General distribution and characteristics of active faults and folds in the Queenstown Lakes and Central Otago districts, Otago

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EXECUTIVE SUMMARY

This report presents a general outline of the locations and character of active geological faults and folds in the Queenstown Lakes and Central Otago districts. The work described in this report is based on a desktop review of information from regional-scale geological mapping, and from more detailed published or open-file geological studies relevant to understanding active faults in the two districts. This project involved the compilation of a Geographic Information System (GIS) dataset that gives the locations of active faults and folds delineated in the two districts. The interpretation and geographic positioning of the fault and folds was aided, where available, by topographic information from airborne lidar scans (laser radar), and from satellite, aerial or ground-based photographic archives.

A fault is a fracture within the rock of the Earth's crust, along which movement has occurred. Commonly, strain builds up in the rock of the Earth's crust and is released suddenly by a slip event (rupture) on a fault, causing an earthquake. Folds represent bending or buckling of rock and are usually associated with an underlying fault. A fault or fold is termed 'active' where it has moved in the geologically–recent past, particularly where the movement has been sufficiently large to have emerged at the ground surface, forming offset and breakage of the ground (fault), or buckling or tilting of the ground (fold). Old landforms of uniform character, such as river terraces formed during the last ice age which ended about 18,000 years ago, are well suited for revealing the presence of active faults or folds, because they may be old enough to have experienced several rupture events and display large offsets or buckles. In areas where the land surface is younger than the most recent fault or fold movements, the presence and location of any active faults or folds may be 'concealed' from view beneath the landform. In this way, active faults or folds are most easily recognised where the landforms are old (e.g. ice-age river terraces), but much more difficult to recognise in areas where landforms are young (e.g. river floodplains).

Commonly, an active fault reaches the ground via a zone of splintering, which in some cases may be as much as several kilometres wide. Individual splinters (strands) can be expressed as fault offsets of the ground surface, as ground-surface folds, and commonly as a mixture of both. Although some individual strands have been named separately, the GIS dataset applies an overall specific name to each active fault structure, whose movements at depth have produced an array of ground-surface fault and/or fold strands. Many of the faults have been named previously, and those names are used here unless reasons exist for applying a different name. As described in this report, a total of 48 named active, possibly active or potentially active faults have been delineated at the ground surface in the Queenstown Lakes and Central Otago districts.

The levels of certainty in recognising an active fault and fold, and their clarity of expression at the ground surface, are included in the GIS dataset. The report contains a tabulation of estimated average slip rate and surface-deformation recurrence interval for each fault, in relation to Ministry for the Environment guidelines on planning for development of land on or close to active faults. Also highlighted in the report is increasing recognition that in the Otago region, many of the faults undergo long periods without movement, which makes it difficult to estimate their level of activity. This difficulty is accommodated by the addition of a classification category of 'potentially active', to encompass faults that despite showing no indications of geologically-recent activity, have characteristics that mean the possibility of future activity should not be ruled out.

Potential hazards associated with active faults include: (i) sudden ground-surface offset or buckling at the fault which may result, for example, in the destruction or tilting of buildings in

the immediate vicinity; (ii) strong ground shaking from locally-centred large earthquakes, and; (iii) related earthquake-induced effects such as landsliding and liquefaction in areas susceptible to such processes. No large, ground-rupturing, earthquakes have been centred within the Queenstown Lakes or Central Otago districts since European settlement in the mid-1800s. However, the nature of hazards posed by active faults was well demonstrated during the 2010 Darfield and 2016 Kaikōura earthquakes, both of which caused ground-surface rupture and land shift along faults and the effects of severe ground shaking were experienced across wide areas. The landform record shows definitive evidence for prehistoric fault deformation having occurred at various locations in the Queenstown Lakes and Central Otago districts. This highlights that active fault or fold features in the Otago region should be assessed for their hazard potential.

The GIS map of active faults and folds in the Queenstown Lakes and Central Otago districts is derived from regional (~1:250,000) scale geological information, and is of a generalised nature, with details omitted to aid the clarity of presentation. Information in this report and in the companion GIS dataset highlights areas potentially affected by active fault or fold hazards and the information is intended to help the targeting of any future active fault investigations that may be deemed necessary. This report provides the most up-to-date information available on the locations and nature of active faults and folds in the Queenstown Lakes and Central Otago districts. It is intended to create general awareness of the existence of the potential hazards but the level of detail in the GIS dataset is not sufficient by itself for use in site-specific zoning to avoid fault-generated ground deformation hazards.

1.0 INTRODUCTION

1.1 Background

The geologically-active nature of New Zealand reflects our position astride the active boundary between two large slabs (plates) of the Earth’s crust (Figure 1.1). The forces involved in plate movement (tectonic forces) are immense and cause the rock of the Earth’s crust to buckle (fold) and fracture (fault) in the general vicinity of the boundary between the plates. The plate boundary through the South Island is marked, at the ground surface, by a sideways tear, the Alpine Fault, and in the northern South Island, by a companion set of tears, the Marlborough Fault System. Although these large faults accommodate most of the plate motion, the remainder is distributed over a wider zone across much of the South Island. The Queenstown Lakes and Central Otago districts lie within this wider zone of tectonic deformation.

Movement on the Alpine Fault is predominantly sideways, with the western side of the fault moving northeast, and the eastern side moving southwest as well as a little bit upwards, which has produced the Southern Alps. The technical term for a sideways-moving fault is ‘strike-slip’, while a fault where the movement is mostly up-down is called ‘dip-slip’. In the south-eastern South Island, including the Queenstown Lakes and Central Otago districts, the relatively small proportion of the plate movement not accommodated on the Alpine Fault is distributed on a series of predominantly dip-slip faults, that are the focus of this report.

Although the movement along the plate boundary is continuous over geological time and can be measured by ground and satellite (GPS) surveying, rock of the Earth’s crust is remarkably elastic and can accommodate a lot of bending before letting go and breaking suddenly (rupturing) along a fault, causing an earthquake. On large faults, the break may be big, and extend up to the Earth’s surface, causing sudden offset and breakage (faulting), and/or buckling and warping (folding), of the ground surface, accompanied by a large earthquake. The 2010 Darfield and 2016 Kaikōura earthquakes provided good examples of the nature and effects of large, ground-surface-rupturing earthquakes on geological faults (e.g. Barrell et al. 2011; Litchfield et al. 2018) (Figure 1.2).

In favourable settings, prehistoric fault offsets and/or fold buckles of the ground may be preserved by way of distinctive landforms, and these landforms allow us to identify the locations of active faults and folds. In New Zealand, an active fault is commonly defined as a fault that has undergone at least one ground-deforming rupture within the last 125,000 years or at least two ground-deforming ruptures within the last 500,000 years. An active fold may be defined as a fold that has deformed ground surfaces or near-surface deposits within the last 500,000 years. Unfortunately, there are few reliable ‘clocks’ in the natural landscape (i.e., deposits or landforms with a known age) and, for practical purposes, it is common to identify as active any fault or fold that can be shown to have offset or deformed the ground surface, or any unconsolidated near-surface geological deposits (Figures 1.2, 1.3). This approach for identifying active faults or folds is used on most geological maps published in New Zealand and is followed in this report. It is also common to assess the significance of hazards associated with an active fault or fold by estimating how often, on average, it has undergone a ground-deforming rupture or deformation event (recurrence interval). The average recurrence interval is a primary consideration in Ministry for the Environment guidelines for the planning of land-use or development near active faults (Kerr et al. 2003; referred to henceforth as the MfE active fault guidelines).

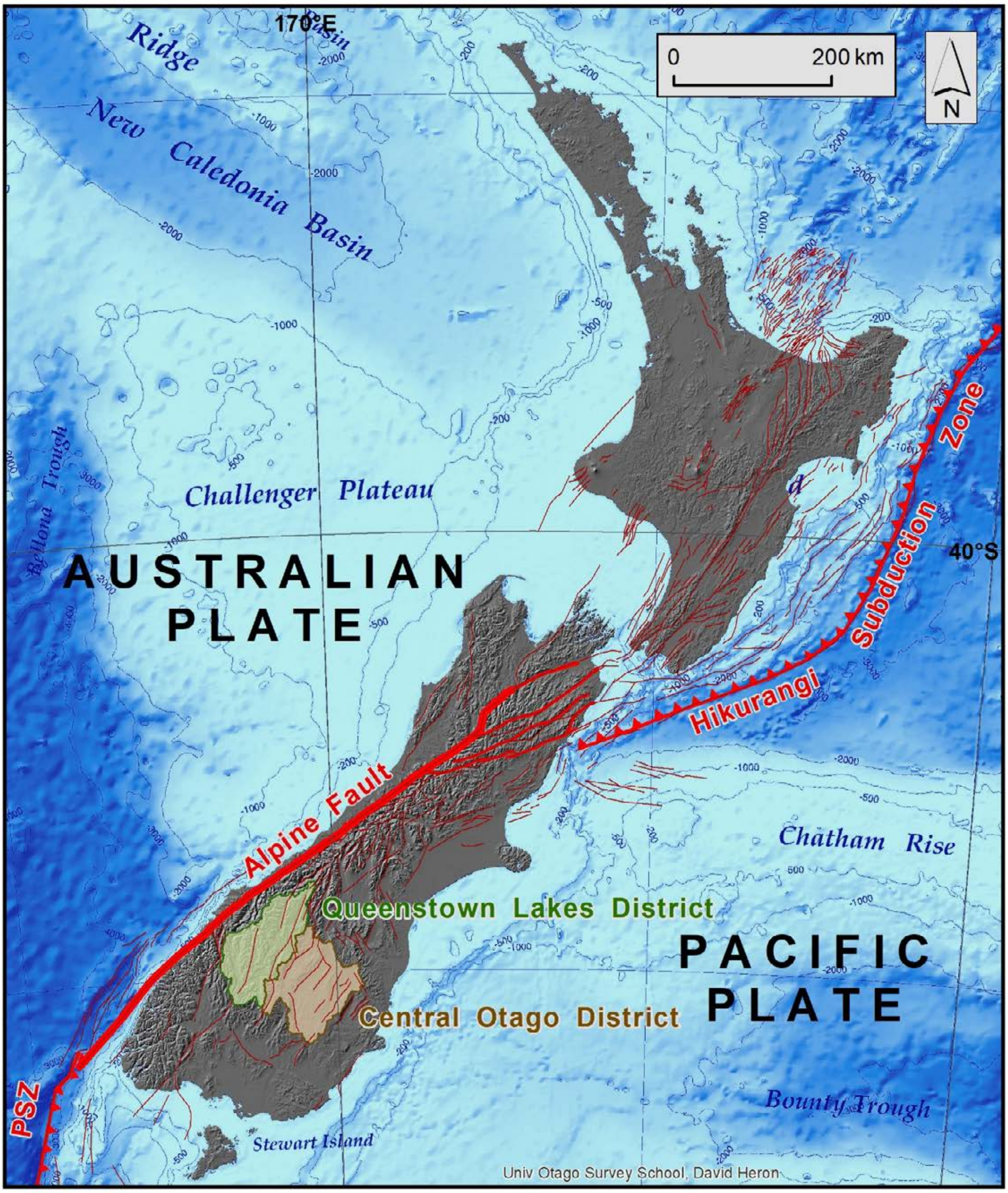

Figure 1.1 The tectonic setting of the Queenstown Lakes and Central Otago districts. The junction between the Australian and Pacific plates of the Earth's crust passes through New Zealand. The Pacific Plate pushes westward against, and under, the Australian Plate at the Hikurangi Subduction Zone, while at the Puysegur Subduction Zone (PSZ), the Australian Plate is being pushed down alongside the southwestern South Island. The Alpine Fault (thick red line) and the Marlborough Fault System (medium thickness red lines) transfer most of the plate motion between the two subduction zones, with the remainder accommodated across a wider zone of deformation marked by other active faults (thin dark red lines; from Litchfield et al. 2014). The offshore image is the New Zealand Continent map (GNS Science) showing shallower water in light blue and deeper water in darker blue. Bathymetric contours are in metres below sea level.

In the south-eastern South Island, including the Otago region, there are indications that many of the faults undergo episodes of several successive ruptures, interspersed with periods without rupture (e.g. Beanland and Berryman 1989; Litchfield and Norris 2000). This part of New Zealand also lies somewhat away from the locus of plate boundary deformation, and rates of strain on the Earth's crust are relatively slow. Recent research has shown that only half of the large historic earthquakes in New Zealand have occurred on faults that would have been recognised as 'active' under today's criteria (Nicol et al. 2016). A recent research study in coastal Otago advocated the consideration, in a seismic hazard context, of faults that have been active within the past few million years (Villamor et al. 2018). Accordingly, the present project has incorporated all faults that show substantial offset of the Otago peneplain, a prominent landscape feature that is the remains of an ancient land surface that was, originally, nearly flat and low-lying (see Section 3.1 for additional information).

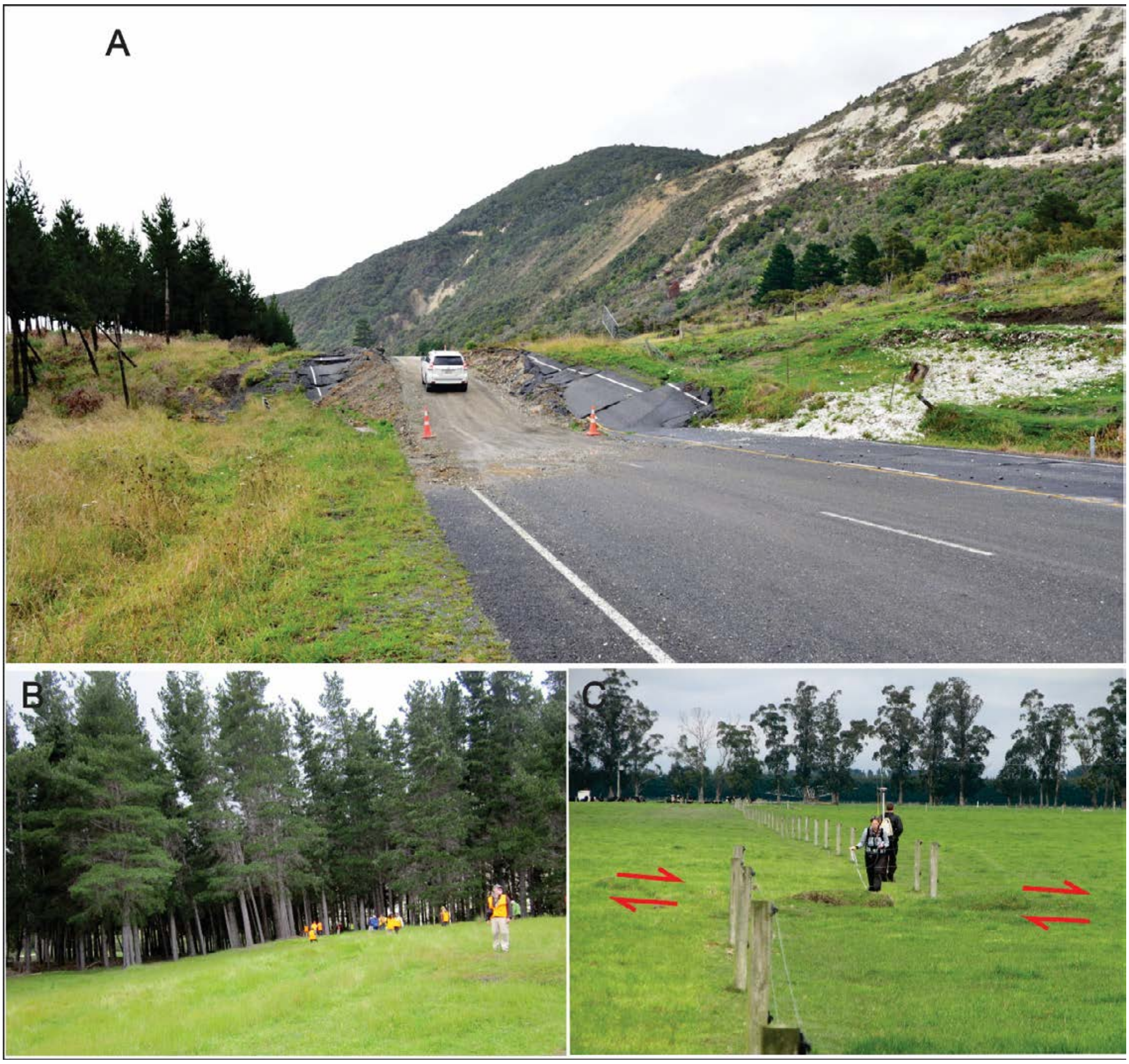

Figure 1.2 Illustrations of recent historical fault rupture deformation of the ground surface in New Zealand. **A**: Offset of State Highway 1 across the Papatea Fault, north of Kaikōura, that occurred during the 2016 Kaikōura Earthquake. The movement included several metres of upthrow as well as several metres of sideways shift to the left. Photo: GNS Science VML ID: 210453; D.B. Townsend. **B**: Monoclinal fold associated with the Papatea Fault rupture during the Kaikōura Earthquake, illustrated well by the tilting of the pine trees. The ground here was flat prior to the earthquake. Photo: GNS Science; D.J.A. Barrell. **C**: A fence offset sideways by ~4.5 m of strike-slip rupture on the Greendale Fault during the 2010 Darfield Earthquake. Photo: GNS Science VML ID: 137457; N. J. Litchfield. Half-arrows either side of the fault indicate the direction of movement, which here involved a shift to the right.

There are many active geological faults and associated folds recognised in the Otago region. As part of ongoing improvements in the recognition and mitigation of natural hazards, Otago Regional Council engaged the Institute of Geological and Nuclear Sciences Limited

(GNS Science) to summarise the state of knowledge regarding active faults in the Queenstown Lakes and Central Otago districts. This report presents that summary and is a companion to a similar report that addresses the Waitaki District (Barrell 2016).

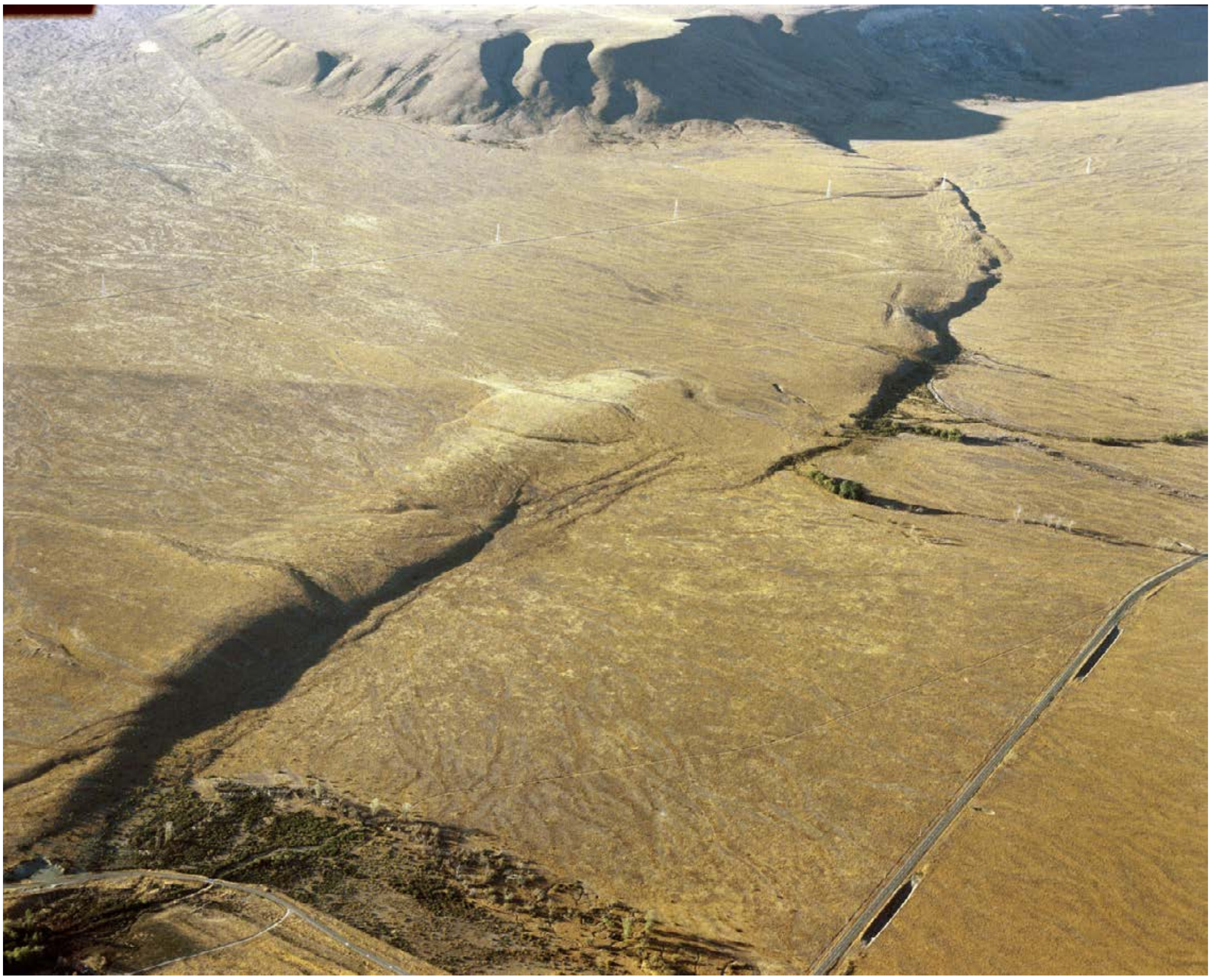

Figure 1.3 A northward oblique aerial view of ground-surface deformation across the Ostler Fault Zone, in the Waitaki District of Canterbury, about 12 km southwest of Twizel.The fault zone runs from lower left to upper right and has offset and buckled a ~22,000-year-old glacial meltwater outwash plain, with well-preserved relict braided channels (Putnam et al. 2013). This location is one of the best expressed examples of fault deformation in New Zealand, because it is entirely across old landforms. This view shows complicated elements of main and subsidiary fault offsets and folds, across a zone that is several hundreds of metres wide. All these elements form part of a single entity, the Ostler Fault Zone. This figure is taken from Barrell (2016), where a more detailed description of the features in this view is provided. Photo: GNS Science, CN576/B and VML ID: 5151. D.L Homer, taken 1995.

1.2 Scope and Purpose

This project comprised an office-based review of existing information, focused on delineating the locations and evaluating the characteristics of known or suspected active faults and folds in the Queenstown Lakes and Central Otago districts. The main product of the project is a Geographic Information System (GIS) map dataset that includes information on the certainty of identification of an active fault or fold feature, and the clarity of its topographic expression at the ground surface. The report includes tabulated information on estimated degree of activity, expressed as average slip rate and earthquake recurrence interval, for each fault (see Section 5). Also indicated are relationships between information in this dataset and the MfE active fault guidelines (Kerr et al. 2003) for fault complexity categories (well defined, distributed, or uncertain) and estimated recurrence interval classes.

The main aim of the work is to provide datasets that highlight locations in the Queenstown Lakes and Central Otago districts where active faulting may be a hazard to look for and be aware of. The information in this report is intended to assist local authorities in delineating the general areas of the Queenstown Lakes and Central Otago districts that are potentially subject to active fault and fold hazards, particularly those hazards related to ground-surface fault rupture and/or folding deformation.

