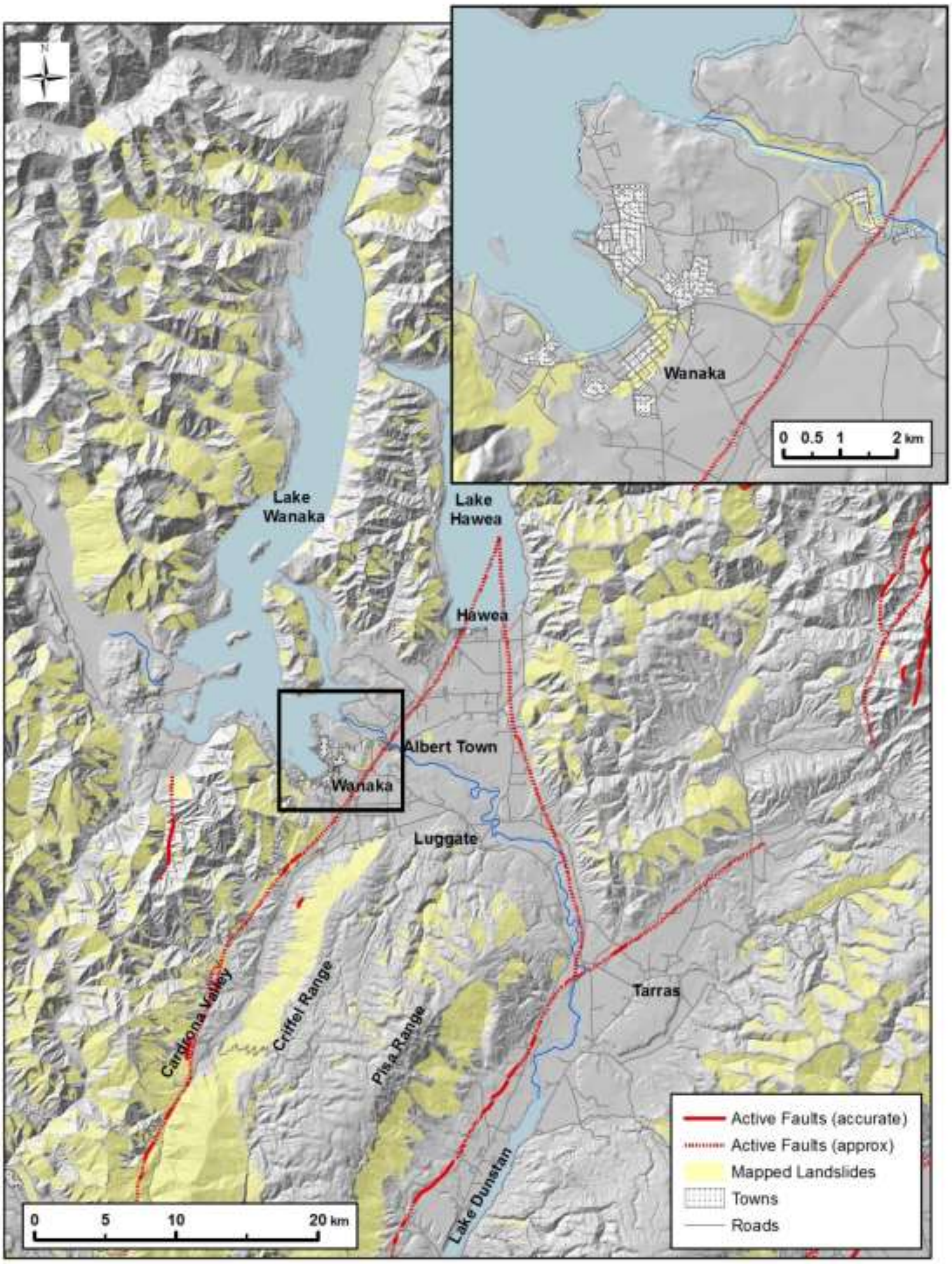

Figure 25. Mapped areas subject to mass-movement hazards in the Upper Clutha area (ORC Otago Natural Hazards Database). Inset shows area around Wanaka township.

3.4.2.2. Rockfall

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

Mt Iron is a large glacially sculptured *roche moutonnée*[1], 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).

[1] A *roche moutonnée* is a hill shaped by the flow of ice. The side facing the direction of ice flow is typically smooth and streamlined, whereas the down-flow side is usually steep and rough, having been subjected to block plucking. The gentle western slopes of Mt Iron faced into the flow of ice, whereas the east face was in the lee of the flow and left steep and rough from block plucking

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 be a hazard at the base of steep terraces. Prehistoric 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

While rock avalanches are comparatively rare and unpredictable, they can cause total destruction to anything in the runout 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 that 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[2] 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.

[2] Graeme Halliday (Personal communication - Work in prep.)

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

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.

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

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 the lake floor. This fault motion has greater potential to generate a tsunami than strike-slip fault movement.

Large, fast-moving landslides or rock avalanches that 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 will 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, thereby 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).

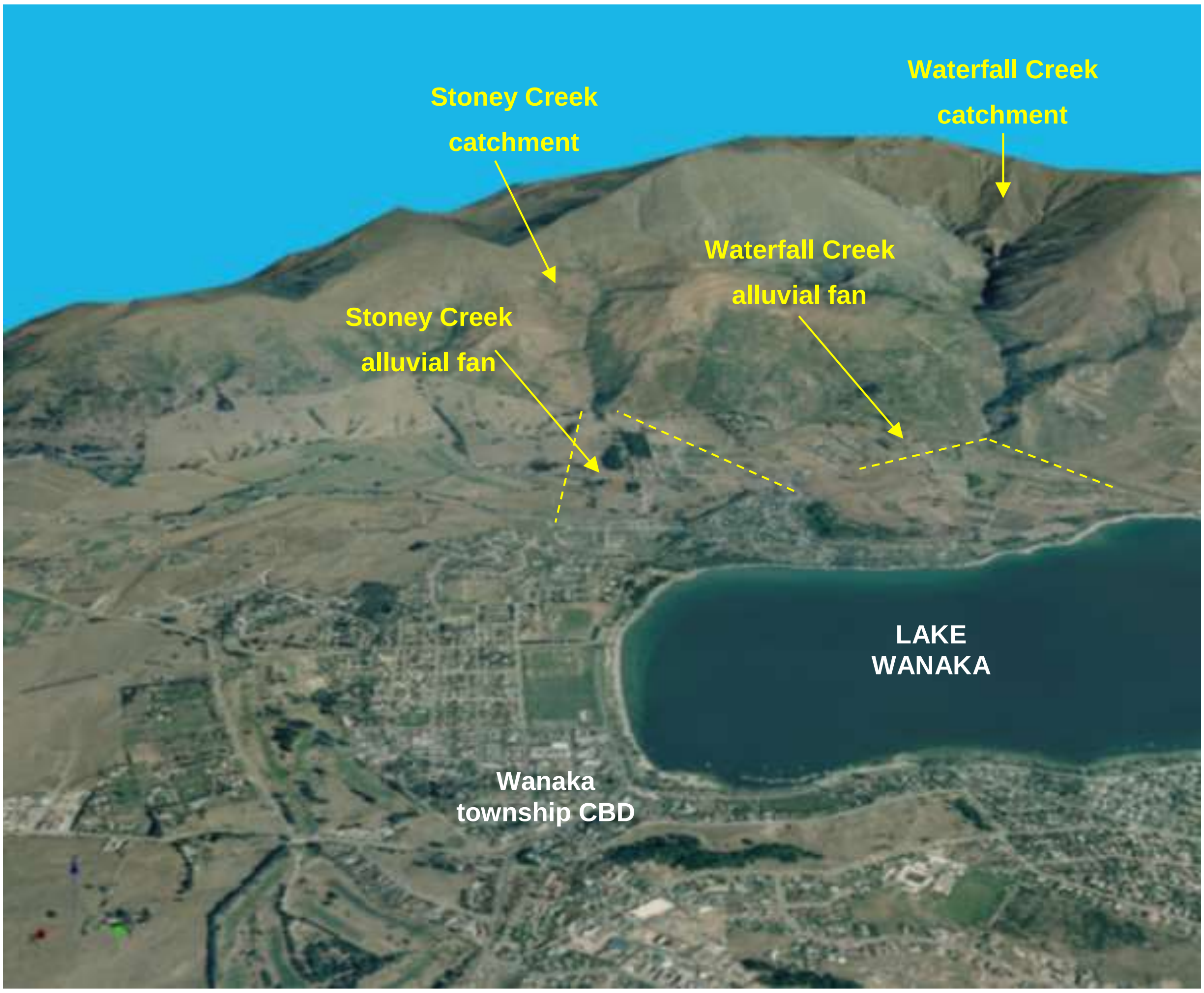

Figure 29. Oblique view towards south of Stoney Creek and Waterfall Creek catchments, and their associated alluvial fans in southern Wanaka (modified from Woods, 2011)

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.