The precision of regional-scale fault mapping is not sufficiently accurate for site-specific use (e.g. at property boundary scales), and specific hazard zonation was outside the scope of the project. The dataset presented here is not intended to be used directly for hazard zoning, but rather to serve as a tool for hazard zoning prioritisation. Thus, a goal of the dataset is to highlight areas where more detailed mapping and site-specific fault avoidance zonation should be considered if substantial building or other infrastructural development is proposed.

2.0 INFORMATION SOURCES

At least four different nationwide datasets in New Zealand provide information on active faults. One is the GNS Science 1:250,000 scale QMAP (Quarter-Million scale map) regional geological map digital database (Heron 2014), which provides, via mapped lines, the general locations and geological characteristics of active faults and folds. Another is the publicly-available New Zealand Active Faults Database (NZAFD; see reference list and also Langridge et al. 2016), which represents the locations of active faults at a nominal scale of 1:250,000, and indicates the general degree of fault activity. In the south-eastern South Island, the NZAFD is based mainly on the QMAP dataset. A third dataset is a national-scale model of active faults (New Zealand Active Fault Model; NZAFM), described by Litchfield et al. (2013, 2014). The NZAFM shows highly generalised locations of active faults, at a nominal scale of about 1:1,000,000. The main purpose of the NZAFM is to quantify the kinematics of near-surface permanent deformation across New Zealand resulting from plate motion. A fourth dataset is the New Zealand National Seismic Hazard Model (NSHM; Stirling et al. 2012), which employs highly generalised locations and characteristics of active faults as earthquake sources for estimating probabilities of levels of earthquake ground-shaking at locations throughout New Zealand. The NSHM linework depicting the locations of active fault earthquake sources is approximately the same as in the NZAFM. A fifth type of active fault dataset comprises information of district or regional-extent held by territorial or regional governmental authorities. An example is Environment Canterbury's 1:250,000-scale active fault datasets, described by Barrell et al. (2015). The active fault dataset described in the present report is of the fifth type.

The five types of active fault datasets have differing purposes, and some are more locationally-accurate at different scales. Most of the datasets have differences in regard to fault locations and extents. The locations of active faults represented geographically in the NZAFM and NSHM are much less detailed and less accurate than in the other datasets.

For the present project, the QMAP dataset was the primary information source, because it encompasses active faults and folds, whereas the NZAFD dataset is confined to active faults. The nationwide QMAP digital dataset (Heron 2014) is derived from a sheet-by-sheet series of published geological maps, represented in the Queenstown Lakes and Central Otago districts by the Wakatipu map (Turnbull 2000; westernmost parts of both districts), Haast map (Rattenbury et al. 2010; headwaters of the Wanaka and Hawea catchments), Murihiku map (Turnbull and Allibone 2003; southernmost part of Central Otago District) and the Waitaki map (Forsyth 2001; eastern part of Central Otago). Appendix 1 presents a brief description of the GIS structure of the active fault and fold dataset that forms a companion to this report. Additions and refinements to the QMAP input dataset are described in Appendix 2 of this report. Some more detailed studies have contributed to the information provided in this report and the companion digital dataset. Where relevant, those studies are discussed in Appendix 2, along with general commentary on aspects of the existing information and explanations of the interpretations adopted in this report for each active fault. The interpretation and geographic positioning of the fault and fold features as aided, where available, by topographic information from airborne lidar scans (laser radar), and by information from satellite, aerial or ground-based photographic archives, including Street View accessible through Google internet services.

Although the work described in this report did not include site investigations or field inspections, the writer has extensive experience of the assessment area, arising from previous geological investigations and inspections over the past 25 years.

3.0 GEOLOGICAL OVERVIEW

3.1 Rocks and Landforms

In the south-eastern South Island, including the Queenstown Lakes and Central Otago districts, the oldest underlying rock (basement rock) consists mainly of hard sedimentary rock (‘greywacke’) and its metamorphosed equivalent (schist). These ancient rocks, of Permian to Jurassic age (between 300 and 145 million years old) were buried by a blanket of younger sedimentary rocks (cover rocks) including coal measures, quartz sands, mudstones, limestones and gravelly conglomerates, and some volcanic rocks, ranging in age from ~110 million years ago (middle of the Cretaceous Period) to about 2.5 million years ago. Collectively, the basement and cover rocks constitute what may be called ‘bedrock’. The cover rocks provide useful reference markers for identifying faults and folds. The well-developed sedimentary layering readily shows offsets due to faulting, while the tilting of these layers may reveal the effects of folding. In much of the hill to mountain terrain of Otago, uplift and erosion has stripped away large areas of the cover rock blanket, exposing the underlying basement rock that forms the main ranges. In many places, remnants of the cover rocks lie preserved on the downthrown, low-lying, sides of major faults. The cover rocks are more widely preserved in eastern Otago.

A valuable reference landform in Otago is the exhumed boundary between the basement and cover rocks (Otago peneplain) that is extensively preserved across Central Otago. Part of a widespread ancient land surface (Waipounamu Erosion Surface; Landis et al. 2008), the Otago peneplain was originally nearly flat and of gentle relief but following the development and propagation of the Australia-Pacific plate boundary through New Zealand about 20 million years ago, the Otago peneplain has been progressively offset and buckled by fault movement and fold growth associated with plate boundary deformation. Across the region, in many cases it is not clear when fault movement began. The best indications come from two faults that strike north-northwest. On the Blue Lake Fault, uplift was underway in the Middle Miocene epoch, sometime between 11 and 19 million years ago (Henne et al. 2011), while uplift and exhumation of the peneplain had occurred on the northeast side of the Waihemo Fault System by ~15 million years ago, shown by the dating of volcanic rocks that rest directly on basement rock (Coombs et al. 2008). General indications are that the northeast-striking faults, such as the Dunstan Fault Zone, developed after the north-northwest striking faults, because at least some of the latter faults have been deformed or offset by movement on the northeast-striking faults. It is suspected that most of the movement of the northeast-striking faults, with formation of the basin and range relief of Central Otago, has occurred in the past few million years, though evidence for this is patchy, and uncertainties remain (Villamor et al. 2018).

The youngest deposits of the districts are unconsolidated sediments whose nature and distributions are primarily a consequence of tectonic uplift and erosion of the mountain ranges and fluctuating climatic conditions during the latter half of the Quaternary Period (from about 1 million years ago to the present day). Uplift and erosion produced voluminous sediment that has been laid down in the basins, valleys and plains on top of the basement or cover rocks. A major feature of the Quaternary Period has been a cycle of large-scale natural shifts in global climate, with periods of generally cool conditions (glaciations, or ‘ice ages’) separated by periods of warmer climate (‘interglaciations’), such as that existing today. Ice-age glaciers that formed in the Southern Alps flowed down the main valleys of western Otago. Lakes Wakatipu, Wanaka and Hawea occupy troughs formed at the downstream ends of those glaciers. The last glaciation ended about 18,000 years ago, after which ice rapidly retreated into the mountains (e.g. Barrell et al. 2013). Wanaka and Hawea townships are built on terminal moraines formed by glaciers.

3.2 Recognition of Active Faults and Folds

The key evidence for recognising active faults or folds is the offset or buckling of landforms or young geological deposits. This is seen most clearly on old river terraces or river plains, where the original channel and bar patterns of the former riverbed are ‘fossil’ landforms dating from when the river last flowed at that location. Topographic steps or rises that run across such river-formed features could not have been created by the river, and therefore result from subsequent deformation of the ground. If factors such as landsliding can be ruled out, these topographic features may confidently be attributed to fault or fold movements (e.g. Figure 1.2, Figure 1.3 & Figure 3.1).

In this report, and the companion GIS dataset, a distinction is made between the style of active deformation, whether predominantly by fault offset of the ground (fault scarp), or by folding (buckles, tilts or flexures) of the ground. Folds are subdivided into ‘one-sided folds’, or monoclines, and ‘two-sided folds’, either up-folds (anticlines) or down-folds (synclines) (Figure 3.1). Monocline is the only class of active fold included in the companion GIS dataset.

Two end-members of fault movement type are shown in Figure 3.1; a dip-slip fault which has up-down movement, and a strike-slip fault which has horizontal (sideways) movement. In practice it is not uncommon for a fault to display a combination of both types of movement; such faults are called ‘oblique-slip’ and have movement that is partly up-down and partly sideways (see Figure 1.2A). Most dip-slip fault planes are inclined (i.e. are not vertical), and there are two basic types of movement. Where the rock on the upper side of the inclined dip-slip fault shifts upwards along the fault, it is called a reverse fault, and results from compressional forces. Where the rock on the upper side of the inclined dip-slip fault shifts downwards along the fault, it is called a normal fault, and results from tensional forces.

The fault and fold styles illustrated in Figure 3.1 are idealised examples. They do not show the range of variations and complexity that may exist (e.g. see Figure 1.3). To find such simple examples in nature as displayed in Figure 3.1 would be an exception rather than a rule. The steepness of inclination (dip) of the fault may vary considerably (Figure 3.1). Where a fault has a gentle dip (i.e. is closer to horizontal than vertical), each successive movement commonly results in the upthrown side ‘bulldozing’ outward, over-riding the ground and encroaching over anything in its immediate vicinity. The destroyed building in the upper diagram of the lower panel of Figure 3.1 attempts to convey an impression of a bulldozer effect.

There is rarely an exact distinction between a fault and a monocline at the ground surface. Fault scarps are commonly associated with some buckling of the ground and near-surface layers, particularly on the upthrown side of a reverse fault scarp (Figure 3.1; also see Figure 1.3). In some cases, part of the fault movement may have broken out on a series of smaller subsidiary faults near the main fault. In the case of monoclines or anticlines, subsidiary faults may also occur over buried faults that underlie these folds, resulting in small ground surface offsets. An important message is that on any active fault or fold, there commonly are elements of both faulting and folding close to the ground surface (Figure 3.2). The amount of deformation due to faulting, relative to the amount expressed as folding, may vary over short distances (Figure 1.3).

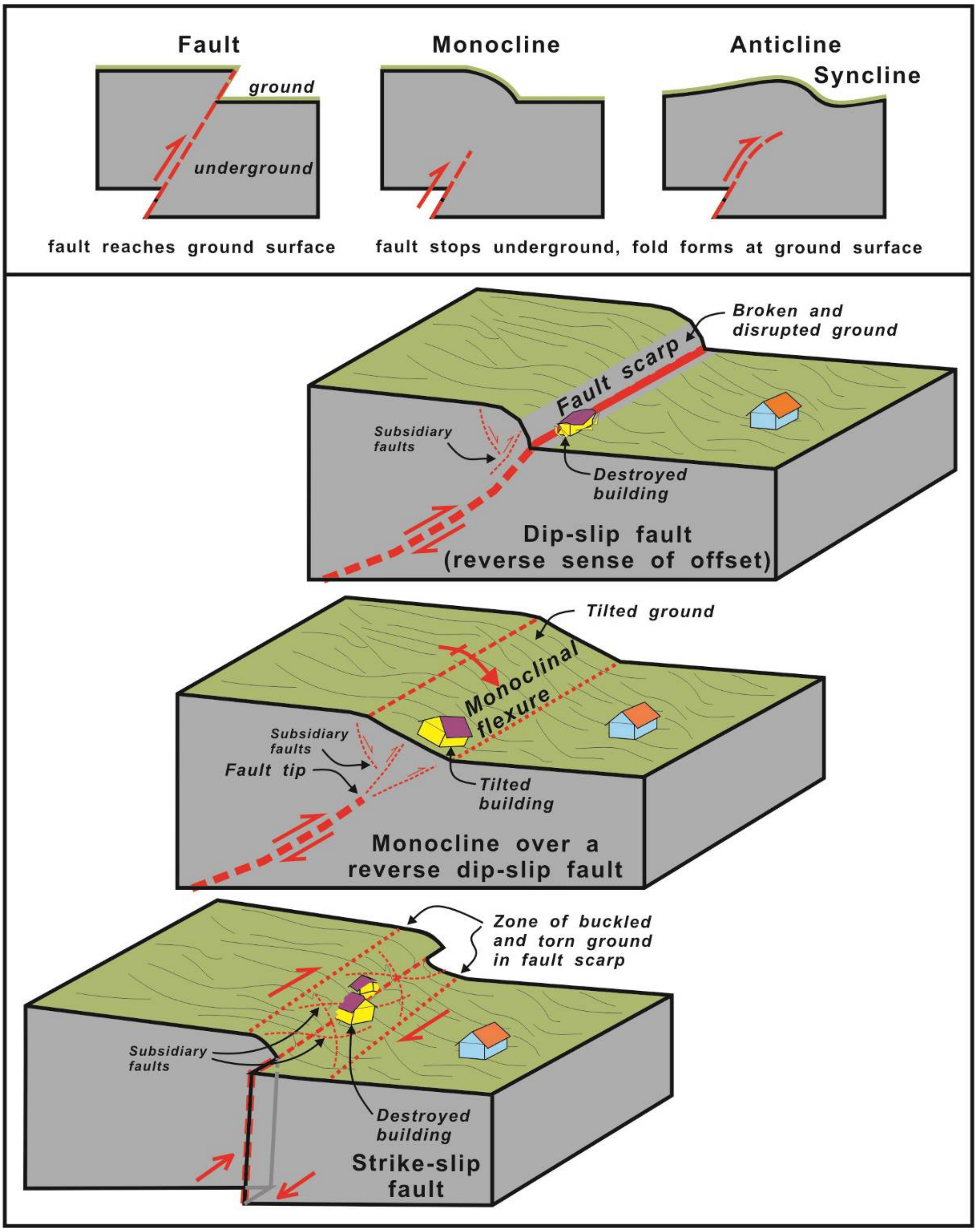

Figure 3.1 Diagrams illustrating styles of active faults and folds. The diagrams show general concepts rather than actual details and are not drawn to an exact scale. Upper panel: Cross-section (vertical slice) diagrams illustrating an active fault, active monocline and active anticline and syncline. Most folds are, as shown here, thought to have formed over faults whose ruptures have not made it all the way to the ground surface. Lower panel: perspective block diagrams showing typical ground-surface expressions of faults and monoclines. The diagrams include hypothetical examples of effects on buildings of a fault rupture or monocline growth event.

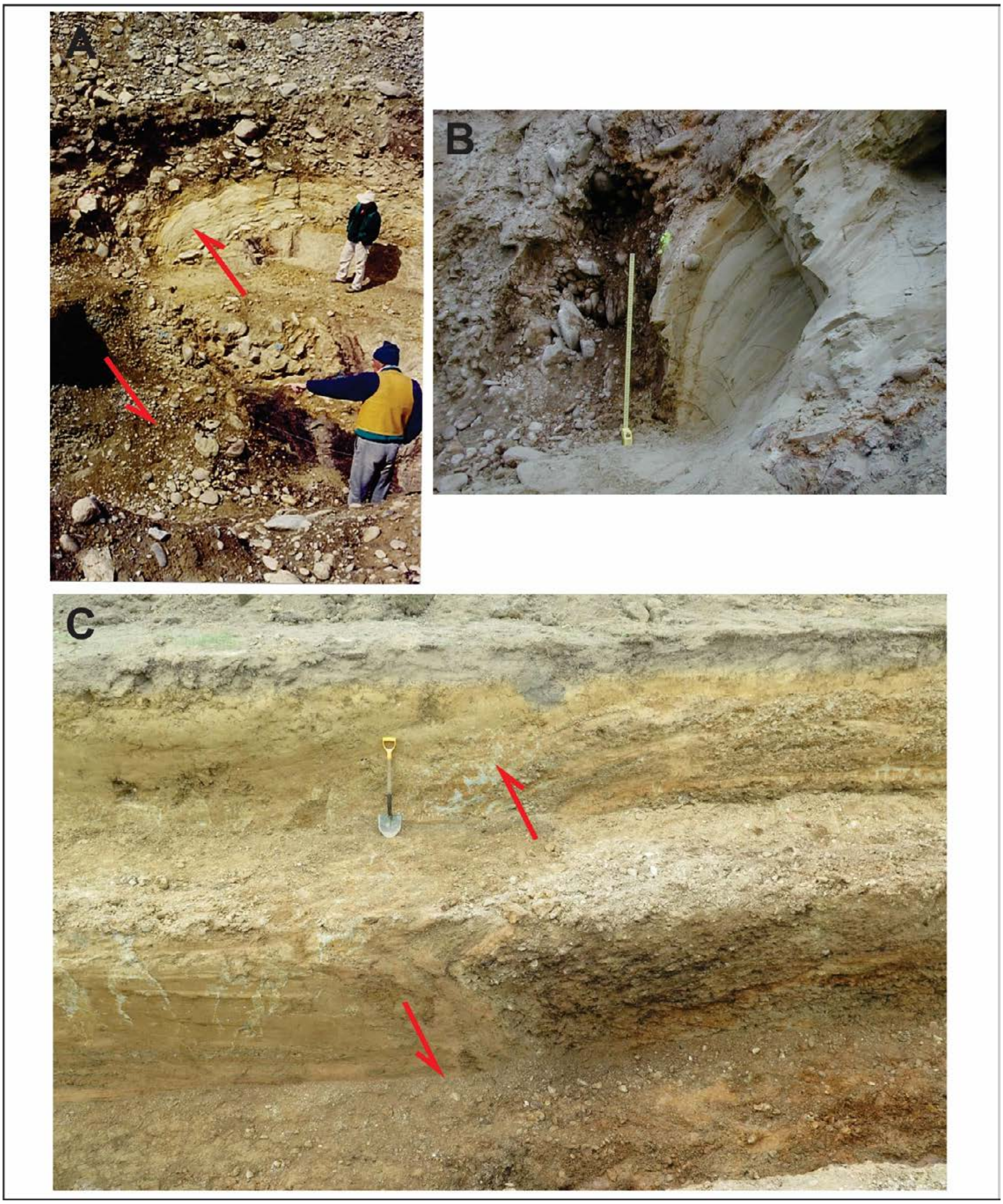

Figure 3.2 Illustrations of faults exposed in investigation trenches. Red half-arrows indicate the relative sense of fault displacement. **A & B**: The Waitangi Fault exposed in 1999 in a trench 700 m downstream of Aviemore Dam, Waitaki District of Canterbury (Barrell et al. 2009). A: the fault runs upper left to lower right and a bed of yellow sand has been pushed up and buckled over against river gravel to the left. B: detail of the fault contact after further excavation and cleaning. The yellow tape measure (extended 1 m) provides scale. Layering in the sand has been dragged down nearly vertical against the fault, while elongate river stones immediately left of the sand bed have been dragged up into vertical alignments. **C**: A view of the wall of a trench excavated across the Titri Fault near Milton in coastal Otago, Clutha District, in 2016. Yellow-brown stream gravel (right of centre) has been thrust up and buckled over against yellow-brown silt (loess) to the left. Detailed examination and mapping of the materials, and dating of the sediments, provides evidence for at least two separate rupture events here, within the past ~38,000 years. The 1-m long shovel illustrates scale. Photos: GNS Science, D.J.A. Barrell.

In practice, where the zone of ground deformation is quite narrow, it is interpreted as a fault, and where it is broad, it is interpreted as a fold (e.g. monocline) (see Figure 3.1). The only way to determine the accuracy of this interpretation is to excavate a trench across the deformed zone to see whether, or to what extents, the near-surface deposits have been offset, or merely folded (Figure 3.2). Sometimes, natural exposures in stream banks provide the necessary information. This highlights a key issue; without detailed work involving examination of what lies within the first few metres beneath the ground surface, we can at best only make informed guesses about the exact locations, form and likely future consequences of fault or fold activity.

It is common to find some surprises as a result of more detailed geological examination of active faults or folds. For example, a broad fault scarp, that might be expected to include a considerable amount of folding may, upon excavation, turn out to have a well-defined fault offset with very little folding. This could occur because after a surface deformation event, natural landscape processes tend to smooth-over the effects. For instance, a steep face of bare broken ground in a fault scarp will settle, subside, and compact due to factors such as rainstorms, frost heave, and soil formation. Over longer periods, wind-blown dust (loess) emanating from river beds tends to accumulate most thickly in hollows and depressions, further smoothing any irregularities produced by fault offset of the ground.

An important message is that while landforms provide important clues as to the general location of active faults or folds, many details of these features which may be relevant to land-use, development and hazard mitigation cannot be obtained without more detailed site-specific investigations (e.g. Figure 3.2).

3.3 Seismicity

The Otago region has experienced very little locally-centred seismicity since European settlement. Most of the earthquakes that have been felt in Otago since European settlement have been centred outside the region, mainly originating in the Fiordland area, close to or on the plate boundary. This pattern is illustrated by the seismicity of the past 30 years (Figure 3.3).

The moment-magnitude 5.8 Matukituki Earthquake on 4th May 2015[1] was the largest earthquake centred within Otago since European settlement. Originating at shallow depth (~9 km) and centred about 30 km northwest of Wanaka, the earthquake was felt strongly in the Wanaka area, but caused only minor damage (Cox et al. 2015). The earthquake was studied using the recorded seismic waveforms and aftershock distributions (Warren-Smith et al. 2017). It was concluded that the rupture occurred on a steeply north-northwest dipping (~70°) fault plane, aligned almost east-west (strike azimuth of 70° east of north). The sector of the fault plane that ruptured lay between 7 and 15 km underground, and was about 5 km long. The movement was strike-slip, with a right-lateral (dextral) sense. The orientation of the subsurface fault that ruptured does not correspond to any identified surface fault, active or inactive. The Matukituki Earthquake highlights four points. The first is that a fault rupture producing an earthquake of close to magnitude 6 is, in this region, well short of being large enough to be able to break up to the ground surface. Second is that the orientation and sense of movement was unexpected, in regard to the much larger known and suspected active faults expressed at the ground surface in Otago. Third, and underscored by the unexpected patterns

[1] Moment magnitude (M_W) is a measure of the total seismic energy released in an earthquake and is usually calculated from low-frequency waveforms recorded on seismographs. It is a better measure of the size of large earthquakes than the Richter, or local, magnitude (M_L), which is based on the largest size of ground motions recorded on seismographs. Richter magnitude is difficult to estimate accurately for strong earthquakes, because the seismographs have difficulty recording the full amplitude of very large ground motions.

of fault movement and deformation observed during the Canterbury earthquake sequence of 2010–2011 and the Kaikōura Earthquake of 2016, is that there is still much to learn about earthquake processes in New Zealand. Finally, the Matukituki Earthquake shows that despite the low historical seismicity, Otago is undoubtedly subject to earthquake activity.

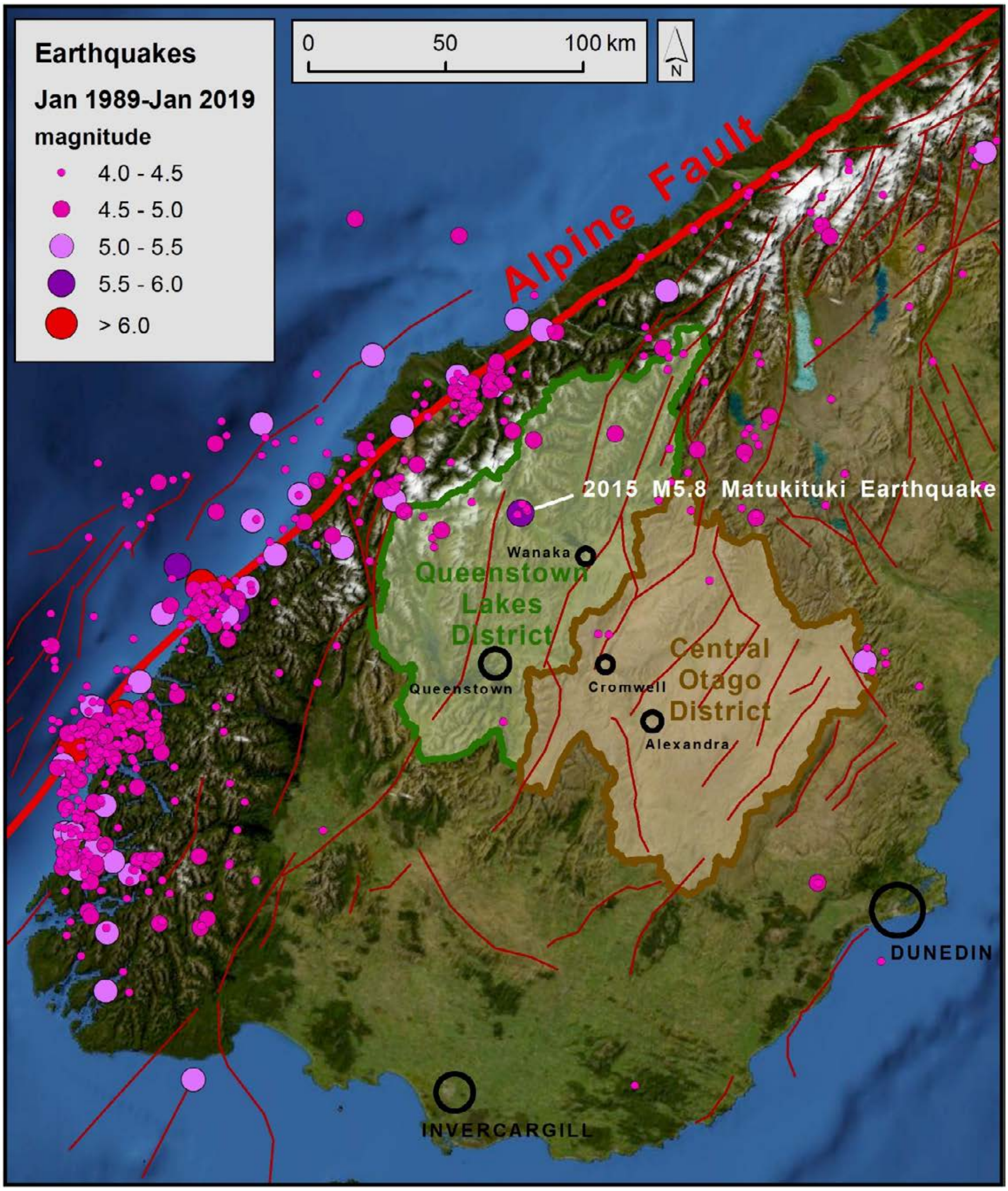

Figure 3.3 Recorded earthquakes in the southern South Island over the past 30 years (1 January 1989–1 January 2019). Earthquake locations are from the GeoNet earthquake catalogue (www.geonet.org.nz). The red lines are active faults as depicted in the New Zealand Active Fault Model (Litchfield et al. 2014). The background image is the NASA 'Blue marble' global base map.

4.0 CLASSIFICATION OF ACTIVE FAULTS AND FOLDS

4.1 Descriptive Classification

The original information on the active faults and folds of the Queenstown Lakes and Central Otago districts was extracted from the QMAP digital dataset (Heron 2014). The QMAP was compiled for presentation at 1:250,000-scale, where 1 cm on a map represents 2.5 km on the ground. For this report, the existing mapping has been re-examined and additions, and some refinements, have been made to the mapping of active faults and folds. These modifications include addition of some previously unmapped features and the reclassification of some existing mapped features. Appendix 2 provides commentary on the mapping and interpretations of the active faults and folds.

Following the approach used in the QMAP digital data structure, faults and folds are separate entities (feature classes) within the GIS dataset. Three data fields (also known as 'attribute' fields) have been added to the active faults and folds feature classes (see Appendix 1 and Table 5.1). The names of these fields are:

- ORC_name (local names for the mapped fault/fold feature; see below)
- Certainty (likelihood that the mapped feature is an active fault/fold; see below)
- Surf_form ('Surface form', indicating how well defined is the surface expression of the mapped feature; see below)

The GIS dataset provides the following information: (i) whether a feature is a fault or a fold; (ii) the level of the certainty with which each feature is recognized as active (definite, likely or possible) or as potentially active, and; (iii) an interpretation of the surface distinctiveness of each feature at the ground surface (well expressed, moderately expressed, not expressed, unknown). Commonly, a single active fault at depth is expressed at the ground surface as a zone of splintering. An individual line of splinters (fault strand) may comprise fault offsets of the ground surface (fault scarps) or ground-surface folds (fold scarps), and commonly a mixture of both. A fault zone may include several lines (traces) of semi-parallel strands and a fault zone can in some cases be several kilometres wide. Some strands have previously been named separately, and this name is retained in the GIS dataset, but the various strands that comprise an active fault are grouped under a common name (ORC_name). This is done to highlight that, collectively, the strands are regarded as part of a single active fault structure, whose movements at depth have produced an array of ground-surface fault and/or fold deformation.

Many of the active faults have been named previously, and those names are used in this dataset unless reasons exist for applying a different name, as explained in Appendix 2. The QMAP dataset only included names for faults or folds where a name had previously been published, and this is the main reason for adding an attribute that assigns a local name to all mapped features (ORC_name). By and large the local name corresponds to any previously used name (in QMAP or the NZAFD). In places where no name has previously been given to an active fault/fold feature, the ORC_name has been taken from a nearby named topographic feature or locality. Where names are newly proposed in this report, and thus regarded as informal, the term fault or fold is in lower case type (e.g. Cluden fault zone). For previously published names, a capital 'F' is used. The basis of all new names is explained in Appendix 2. In this dataset, the name of a fault includes the term 'zone' where it contains individually-named components, comprises distinct, approximately parallel multiple strands, or if the term 'fault zone' has been used extensively in previous work on the fault. In this and subsequent sections of the report, the term ‘fault’ is used to encompass faults as well as any associated folds, unless in specific reference to a fold feature. Any references to individual fault or fold strands are identified as such, and the term fault, or fault zone, pertains to an overall active fault structure.

The purpose of the Certainty field is to indicate the level of confidence in the interpretation of the deformation features. In the Certainty field, the term ‘definite’ is applied to those features whose existence can only be explained by active fault deformation. Features designated as ‘likely’ are most probably due to active fault deformation, but it is not possible to rule out other origins, such as having been formed by erosion. In instances where there is some reason to suspect the presence of an active fault, but there is a lack of direct evidence because, for example, the landforms are unsuitable (e.g. too young) to have preserved any direct indications of young movement, the feature is designated as ‘possible’. Another category is added in this project, for faults that could possibly move in the future (‘potentially active’) even though they have not done so in the recent geological past. Features identified as having a Certainty of ‘possible’ or ‘potentially active’ should not be treated as delineated active faults unless further positive information is obtained. They are identified to highlight areas that are worth a closer look for the possible existence of active fault hazards.

Several of the active faults of the Queenstown Lakes and Central Otago districts have been subject to close examination in the field, whereas other faults have been identified primarily using aerial photographs or other imaging such as Google Earth, or in reconnaissance walkover. In all cases, the geometries and locations of active faults as depicted in the QMAP-based datasets are very generalised. At the scale of QMAP, none is located more accurately than plus or minus (±) 100 m, at best, and ± 250 m as a general rule. The Surf_form field provides a preliminary estimate of how well defined the surface expression of a feature is likely to be, were it to be subjected to a detailed, site-specific, examination. Features that are ‘well expressed’ should be able to be located to better than ± 50 m. Those that are identified as ‘moderately expressed’ should be able to be located to better than ±100 m. Those labelled as ‘not expressed’ do not have any known physical expression on the ground, because they lie in areas of landforms that are probably younger than the most recent deformation. Features are labelled as ’unknown’ if it is unclear whether or not there may be physical evidence that would aid in locating the position of the fault. The purpose of the Surf_form field is to assist in the planning and targeting of future investigations aimed at a more rigorous characterisation of active fault hazard, should any further work be proposed. For example, features designated as ‘well expressed’ are likely to be able to be mapped and delineated more quickly, and to greater precision, than features identified as ‘moderately expressed’.

4.2 Activity Classification

Two common ways of expressing the degree of activity of an active fault (and any related folding) are average slip rate and average recurrence interval. Either of these parameters provides a way to compare the levels of activity of faults across a wide area (e.g. Queenstown Lakes and Central Otago districts). In this report, an activity estimate is assigned to a fault as a whole. The one activity estimate applies to its component fault strands and any associated monoclinal fold strands. This assumption may not be true in detail, for example if one strand of a fault were to rupture in an earthquake while another strand does not. However, a single activity estimate is regarded here as the appropriate approach to use, because at present there is little if any information on the past rupture behaviour of individual fault strands.

The behaviour of any particular active fault comprises a relatively long period of no movement, during which strain slowly builds up in the subsurface rock, until the fault moves (ruptures) in a sudden slip event, causing an earthquake. For a fault whose largest slip events are sufficient to produce ground-surface rupture (as applies to all mapped active faults in this report), each slip event typically involves sudden movement on the fault of as much as several metres (see Figure 1.2). The amount of fault offset of a geological deposit or a land surface feature, such as a river plain, divided by the estimated age of the deposit or the land surface feature, provides an average slip rate, usually expressed in millimetres per year (mm/yr). This does not mean that the fault moves a certain amount each year but is simply a way of assessing its degree of activity. A fault with a larger (faster) slip rate (say 2 mm/yr) generally experiences a ground-surface rupturing earthquake more frequently than does a fault with a smaller (slower) slip rate (e.g. 0.2 mm/yr).

In most cases throughout Otago, the precise ages of geological deposits and landforms are not known. Instead, geologists usually rely upon provisional age estimates based on regional geological comparisons. By this approach, ages obtained by geological dating of a specific type of landform somewhere in New Zealand are applied to landforms of similar characteristics in another region. For example, geological dating in the upper Waitaki River catchment has shown that the last ice age ended about 18,000 years ago, when the large valley glaciers started to melt away rapidly (Putnam et al. 2013). On that basis, an age of 18,000 years is adopted for glacial landforms in the catchments of lakes Wakatipu, Wanaka and Hawea, in order to estimate the activity of faults that have offset those landforms. With different types of landforms or geological deposits, other criteria such as the degree of weathering, and maturity of soil development, are used to estimate ages for calculating fault activity rates. The approach and reasoning used to estimate the activity of each fault addressed in this report is explained in Appendix 2.

Average recurrence interval is the average length of time that elapses between ground-surface rupturing earthquakes and is a more explicit measure of how frequently surface-rupture earthquakes occur. Recurrence interval is an important quantity because it forms the basis for risk-based evaluation of ground-surface fault rupture hazard in relation to the MfE active fault guidelines that aim to minimise the risks of building across active faults (Kerr et al. 2003). Recurrence intervals range from being as short as a few hundred years for the most active faults in New Zealand (e.g. Alpine Fault), to as much as many tens of thousands of years for other faults. This means that the historically-documented record of earthquakes is too short to be of use for evaluating the average recurrence interval of an active fault. Instead, the geological record of deformation of young deposits and landforms is the main source of evidence for defining a recurrence interval for an active fault.

Recurrence interval is more difficult to quantify than slip rate, because the direct determination of a recurrence interval depends on the ability to establish the ages of at least two, preferably more, past surface-rupture earthquakes on a fault. Determining recurrence intervals, as well as obtaining accurate values for slip rates, requires detailed geological investigations on a fault, with measurement of past offsets, and dating of geologically-young deposits. However, few faults in the Otago region have been investigated in that amount of detail.

Another approach for estimating recurrence interval has been developed from research into historical ground-surface fault ruptures internationally and in New Zealand. That work has identified generally applicable relationships that allow one fault parameter to be calculated from another parameter. For example, the size of a single-event fault rupture displacement can be estimated from the length of the fault. That methodology provides a means for estimating fault activity characteristics for faults where detailed geological investigations have not been carried out and has been applied to such faults in the 2010 version of the NSHM (2010 NSHM; Stirling et al. 2012). The 2010 NSHM methodology calculates, among other things, values for recurrence interval and single-event displacement from estimates of fault length, fault dip (the inclination from horizontal of the fault plane) and slip rate; those estimates are usually determined by an expert panel of geoscientists, drawing on available geological information.

The present project used the 2010 NSHM approach to estimate provisional recurrence interval values for newly defined active and potentially active faults not currently in the 2010 NSHM. This differs from the approach used previously for the Waitaki District (Barrell 2016), which applied a method that assumed a fixed representative value for single-event displacement size and used that along with estimated slip rate to calculate an inferred recurrence interval. An important point is that, except in the case of the few faults that have been investigated in detail and useful results obtained, the slip rate and recurrence interval estimates presented in this report should be regarded as preliminary, until more direct estimates are obtained from site-specific geological investigations of the fault. The estimates in this report are intended primarily to indicate an approximate recurrence interval that may be expected for each fault, allowing the activity of a fault to be placed into general context with the MfE active fault guidelines (Kerr et al. 2003).

This project has made a further addition to the approach used for the Waitaki District (Barrell 2016). Previous compilations only included faults displaying physical evidence for geologically recent activity, thus according with existing definitions of ‘active fault’ (Langridge et al. 2016). However, recent research in coastal Otago (Villamor et al. 2018) has led to a recommendation for including all faults that have experienced substantial movement in the wider geological past, specifically within the past 20 million years since the present plate boundary has been active through the New Zealand region. The inclusion of many more faults in the dataset has little impact on seismic hazard estimation in Otago for faults that have experienced considerable movement in the deeper past, but little if any in geologically more recent times. Those faults are assessed as having very slow slip rates and therefore long recurrence intervals, and thus statistically contribute little to the overall earthquake hazard in the region.

There is considerable uncertainty in the estimated fault activity parameters, but the level of uncertainty is difficult to quantify. This is because there is uncertainty in estimating the size of fault offset of a landform (e.g. estimated from aerial photos), and uncertainty in the age assigned to the landform (e.g. inferred from regional geological comparison – see earlier paragraph). It is not considered meaningful for the present report to try and quantify activity uncertainties, for example by giving a range of estimated values for slip rate or recurrence interval. That would be a desirable goal of future assessments of specific active faults, where detailed geological investigations have been undertaken. However, the present report just gives a single best-estimate value for slip rate, from which a single recurrence interval is calculated using 2010 NSHM methodology. Should anyone wish to apply a level of uncertainty to those values, an uncertainty of ±50% of the stated slip rate or recurrence interval is deemed here to be a useful working representation of the uncertainty.

It is important to appreciate that all of the fault activity estimates in this report, and in preceding datasets, are no more than working best estimates. The main use of those estimates is for enabling comparison of the relative activities of different faults, and providing context for identifying and managing associated hazards, typically via the derived parameter of recurrence interval. A last point to note is that the information on degree of fault activity in this report, notably the extended reviews and discussions in Appendix 2, is more comprehensive than that contained in the NZAFD, as it stood in December 2018, and also builds on and refines information and estimates presented by Van Dissen et al. (2003), Stirling et al. (2012) and

Litchfield et al. (2013, 2014) and references therein. The information in this report also updates the active fault locations as illustrated and discussed by Mackey (2015).

4.3 As-Yet Undetected Active Faults

The Canterbury earthquake sequence of 2010–2011 occurred on a series of previously unknown faults. There are two main reasons why nothing was known about those faults. First, they have a low rate of activity (the average time between surface-rupture earthquakes is many thousands of years), and second, the Canterbury Plains consist of relatively young deposits and landforms, which mask most of the underlying geology, including faults (Hornblow et al. 2014). The 2016 Kaikōura Earthquake involved the rupture of multiple faults, several of which were not previously known to be active faults (Litchfield et al. 2018). Somewhat different circumstances prevail in Otago, where most areas are not buried by young sediments, and many of the faults are clearly expressed in the geology, and topography, especially where hard basement rock has been uplifted to form a range of hills or mountains on one side of the fault. Nevertheless, it is conceivable that there may be other active faults, in areas of relatively young landforms, whose presence is yet to be detected. This means that the active faults of the Queenstown Lakes and Central Otago districts, that have a preserved record of previous ground-surface deformation of young deposits or landforms, should be regarded as a minimum representation of the active faults of these districts.

The active faults and associated folds that are known about can be taken into account in planning, engineering and hazard mitigation or avoidance. Although little can be done to avoid hazards from faults whose presence/location is unknown, modern building and design standards in regard to earthquake shaking do make allowance for minimising adverse effects of a large, nearby, earthquake, even if there is no known active fault nearby. However, there is good confidence that the more active faults of the two districts have been identified and characterised in this report. This is because such faults are likely to have left distinctive landform indicators of their presence. The more active faults present the largest hazard statistically, because they have a greater chance of rupturing again in the geological near-future than faults of lesser activity. However, and unfortunately, that does not necessarily mean that a higher activity fault will be the next one(s) to rupture. This is because there are many more low activity faults than there are high ones.

4.4 Earthquake Magnitudes

For an active fault to be recognisable at the ground surface, it indicates that past ruptures must have been sufficiently large to have broken through to the ground surface. For the types of faults that occur in the eastern South Island, the amount of slip required for a fault to rupture the ground surface will generate a large earthquake, of magnitude somewhere between the high sixes and mid-sevens (e.g. Pettinga et al. 2001). That is reinforced by the example of the 2015 magnitude 5.8 Matukituki Earthquake, which did not cause surface rupture (Section 3.3).

Active folds indicate the presence of underlying active faults whose ruptures have not reached the ground surface. Conceivably, subsurface ruptures sufficient to generate surface folds may produce earthquakes of lesser magnitudes (e.g. in the low to mid sixes). These considerations were borne out in the Darfield Earthquake, where the surface-rupturing Greendale Fault movement had an estimated magnitude of 7.0, while the subsurface Charing Cross and Hororata ruptures had estimated magnitudes of 6.4 and 6.3 respectively and did not cause surface rupture, but did produce subtle, instrumentally-measurable, ground shifts (Beavan et al. 2012). Surface fold growth resulting from non-surface-rupturing faults does not necessarily mean that the earthquakes were not large. For example, a gently-inclined non-surface-rupturing fault may be able to generate an earthquake at least as large as one generated by a steeply-inclined, surface-rupturing fault, such as the Greendale Fault.

Each of the active faults identified in this report should be assumed to be capable of generating earthquakes with magnitudes between the high sixes to mid-sevens, depending on the length of the fault, with longer faults having potential to generate larger earthquakes within this magnitude range. For the 48 active faults discussed in this report, the 2010 NSHM methodology calculates an indicative earthquake magnitude in the range of magnitude 6.8 to magnitude 7.6, with a mean across all 48 active faults of magnitude 7.1.

5.0 DISTRIBUTION AND CHARACTERISTICS OF ACTIVE FAULTS

5.1 Overview

A regional-scale map of the active and potentially active faults delineated in the Queenstown Lakes and Central Otago districts is presented in Figures 5.1 to 5.3, which collectively provide three overlapping panels of the assessment area. Descriptions of the representative characteristics of the categories of active faults and associated active folds used in this report, as well as indicative correlations to the fault complexity classification of the MfE active fault guidelines (Kerr et al. 2003), are presented in Table 5.1. Table 5.2 summarises the main features of each of the delineated active and potentially active faults. The table includes an assessment of the degree of activity of each fault. Appendix 2 provides extended descriptions of the mapping, geological interpretations and activity estimations for each fault.

In many cases, rupture on an active fault may have broken out discontinuously, or in multiple places, on the ground. Some individual faults may converge, or abut one another, and some faults comprise a zone of surface deformation, in which some fault strands have been given individual names. To aid clarity of illustration, each named fault in Figures 5.1–5.3 has been accentuated by a coloured area (‘extent of named area’). In the cases where a fault comprises multiple strands, this helps show which strand belongs to which active fault.

Of the 48 active faults (comprising a total of 55 named fault features in Figures 5.1–5.3) identified in the Queenstown Lakes and Central Otago districts, 21 are classified as comprising ‘definite’ or ‘likely’ components and can be regarded respectively as known or suspected active faults. Of the remaining faults, six are classed as ‘possible’ active faults and another 21 are classified as ‘potentially active’. The classification of ‘possible’ indicates there is reason to think of those faults as having a greater likelihood of future activity than faults classified as ‘potentially active’.

Only nine faults are assessed as having a recurrence interval of less than 10,000 years, namely the Dunstan Fault Zone, Gimmerburn Fault Zone, Highland Fault, Lindis Pass Fault Zone, Livingstone Fault, Motatapu Fault, Nevis Fault Zone, NW Cardrona Fault, and the Timaru Creek Fault. It should be noted that the Highland Fault and Motatapu Fault are regarded as probably rupturing together and collectively only represent one earthquake source. The most active fault delineated in each district is the NW Cardrona Fault in Queenstown Lakes, with an estimated recurrence interval of 5500 years, and the Lindis Pass Fault Zone in the Central Otago, whose estimated recurrence interval is 5600 years. However, the Lindis Pass Fault Zone lies only partly in the Waitaki District. The most active fault contained entirely within Central Otago is the Dunstan Fault Zone, whose estimated recurrence interval is 7000 years.

A point to note is that for most of the faults discussed in this report, there is no information on when the most recent ruptures occurred, and this means that there is little or no information on where the faults are currently sitting within their rupture cycles.