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 the 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. Furthermore, 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 valleys. 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 section focuses on the Wakatipu Basin, which encompasses 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 Valley, 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, are capable of generating large earthquakes on the order of M_W 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.

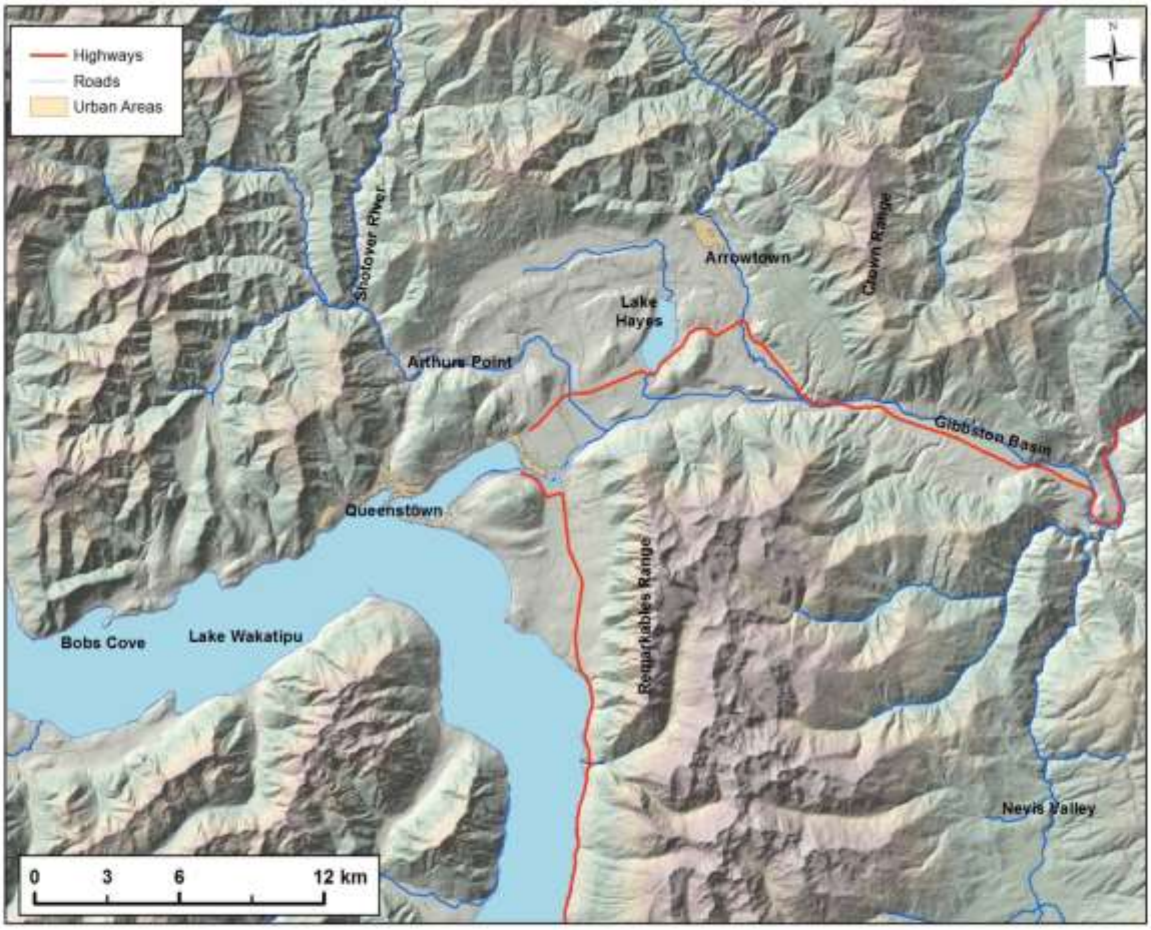

Figure 32. Wakatipu region study area and prominant geographic features. The report focuses on the populated areas surrounding Queenstown and Arrowtown, Bobs Cove and the Kawarau Gorge, down to the Gibbston Basin.

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 five 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.

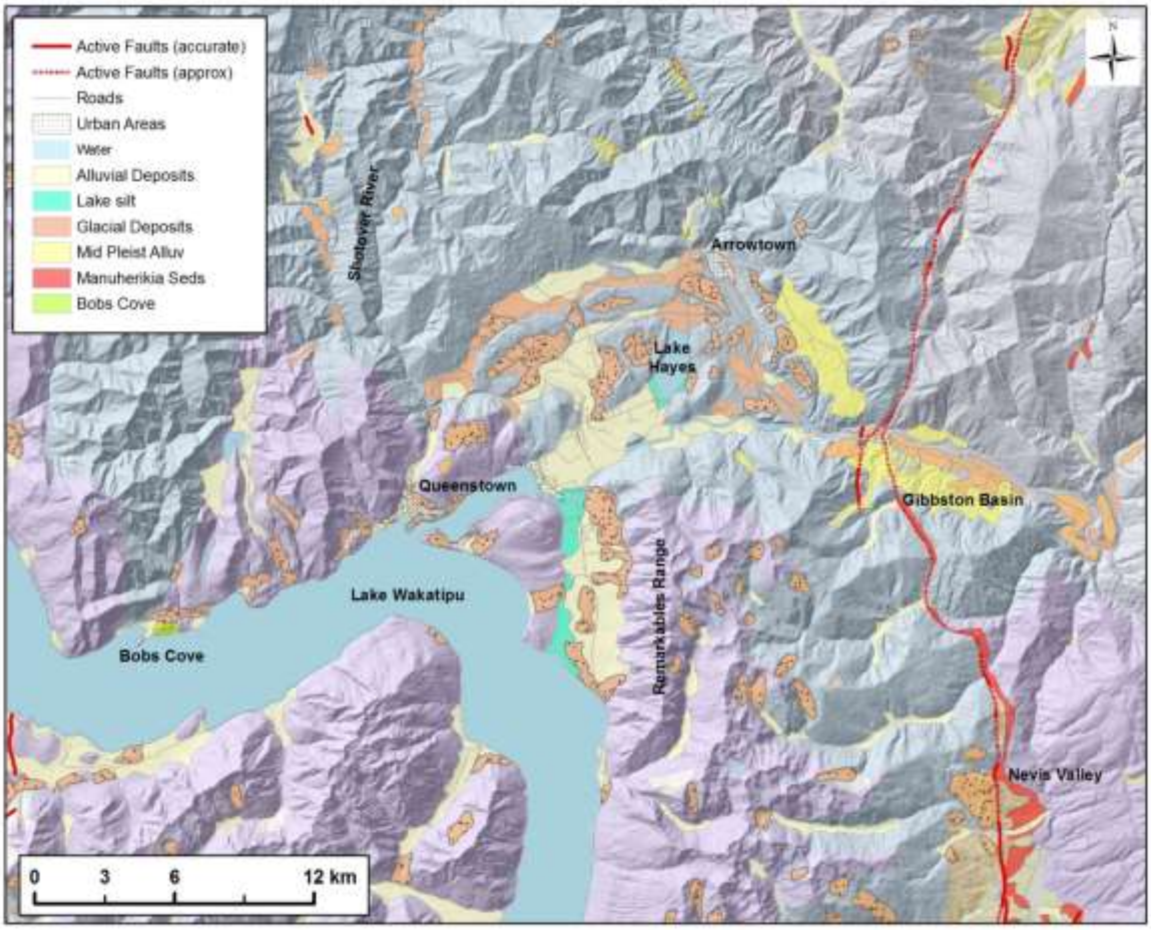

Figure 33. Geology of the Wakatipu area. The pale blues and purples are varying metamorphic grades of schist bedrock. Glacial (undifferentiated) and alluvial deposits occupy most of the valleys and lower hillslopes. Lake silts were deposited during a higher lake level. Isolated outcrops of the Tertiary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

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 show evidence of postglacial deformation.