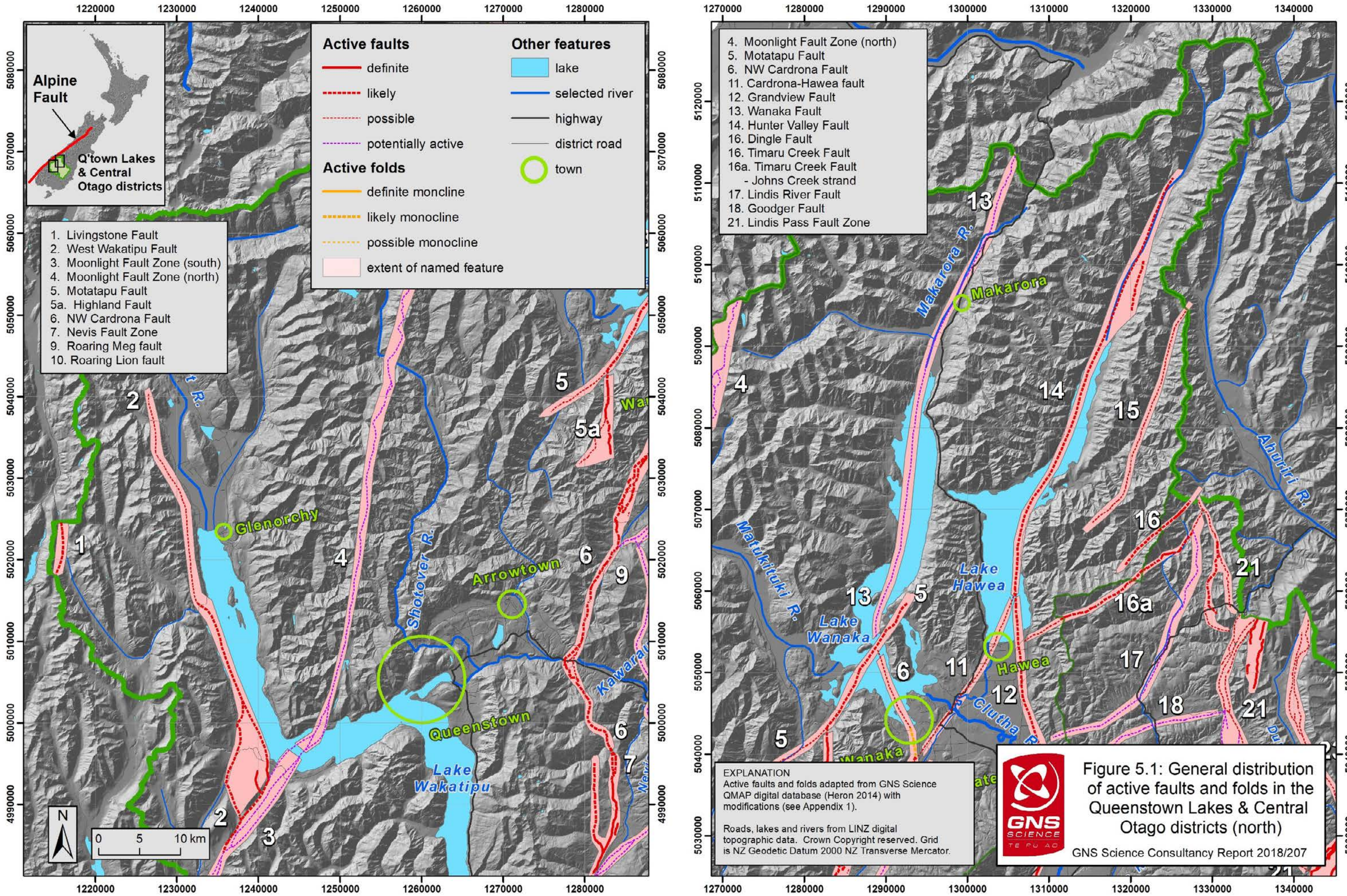

Figure 5.1 General distribution of active faults and folds in the Queenstown Lakes and Central Otago districts (northern panels). The pink areas indicate groupings of fault or fold strands that collectively form part of a single numbered active fault. The pink areas are purely illustrative and do not imply anything about the location or extent of fault-related ground deformation. Each fault that intersects the outer boundary of the combined districts (thick green line) extends into the neighbouring district(s). The location of the overlapping map panels is shown in the inset at top left.

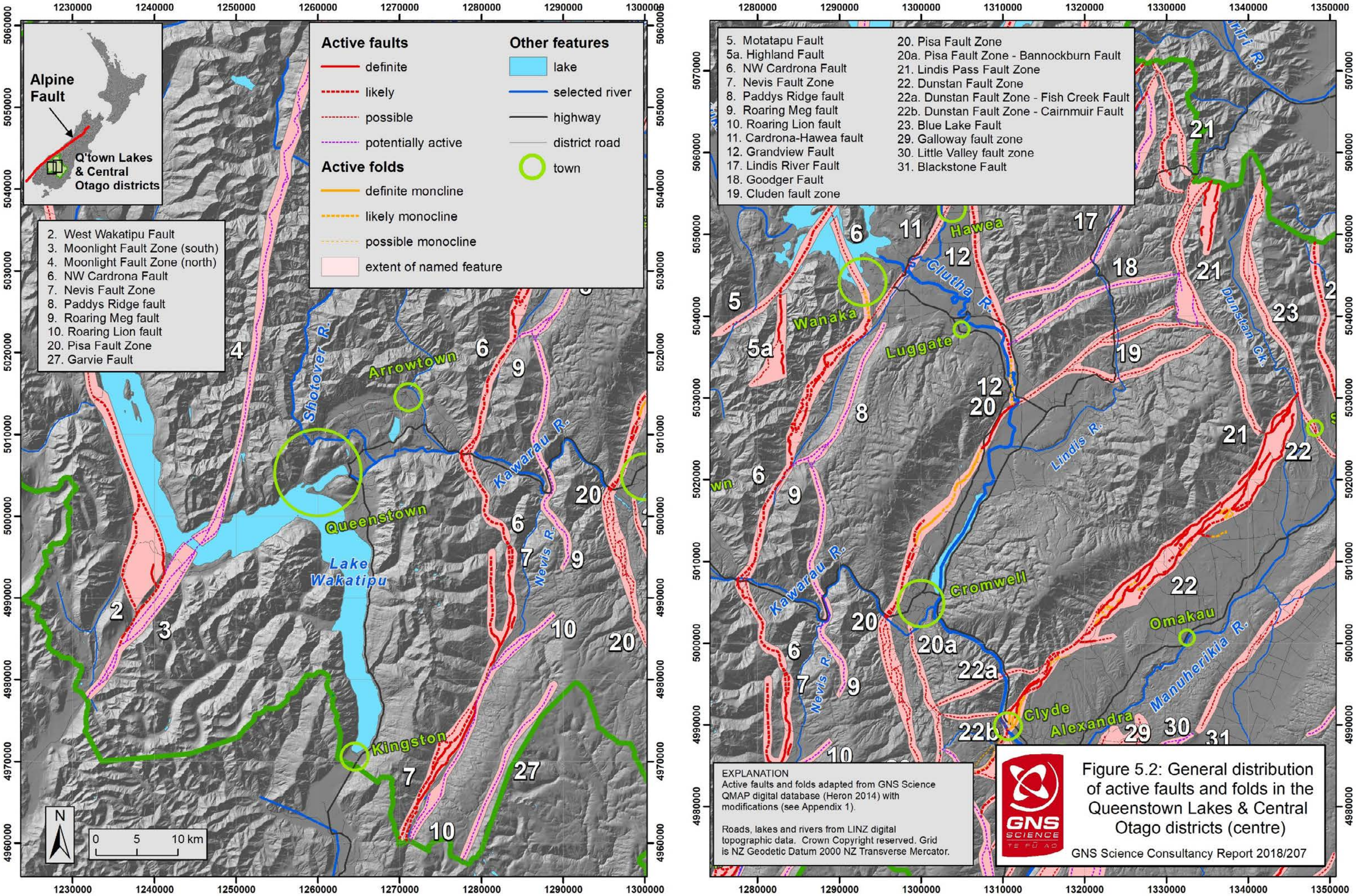

Figure 5.2 General distribution of active faults and folds in the Queenstown Lakes and Central Otago districts (centre panels). The pink areas indicate groupings of fault or fold strands that collectively form part of a single numbered active fault. The pink areas are purely illustrative and do not imply anything about the location or extent of fault-related ground deformation. Each fault that intersects the outer boundary of the combined districts (thick green line) extends into the neighbouring district(s). The location of the overlapping map panels is shown in the inset at top left.

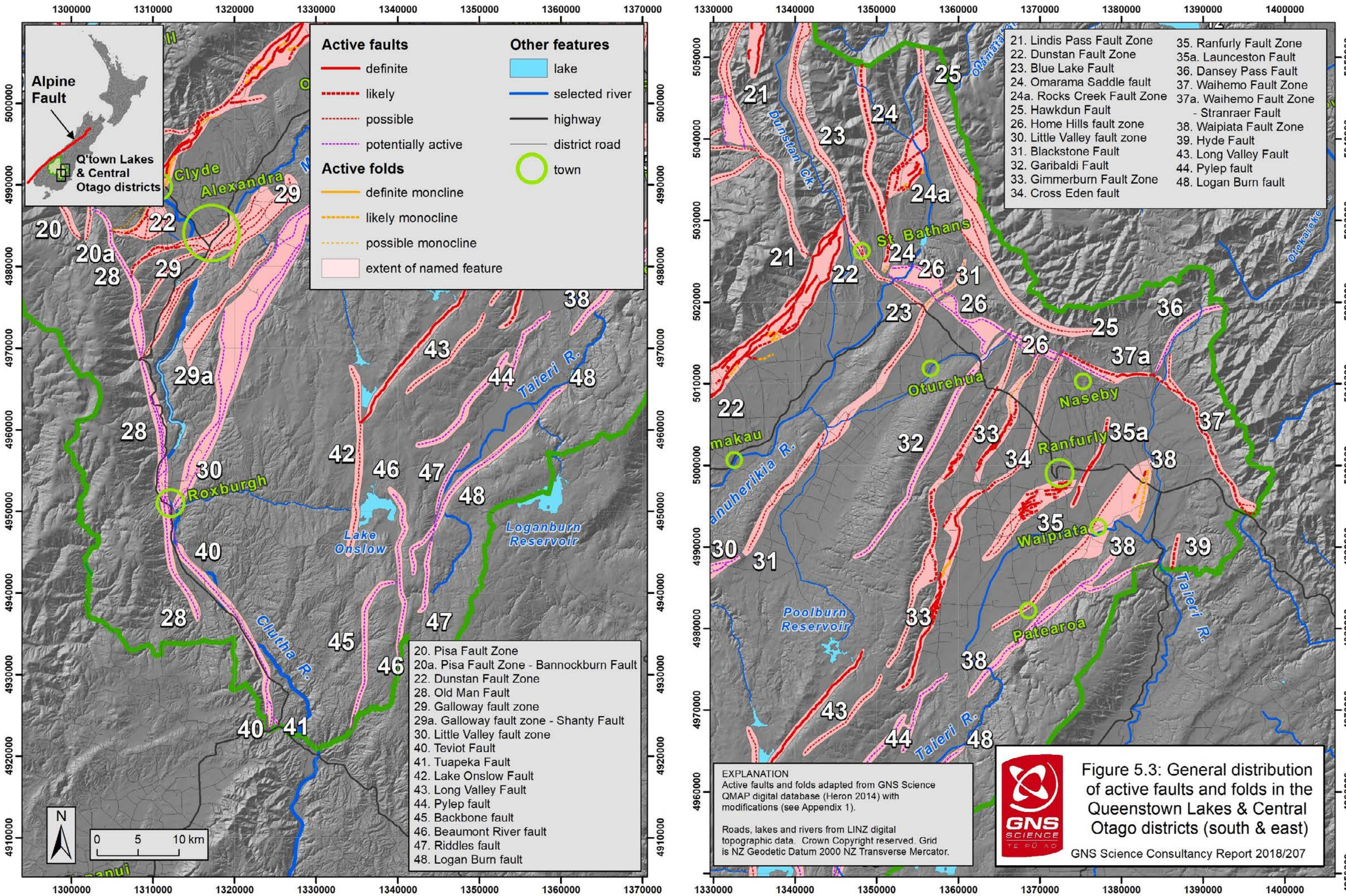

Figure 5.3 General distribution of active faults and folds in the Queenstown Lakes and Central Otago districts (southern and eastern panels). The pink areas indicate groupings of fault or fold strands that collectively form part of a single numbered active fault. The pink areas are purely illustrative and do not imply anything about the location or extent of fault-related ground deformation. Each fault that intersects the outer boundary of the combined districts (thick green line) extends into the neighbouring district(s). The location of the overlapping map panels is shown in the inset at top left.

Table 5.1 Categories and terms used in this report to describe active faults and folds in the Queenstown Lakes and Central Otago districts.

Category	Characteristics	Certainty	Surface form	Nature of evidence	Fault complexity (based on definitions in Kerr et al. (2003))
Active fault	Deformation predominantly in the form of breakage and offset of the ground surface. This is presumed to occur in sudden events accompanied by a large earthquake. May also include some monoclinal or anticlinal folding	definite	well expressed	Sharp step in ground surface that cannot be attributed to other geological factors (e.g. river erosion or landslide movement)	Well-defined deformation
		definite	moderately expressed	Poorly-defined step(s) in ground surface that cannot be attributed to other geological factors	Well-defined or distributed deformation
		definite	not expressed	No surface expression (i.e. evidence concealed or eroded away) but lies along trend from nearby definite active fault	Uncertain deformation
		likely	well expressed	Sharp step(s) in the ground surface that cannot readily be attributed to other geological factors	Well-defined deformation
		likely	moderately expressed	Poorly-defined steps in the ground surface that cannot readily be attributed to other geological factors	Uncertain deformation
		likely	not expressed	No surface expression, but lies along trend from nearby likely active fault	Uncertain deformation
		possible	moderately expressed	Coincides with a definite or likely fault in bedrock, along trend from nearby definite or likely active fault; includes steps or topographic features that may possibly relate to fault activity, but other origins are reasonably likely.	Uncertain deformation
		possible	not expressed	No surface expression (i.e. evidence concealed or eroded away) but lies along trend from nearby likely or possible active fault	Uncertain deformation
		possible	unknown	No known surface expression, but likely that evidence for/against activity may be found on further investigation	Uncertain deformation
		potentially active	moderately expressed	Geological evidence (e.g. visible fault crushed rock) for estimating the specific location of a potentially active fault	No recognised deformation
		potentially active	not expressed	Little or no information from which to estimating the specific location of a potentially active fault	No recognised deformation
Active monocline	Deformation predominantly in the form of tilting, buckling or warping of the ground surface. Growth of the fold is presumed to occur in sudden events accompanied by a large earthquake. May also include some subsidiary fault offsets	definite	well expressed	Broad step or rise in ground surface that cannot be attributed to other geological factors	Distributed deformation
		definite	moderately expressed	Poorly-defined broad step(s) or rise in ground surface that cannot be attributed to other geological factors	Distributed deformation
		definite	not expressed	No surface expression (i.e. evidence concealed or eroded away) but lies along trend from nearby definite or likely active monocline	Uncertain deformation
		likely	moderately expressed	Broad steps or rises in the ground surface that cannot readily be attributed to other geological factors	Uncertain deformation
		likely	not expressed	No surface expression (i.e. evidence concealed or eroded away) but lies along trend from nearby likely active monocline	Uncertain deformation
		possible	moderately expressed	Coincides with a definite or likely monocline in bedrock, or a broad rise of uncertain origin, along trend from nearby definite or likely active monocline	Uncertain deformation
		possible	not expressed	No surface expression (i.e. evidence concealed or eroded away) but lies along trend from nearby likely or possible active monocline	Uncertain deformation
		possible	unknown	No known surface expression, but likely that evidence for/against activity may be found on further investigation	Uncertain deformation

Definite = clear evidence for the existence of an active fault or fold

Likely = good reason to suspect the existence of an active fault or fold

Possible = some reason to suspect the existence of an active fault or fold

Potentially active = a known or suspected fault without identified geologically recent activity, but which could conceivably experience activity in the future

Well expressed = likely to be able to be located to better than +/- 50 m in site-specific investigations

Moderately expressed = likely to be able to be located to better than +/- 100 m in site-specific investigations

Not expressed = able to be located only by large-scale subsurface site-specific investigations

Unknown = probable that evidence for or against an active feature would be found in targeted site-specific investigations

Table 5.2 Summary of evidence and estimated deformation characteristics of active faults and folds recognised in the Queenstown Lakes and Central Otago districts. Refer to text and appendices for further information. In the 'Name' column, a lower case last term (e.g. fault) indicates a newly applied name (this report) while upper case (e.g. Fault) indicates a previously published name. Calculated recurrence interval (RI) values are rounded to the nearest hundred years for values <10,000 years, the nearest thousand years for values <30,000 years, and to the nearest 5000 years for longer RIs.

Name	**Observed characteristics**	**References**	**Deformation estimates**					
Representative name for feature (number in Figures 5.1–5.3)	*Description of feature(s)*	*Main source(s) of information on character or activity of feature*	*Basis of estimates*	*Classification*	*Assigned net slip rate (mm/yr)*	*Calculated recurrence interval (RI) - years*	*Comments*	*Indicated RI Class (following Kerr et al. 2003)*
Backbone fault (45)	Inferred fault zone(s) in bedrock, with indicated offset of peneplain	This report	Air photo interpretation; geomorphologic interpretation	Potentially active fault	0.05	35,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Beaumont River fault (46)	Inferred fault zone(s) in bedrock, with indicated offset of peneplain	This report	Air photo interpretation; geomorphologic interpretation	Potentially active fault	0.05	50,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Blackstone Fault (31)	Fault in bedrock with offset of peneplain and suspected offset of geologically young landforms	Markley and Norris (1999); Litchfield et al. (2013); this report	Air photo interpretation; regional geologic mapping; geomorphologic interpretation	Possible active fault	0.14	22,000	Identified as the Raggedy Fault Zone in NZAFM and NSHM	Class IV (>5,000 to ≤10,000 years
Blue Lake Fault (23)	Fault zone(s) in bedrock, with offset of peneplain	Madin (1988); Henne et al. (2011); Litchfield et al. (2013); this report	Air photo interpretation; regional geologic mapping; geomorphologic interpretation	Possible active fault	0.07	40,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Cardrona-Hawea fault (11)	Fault zone(s) in bedrock, with offset of peneplain	Turnbull (2000); this report	Regional geologic mapping; lidar data; geomorphologic interpretation	Possible active fault	0.05	30,000	Formerly the northeastern part of the NW Cardrona Fault. No known evidence for geologically young fault movement	Class VI (>20,000 years)
Cluden fault zone (19)	Fault zone in bedrock, with offset of peneplain; possible deformation of old sediments and landforms	Beanland & Berryman (1989); this report	Air photo interpretation; regional geologic mapping; geomorphologic interpretation	Possible active fault	0.10	17,000	Represents in part the Lindis Peak segment of the Pisa Fault Zone	Class V (>10,000 to ≤20,000 years)
Cross Eden fault (34)	Fault zone(s) in bedrock, with indicated offset of peneplain	Bishop (1979); this report	Air photo interpretation; regional geologic mapping; geomorphologic interpretation	Possible active fault	0.05	35,000	No known evidence for geologically young fault movement, except at southwest end with suspected slip transfer from Gimmerburn Fault Zone	Class VI (>20,000 years)
Dansey Pass Fault (36)	Fault zone(s) mapped in bedrock, with indicated offset of peneplain	Bishop (1976, 1979); this report	Air photo interpretation; regional geologic mapping	Possible active fault	0.05	40,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Dingle Fault (15)	Fault zone(s) mapped in bedrock, considered to potentially be active.	Turnbull (2000); Litchfield et al. (2013); this report	Geodynamic modelling; air photo interpretation; regional geologic mapping	Potentially active fault	0.05	55,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Dunstan Fault Zone (22)	Fault zone(s) in bedrock, with deformed geologically young sediments and landforms	Beanland et al. (1986); Madin (1988); Litchfield et al. (2013); this report	Air photo interpretation; field inspection & surveying; trenching & dating; lidar data; regional geologic mapping	Definite, likely and possible active fault and fold strands	0.60	7000		Class IV (>5,000 to ≤10,000 years)
Galloway fault zone (29)	Fault zone(s) in bedrock, with suspected deformed geologically young landforms	Turnbull (2000); this report	Air photo interpretation; regional geologic mapping; lidar data; geomorphologic interpretation	Likely and possible active fault strands	0.10	15,000		Class V (>10,000 to ≤20,000 years)
Garibaldi Fault (32)	Fault in bedrock, with offset of peneplain	Forsyth (2001); this report	Air photo interpretation; regional geologic mapping.	Potentially active fault	0.05	45,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Garvie Fault (27)	Fault zone in bedrock, with indicated offset of peneplain	Turnbull (2000); this report	Air photo interpretation; regional geologic mapping.	Potentially active fault	0.05	75,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)

Name	Observed characteristics	References	Deformation estimates					
Representative name for feature (number in Figures 5.1–5.3)	*Description of feature(s)*	*Main source(s) of information on character or activity of feature*	*Basis of estimates*	*Classification*	*Assigned net slip rate (mm/yr)*	*Calculated recurrence interval (RI) - years*	*Comments*	*Indicated RI Class (following Kerr et al. 2003)*
Gimmerburn Fault Zone (33)	Fault zones in bedrock with deformed geologically young sediments and landforms	Bennett et al. (2005, 2006); Litchfield et al. (2013); this report	Air photo interpretation; regional geologic mapping; geomorphologic interpretation	Definite, likely, possible and potentially active fault strands	0.40	7400		Class IV (>5,000 to ≤10,000 years
Goodger Fault (18)	Fault zone in bedrock, with indicated offset of peneplain	Turnbull (2000); this report	Air photo interpretation; regional geologic mapping.	Potentially active fault	0.05	30,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Grandview Fault (12)	Fault in bedrock with deformed geologically young sediments	Beanland & Berryman (1989); Turnbull (2000); Litchfield et al. (2013); this report	Geological drilling investigations; regional geologic mapping	Likely active fault	0.10	22,000		Class VI (>20,000 years)
Hawkdun Fault (25)	Fault zone in bedrock, with offset of peneplain	Bishop (1976); Forsyth (2001); this report	Air photo interpretation; regional geologic mapping;	Possible active fault	0.07	55,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Highland Fault (5a)	Up to 3 m offset of hillslope landforms	Turnbull (2000); this report	Air photo interpretation; regional geologic mapping;	Definite and likely active fault strands	0.32	6500	Interpreted as a strand of the Motatapu Fault or NW Cardrona Fault, and not an independent rupture source. Motatapu Fault slip rate and RI are applied.	Class IV (>5,000 to ≤10,000 years
Home Hills fault zone (26)	Fault zones in bedrock	Bishop (1976, 1979); Forsyth (2001); Henne et al. (2011); this report	Air photo interpretation; regional geologic mapping;	Potentially active fault	null	null	No known evidence for geologically young fault movement. Equates in part to Stranraer Fault and Waihemo Fault System. Included for possibility of transferred secondary slip	Class VI (>20,000 years)
Hunter Valley Fault (14)	Inferred fault zone(s) in bedrock, with indicated offset of geologically young landforms	Litchfield et al. (2013); this report	Air photo interpretation; regional geologic mapping;	Likely active fault	0.32	12,000	Also known as the Hunter fault zone (Litchfield et al. 2013)	Class V (>10,000 to ≤20,000 years)
Hyde Fault (39)	Fault in bedrock, with offset of peneplain	Norris and Nicolls (2004); Litchfield et al. (2013); this report	Air photo interpretation; regional geologic mapping;	Likely active fault	0.25	13,000	Slip rate and RI taken directly from 2010 NSHM. The 'likely' classification reflects uncertainty whether the most recent rupture(s) extended into Central Otago	Class V (>10,000 to ≤20,000 years)
Lake Onslow fault (42)	Inferred fault zone(s) in bedrock, with offset of peneplain	This report	Air photo interpretation; geomorphologic interpretation	Potentially active fault	0.05	30,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Launceston Fault (35a)	Inferred fault in bedrock with deformed geologically young landforms	Litchfield et al. (2013); this report	Air photo interpretation; geomorphologic interpretation	Definite active fault	0.10	17,000	Regarded as a component of the Ranfurly Fault Zone	Class V (>10,000 to ≤20,000 years)
Lindis Pass Fault Zone (21)	Fault zones in bedrock with deformed geologically young sediments or landforms	Litchfield et al. (2013); Barrell (2016); this report	Air photo interpretation; regional geologic mapping;	Definite, likely and possible active fault strands	0.47	5600		Class IV (>5,000 to ≤10,000 years

Name	Observed characteristics	References	Deformation estimates					
Representative name for feature (number in Figures 5.1–5.3)	*Description of feature(s)*	*Main source(s) of information on character or activity of feature*	*Basis of estimates*	*Classification*	*Assigned net slip rate (mm/yr)*	*Calculated recurrence interval (RI) - years*	*Comments*	*Indicated RI Class (following Kerr et al. 2003)*
Lindis River Fault (17)	Fault in bedrock, with offset of peneplain	This report	Air photo interpretation; regional geologic mapping;	Potentially active fault	0.05	50,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Little Valley fault zone (30)	Fault zone(s) in bedrock, with offset of peneplain	Turnbull (2000); this report	Air photo interpretation; regional geologic mapping; geomorphologic interpretation	Potentially active fault	0.05	60,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Livingstone Fault (1)	Major fault in bedrock, with suspected offset of geologically young landforms	Litchfield et al. (2013); this report	Regional geologic mapping; air photo interpretation	Likely active fault	1.00	6400	Referred to as the Hollyford active fault earthquake source by Stirling et al. (2012)	Class IV (>5,000 to ≤10,000 years
Logan Burn fault (48)	Inferred fault in bedrock, with offset of peneplain	This report	Air photo interpretation; regional geologic mapping; geomorphologic interpretation	Potentially active fault	0.05	60,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Long Valley Fault (43)	Fault in bedrock, with offset of peneplain and geologically young landforms	Litchfield et al. (2013); this report	Air photo interpretation; regional geologic mapping; field inspection; geomorphologic interpretation	Definite active fault	0.18	7900		Class IV (>5,000 to ≤10,000 years
Moonlight Fault Zone - north section (4)	Major fault zone(s) in bedrock, with indicated large offset of mid-Cenozoic strata	Turnbull et al. (1975); Turnbull (2000); Litchfield et al. (2013); this report	Regional geologic mapping; air photo interpretation	Potentially active fault	0.05	140,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Moonlight Fault Zone - south section (3)	Major fault zone(s) in bedrock, with indicated large offset of mid-Cenozoic strata	Turnbull et al. (1975); Turnbull (2000); Litchfield et al. (2013); this report	Regional geologic mapping; air photo interpretation	Potentially active fault	0.05	120,000	No known evidence for geologically young fault movement. The lesser RI is because the south section has a shorter length than the north section	Class VI (>20,000 years)
Motatapu Fault (5)	Suspected fault zone in bedrock, with suspected 5 m offset of glacial landforms	Turnbull (2000); this report	Regional geologic mapping; air photo interpretation	Likely and possible active fault strands	0.32	6500		Class IV (>5,000 to ≤10,000 years
Nevis Fault Zone (7)	Fault zone(s) in bedrock, with deformed geologically young sediments and landforms	Beanland & Barrow-Hurlbert (1988); Litchfield et al. (2013); this report	Air photo interpretation; regional geologic mapping; field inspection & trenching; geomorphologic interpretation	Definite and likely active fault strands	0.40	9000		Class IV (>5,000 to ≤10,000 years
NW Cardrona Fault (6)	Fault zone(s) in bedrock, with deformed geologically young sediments and landforms	Beanland & Barrow-Hurlbert (1988); Turnbull (2000); Litchfield et al. (2013); this report	Air photo interpretation; regional geologic mapping; lidar data; field inspection & surveying; trenching & dating; geomorphologic interpretation	Definite, likely and possible active fault and fold strands	0.38	5500		Class IV (>5,000 to ≤10,000 years)
Old Man Fault (28)	Fault zone(s) with slight deformation of geologically young sediments	Stirling (1990); Hull & Stirling (1992); Litchfield et al. (2013); this report	Regional geologic mapping; air photo interpretation; field inspection	Potentially active fault	0.01	~360,000	Slight offset (<5 m) of 'Lindis Formation' river gravels of assessed age ~330,000 years	Class VI (>20,000 years)
Omarama Saddle fault (24)	Inferred fault zone(s) in bedrock, with indicated offset of peneplain and localised offset geologically young landforms	Barrell (2016); This report	Air photo interpretation; regional geologic mapping; geomorphologic interpretation	Definite and likely active fault strands	0.2	12,000		Class V (>10,000 to ≤20,000 years)

Name	Observed characteristics	References	Deformation estimates					
Representative name for feature (number in Figures 5.1–5.3)	*Description of feature(s)*	*Main source(s) of information on character or activity of feature*	*Basis of estimates*	*Classification*	*Assigned net slip rate (mm/yr)*	*Calculated recurrence interval (RI) - years*	*Comments*	*Indicated RI Class (following Kerr et al. 2003)*
Paddys Ridge fault (8)	Fault zone(s) in bedrock, with offset of peneplain	Beanland & Barrow-Hurlbert (1988); Turnbull (2000); this report	Air photo interpretation; regional geologic mapping; geomorphologic interpretation	Potentially active fault	0.05	30,000	Also known as SE Cardrona Fault. No known evidence for geologically young fault movement	Class VI (>20,000 years)
Pisa Fault Zone (20)	Fault zone(s) with deformed geologically young sediments and landforms	Beanland & Berryman (1989); Litchfield et al. (2013); this report	Air photo interpretation; regional geologic mapping; field investigations & trenching; geomorphologic interpretation	Definite, likely and possible active fault and monocline strands	0.10	30,000	A northeastern extension of the Pisa Fault Zone (Pisa-Lindis Peak branch) is redefined here as the Cluden fault zone	Class VI (>20,000 years)
Pylep fault (44)	Fault zone(s) in bedrock, with offset of Otago peneplain	This report	Air photo interpretation; regional geologic mapping; geomorphologic interpretation	Potentially active fault	0.05	30,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Ranfurly Fault Zone (35)	Deformed geologically young landforms	Litchfield et al. (2013); this report	Air photo interpretation; geomorphologic interpretation	Definite, likely and possible active fault strands	0.10	17,000	The Launceston Fault is regarded as a northern continuation of the Ranfurly Fault Zone	Class V (>10,000 to ≤20,000 years)
Riddles fault (47)	Inferred fault zone(s) in bedrock, with indicated offset of peneplain	This report	Air photo interpretation; regional geologic mapping; geomorphologic interpretation	Potentially active fault	null	null	No known evidence for geologically young fault movement. Thought to be offset by younger faults. Included for possibility of transferred secondary slip	Class VI (>20,000 years)
Roaring Lion fault (10)	Fault zone(s) in bedrock, with offset of peneplain	Turnbull (2000); this report	Regional geologic mapping; geomorphologic interpretation	Possible active fault	0.05	65,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Roaring Meg fault (9)	Fault zone(s) in bedrock, with offset of peneplain	Beanland & Barrow-Hurlbert (1988); Turnbull (2000); this report	Regional geologic mapping; geomorphologic interpretation	Potentially active fault	0.05	40,000	Approximates the previously named Gentle Annie Fault. No known evidence for geologically young fault movement	Class VI (>20,000 years)
Rocks Creek Fault Zone (24a)	Fault zone(s) in bedrock, with offset of peneplain and deformed geologically young landforms	Beanland & Fellows (1985); Madin (1988); this report	Air photo interpretation; regional geologic mapping; field inspection & trenching; geomorphologic interpretation	Definite and likely active fault and monocline strands	0.2	12,000	Interpreted to be a splay of the Omarama Saddle fault; slip rate and RI of that fault adopted for Rocks Creek Fault Zone	Class V (>10,000 to ≤20,000 years)
Teviot Fault (40)	Inferred fault zone in bedrock, with indicated offset of peneplain	This report	Air photo interpretation; regional geologic mapping; geomorphologic interpretation	Potentially active fault	0.01	225,000	No known evidence for geologically young fault movement	Class VI (>20,000 years)
Timaru Creek Fault (16)	Fault zone in bedrock, with deformed geologically young landforms	This report	Air photo interpretation; regional geologic mapping;	Definite, likely and possible active fault strands	0.32	6100	Includes the previously named Timaru Creek Fault and the Johns Creek Fault (16a)	Class IV (>5,000 to ≤10,000 years
Tuapeka Fault (41)	Fault zone in bedrock with suspected offset of geologically young landforms	Turnbull and Allibone (2003); this report	Air photo interpretation; regional geologic mapping;	Likely active fault	null	null	Only the northernmost part lies in Central Otago District, remainder is in Clutha District. Nominal RI Class is applied here, pending future assessment	Class VI (>20,000 years)

Name	Observed characteristics	References	Deformation estimates					
Representative name for feature (number in Figures 5.1–5.3)	*Description of feature(s)*	*Main source(s) of information on character or activity of feature*	*Basis of estimates*	*Classification*	*Assigned net slip rate (mm/yr)*	*Calculated recurrence interval (RI) - years*	*Comments*	*Indicated RI Class (following Kerr et al. 2003)*
Waihemo Fault Zone (37)	Fault zones in bedrock with suspected offset of geologically young landforms	Litchfield et al. (2013); this report	Air photo interpretation; regional geologic mapping; geomorphologic interpretation	Likely active fault	0.12	50,000		Class VI (>20,000 years)
Waipiata Fault Zone (38)	Fault zone in bedrock with suspected deformation of geologically young landforms	Litchfield et al. (2013); this report	Air photo interpretation; regional geologic mapping; geomorphologic interpretation	Definite, likely and possible active fault and monocline strands	0.10	24,000		Class VI (>20,000 years)
Wanaka Fault (13)	Inferred fault zone(s) in bedrock.	Turnbull (2000); Litchfield et al. (2013); this report	Geodynamic modelling; regional geologic mapping	Potentially active fault	0.05	85,000	No known evidence for geologically young fault movement. Referred to as the Makarora Fault by Litchfield et al. (2013)	Class VI (>20,000 years)
West Wakatipu Fault (2)	Fault zone(s) in bedrock, with post-glacial landform offsets at southern end	Turnbull et al. (1975); Turnbull (2000); this report	Air photo interpretation; regional geologic mapping; geomorphologic interpretation	Definite, likely and possible active fault strands	0.19	20,000	Post-glacial fault scarps previously attributed to Moonlight Fault reassigned to West Wakatipu Fault	Class V (>10,000 to ≤20,000 years)

5.2 Comparison with Previous Assessments

The present project has delineated 48 active and potentially active faults thought to be capable of generating ground-surface rupturing earthquakes, noting that the total of 55 named fault features in Figures 5.1–5.3 and Table 5.2 includes several regarded as only able to rupture together with other faults. In comparison, the 2010 NSHM identifies a total of 19 active fault earthquake sources partly or entirely within the limits of the combined Queenstown Lakes and Central Otago districts, whereas the NZAFM defined 23 active faults, due to an additional four faults being interpreted as active. The NZAFD, which in this region is based largely on interpreted active fault scarps from the QMAP dataset, mostly shows scattered, disconnected, active fault strands rather than entire active fault structures, as are portrayed in the NZAFM, for example. The present active fault dataset provides a full update of information on active faults in the combined Queenstown Lakes and Central Otago districts. The information on active faults in this report is more comprehensive than the current version (December 2018) of the NZAFD, and the information provided in the report by Mackey (2015) for Queenstown Lakes District, which was based on NZAFD linework.

5.3 Assessment of Fault Activity Estimates

The delineation of many more additional faults in the present project compared to previous assessments raises some issues for fault activity estimation. The estimation of fault slip rates for the 2010 NSHM and the NZAFM took account of the inferred strain from plate convergence across the South Island. In both those datasets, fault characterisation parameters based on geological investigation or landform interpretation evidence were adjusted to achieve a satisfactory accord with predicted plate deformation strain.

This issue was taken into consideration for the new fault dataset presented in this report. For each of the potentially active faults, for which there is no recognised evidence of fault deformation of geologically-young landforms, a nominal slip rate of 0.05 mm/yr has been assigned. The reason for selecting that nominal value is that in the south-eastern South Island, faults with a slip rate of about 0.1 mm/yr generally show some landform indicators of fault deformation, such as uplifted old terraces, or elevated hill terrain, on the upthrown side of line of the fault, for example the Pisa Fault Zone in Central Otago (Beanland and Berryman 1989) and the Titri Fault in coastal Otago (Barrell et al. 2019). A nominal slip rate of 0.05 mm/yr is considered here to be a first-approximation value that is compatible with an absence of preserved landform evidence of geologically-recent fault deformation. A 'reality-check' comparison can be made by summing the slip rates of all the faults partly or entirely in the combined districts in the 2010 NSHM, the NZAFM, and the present dataset. While this approach is not a good measure of plate deformation strain relative to the plate boundary, it does give an approximation of internal deformation rate within a three-dimensional block of the Earth's crust in the combined area of the two districts. In both the 2010 NSHM and the NZAFM, the summed slip rate is ~9.0 mm/yr, whereas the summed slip rate for the 48 faults in the new dataset is 7.7 mm/yr. This indicates that the slip rates applied in the new dataset are broadly in overall accord with those of the 2010 NSHM and NZAFM datasets. If the nominal 0.05 mm/yr slip rate were adjusted upward to 0.07 mm/yr, the summed total slip rate would match that of the 2010 NSHM and NZAFM. It was considered preferable to retain a 'round-number' nominal slip rate of 0.05 mm/yr for this dataset, to emphasise its nominal nature, rather than adjust it artificially to allow the summed slip rate of the new dataset to exactly match that of the 2010 NSHM and NZAFM.

The nominal slip rate of 0.05 mm/yr is applied to 18 of the faults delineated in the new dataset. A slip rate was not applied to a further three faults (Home Hills fault zone, Riddles fault and Tuapeka Fault). The first two are interpreted to have been cut off at depth by other active faults and are inferred to not be capable of independent earthquake rupture. They are included in this dataset because of a possibility that they could experience secondary slip transferred from the rupture of adjacent active faults. The Tuapeka Fault lies in the Clutha District, and only its northern tip extends into Central Otago. Although Villamor et al. (2018) assigned the Tuapeka Fault a slip rate of no more than 0.01 mm/yr, it seems desirable to await a fuller assessment of the fault, as part of an anticipated companion active fault assessment for the Clutha District, before confirming a slip rate estimate for the Tuapeka Fault.

Using the 2010 NSHM calculation methodology, all of the faults assigned a nominal 0.05 mm/yr slip rate have a recurrence interval of more than 20,000 years, thus equating to recurrence interval Class VI in the MfE active fault guidelines (Kerr et al. 2003). This class is also applied to the three faults that were not given a slip rate. A total of 18 faults have calculated recurrence intervals between 10,000 and 20,000 years (Class V), and the remaining nine faults have calculated recurrence intervals of between 5,000 and 10,000 years (Class IV).

5.4 Discussion of Fault Activity Close to Population Centres

5.4.1 Queenstown Area

The major change for the Queenstown area arising from the present assessment is that the Moonlight Fault, previously regarded as one of the most active faults in the area, with a recurrence interval of between 6,000 and 7,000 years (Stirling et al. 2012), has had its level of activity greatly downgraded, with its recurrence interval recalculated as more than 100,000 years. Instead, the fault offset landform features previously considered to be associated with the Moonlight Fault are now attributed to the West Wakatipu Fault, for which a recurrence interval of 20,000 years is calculated.

There is no change in activity status for the NW Cardrona Fault which crosses the Kawarau valley at the western end of the Gibbston basin (Figure 5.4). The mapped location of the main, ‘definite’, strand of the fault there has been refined, aided by lidar data. Also, the Nevis Fault Zone was previously mapped as crossing the floor of the Gibbston basin. In the present dataset, the NW Cardrona Fault is extended to ~12 km south of Gibbston. The northern end of the Nevis Fault Zone is now placed at the repositioned southern end of the NW Cardrona Fault.

Overall, the downgrading of activity level of the Moonlight Fault means that the chance of fault rupture and related hazards occurring due to a local-source earthquake is reduced for the Lake Wakatipu area compared to previous estimates. Were rupture to occur on the more active faults in the area (NW Cardrona Fault, Nevis Fault Zone and West Wakatipu Fault, in order of increasing recurrence interval), there would be a large earthquake centred within 30 km or so of Queenstown, which would cause strong ground shaking effects in the Wakatipu area.

5.4.2 Wanaka and Hawea Area

The major change for the Wanaka area is the recognition, due to the availability of detailed topographic information from lidar, that the most recent surface ruptures of the NW Cardrona Fault appear to have extended north from the Cardrona valley, near the foot of the Mt Alpha range, through part of Wanaka township (Figures 5.5, 5.6). Previously, the NW Cardrona Fault was thought to extend northeast to Lake Hawea, passing beneath Albert Town and part of

Lake Hawea township. The interpreted surface deformation through the Wanaka area is in the form of a monoclinal fold, that is most clearly expressed across old lake-beach landforms of an assessed age of no older than 18,000 years. The fold affects a ~100 to ~200 m wide zone of ground that has been up-warped to the west by ~4 or 5 m. The effect has been to impart a gentle easterly tilt to the ground across that zone. This interpretation is currently classed as 'likely', pending more detailed investigation and assessment. Preliminary assessment of lidar data suggests that younger lake-beach landforms show lesser amounts of deformation, indicating that the ~4 to 5 m high warp on older landforms is the result of at least two movement events.

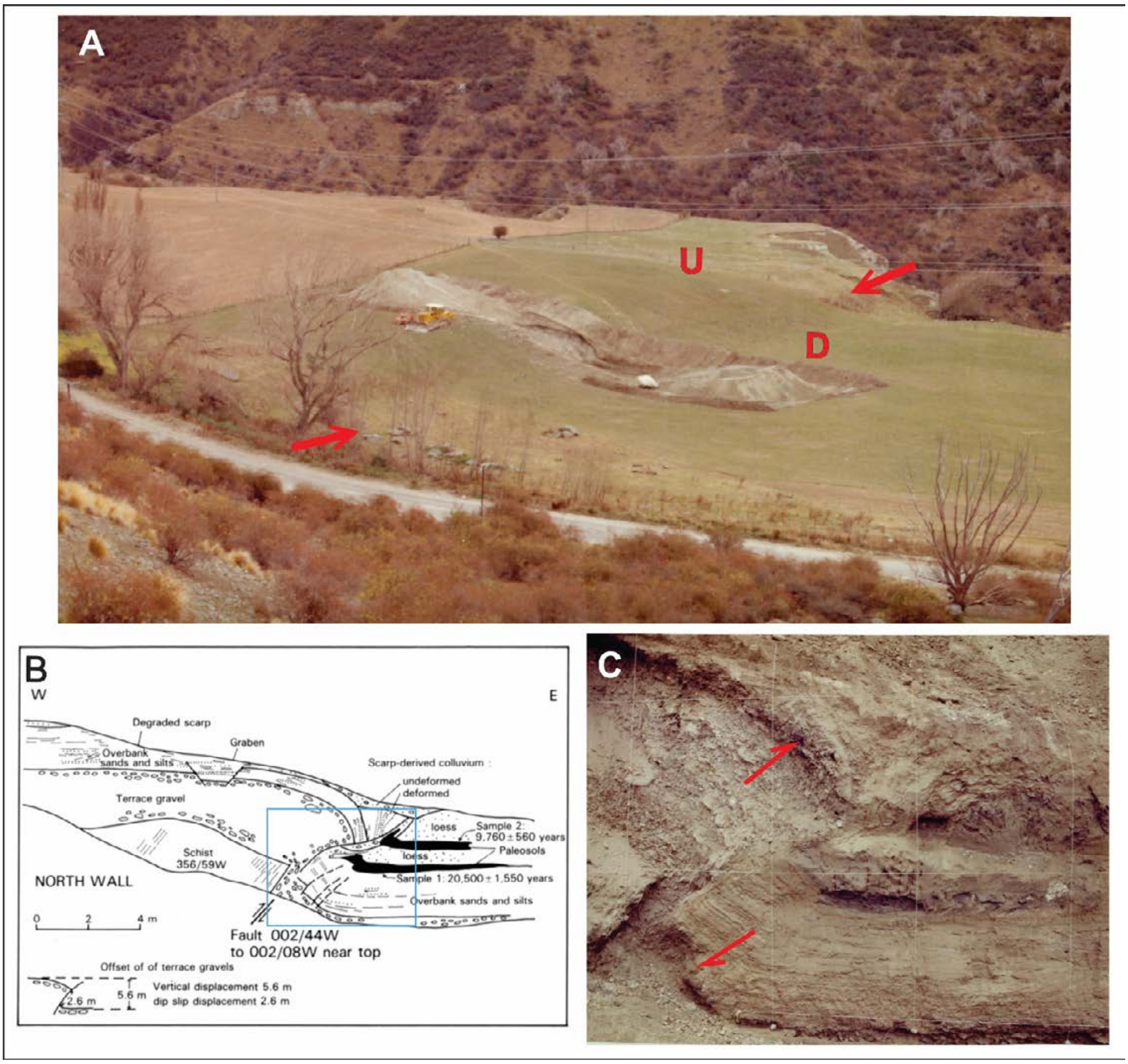

Figure 5.4 Views of a geological investigation trench excavated across the NW Cardrona Fault in the Kawarau valley at Gibbston in 1984. The fault scarp lies about 0.5 km east of the Kawarau Bridge bungy jump carpark, and about 0.6 km west of the Gibbston Valley Winery; the fault scarp is readily visible from the highway. **A**: View north from the slopes of Cowcliff Hill above State Highway 6 (foreground). The fault scarp runs across the river terrace (red arrows highlight the foot of the scarp, with up and down sides lettered). Bulldozer near the left-hand end of the trench illustrates scale. Photo from unpublished report by Beanland and Fellows (1984). **B**: Geological log of the northeastern wall of the trench, from Beanland and Barrow-Hurlbert (1988). Blue box indicates approximate field of view in panel C. Dates for samples 1 and 2 are uncalibrated radiocarbon ages; refer to Appendix 2 for ages recalculated using modern calibration. **C**: View of buckled and offset geological materials in the northeast wall of the trench; refer to panel B for description of materials. Red half-arrows highlight sense of fault movement. Photo from unpublished report by Beanland and Fellows (1984).