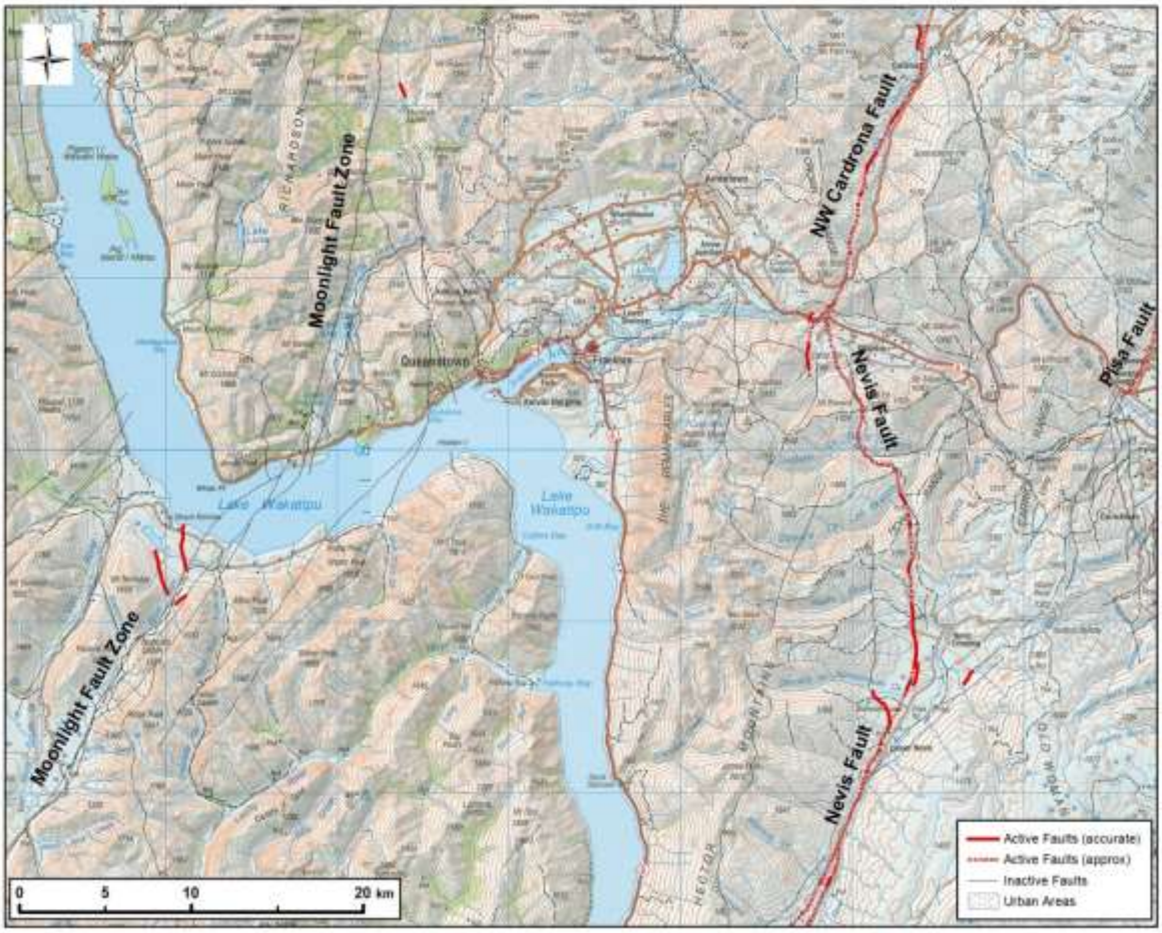

Figure 34. Topographic map of Wakatipu area showing active and inactive faults (New Zealand Active Fault Database, GNS))

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.

Fault name	Fault length (km)	Slip sense	Slip rate (mm/yr)	Moment magnitude (M_W)	SED (m)	Rec. interval (yrs)	Q-town dist. (km)
Alpine	411	SS	27	8.1	9.2	340	85
Cardrona north	34	RS	0.38	7.0	2.4	6200	40
Cardrona south	28	RS	0.38	6.7	2	5100	21
Grandview	32	RV	0.1	7.0	2.2	22000	60
Pisa	47	RV	0.1	7.2	3.3	31000	38
Nevis	69	RV	0.4	7.5	4.8	12000	22
Dunstan	63	RV	0.63	7.4	4.4	7000	55
Ostler	68	RV	1.43	7.4	4.7	3310	110
Moonlight north	88	RV	1	7.6	6.1	6100	8
Moonlight south	100	RV	1	7.6	7	7000	37

Table 4.1 **Major active faults near the Wakatipu Basin. SED = Single event displacement, Q-town dist. = Closest point of fault to Queenstown. Slip sense: RV = Reverse, SS = Strike slip, RS = Reverse slip. (Stirling *et al*., 2012). Note that the recurrence intervals are estimates.**

The Moonlight Fault Zone is a major fault structure that strikes NW-SE across the middle of Lake Wakatipu. The fault is considered to be 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 that 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, which is 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 6,000 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 Manapouri. The southern section of the Moonlight Fault is 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 7,000 years.

4.1.3. Glacial history

The Wakatipu Basin 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 about 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, about 500 m above the current lake level.

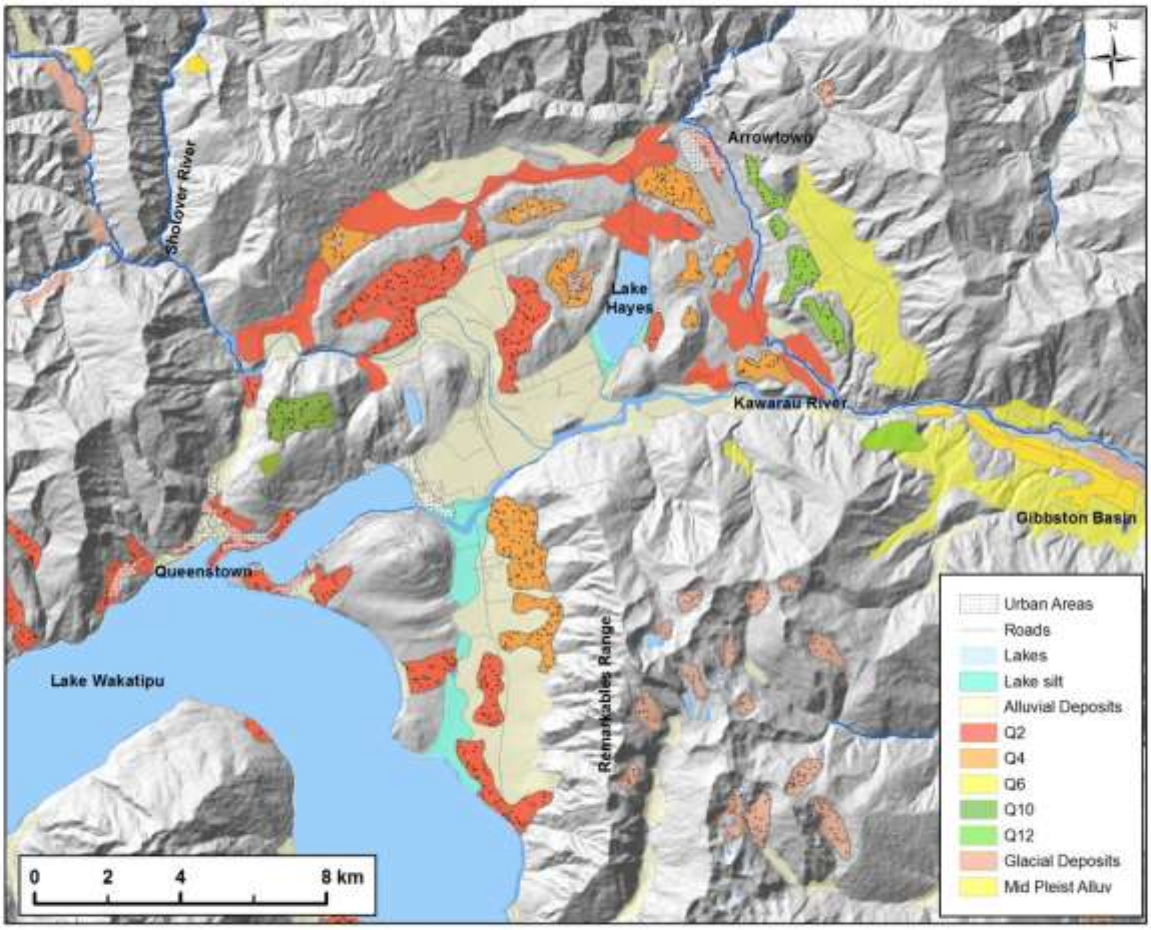

Figure 35. Glacial deposits in the Wakatipu area. 'Q' denotes glacial age based on Oxygen isotope stage (See Appendix C.) (Modified from QMAP (Turnbull, 2000))

About 17,000 years ago, the ice retreated, leaving a large lake at a level of ~351m, 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).