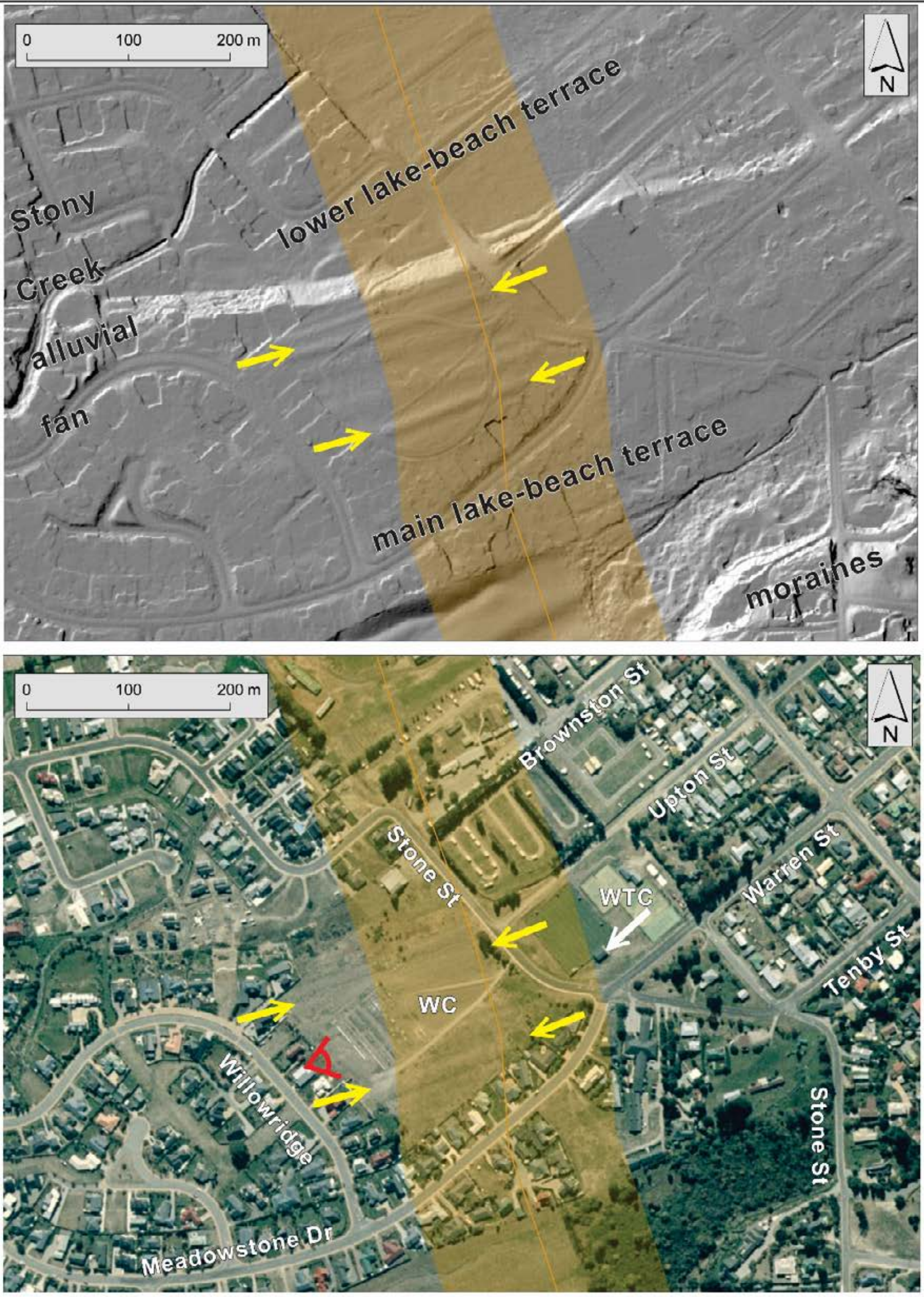

Figure 5.5 Map views highlighting the location of a suspected monocline fold through Wanaka township, close to Wanaka Cemetery (WC). **Upper panel**: A high-resolution topographic relief model generated from lidar, with the main landform features annotated. The thin orange line marks the centreline of the monocline fold, as positioned in the GIS dataset described in this report. The certainty that this feature is an active fold is classified as 'likely'. The orange colour band illustrates, schematically, the approximate width of the tilted ground across the fold. West and east of the colour band, the lake-beach terrace landform is approximately flat, but across the colour band, the ground has a gentle eastward tilt. Yellow arrows highlight two beach ridges, created by wave action at former shorelines of a much larger Lake Wanaka, that are well-resolved in the lidar model. **Lower panel**: Same map area, with a high-resolution aerial photo background (Otago 0.75m Rural Aerial Photos (2004–2011); Terralink and Otago Regional Council). The yellow arrows are in the same position as in the upper panel and illustrate that the beach ridges are evident in aerial photos as well as in the lidar model. The red symbol indicates the vantage point and field of view of the Figure 5.6 photo; the white arrow indicates a building at Wanaka Tennis Club (WTC) that is also arrowed in Figure 5.6).

This new interpretation, while still requiring a more detailed assessment for confirmation, may explain a long-standing geological puzzle. Relatively young landforms have been offset by ruptures of the NW Cardrona Fault in the Cardrona valley, but there is no indication of fault offset of the somewhat older glacial landforms between Albert Town and Lake Hawea. There is undoubtedly a fault in bedrock extending through that area, but in the present dataset that fault is renamed the Cardrona-Hawea fault and is assessed as having a much lesser level of activity (calculated recurrence interval 30,000 years) compared to the NW Cardrona Fault (calculated recurrence interval 5,500 years).

Figure 5.6 A view east across a likely monocline fold at Wanaka Cemetery. Figure 5.5 shows the approximate location of monocline relative to this photo location. Even though the photograph looks across an originally-flat lake-beach landform and was taken at ground level on the up-warped side of the suspected monocline, the roofs of buildings in the distance, on the down-warped side, are at or below the horizonal line of sight. The white arrow denotes the roof of a building at Wanaka Tennis Club, which is also marked in Figure 5.5 along with the photo location. Photo: GNS Science. D.J.A. Barrell.

Another change is the incorporation of the Highland Fault into an active fault context (Figure 5.7). The fault is assessed as being too short to be an independently rupturing active fault structure, and it is suggested to be part of the surface expression of rupture on another fault. The NW Cardrona Fault is one possible associate, but with the detection of 'likely' post-glacial offset on the Motatapu Fault, the interpretation favoured here is that the Motatapu and Highland Fault together form a single active fault. One possibility is that this fault may usually rupture in unison with the NW Cardrona Fault, which potentially is plausible because they have similar estimated recurrence intervals (5,500 years for the NW Cardona Fault and 6500 years for the Motatapu Fault). Alternatively, the combined Motatapu/Highland fault structure may be an independent source of a large, locally-generated earthquake.

An issue arising is that with the likely presence of the Motatapu Fault and NW Cardrona Fault extending beneath Lake Wanaka, a future earthquake rupture that deforms or displaces the lake bed is likely to create a localised tsunami. This is also potentially the case with the Wanaka Fault beneath the northern arm of Lake Wanaka, and the Hunter Valley Fault beneath Lake Hawea, although those two faults are assessed as being of low activity, with relatively long recurrence intervals.

Overall, this re-assessment has not markedly altered the expected chance of fault rupture and related hazards occurring due to a locally sourced earthquake in the Wanaka and Hawea area. However, the locus of potential fault-related ground deformation has been revised, with the NW Cardrona Fault now likely passing beneath part of Wanaka township. The Cardrona-Hawea fault that passes under Albert Town and Lake Hawea township is regarded as having a much lesser average rate of activity than previously assumed.

Figure 5.7 A view east across a geologically-young fault offset of hillslope landforms on the Highland Fault, in the catchment of Fern Bern, about 12 km west of Wanaka township. The fault scarp position is highlighted by red arrows, and the sense of up versus down movement is lettered. The fault scarp is upthrown on the downhill side. Photo: GNS Science, CN 10350/31H and VML ID 5035. D.L. Homer, taken 1987.

5.4.3 Upper Clutha Valley

Overall, there is no change at Luggate or Cromwell in the risks of fault rupture and related hazards occurring due to a local-source earthquake. Aside from changes in interpretation of the associations between the Grandview Fault and Pisa Fault Zone, including the newly-defined Cluden fault zone and the addition of the Bannockburn Fault as a strand of the Pisa Fault Zone, the active faults in the immediate vicinity of the upper Clutha valley (downstream of the Wanaka-Hawea basin), are assessed as low-activity faults, with recurrence intervals of more than 10,000 years. The reinterpretation that the Pisa Fault Zone extends south along the foot of the Carrick Range as a ‘possible’ active fault, and inclusion of the Bannockburn Fault strand in the fault zone, places Bannockburn in the potential frame of fault rupture and related hazards. However, risks are low because of the indicated very long recurrence interval for ground-rupturing earthquakes on the Pisa Fault Zone.

5.4.4 Clyde and Alexandra Areas

Geological investigations over the past 15 years have shown that geologically-recent deformation associated with the Dunstan Fault Zone has extended southwest towards Clyde, rather than diverting west-southwest along the southern margin of the Cairnmuir Mountains, as was thought previously (e.g. Turnbull 2000). A monocline fold has deformed old, high-level, river terraces immediately north of Clyde township (Figure 5.8), but there has been no discernible deformation of the lower river terraces upon which Clyde is situated. Further investigations and assessment would be needed to determine potential ground deformation hazards and risks for Clyde in relation to a future rupture of the Dunstan Fault Zone.

Figure 5.8 Views of a Dunstan Fault Zone monocline fold immediately northeast of Clyde. **Upper panel**: A panorama looking northwest towards a broad topographic step that is a monocline scarp, highlighted by red arrows and up versus down letter annotation. The arrowed drilling rig illustrates scale. The monocline extends north-northeast across high-level terraces of the Clutha River. Clyde township lies on low terraces of the Clutha River, immediately to the left of this view. **Lower panel**: Named the ‘Reservoir-3 monocline’, the fold scarp was examined in a geological investigation trench, positioned at the point of the left-hand arrow in the upper panel. In this northward view, the trench showed that the Clutha River sediments here are tilted by monocline movement. The sediments have a dip from horizontal of between 4° to 5°, whereas the usual depositional angle of Clutha River sediments is less than 1°. Geological dating showed that the river sediments are at least 200,000 years old, and the overall investigation finding was that the monoclinal warp of the river deposits is between 20 and 25 m high, up to the northwest. Photos: GNS Science, D.J.A. Barrell, taken April 2005 (upper) and February 2006 (lower).

Prominent fault zones in bedrock that pass through the Alexandra area (Turnbull 2000) have been classified as ‘possible’ active and identified here as the Galloway fault zone. This is based on the detection in lidar of a 'likely' fault scarp at the southern margin of the Blackmans Fault strand of the Galloway fault zone near Earnscleugh Flats, but evidence for geologically-recent elsewhere along the fault zone is inconclusive. The scarcity of surface expression of such movements highlights that, if it is an active fault, it has a long recurrence interval, calculated here as ~15,000 years.

5.4.5 Roxburgh Area

Through the Roxburgh area, the Clutha valley follows the line of the Old Man Fault, and the closely aligned Teviot Fault. Geological evidence indicates that very little movement has occurred in the past 300,000 years or so (Hull and Stirling 1992), and both are classified as having very long recurrence intervals.

5.4.6 Maniototo Area

The Stranraer Fault lies about 2 km northeast of Naseby and has displaced medium to high-level terraces in the Little Kye Burn valley, but not the lower terraces (Figure 5.9). The Stranraer Fault is regarded as a strand of the Waihemo Fault Zone, and a recurrence interval of 60,000 years is calculated, indicating that it is a low activity fault.

Figure 5.9 View of the scarp of the Stranraer Fault (Waihemo Fault Zone) across middle to high-level terraces of the Little Kye Burn valley, about 6 km east of Naseby. The base of the fault scarp is denoted by the red arrows and the dotted red line, while the sense of movement is highlighted by up versus down lettering. As seen here looking northwest from Little Kyeburn Road, 3 km north of the Dansey Pass Road intersection, the scarp appears to be about 10 m high on the middle terrace, and about 15 to 20 m high on the high terrace. The low terrace is probably ~18,000 years old and has not offset by the fault. Photo: GNS Science, D.J.A. Barrell, taken January 2018.

The Ranfurly Fault Zone lies 1 km or so south of Ranfurly township. Scarps from the most recent rupture(s) of the fault zone displace low terraces on the Ewe Burn valley floor, and the closely aligned Launceston Fault to the north has offset hillslope landforms, with upthrow on the downhill side. Collectively, an earthquake rupture having occurred since the end of the last glaciation is indicated, but the fault scarps are not much higher across adjacent, much higher and older, river terrace landforms. This indicates that, despite a geologically recent fault rupture having occurred, the recurrence interval is long, assessed here as being about 17,000 years.

6.0 IMPLICATIONS FOR HAZARDS

Since European settlement in the Queenstown Lakes and Central Otago district, there have been no known ground-surface fault rupture events. The geological record and landforms show clear evidence for many zones of geologically-recent (though pre-dating European settlement) fault and fold deformation of the ground surface. This highlights that it would be prudent to treat the active fault or fold features of the Queenstown Lakes and Central Otago districts as potentially hazardous. Figures 1.2 and 1.3 illustrate examples of the types of ground-surface deformation hazards associated with active faults or active monoclines, noting that at any location, elements of both faulting and folding may be present within a deformation zone. Faults present the most focused form of ground deformation, in regard to direct rupture, while monocline movement involves broader tilting of the ground surface. Monocline growth is likely to occur in a sudden event, associated with rupture of an underlying fault.

The geological estimates presented in this report indicate that none of the faults in the Queenstown Lakes and Central Otago districts has a recurrence interval of less than 5,000 years, only nine have assessed recurrence intervals of less than 10,000 years, and the rest are considered to have recurrence intervals of more than 10,000 years. For many of those inferred low-activity faults, there is uncertainty as to whether they should in fact be considered active, but their potential for future activity cannot be ruled out. Nonetheless, there are several undoubtedly active faults in the Queenstown Lakes and Central Otago districts and every reason for authorities and residents to be prepared for the occurrence of ground-surface rupturing fault movements, and resulting large, locally damaging earthquakes, over future decades to centuries. It is important to appreciate that the mapped delineation of the active faults and folds of the Queenstown Lakes and Central Otago districts presented in this report has been done at a regional scale (1:250,000). The level of precision is not adequate for any site-specific assessment of hazards (e.g. planning for building or other infrastructure developments). In addition, several of the fault/fold features that have been mapped have not yet been proven to be active. For features classed as ‘likely’, or ‘possible’, it would be desirable to prove one way or the other whether they are hazardous active faults/folds, before undertaking any hazard planning, zonation or mitigation in respect to these features.

It is reiterated that the information presented in this report, and the accompanying GIS layers, is primarily intended for indicating general areas where there may be an active fault ground-deformation hazard to look for, and where site-specific investigations may be necessary prior to development.

7.0 CONCLUSIONS

1. Regional geological mapping has identified a number of active fault and fold features in the Queenstown Lakes and Central Otago districts. In total, 48 known, suspected, possible or potentially active faults are delineated. The existence of most of these faults was already known, and they have previously been shown on published geological maps, for example, although many were classified as 'inactive'.
2. A GIS dataset of information on the active faults and folds accompanies this report. For each mapped fault and fold, an attribute of 'certainty' indicates the level of confidence in the mapping of the feature, whether 'definite', 'likely' or 'possible'. Also included is a classification of 'surface form', whether 'well expressed', 'moderately expressed', 'not expressed' or 'unknown'. The surface form classification provides a provisional estimate of how easy it would be to pinpoint the location of the particular fault or fold feature on the ground.
3. Table 5.2 summarises what exists in the way of geological evidence for the degree of activity of each feature. Average slip rate is a common way to compare the level of activity of a fault or fold. This can also be expressed as an average recurrence interval for deformation events, aided by some assumptions. The recurrence interval estimates provide a linkage to Ministry for the Environment active fault planning guidelines.
4. The information presented here is not sufficiently precise for site-specific hazard assessment. Instead, the information is intended to highlight those areas which, at the current state of knowledge, are potentially affected by active fault or fold hazards. The information may help to target site-specific investigations that may be desirable, or required, prior to development, and allow identification of lifeline vulnerabilities and emergency management response plans.

8.0 ACKNOWLEDGEMENTS

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APPENDICES

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APPENDIX 1 GIS DATASET

The GIS dataset referred to in this report comprises an ArcGIS file geodatabase, containing three Feature Classes:

- CODC-QLDC_active faults_Feb 2019
- CODC-QLDC_active folds_Feb 2019
- CODC-QLDC_active fault entity_Feb 2019

The original attribute fields for first two feature classes were extracted from the QMAP (Quarter-Million-scale geological mAP) 'seamless' dataset (Heron, 2014), sourced from map data represented in the Queenstown Lakes and Central Otago districts by the Waitaki map (Forsyth 2001), and in the far northwestern part of the Waitaki District by the Aoraki map (Cox & Barrell 2007), Haast map (Rattenbury et al. 2010) and Wakatipu map (Turnbull 2000).

In order to make clear the linkage between the QMAP dataset and the amended dataset prepared as part of this project, several attribute fields of the QMAP dataset are retained, comprising ‘NAME’, ‘ZONE’, ‘DOWN_QUAD’, ‘QMAP_NAME’ and ‘QMAP_NUMB’. In addition, for the folds feature class, the QMAP fields of ‘TYPE’ and ‘FACING’ are retained. New fault or fold features in the dataset can be identified by an absence of data attributes in QMAP_NAME and QMAP_NUMB database fields.

For this project, three new feature classes are added:

- ORC_name (local names for the mapped features)
- Certainty (see report text)
- Surf_form (see report text)

Unless indicated otherwise, all the data have been compiled at a regional scale (1:250,000) and the locations of active faults and folds should be regarded as having a general accuracy of ± 250 m, and at best, ± 100 m. The geographic coordinate system for the data is New Zealand Geodetic Datum 2000.

Interested readers can examine and query the QMAP digital database (Heron, 2014) online at GNS Science, www.gns.cri.nz, search term < QMAP digital data webmap >.

APPENDIX 2 COMMENTARY ON ACTIVE FAULT MAPPING

A2.1 Background Information

The information in this Appendix is largely of a technical nature and written for a technical audience. Its primary purpose is to set out the knowledge basis for the interpretation of faults and folds in this report. Readers of this Appendix may find it of benefit to refer to Google Earth, and topographic maps, such as may be accessed from www.topomap.co.nz.

The source of information on active faults and folds described in this report is from the 1:250,000-scale Geological Map of New Zealand, dubbed 'QMAP' because the map is at 'quarter-million' scale. Compiled between the mid-1990s and 2010, the maps were published as ~160 km by ~160 km individual sheets in a nationwide cut-up. The Queenstown Lakes and Central Otago districts are encompassed by four published map sheets, with accompanying descriptive booklets, comprising the Wakatipu map (Turnbull 2000), Haast map (Rattenbury et al. 2010; headwaters of the Wanaka and Hawea catchments), Murihiku map (Turnbull and Allibone 2003; southernmost part of Central Otago District) and the Waitaki map (Forsyth 2001; eastern part of Central Otago). Subsequently, all the digital datasets from which these maps were generated were compiled into a nationwide 'seamless' dataset, published in digital form on DVD (Heron 2014). The subsets of 1:250,000 scale faults and folds that form the Queenstown Lakes and Central Otago district dataset presented in this report were extracted from the Heron (2014) seamless QMAP dataset.

The classification of active faults and folds in the QMAP dataset, especially in the eastern South Island sheets, is largely evidence-based. Where there is observed evidence for geologically-recent movement, such as offset landforms or offset young deposits, the fault, and closely adjacent sectors of the fault, were attributed as 'active', whereas other, more distant, sectors of the same geological fault were attributed as 'inactive'. While the subdivision of a fault into active and inactive sector is somewhat artificial (a fault is either entirely active or it is not), it provided a way of emphasising evidence of recent activity on a fault in a particular area (attributed as 'active') and distinguishing that from faults whose existence is identified on geological criteria, but for which there is no specific evidence for or against recent movement. Thus, in the QMAP dataset, particularly in the eastern South Island, the attribution of a fault as 'inactive' means that rather than the fault being definitively 'inactive', there is no known evidence demonstrating that it is active. Much of the QMAP delineation of faults classified as 'active' in the central to lower South Island has been taken up, with little modification, into the New Zealand Active Faults Database (NZAFD; Langridge et al. 2016).

Subsequently, a more conceptual interpretation of fault activity in the Southern Alps was published by Cox et al. (2012), which identifies a considerable number of what are called 'potentially active' faults. A similarly generalised nationwide interpretation of active faults (the New Zealand Active Fault Model – NZAFM), was published by Litchfield et al. (2013, 2014). In the South Island, the information in the NZAFM is largely derived from reviews undertaken by the GNS Science earthquake geology team between 2005 and 2008, as described in Litchfield et al. (2013, 2014) The NZAFM datasets indicate the generalised location (at a scale of the order of 1:1,000,000) of faults that are known or inferred to be active, based on a range of geological considerations. In similar vein, many of the generalised faults depicted by Litchfield et al. (2013, 2014) are incorporated, again in highly generalised form, in the current version, compiled in 2010, of the National Seismic Hazard Model (NSHM; Stirling et al., 2012). The 2010 NSHM dataset focuses on identifying the location of faults that are considered to be potential sources of large earthquakes. The 2010 NSHM dataset is used primarily to generate statistical estimates of the likely maximum intensity of earthquake motions at any specified location in New Zealand, over specified time ranges (e.g. 500 years, 2500 years). For simplicity, any references made henceforth to the Litchfield et al. (2013) detailed report, and the Stirling et al. (2012) paper and associated datasets, are respectively the NZAFM and 2010 NSHM.

The dataset presented in this report is based on the 1:250,000-scale QMAP fault and fold dataset, unless indicated otherwise. In a number of places, refinements have been made to fault locations using lidar data or high-resolution colour aerial imagery, the latter accessed through the Google Earth platform, and through an imagery base map service delivered with the ArcGIS mapping software used for this project. In some cases, archival black and white aerial photography held by the GNS Science Dunedin Research Centre was examined, interpreted geomorphologically by the writer, and used to assist improved locational mapping of fault-related landforms. Commentary on these refinements, and the addition of any newly-identified, or reinterpreted, fault features, is provided in this appendix.

Extensive reference is made to the ‘Otago peneplain’, which is a key geological reference entity for assessing tectonic deformation in the eastern to south-eastern South Island. It is part of the Waipounamu Erosion Surface (Landis et al. 2008), which marks a major unconformity on top of Mesozoic-age rock, and at the base of younger sedimentary cover strata that were deposited on the older rock. In the project area, the peneplain is recognised as the top of schist or greywacke rock, where formerly overlying cover strata have been largely or completely eroded away, but with little erosional modification of the underlying rock (e.g. denudation of less than a few tens of metres).

The methodology of the 2010 NSHM was used for this project to calculate recurrence intervals for faults not previously in the 2010 NSHM, or for faults whose lengths have been revised. The 2010 NSHM methodology calculates, among other things, values for recurrence interval and single-event displacement from estimates of fault length, fault dip (the inclination from horizontal of the fault plane) and slip rate. Those estimates are usually determined by an expert panel of geoscientists, drawing on available geological information. For the present report, they were undertaken by the writer, in order to produce preliminary estimates, as explained for each fault in this appendix. It is expected that a panel approach would be used if new faults identified here are in future taken into the NSHM environments.

In this appendix, faults are discussed in alphabetical order. The adopted slip rate and recurrence interval estimates are compiled in Table 5.2 in the body of the report.

A2.2 Backbone fault (feature 45; Figure 5.3)

The north striking Backbone fault is a newly recognised feature on the western flank of the Lammerlaw Range, with an indicated a vertical separation of the peneplain of between ~100 and 200 m, up to the west. The feature as defined here is not included in the QMAP, NZAFD, NZAFM or 2010 NSHM datasets, but see later paragraph regarding a nearby short active fault feature on QMAP.

The name is taken from Backbone Ridge, in the Little Beaumont Stream catchment. It is an inferred fault, because there are no known recorded geological field observations of fault outcrop and the fault is positioned along the foot of the topographic escarpment. It is assumed to be a west-dipping reverse fault. In this dataset, it is mapped as extending from the Tuapeka Fault, just outside the Central Otago District, north to enclose Teviot Swamp, high on the

Lammerlaw Range. It approaches, but does not cross, the Beaumont River fault escarpment (see below).

The Backbone fault lies close to a short (~1 km long) segment of active fault depicted in QMAP and included in the NZAFD. However, review of archival aerial photos and high-resolution colour aerial imagery indicates that the topographic lineament previously interpreted as a fault scarp is more likely related to slope movement, and the short active fault feature is deleted from this dataset.

Following on that that revised interpretation, there are no discernible offsets of geologically young landform features and the Backbone fault is classified here as a ‘potentially active’ fault. For the estimation of activity parameters, the Backbone fault is assigned a dip of 60°, length of 24 km and a nominal slip rate of 0.05 mm/year. Using the 2010 NSHM methodology, a recurrence interval of ~35,000 years is calculated.

A2.3 Beaumont River fault (feature 46; Figure 5.3)

The north striking Beaumont River fault is a newly recognised feature across which there is an indicated vertical separation of the peneplain of between ~100 and 200 m, up to the east. It is an inferred fault, because there are no known recorded geological field observations of fault outcrop. It is not included in the QMAP, NZAFD, NZAFM or 2010 NSHM datasets.

The fault is positioned along the topographic escarpment, using a variety of landform features visible in high-resolution colour aerial photography. These include prominent gaps in rock outcrop, arrays of small landslides, and prominent seepage lines in the slope. Along sections without any other information, the fault is drawn at the foot of the escarpment.

The fault escarpment forms the eastern margin of the Beaumont River catchment, from which the fault name is taken. The fault crosses the crest of the Lammerlaw Range, and for most of its length, approximates the drainage divide between the Clutha and Taieri catchments. The southernmost ~15 km of the fault lies in the Clutha District. It is mapped as extending from the Tuapeka Fault north to the eastern side of Lake Onslow. Beyond there, a broad, slightly asymmetric hanging-wall anticline extends north a further 8 km, before petering out approaching the Long Valley Fault.

There are no discernible offsets of geologically young landform features, and the Beaumont River fault is classified here as ‘potentially active’, ‘not expressed’. For the estimation of activity parameters, the Beaumont River fault is assigned a dip of 60°, length of 36 km and a nominal slip rate of 0.05 mm/year. Using the 2010 NSHM methodology, a recurrence interval of ~50,000 years is calculated.

A2.4 Blackstone Fault (feature 31; Figures 5.2–5.3)

The Blackstone Fault marks the eastern side of the Raggedy Range to Blackstone Hill ridge, whose axis is an anticlinal fold. It is unclear the extent to which that margin of the ridge is an over-steepened anticline limb (e.g. Markley and Norris 1999), or an emergent fault. Several suspected fault scarps have been depicted along the margin of the range (Forsyth 2001). There is poor coverage from archival aerial photos, and no lidar coverage. In order to highlight the uncertainties on this structure, the QMAP linework is adopted without modification, and all the mapped fault strands are classed as ‘possible’.

This fault is identified by the name ‘Raggedy’ in the NZAFM and 2010 NSHM. The name ‘Blackstone Fault’ has been in long-standing geological usage and is applied in both editions of the QMAP dataset (Mutch 1963, Forsyth 2001). That name thus has precedence and is retained in the present dataset. The slip rate of 0.5 mm/yr assigned in the 2010 NSHM is judged too fast to accord with the poor topographic expression of ‘possible’ fault scarps. The rate of 0.14 mm/yr used in the NZAFM is considered more suitable and is adopted here.

A2.5 Blue Lake Fault (feature 23; Figures 5.2–5.3)

The Blue Lake Fault is a major north-northwest striking fault which has produced vertical separation of the peneplain of as much as ~1000 m, largest in the central sector of the fault and diminishing progressively north and south. Henne et al. (2011) present evidence that the Blue Lake Fault was initiated in the mid-Cretaceous as a major normal fault, downthrown to the east. In the Late Cenozoic, movement was reversed, resulting in the uplift of the St Bathans Range. At the Manuherikia River, evidence is presented for minor reverse movement of the fault during the Miocene, and relatively little movement subsequently (Henne et al., 2011). The southern limit of the fault is placed at its intersection with the Blackstone Fault at Pennyweight Hill, where the post early-mid Miocene throw displacement is no more than ~100 m (Beanland and Forsyth 1988), who also reported that the Blue Lake Fault does not cross the Blackstone Fault, whose prominent expression is an anticline.

At the Manuherikia River, three parallel fault strands are indicated, and were referred to as the Blue Lake Fault Zone by Henne et al. (2011). However, the north-eastern strands have previously been referred to as the Stranraer Fault by Madin (1988) and as the Waihemo Fault System by Forsyth (2001). In order to minimise confusion and reduce any connotations of direct association with other faults, these two north-eastern parallel strands are referred to in this dataset as the Home Hills fault zone (see separate section).

Topographic steps along a ~ 7 km long stretch of the Blue Lake Fault on the eastern side of the Dunstan Creek valley, down to the west, interpreted as fault scarps on QMAP, appear on modern imagery to be the result of landslide movement, with headscarps in places offsetting scree aprons upslope, and toe thrusts breaking out within sheared schist of the Blue Lake Fault zone. The landslide interpretation is strongly favoured because elsewhere along the fault, there are no offsets of landforms of comparable age to those that are offset prominently along the ~7 km long sector of the fault. With the new interpretation, there is no compelling evidence for Late Quaternary surface rupture of the Blue Lake Fault.

The Dunstan Fault Zone appears to die out against the Blue Lake Fault and raises the possibility of motion transfer from that fault to the Blue Lake Fault. For that reason, the Blue Lake Fault is identified here as a ‘possible’ active fault. It is classified as ‘not expressed’, except for the 7 km long sector interpreted as having experienced landslide movement, which is classified as ‘moderately expressed’.

In the 2010 NSHM, a slip rate of 0.47 mm/year is applied to the Blue Lake Fault, and a recurrence interval of 6080 years was calculated. This originates from the interpretation that the landform offsets, here attributed to landslide movement, were formed by fault rupture. The stratigraphic evidence for syn-depositional movement of the Blue Lake Fault in the Middle Miocene allows the use of an approach that differs from other faults in the region, for which there is evidence of post-Middle Miocene movement, but no constraint on when, post-Middle Miocene, their movement began. For the Blue Lake Fault, a slip rate is obtained here by dividing the ~1000 m maximum offset of the peneplain, by an assumed initiation at ~15 million years ago. This returns a long-term average vertical slip rate of 0.07 mm/year. In conjunction with an assumed pure dip-slip motion, an adopted fault dip of 70° east and fault length of 41 km, the latter two from the 2010 NSHM, a revised recurrence interval of ~40,000 years is calculated. This estimate acknowledges the possibility that the Blue Lake Fault has been a slow slip rate throughout its history. Alternatively, if the fault has been more active in the past, for example during the Miocene, the slip rate estimated here is likely to be a maximum, and the recurrence interval a minimum, for the recent geological past.

A2.6 Cardrona-Hawea fault (feature 11; Figures 5.1–5.2)

Geological relationships indicate the presence of a substantial northeast-striking fault, upthrown on its north-western side, extending from near the Cardrona/Clutha river confluence towards Lake Hawea. The fault lies somewhere between the basement rock massif of Mt Iron, and steeply-dipping Cenozoic-age sedimentary strata exposed in the banks of the Clutha and Hawea rivers near Albert Town. The fault is further extrapolated northeast between Mt Maude, composed of basement rock standing 1 km above the Wanaka/Hawea basin, and Camp Hill, on whose northwest side is an exposure of gently-dipping Cenozoic strata resting on bedrock.

New information that has led to the NW Cardrona Fault being repositioned northwards near Wanaka, at least in regard to its most recent ruptures, necessitates a status change for the northeast-striking fault that extends northeast between Wanaka and the Hawea area. It is not known whether it was formerly part of the NW Cardona Fault, or is simply a similar, but separate, fault. In this dataset, this fault is renamed the Cardrona-Hawea fault, to avoid any confusion in regard to recent (post-glacial) activity of the NW Cardrona Fault.

Lidar confirms previous visual assessments that the surfaces of glacial outwash plains, assessed as being 18,000 years old, are not deformed across the line of the Cardrona-Hawea fault, indicating that this fault has not experienced surface rupture in at least in the past ~18,000 years. Due to indications of geologically young activity on the faults against which it terminates, it is classified here as a ‘possible’ active fault. It characterised as a 60° northwest dipping fault, with a nominal slip rate of 0.05 mm/year, and length of 23 km, extending from the NW Cardrona Fault in the southwest, northeast beneath Lake Hawea township to a presumed three-way intersection with the Grandview Fault and Hunter River faults (see separate sections). Using 2010 NSHM methodology, a recurrence interval of ~30,000 years is calculated.

A2.7 Cluden fault zone (feature 19; Figure 5.2)

As discussed in the section on the Pisa Fault Zone, what was formerly interpreted as the north-eastern sector of the Pisa Fault is interpreted here as a separate entity. It comprises three northeast-striking strands showing offset of the peneplain, with local remnants of overlying Cenozoic strata. Displacement on each strand is up to the northwest. They are collectively named the Cluden fault zone, after nearby Cluden Stream. The two north-western strands are closely spaced, being no more than 2 km apart. Each has as much as ~100 m vertical separation of the peneplain, while the third strand lies as much as 4 km to the southeast and has as much as ~200 m of vertical separation of the peneplain. Their collective vertical separation of the peneplain is about 300 to 400 m. They appear to terminate to the northeast against the Longslip Fault (Lindis Pass Fault Zone). To achieve sufficient length to have produced the observed peneplain displacement, the Cluden fault zone must extend southwest to near the southern end of the Grandview Fault. This affords a maximum length of ~26 km for the Cluden fault zone.

Previous workers have suggested that to the northeast, the Pisa Fault Zone continues along the foot of the Lindis Peak range (Officers 1984; Halliday 1986; Beanland and Berryman 1989).

The major difference of interpretation here is that the uplift of the Lindis Peak range is attributed to the Goodger Fault on its north-western side, meaning that the south-eastern face of the range is not a range-front fault scarp, as previously interpreted, but rather a dip slope off the uplifted block.

Although the interpretation is not explained, Figure 1 of Halliday (1986) shows a ~600 m wide, ~50 m amplitude monoclinal fold in the post-Lindis lake sediments under the Clutha River channel, about 5 km west of Tarras, on the projected line of the Pisa Fault (now referred to here as the Cluden fault zone), There is a note written on the map that lake sediments there have dips of as much as 9°. The only surface deformation feature interpreted in this immediate area on QMAP comprises a warp on a terrace of correlated 'Luggate' age, near Jolly Road. However, the area lies just within lidar coverage. Examination of the lidar suggests that these landforms are probably old alluvial fan remnants built out onto a river terrace. It is possible that the apparent gradient anomaly could be due to overlapping alluvial fan surfaces, and for that reason, the feature is classified as 'possible', 'moderately expressed' in this dataset.

Farther to the west, where the two north-western strands have merged, aerial imagery indicates that there is a linear, though vague, topographic step, up to the northwest and 10 or 15 m high, running across old, very dissected, alluvial fans surfaces. It is classified here as a 'moderately expressed' 'possible' fault scarp.

A potentially important topographic feature is evident at Cluden Hill saddle on SH 8, ~7 km east-northeast of Tarras village. To the north are dissected moraine/outwash terraces that stand ~50 m higher than very extensive moraine/outwash terrace remnants to the south. They have been interpreted and mapped as two different sets of glacial landform sets, the older 'Lowburn' landform set to the north, and the younger 'Lindis' landform set to the south. This change is on the projection of the main strand of the fault, and it is tentatively suggested that at this location, these terraces were originally a single landform set that has subsequently been deformed by fault movement. This tentative interpretation is highlighted by classifying the fault near Cluden Saddle as 'moderately expressed'.

Overall, the three strands of the Cluden fault zone are inferred to merge towards the west into a single strand. Apart from the 'moderately expressed' features discussed above, other parts of the fault zone are classified as 'possible', and 'not expressed'.

For consistency with previous work, the Cluden fault zone is characterised with similar parameterisation as applied to the Pisa and Grandview faults in the 2010 NSHM, with a net slip rate of 0.1 mm/year. Inferring a fault plane dipping 60° west-northwest and a fault length of 26 km returns a recurrence interval of ~17,000 years.

A2.8 Cross Eden fault (feature 34; Figure 5.3)

The Ranfurly geological map (Bishop 1979) showed a short northeast-southwest striking un-named fault concealed under the valley floor of Ewe Burn East Branch. Geological relationship either side of the stream valley imply that the fault has at least several hundred metres upthrow to the east. To the east, schist outcropping at Quartz Reef Hill is overlain by the Cenozoic cover rock strata dipping gently to the southeast through the Naseby area, whereas Late Cenozoic Maniototo Conglomerate lies on the western side of the valley. As mapped (Bishop 1979), and incorporated directly into QMAP (Forsyth 2001), the fault has been shown as only ~2.5 km long. It is likely that this was done because it was unclear where to draw its southern continuation. Strikes of southeast, south, or southwest are equally possible. In order to give the fault a plausible length to account for the geological relationships, I have extrapolated it to the southwest, along the eastern margin of a belt of steep and locally folded Cenozoic strata, whose bedding traces are in places visible in aerial imagery. Although these dipping strata have not previously been reported, and no structural attitudes measured, the aerial photographic evidence is judged sufficient basis for the faulting interpretation made here, of a 60° eastward dipping reverse fault, of 25 km length. The fault name is taken from Cross Eden Creek, which flows southwest for ~4 km along the line of the fault, an unusual drainage direction for this sector of the Maniototo Plain.

There are no indications of geologically-young offsets on the fault, except at its southwestern end where these is a 'well expressed' 'likely' scarp. The interpretation is made here that it is probably represents slip transferred from a strand of the Gimmerburn Fault Zone, which does deform geologically-young landforms.

A2.9 Dansey Pass Fault (feature 36; Figure 5.3)

Mapped in bedrock by Bishop (1976), the Dansey Pass Fault is thought to be associated with Cretaceous normal movement that led to deposition of the Kyeburn Formation (Bishop and Laird 1976), with substantial reversal of movement in the Late Cenozoic, there are no known offsets of geologically-young landforms, and it is classified as 'potentially active'.

The Stranraer Fault was also involved in the Cretaceous normal faulting regime, and there is a geologically-recent on that fault (see Figure 5.9 in the body of the report). The question arises as to whether the Stranraer Fault movement also involved the Dansey Pass Fault. However, there are scarps on the adjacent Waihemo Fault Zone to the east, similar in form to that of the Stranraer Fault, and on balance, an association is made in this dataset between the Stranraer Fault and Waihemo Fault Zone.

A length of 28 km and nominal slip rate of 0.05 mm/yr are applied to the Dansey Pass Fault, and a recurrence interval of ~40,000 years is calculated.

A2.10 Dingle Fault (feature 15; Figure 5.1)

This northeast-striking fault is mapped in bedrock (Turnbull 2000; Rattenbury et al. 2010), based on a difference in basement rock type either side of the fault (schistose greywacke to the northwest, semischist to the southeast). It has been identified as a 'potentially active' fault by Cox et al. (2012) and Litchfield et al. (2013, 2014). The peneplain is not preserved in this area, and it is not known whether or not there has been any Late Cenozoic deformation. Its inclusion in this dataset, and that of Barrell (2016), is on account of its inclusion in the NZAFM. It is not included in the 2010 NSHM.

There have been inconsistencies in the naming of this fault, and this is discussed in the report by Barrell (2016). The position of the Dingle Fault in this dataset is taken from the QMAP digital dataset (Heron 2014) and differs slightly from the more generalised depictions of its location given by Cox et al. (2012) and Litchfield et al. (2013, 2014).

As there is no evidence for any landform offsets along the Dingle Fault, it is classified here as 'potentially active', with a surface form attribute of 'not expressed'. The northern ~11 km of the mapped fault lies in the Waitaki District (Barrell 2016). Using 2010 NSHM methodology, with a nominal length of 40 km, a dip of 60° southeast and nominal slip rate of 0.05 mm/year, a recurrence interval of ~55,000 years is calculated.

A2.11 Dunstan Fault Zone (feature 22; Figures 5.2–5.3)

The northeast-striking Dunstan Fault Zone is the most thoroughly investigated active fault in Otago, due to its proximity to the Clyde Dam. Investigations in the early 1980s were reported by Officers (1983), with a summary published by Beanland et al. (1986). Further work, involving trenching of fault scarps and dating of past movements was carried out in the mid-2000s (GNS Science, unpublished data 2007), as part of an earthquake hazard reassessment for the Contact Energy, owner and operator of the Clyde Power Station.

Lidar information has become available along the Dunstan Fault Zone since the above studies and has been used to adjust the fault strand locations in the QMAP dataset to more accurate positions. Only new findings or significant changes to previous mapping are outlined below, from northeast to southwest.

About ~8 km northeast of Lauder village, lidar information indicates a previously unreported fault scarp, about ~1.2 km long, immediately north of Lauder Creek farm homestead. This east-trending scarp offsets a flight of stream terraces by between 2 and 4 m, upthrown to the south. It can be traced using lidar profiling farther east as a broad monocline for at least 2 km, with an amplitude of uplift of ~1 m to the south. Notably, this scarp lies southeast (basinward) of the main scarps of the Dunstan Fault Zone and is upthrown the other way. Without having more context for it, it is included here within the Dunstan Fault Zone, identified as the 'Lauder strand'. It is classified a 'likely' feature, until such time as any future field investigations are carried out.

A similar feature occurs at Devonshire Road, ~8 km northwest of Omakau, where a northeast-trending fault scarp crosses a broad stream plain, known as the Devonshire Fan, and has ~1 to 2 m upthrow to the southeast. It is classified as 'likely' because there is a small possibility that it may have been cut by stream action. To the northeast, it intersects the Dunstan Fault Zone scarps immediately north of Wallington Road. To the southeast, the fault scarp meets the terraced valley of Chatto Creek, and the current limit of lidar coverage, and cannot be traced further in that direction. It is classified in this dataset as the Dunstan Fault Zone - Wallington strand.

A third similar feature has been identified using lidar information at Moutere Disputed Spur Road, ~12 km west of Omakau. A ~1.7 km long, east-trending topographic step, up to the south, crosses high-level stream terraces on the northern side of the Young Hill Creek valley. The step is as much as several metres high and is judged a 'definite' fault scarp because the topographic profile along the base of the topographic step is horizontal. Therefore, the step cannot have been formed by stream action, because that would have required a downstream gradient for water flow. To the west, the scarp meets the line of the Dunstan Fault Zone. To the east the terrain is more irregular and gullied, and the feature is difficult to trace. It is extrapolated for 2 km beyond the 'definite' scarp along the margin of higher ground to the south, to the edge of lidar coverage, and stopped there. It is identified in this dataset as the Dunstan Fault Zone - Disputed Spur strand.

Lidar profiling does not support the existence of the 'Kilmarnock' trace on the western side of the Campbell Creek valley, ~14 km northeast of Clyde, or the 'Brassknocker - 2' trace on the coalesced alluvial fan of Young Hill Creek and Dry Creek, ~11 km northeast of Clyde, as depicted on maps in Officers (1983) and included on QMAP. Both traces are drawn as arcuate steps across broad alluvial fan landforms and described as 'subtle' steps up the northwest. They approximately follow the topographic contour on each fan. Because there is no step revealed by lidar information, each is interpreted to mark an upstream increase in gradient on each fan that, viewed from down-fan positions, may have looked like a step running across each fan. Here, they are both interpreted to be related to stream depositional processes and both have been removed from this active fault dataset.

Lidar information reveals that the Waikerikeri - 2 trace of Officers (1983) breaks into two separate fault scarps immediately to the northeast of an early 1980s trench investigation site in Waikerikeri valley, ~5 km northeast of Clyde. The north-western scarp (classified in this dataset as Waikerikeri-2a) continues northeast parallel to the Waikerikeri-1 fault scarp, and between 150 and 200 m southeast of it, as mapped by Officers (1983).

The south-eastern scarp (identified here as Waikerikeri - 2b) has not previously been reported. It diverges east-northeast from the Waikerikeri - 2 fault scarp, crosses the Waikerikeri Creek valley. Lidar indicates that along the Waikerikeri - 2b fault, there are low scarps (0.5 to 1 m high) across the floors of incised minor tributary valleys draining to Waikerikeri Creek, and a scarp of similar height is indicated across part of the Waikerikeri Creek valley floor. Due to the smallness of the valley-floor scarps, it has been classified as ‘likely’, until such time as future field investigation is undertaken. As there is no indication of valley floor displacement along either the Waikerikeri-1 or Waikerikeri-2a faults, it appears that the most recent fault surface rupture in the Waikerikeri area was along the Waikerikeri - 2b fault.

To the northeast, the Waikerikeri - 2b strand is inferred to links to a prominent, also unreported, fault scarp on the Waikerikeri fan, ~6 km northeast of Clyde. Farther northeast, that scarp links with the Kelliher-3 and Kelliher-2 fault scarps identified by Officers (1983).

The Waikerikeri-3 fault trace of Officers (1983), and included in the QMAP dataset, was disproved as a tectonic feature by a 2004 trenching investigation (GNS Science, unpublished data, 2007), and is not included in this dataset.

Southwest of Waikerikeri towards Clyde, investigations during the mid-2000s (GNS Science, unpublished data 2007) have shown that the most recent Dunstan Fault Zone deformation has been concentrated on a monoclinal fold, identified in this dataset as the Reservoir-3 monocline. Movement has warped the prominent and extensive river terrace beside Clyde on the north-eastern side of the Clutha River valley, up to the northwest by ~20 m. This terrace has also been warped by two monoclines, both up to the southeast, lying ~0.4 km (Reservoir-2 monocline, ~2 m high) and ~1 km (Reservoir - 1, ~7 m high) noth-west of the Reservoir-3 monocline. Those smaller monoclines are interpreted to link northwards to the Waikerikeri-1 fault scarp. At Clyde, there is no discernible deformation the lower level terraces of the Clutha River, on which most of Clyde township lies, on the line of those monoclines. This indicates that no monoclinal growth events have occurred since those lower terraces were formed. The Reservoir-3 monocline is extrapolated beneath Clyde as ‘not expressed’ to an inferred meeting with the Earnscleugh Fault.

There is a structural change in the Dunstan Fault Zone at the Clutha River (Figure A2.1). To the northeast, the Reservoir-3 monocline has produced what the available evidence indicates to be a gentle warp of the peneplain surface (GNS Science unpublished data 2007; see Figure 5.8 in the body of the report). Southwest of the river, the Cenozoic strata are dragged into a near-vertical configuration along what has variously been referred to as the Clyde Fault or Earnscleugh Fault (the latter is applied in the QMAP dataset and is used here). Along the Clutha River at the Clyde Dam is the well-documented, north-northwest striking River Channel Fault, which has a steep dip to the east. Near Dairy Creek, immediately upstream of the dam, is a wide zone of steeply southeast dipping sheared and faulted schist, identified in the QMAP dataset as the ‘Cairnmuir Fault – Dairy Creek segment’. A long-standing difficulty in interpreting the southern end of the Dunstan Fault Zone has been resolving the question of the east-striking Cairnmuir Fault, which has produced a 100–200 m offset, up to the north, of the peneplain, and locally dragged the peneplain contact into a vertical bend (Officers 1983). By presumption, it is a north-dipping reverse fault, but what has been referred to as the Cairnmuir Fault Zone, exposed in SH 8 batter near Dairy Creek, dips southeast. Mid-2000s trench investigation of the Cairnmuir Fault at Cairnmuir Flats (GNS Science, unpublished data 2007) found north-dipping fault zones, that could accord with the expectation that the Cairnmuir Fault dips in that direction, but also found no evidence for geological recent surface offsets. For the purpose of this dataset, the steeply east-dipping River Channel Fault, and steeply southeast dipping fault zone in Dairy Creek are presumed to have originally been some sort of a transfer zone between the Earnscleugh Fault, and 'Earnscleugh Structure' monocline, to the southwest, and the Dunstan Fault Zone farther northeast. There is no evidence of recent activity on this inferred transfer system, and notably the fault zone at Dairy Creek has reportedly (McSaveney et al., 1992) not offset the river gravels (inferred to be of 'Lindis' age; see Grandview Fault section) forming the terrace that is warped by the Reservoir monoclines. In this dataset, the Earnscleugh Fault is identified as 'likely' active, because of proximity to undoubted geologically recent movement associated with the Reservoir-3 monocline. The River Channel Fault and 'Dairy Creek segment' are classified here as 'possible' active faults.