About 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 about 2,000 years ago, likely controlled by incision of the Kawarau River into the Shotover delta. From about 2,000 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), with 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 2,000 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, which extended 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, then along the Kawarau River just downstream of the SH6 bridge near Frankton, and in the lowlands between Jacks Point and the Remarkables.

These areas that have a surficial sequence of subaqueous sediments (delta deposits, lake silt) are also the main 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 the present). The Wakatipu area has experienced two earthquakes greater than M_W 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 M_W 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 M_W 5.8 earthquake that occurred on 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).

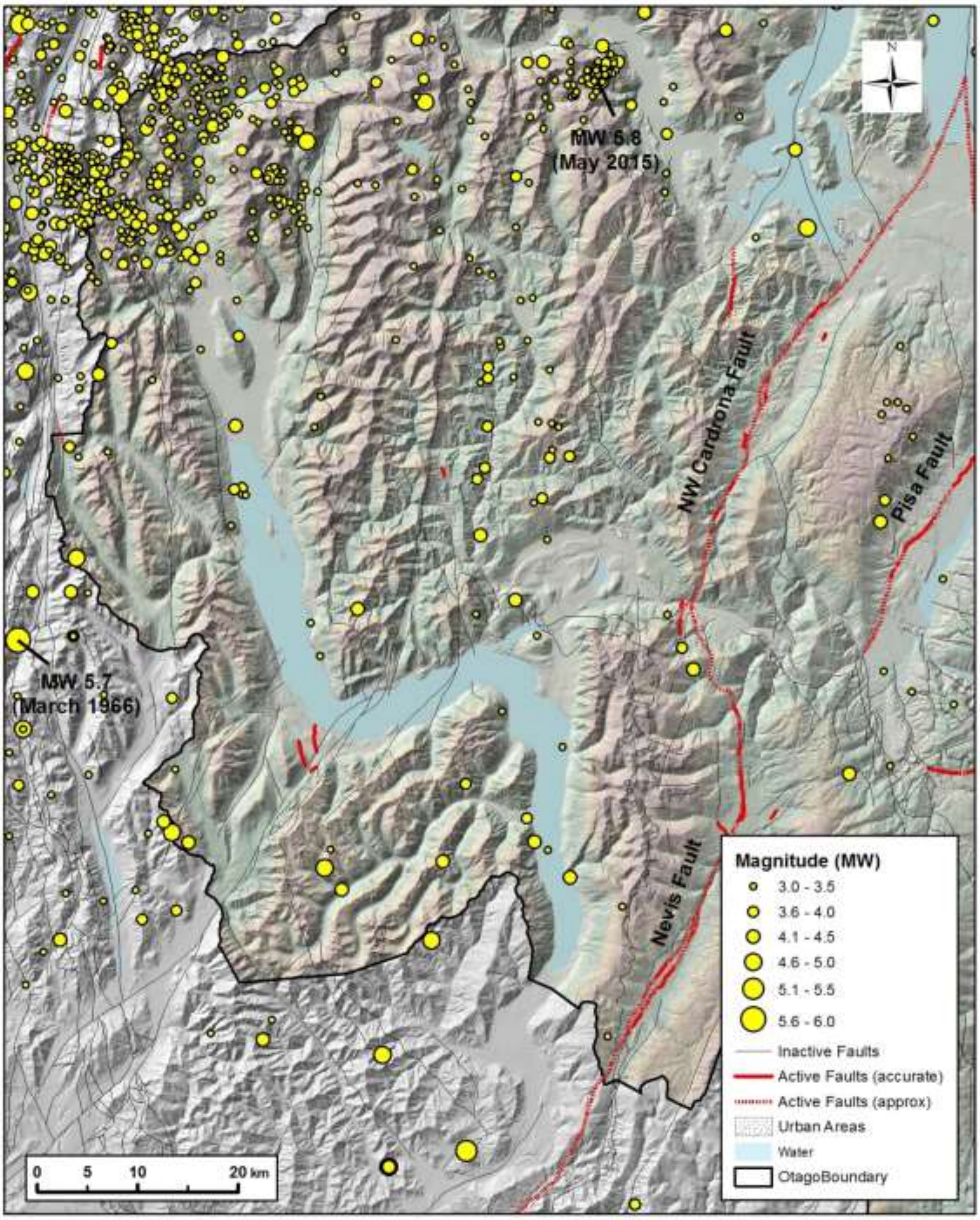

Figure 36. Historic seismicity in the Wakatipu area, with earthquakes larger than M_W 3.0 from 1942 – July 2015. Two earthquakes larger than M_W 5.5 have been recorded over that period (labelled). The highest concentration of earthquakes occurs towards the Alpine Fault in the northwest of the mapped area. The Alpine Fault is 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 that 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 Bobs 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

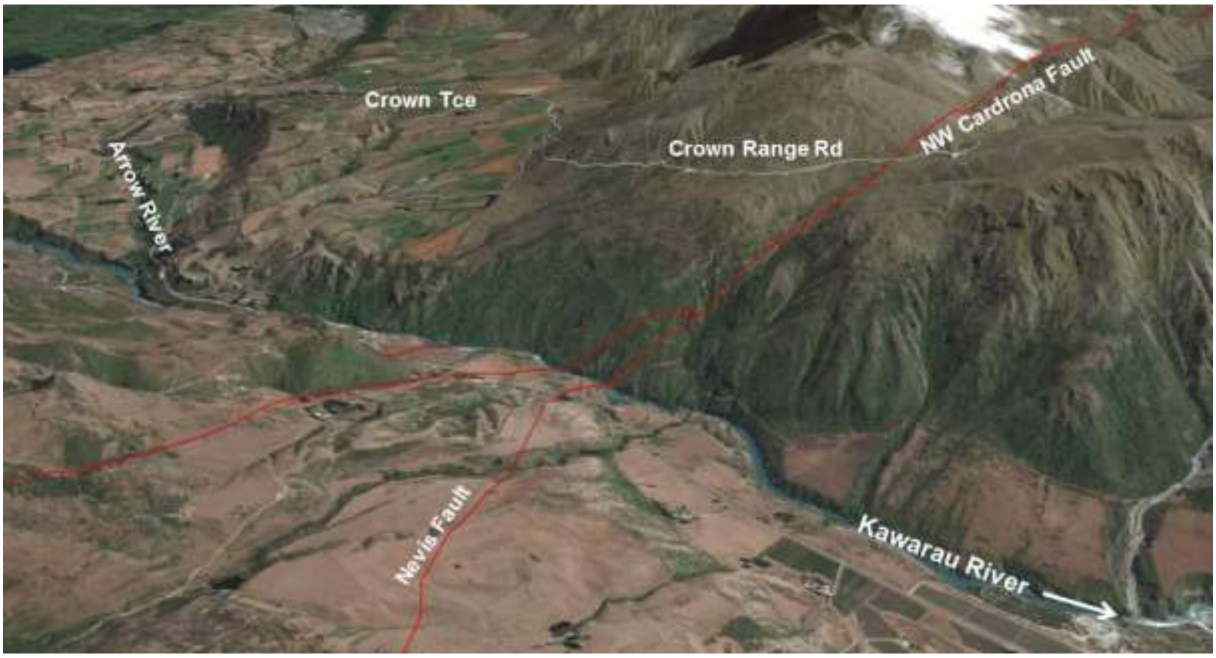

Figure 37. Oblique view of the upper Kawarau Gorge towards the northwest. The Nevis-Cardrona Fault (red) runs across the gorge and continues along the Cardrona Valley. The trench in Figure 38 is across the upstream-most strand (Kawarau Trace). The fault runs through a large landslide complex on the north 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 Nevis-Cardrona Fault System. 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 that 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 that 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 of the fault-zone area are known to cross the valley downstream of the Kawarau suspension bridge used for bungy jumping.

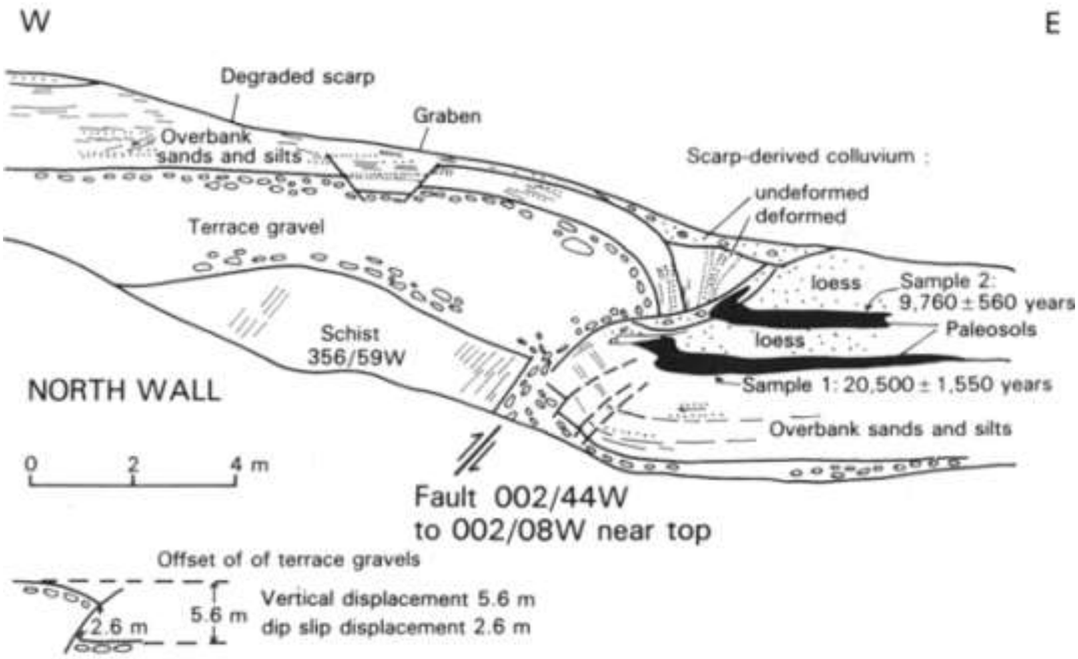

Figure 38. Cross section through the Kawarau trace of the Nevis Fault on the terrace above the Kawarau River. Evidence for three earthquakes can be seen in the deposits, which date to up to 23,000 years old (Beanland and Barrow-Hurlbert, 1998).

Rupture of the Nevis-Cardrona Fault System through the Kawarau Valley would cause direct damage to land and assets on and close to the trace. SH6, 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, and 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 3.3.6, the Wakatipu area, like the Upper Clutha, should 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 2,500 years is MMIX (Figure 39) (Murashev and Davey, 2005).

Based on the 2010 New Zealand National Seismic Hazard Model (Stirling *et al*., 2012), Queenstown shallow-soil sites have an expected maximum PGA of 0.25 g over a 475-year period (Figure 19), and 0.6 g over a 2,500-year period.

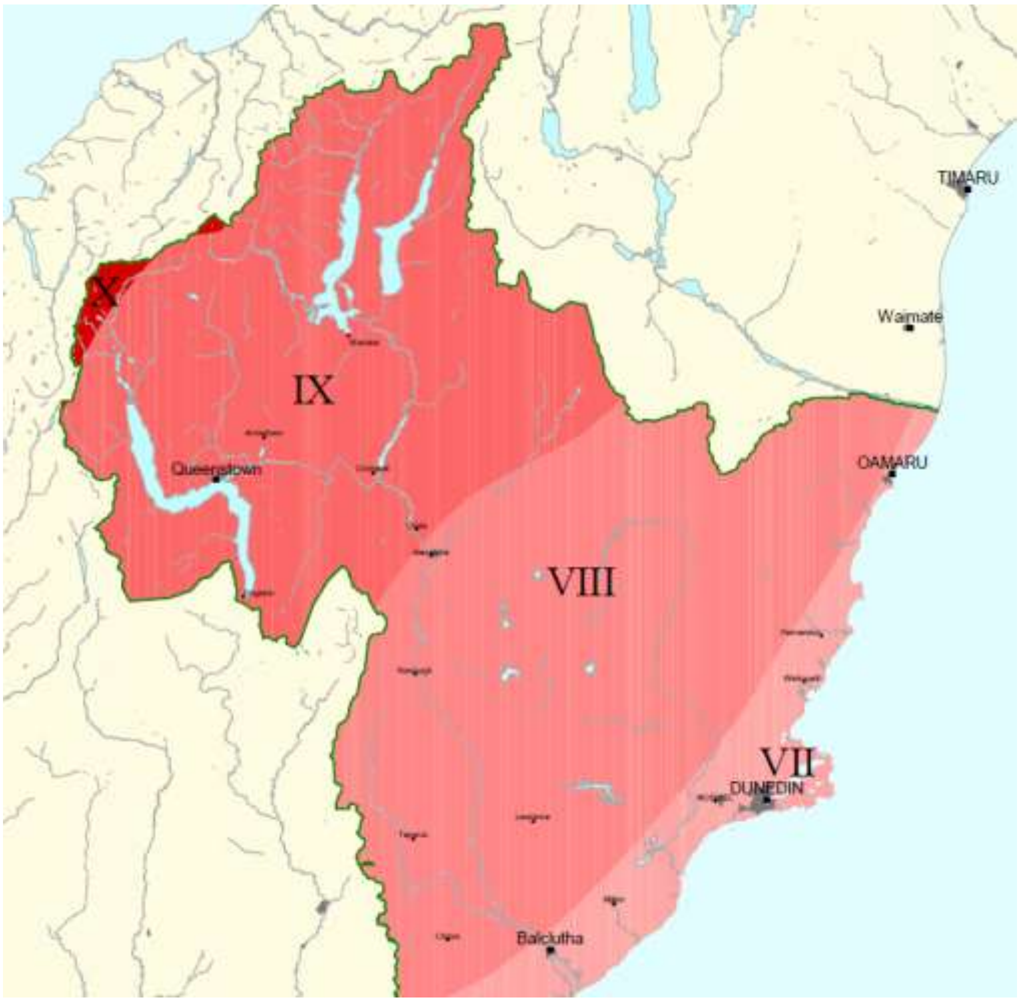

Figure 39. Map of Otago region showing MM intensity expected to be exceeded once in 2,500 years (Murashev and Davey, 2005). (See also Figure 18 for 100-year exceedence map.)

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 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 roads cut through the mountains.

Although the landscape may be attuned to Alpine Fault earthquakes, 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 or 'erratic' 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 those on 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 M_W 5.8 earthquake in May 2015 showed most landscape disturbance such as visible cracking and landslides to be focused on ridgelines (Cox *et al*., 2015).

Seismic waves can also become trapped within sedimentary basins, reflecting off 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 being most damaging to low buildings such as residential dwellings. Shallow soils are probably common among the scoured schist outcrops in the low-relief Wakatipu Basin, near Arrowtown and Lake Hayes.

4.2.6. Tectonic movement

As well as causing strong ground motion, fault movement can permanently deform the ground surface. Faults in the Wakatipu area generally have a reverse mechanism, meaning that the offset is primarily vertical, as opposed to the sideways movements 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 that 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 that 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 focused 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 Tonkin & Taylor study drew upon earlier 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
- saturation, usually through a high water table
- 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.

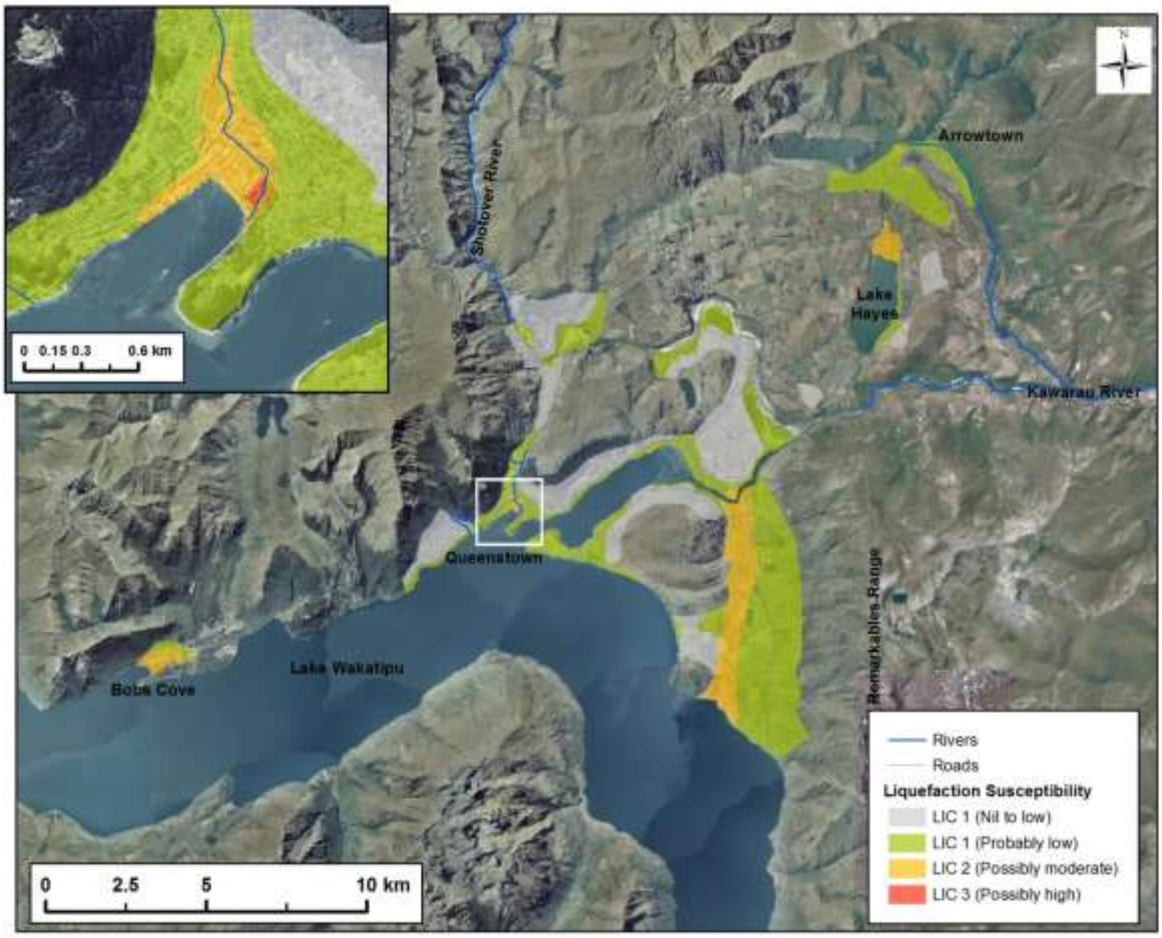

Figure 40. Map of liquefaction risk in the Wakatipu region assessed by Tonkin & Taylor Ltd (2012) for the Queenstown Lakes District Council. The most susceptible layers are river courses and lake-margin areas, particularly areas underlain by lake silts. The inset shows the downtown Queenstown area. The 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 to be 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, including modern deltas, as well as deltas that formed during previous lake high stands and that are now exposed around the lake margin. Downtown Queenstown is largely built upon a delta constructed by outflow from Horne Creek into the formerly enlarged Lake Wakatipu.

- Hollows or depressions across moraines (such as kettle lakes) or outwash surfaces that 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 metres 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 unbuttressed 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, bridges or underground 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 metres) back from the edge of the affected bank.

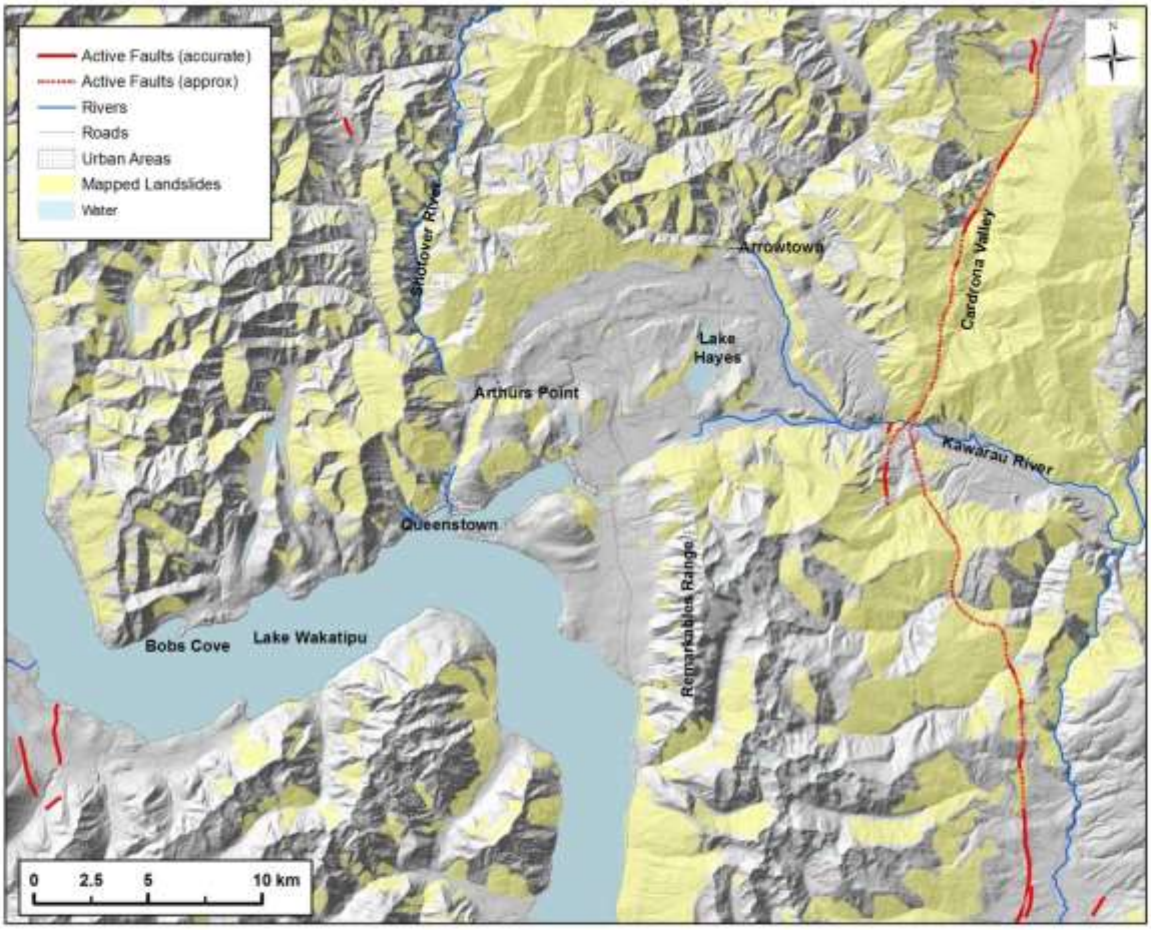

Figure 41. Mapped areas subject to mass movement hazards in the Wakatipu area (ORC Natural Hazards Database)

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 greatest 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 the 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 possibly 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 also likely to be affected by rockfall. The Nevis-Bluff area in Kawarau Gorge is a well-known rockfall site, which has affected 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 the 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. Prehistoric 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 to becoming 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.

Figure 42. Oblique view towards the foothills of the southern Remarkables Range. SH6 runs across the lower view, with Lake Wakatipu on the lower right. Large boulders, probably 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 (Google Earth).

4.3.2.3. Rock avalanches

Rock avalanches are a devastating type of landslide involving the rapid, flow-like motion of rock fragments. The 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 prehistoric 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 runout 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 km^2 (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 they cause total destruction to anything in the runout 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.

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 Coronet Peak between Arrowtown and Arthurs Point. Given the importance of slope hydrology in modulating movement of large landslides, the use of landslide head-scarp 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 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).

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, for example, 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, the Moonlight Fault is not considered active, but it is assigned a presence in the New Zealand 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 that 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 that 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 coincides 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 M_W 9.2 1964 Alaska earthquake, a distance of thousands of kilometres 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 prehistoric earthquake.

The influx of sediment to steep channels will increase the risk of debris flows and channel avulsion, thereby 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 the potential to become more active if the headwaters are innundated 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).

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 the photo is intended to focus the Shotover flow to the right (2013).

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 the elevation of the river-bed level 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 metres along hundreds of metres 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 prehistoric 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 that 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, despite the fact that multiple Alpine Fault earthquakes have shaken the Queenstown Lakes district.

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[3], 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; Tonkin & Taylor, 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 assess the liquefaction risk in areas of future development efficiently.

[3] 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, 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 February 2011 Christchurch earthquake, and other earthquakes on reverse faults, indicates that the hanging wall can experience shaking intensities 50% greater than predicted, due to focusing 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 the potential to generate high-frequency shaking to those areas 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) The most recent scientific assessment of the Nevis and NW Cardrona faults was 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., Akatore, 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 5,000 mapped boulders fell in residential areas, with some runout 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

The outlets of lakes Wakatipu and Wanaka are both 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 kilometres 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 undetected 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.

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Appendix A – Measuring earthquake size and shaking intensity

Earthquake-shaking intensity is traditionally measured using the Modified Mercalli (MM) intensity scale (e.g., Dowrick *et al*. (1996), shown in Appendix E). The MM scale qualitatively describes how strong shaking is at a given location, and ranges from barely felt (MMI) to destruction of buildings (MMXII). The MM 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 components 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 especially 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 PGVs and PGDs, whereas higher-frequency (short period) waves cause higher PGAs.

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 storey 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 NW 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 most severe peak-ground accelerations, and can be highly destructive. In Wanaka, an Alpine Fault earthquake will be dominated by sustained long-period waves.

Beyond buildings, high-frequency seismic waves can affect the natural landscape differently than low-frequency waves. High PGAs 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 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 region's varied geologic history.

For much of the Tertiary[4] period, Central and West Otago were tectonically quiescent low-relief regions 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 five 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 next to and on the underside of faults, but they can be seen locally across the area (Figure 11). Generally, these cover rocks have been stripped of 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 of these older rocks.

Parts of the Wakatipu region were formerly below sea level, indicated by Late Oligocene marine rocks preserved at Bobs 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

[4] 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).

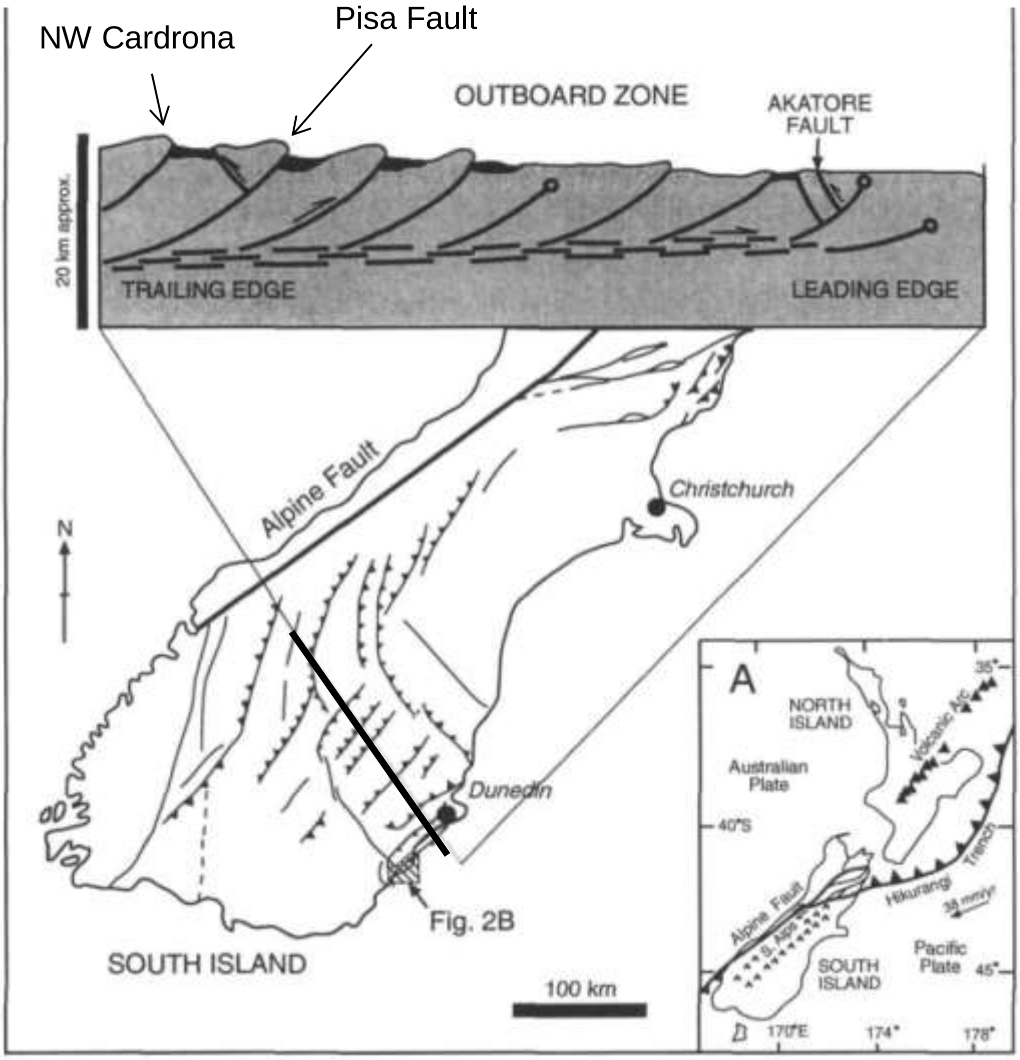


Figure 47. Major faults form a series of tilted blocks across the Otago region. The NW Cardrona Fault and Pisa Fault are the western-most faults (from Litchfield and Norris, 2000).

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 seven 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 that 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 Wanaka and Hawea.

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

Glacial advance	Approximate age (yrs)	Oxygen isotope stage
Hawea	**16 000 – 18 000**	**2**
Mt Iron	**23 000**	**2**
Albert Town	**59 000 – 71 000**	**4**
Luggate	**128 000 – 186 000**	**6**
Lindis	**423 000 – 478 000**	**12**
Loburn	**620 000 – 659 000**	**16**
Northburn	**~ 1Myr**	

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.

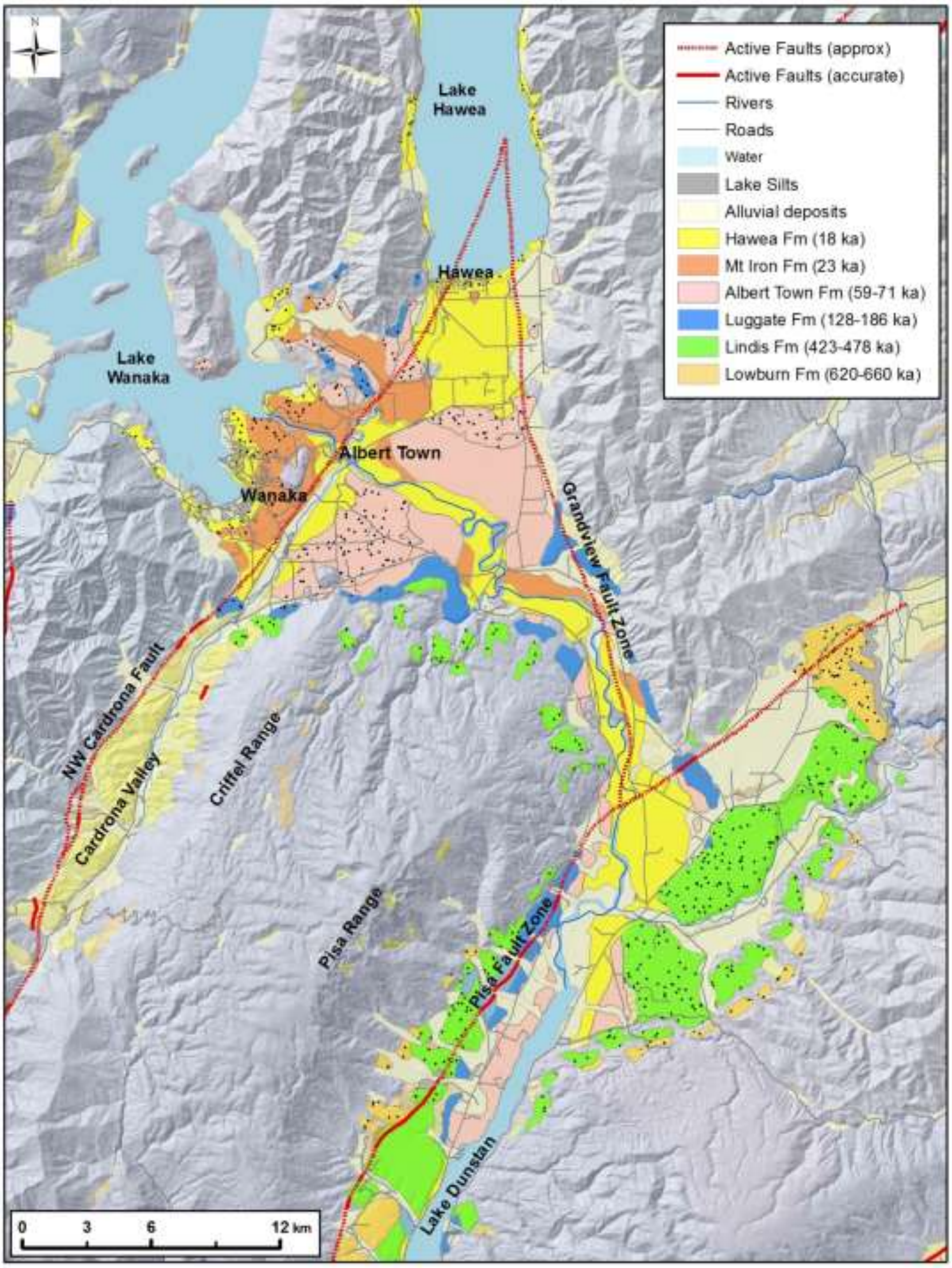
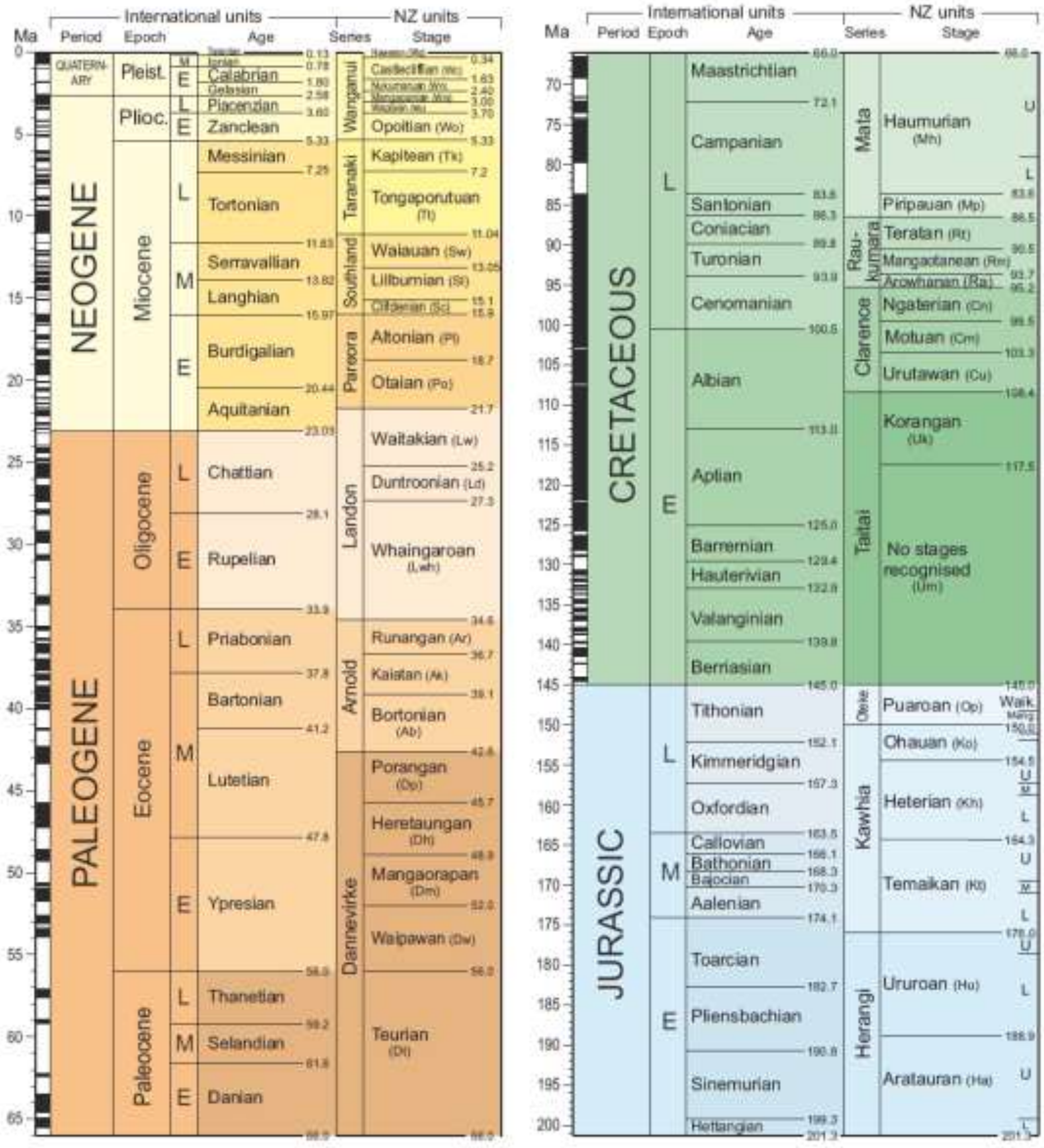


Figure 48. Glacial advances in the Upper Clutha area. Each advance has a moraine (stippled) and an associated outwash plain (modified from QMAP (Turnbull, 2000)).

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 Mt Iron, present gently sloping, ice-scoured faces in the direction of ice flow, but steep, blocky cliffs on the down-stream side, which are 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 to present) (from GNS Science)

Appendix E – Modified Mercalli earthquake intensity scale

Dowrick, D J (1996) 'The modified Mercalli earthquake intensity scale; revisions arising from recent studies of New Zealand earthquakes.' Bulletin of the New Zealand National Society for Earthquake Engineering, 29 (2): 92-106.

Level	Description
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 <u>Type I</u> cracked. A few earthenware toilet fixtures cracked.

Level	Description
MM 6	*People* Felt by all. People and animals alarmed. Many run outside. Difficulty experienced in walking steadily. *Fittings* Objects fall from shelves. Pictures fall from walls. 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* 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.
MM 7	*People* General alarm. Difficulty experienced in standing. Noticed by motorcar drivers who may stop. *Fittings* Large bells ring. Furniture moves on smooth floors, may move on carpeted floors. 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 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, wet or weak soils. Some fine cracks appear in sloping ground. A few instances of liquefaction (i.e. small water and sand ejections).
MM 8	*People* Alarm may approach panic. Steering of motorcars greatly affected.

Level	Description
	Structures 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. *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.
MM 9	*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.
MM 10	*Structures* Most buildings Type I destroyed. Many buildings Type II destroyed. Buildings Type III heavily damaged, some collapse. Structures Type IV damaged, some with partial collapse. Structures Type V moderately damaged, but few partial collapses. A few instances of damage to structures Type VI. Some well-built timber buildings moderately damaged (excluding damage from falling chimneys). *Environment* Landsliding very widespread in susceptible terrain, with very large rock masses displaced on steep slopes. Landslide dams may be formed. Liquefaction effects widespread and severe.
MM 11	*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.

Level	Description
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 such as 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.