The Fish Creek Fault and Cairnmuir Fault components of the Dunstan Fault Zone (features 22a and 22b respectively in Figures 5.1–5.3) are considered likely to be abandoned strands of the currently active fault zone and are classified here as 'possible'.

Farther southwest, towards the intersection of the Dunstan Fault Zone with the Old Man Fault, there is an array of steps attributed to faulting of the peneplain, north of Omeo Creek, near a hillock called Sugar Loaf on topographic maps. The main steps are identified as 'potentially active' faults, and in two cases as monoclines, and all included in the Dunstan Fault Zone. The significance and activity of those fault strands is unknown.

Fault characterisation parameters assigned to the Dunstan Fault in the 2010 NSHM (Stirling et al. (2012), including fault dip of 60° and slip rate of 0.63 mm/yr, differ from those adopted as 'best' values in the NZAFM, comprising dip of 45° and slip rate of 0.9 mm/yr. The NZAFM net slip rate range (between 0.25 and 1.5 mm/yr) and dip range (between 35 and 60°) accord with field-based estimates (GNS Science, unpublished data 2007). However, the field data indicate a long-term average recurrence interval of ~7000 years, which matches the value of 6960 years calculated for the 2010 NSHM (Stirling et al. 2012).

To overcome these discrepancies, Dunstan Fault Zone activity parameters were recalculated for this project, using the 2010 NSHM methodology, aligned with existing field data. The maximum possible length of the Dunstan Fault Zone is ~63 km, that being the distance between the Old Man Fault to the southwest, and the Blue Lake Fault in the northeast, neither of which is crossed by the Dunstan Fault Zone. Using preferred estimates of fault length of 60 km, dip of 45° and slip rate of 0.6 mm/yr, a recurrence interval of 6964 years is calculated, along with a net single-event displacement of 4.2 m, both of which are compatible with field data. Accordingly, slip rate of 0.6 mm/yr and recurrence interval of ~7000 years are adopted in this report.

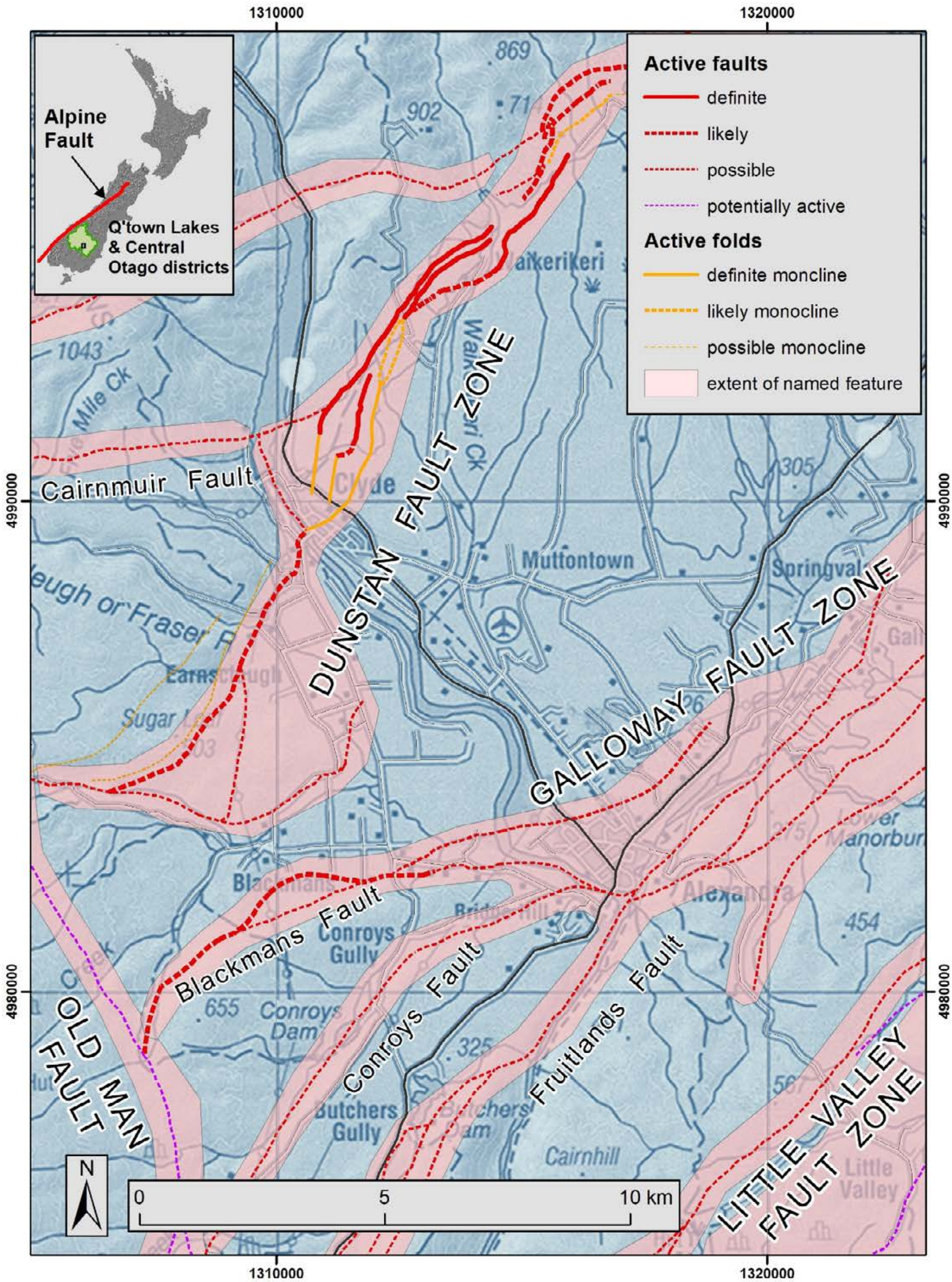

Figure A2.1 Map showing the interpretation and classification of active faults in the Clyde to Alexandra area. The location of the map panel is shown by the black rectangle in the inset at top left.

A2.12 Galloway fault zone (feature 29; Figures 5.2–5.3)

An array of northeast-striking faults, upthrown to the southeast, forms the southwestern margin of the Manuherikia basin, near Alexandra (Figure A2.1). Most are well defined geologically, because the Otago peneplain is extensively preserved on the upthrown side of each fault block, and in places Cenozoic cover strata are preserved on top of the peneplain on the downthrown side. Vertical separation across each fault is between a few tens of metres to as much as 150 m or so. Many of the faults have been named individually, as documented in the QMAP dataset, and the names include the Fruitlands Fault, Conroys Fault, Blackmans Fault and Galloway Fault. The individual faults are no more than 3 km apart and are interpreted here to be splays of a single fault zone at depth. Collectively, the faults are referred to here as the 'Galloway fault zone'. No offset of geologically young landforms or deposits has previously been reported for any of the components of the Galloway fault zone, and these faults are not currently included in the NZAFD, NZAFM or 2010 NSHM.

There is lidar coverage for some parts of the fault zone. The positions of faults as depicted by QMAP have in places been adjusted for this dataset, to accord better with information from lidar, and in areas outside lidar coverage, from high-resolution imagery (aerial and Street View). The only known exposure of any of these faults is on the Conroys Fault, exposed in a cutting on Conroys Road ~1.1 km south of the Chapman Road intersection, where schist rock is thrust over Cenozoic (Manuherikia Group) quartzose sediments on a fault plane dipping southeast at a moderate angle (~40°). On this basis, all components of the Galloway fault zone are regarded as reverse faults. Most of the faults are well defined in the landscape due to the peneplain offset, as illustrated for example in the ~150 m high escarpment of the Fruitlands Fault southeast of the Butchers Dam reservoir, and its north-eastern continuation on which the Alexandra Clock is sited. Despite the prominent peneplain offsets across the Galloway fault zone, there not many places where Quaternary-age sediments straddle the faults, and this hinders the assessment of whether or not there have been any geologically recent surface ruptures.

Close examination of lidar information revealed a topographic step across alluvial fans about 6 km west of the Alexandra town centre, close to the QMAP-defined line of the Blackmans Fault. The step is ~1 to 2 m high, up to the southeast, and is most sharply defined ~0.7 km southwest of the Blackman Road/McIntosh Road intersection. The position of the step midway up an alluvial fan, and alignment across the fan, rather than down the fan as would be expected for a stream-cut feature, suggests that it may be fault-related. Along trend to the southwest and northeast, there are similar, though broader, steps across alluvial fan surfaces. Collectively, these steps are interpreted as marking a 'likely' active fault, either 'well expressed' or 'moderately expressed' depending on the sharpness of the lidar-defined step.

Farther east along strike there is no discernible scarp across the broad floor of Conroys Creek where it emerges onto the main Clutha valley-floor river terrace. About 1 km father east, Earnscleugh Road traverses an old river channel of the Clutha/Fraser river system, cut through rocky terrain and standing a few metres higher than the main Clutha valley-floor river terrace A topographic step runs across an alluvial fan, ~60 m south of Earnscleugh Road and ~0.9 km east of the Conroys Road/Earnscleugh Road intersection. This step is up to the southeast and between 1 and 2 m high. It is however parallel to the grain of schist outcrop in the channel, and also the direction of former river flow down the old channel. Proceeding east, Earnscleugh Road straddles a broad (~60 m wide) topographic step, about 2 m high, on the channel floor. Both these features are classified as 'possible', 'moderately expressed', fault scarps. The potential for origins other than faulting is considered too great to warrant a classification of ‘likely’, even though the topographic steps are broadly along strike from the ‘likely’ fault scarps described above.

Records from bridge construction across the Clutha River at Alexandra indicate the possible presence of faults under the river channel. The following account is from Moore (1978), in relation to the original bridge just upstream of the Manuherikia River confluence: "The bridge, opened on June 2 1882, is a tribute to the skill and craftmanship of our pioneers. The 552-foot structure is founded on two magnificent piers, the larger situated on the Alexandra side of the Molyneaux (*Clutha River*). This pier was the most difficult to build as it required a solid concrete foundation. The schistose rock onto which it was to be founded proved to be but a crust, beneath which lay two feet of soft blue clay, followed by a conglomerate of decomposed rock, quartz, and slate. It was decided to excavate into this and lay a three-foot concrete foundation.”

One possible interpretation is that the pier penetrated schist rock with an underlying fault zone, although there may be other possibilities (e.g. old riverbank slump debris). The excavation for the southern pier of the new bridge encountered a crushed zone within schist rock (McKellar 1954). The zone dips 30–40° north, and although suggested by McKellar to represent the base of a schist slump, he also noted that it was parallel to a suspected fault zone a few hundred metres to the northeast (Galloway Fault of the present dataset). However, the northerly dip of the crushed zone is opposite to that of the Conroys Fault, which projects northeast close to the location of the bridge. It is conceivable that the crushed zone could be a conjugate fault associated with the Conroys Fault zone.

None of the information from the Clutha bridge excavations allows any firm interpretation of faulting. For the purpose of the present dataset, a provisional interpretation is made that the Blackmans Fault and Conroys Fault merge under the Clutha River channel and pass northeast under the Clutha bridge at Alexandra, to meet the Fruitlands Fault and Galloway Fault close to the Clutha/Manuherikia river confluence. Specifically, the merged Blackmans/Conroys fault is positioned under the north pier of the old bridge (which is still preserved), and between the two piers of the new bridge. This working interpretation is considered the best accommodation of the available geological information and is consistent with the overall topographic relief across the fault array. To the southwest, the vertical separations of the Blackmans (~50 m), Conroys (~60 m) and Fruitlands (~150 m maximum) faults is about the same as the elevation change southeast of Alexandra township, between schist rock outcrop (close to peneplain surface) in the lowest reaches of the Manuherikia River, and the crest of the range-front, as traversed by Little Valley Road. All are classified as ‘possible’.

To the northeast, near Galloway, there is a broad northeast trending topographic step, ~1–2 m, high along a Manuherikia valley floor terrace, and in places alluvial fans. Although broadly parallel to the river flow, the step is commonly ~60 to ~80 m wide, and thus has features more in common with a tectonic feature (e.g. a monocline), rather than a river-eroded terrace edge. It is classified here as a ‘possible’, ‘moderately expressed’ fault scarp. At its northeast end, the topographic step does not extend across the combined fan/plain of Dip Creek and the Manuherikia River, so those landforms are presumably younger than the last surface rupture, if it is indeed a fault. It is named the Galloway 2 fault, to distinguish it from the QMAP-named Galloway Fault, another parallel strand of the Galloway fault zone, ~0.5 km to the southeast.

An age of late last glaciation (~18,000 years) is assigned here to the landforms offset by ~1–2 m by the ‘possible’ fault scarps. Although there appears to be no fault-related offset of the main Clutha valley floor terrace that is correlated in QMAP with the ‘Albert Town’ glacial advance (Turnbull 1987, 2000), other evidence indicates this correlation, and implied age, is incorrect (Barrell 2011, and GNS Science unpublished data 2007). Instead, it is considered more likely that the so-called ‘Albert Town’ terrace in the Clyde to Alexandra area is post-glacial and was formed during incision of the Clutha River into the ‘Hawea’ and ‘Mt Iron’ glacial and outwash deposits in the upper Clutha valley. An age of ~10,000 years is considered more likely. On this tentative basis, the most recent ‘possible’ surface rupture(s) on the Galloway fault zone that may have produced a ~1–2 m high scarp, occurred between ~10,000 and ~18,000 years ago. This implies a low slip rate, and relatively long recurrence interval, for the Galloway fault zone. If instead, the suspected fault scarps have a non-tectonic origin, then the estimates are a maximum for its slip rate and minimum for its recurrence interval.

For the purposes of estimating activity parameters for the Galloway fault zone, a length of 22 km is assigned, from a presumed meeting with the Old Man Fault in the southwest, along the Blackmans Fault, through the area of merged faults at Alexandra and to just beyond the mapped north-eastern end of the Galloway 2 fault. Taking the ‘possible’ 1.5 m vertical component of offset of alluvial fans across the Blackmans Fault and assuming an age of 18,000 years for the alluvial fan landforms, in conjunction with an inferred representative fault dip of 60° southeast, implies a slip rate of ~0.1 mm/year. From the length and slip rate estimates, a recurrence interval of ~15,000 years is calculated for the Galloway fault zone using 2010 NSHM methodology.

Between 3 and 5 km southeast of the main strands of the Galloway fault zone is a semi-parallel fault, across which the peneplain is upthrown to the northwest by several tens of metres. The fault extends northeast from near Lake Roxburgh for ~18 km to the Manor Burn valley. It is assumed to be a northwest-dipping reverse fault, and by implication is assumed to be a ‘back-fault’ splay off the Galloway fault zone. It is identified in the dataset as ‘Galloway fault zone – Shanty fault’ (feature 29a of Figures 5.1–5.3), the latter part of the name being taken from Shanty Creek, along whose valley the southwestern part of the fault runs. It is interpreted here that this strand of the Galloway fault zone is not an independently rupturing active fault, but rather is part of the surface expression of the Galloway fault zone.

A2.13 Garibaldi Fault (feature 32; Figure 5.3)

This fault lies on the south-eastern side of North Rough Ridge and shows peneplain offset of as much as several hundred metres. It shows no known offset of geologically-young landforms. Its name has been in long-standing geological usage and is applied in both editions of the QMAP dataset (Mutch 1963, Forsyth 2001). It is assigned a length of 32 km and nominal slip rate of 0.05 mm/yr, from which a recurrence interval of ~45,000 years is calculated.

A2.14 Garvie Fault (feature 27; Figure 5.2)

The northeast-striking Garvie Fault separates the eastern high ridge of the Garvie Mountains from the Dome Burn valley. The fault position is adopted from the QMAP dataset without modification. Only the northern half of the Garvie Fault lies in the Otago region; the southern half is in the Southland region. The Garvie Fault has produced a ~300 to 400 m vertical separation of the peneplain, up to the southeast. There is no evidence for geologically young landform displacement across the fault. It is classified in this dataset as ‘potentially active’. It is proposed here as a potential earthquake fault source, with nominal length of 55 km, a dip of 60° southeast and nominal slip rate of 0.05 mm/year. Using 2010 NSHM methodology, a recurrence interval of ~38,000 years is calculated.

A2.15 Gimmerburn Fault Zone (feature 33; Figure 5.3)

The north to northeast striking Gimmerburn Fault Zone is notable for having great complexity of surface faulting expression, comprising numerous relatively short fault scarps. It is included in the 2010 NSHM and the NZAFM. For ease of reference in the GIS dataset, the fault zone is divided into three general sectors, referred to here as strands.

The 'Gimmerburn Fault Zone – Rough Ridge strand' runs along the southeast side of the Rough Ridge and Little Rough Ridge rangefronts. The rangefronts are up to the northwest, with overall vertical separation of the peneplain of the order of 600 m, diminishing north adjacent to Little Rough Ridge. This strand is assumed to be the surface expression of a northwest-dipping reverse fault. In places, there are closely-spaced en-echelon, left stepping fault scarps, most with upthrow to the northwest. To the south of Brasseys Creek, the fault along the foot of Rough Ridge shows no indication of young scarps. It is classified as 'potentially active' because young scarps are present along the foot of a parallel, unnamed ridge, ~2 to 3 km farther southeast, aligned with a presumption that the most recent activity has emerged on that part of the fault.

The 'Gimmerburn Fault Zone – Sharkey strand' (named after nearby Sharkey Road) diverges northeast from the Rough Ridge strand near Dingo Creek and extends for ~12 km to where it is interpreted to abut the Cross-Eden fault. Stepped ~2.5 km north of there is the start of the 'Gimmerburn Fault Zone – Eweburn strand', which continues northeast for as much as ~20 km towards the valley of Ewe Burn West Branch. Between the Sharkey and Eweburn strands is a belt of deformed Cenozoic strata. This has not previously been reported, but is evident from strike ridges of steeply dipping, and in places tightly folded Cenozoic strata. A similar belt of Cenozoic strata lies between the Eweburn strand and the Cross-Eden fault.

Research on dating the exposure of the peneplain on the upthrown side of the Gimmerburn Fault Zone has been reported, most recently, by Bennett (2005, 2006), building on earlier work analysing drainage pattern development (references therein). There are many assumptions and interpretive challenges in that work, and the results do not as yet place robust constraints on Gimmerburn Fault Zone activity. The fault zone is however an important and complex structure and, in the writer's opinion, is deserving of ongoing research effort.

The 2010 NSHM and NZAFM assign slip rates of 0.5 mm/yr and 0.35 mm/yr respectively to the Gimmerburn Fault Zone. The writer has seen a well-defined fault scarp on the Sharkey strand, just north of the Puketoi Highfield Road and Gibson Road intersection, ~14 km west-southwest of Ranfurly. This appears to be the only specific field estimate of an offset yet reported. It is used here in conjunction with the fault dip of 45° used in the 2010 NSHM and NZAFM, and assumed dip-slip motion, to obtain a net slip value of 0.39 mm/yr. This in turn applied to an adopted fault length of 42 km returns a recurrence interval value of ~7400 years.

A2.16 Goodger Fault (feature 18; Figures 5.1–5.2)

The east-northeast-striking Goodger Fault is mapped and named in the QMAP dataset. It extends for ~22 km between the Grandview Fault in the west and the Longslip Fault to the east. The fault is not included in NZAFM or 2010 NSHM datasets. It is upthrown by between ~300 and 400 m to the southeast, as demonstrated by local preservation of Cenozoic strata in the fault angle, and peneplain remnants. The Lindis Peak range lies on the upthrown side of the Goodger Fault (see sections on the Pisa Fault Zone and Cluden Fault Zone for further discussion). The Lindis River has cut a narrow gorge across the uplifted block, and SH 8 follows the gorge. There is no known evidence for geologically young landform displacement across the fault. The fault position is adopted from the QMAP dataset without modification.

In this dataset the Goodger Fault is classified as 'potentially active', with a length of 22 km, a dip of 60° southeast and nominal slip rate of 0.05 mm/year. Using 2010 NSHM methodology, a recurrence interval of ~30,000 years is calculated.

A2.17 Grandview Fault (feature 12; Figures 5.1–5.2)

This north-striking structure is mapped along the east side of the Wanaka-Hawea basin. The geological basis for its recognition is the presence of Cenozoic strata in the basin, compared to the prominent range-margin along the eastern side of the basin formed in basement rock. Geological investigations for possible dam sites on the Clutha River between 6 and 12 km downstream of Luggate, including mapping and drilling, indicate the presence of a north-south trending monoclinal fold in old glacial lake silt below the valley floor. It has an indicated vertical amplitude of as much as ~80 m and is down-warped to the west (Officers 1984; Halliday 1986; Beanland and Berryman 1989). It is interpreted to reflect deformation due to movement of the Grandview Fault. In the southernmost 6 km, where defined by geological investigation, it is mapped as a concealed monocline. Farther north, it is shown as a concealed fault as per the QMAP dataset (Turnbull 2000; Heron 2014). In that area, there are no data on the position of the fault, other than that it must lie at or west of the foot of the Grandview range.

The age of the lake silt is uncertain, and this makes it difficult to calculate deformation rates. Previous workers all agree with an assumption that the silt was deposited in a glacier trough following ice recession from the "Lindis" advance moraines, which form a prominent belt of terraces southeast of Tarras and down-valley towards Cromwell. Previous age estimates for the lake silt range from 35 to 70 ka (Officers 1984), 90 to 120 ka (Beanland and Berryman 1989) and ~450 ka (McSaveney et al. 1992; Turnbull 2000), based on inferred correlation to global ice ages cycles. Barrell (2011) suggested a correlation to the Nemona Glaciation, with an age of approximately 330,000 years.

No change is proposed here to the parameterisation of the Grandview active fault earthquake source as done in the 2010 NSHM, which applies a net slip rate of 0.1 mm/year to a fault plane dipping 60° east, a fault length of 32 km, and calculates a recurrence interval of ~22,000 years.

A2.18 Hawkdun Fault (feature 25; Figure 5.3)

This major north-northwest-striking fault has uplifted the Hawkdun Range, with as much as ~1 km vertical separation of the peneplain, up to the northeast (Bishop 1976). There are no identified geologically young offsets of landform features, and the fault has long been regarded as inactive and is not included in the 2010 NSHM or NZAFM. Because it is abutted by the Omarama Saddle fault and Rocks Creek Fault Zone, it is suggested here that ruptures on those faults could result in secondary slip on the Hawkdun Fault and it is classified in this dataset as a 'possible' active fault. The Hawkdun Fault has a similar strike and amount of Late Cenozoic offset to that of the Blue Lake Fault. Furthermore, uplift and erosion due to initiation of movement on the Hawkdun, Blue Lake and Waihemo faults is thought to have contributed sediment to Middle and Late Miocene depocentres in Central Otago (Youngson et al. 1998). Using the same approach as applied to the Blue Lake Fault, dividing the ~1000 m maximum offset of the peneplain, by an assumed initiation at ~15 million years ago returns a long-term average vertical slip rate of 0.07 mm/year. Assuming pure dip-slip movement and resolving the vertical rate onto an assumed fault-plane dip of 70° together with a fault length of 57 km, a recurrence interval of ~55,000 years is calculated for the Hawkdun Fault using 2010 NSHM methodology.

A2.19 Highland Fault (feature 5a of Figures 5.1–5.2)

Shown as an active fault in the QMAP dataset, and subsequently included in the NZAFD, the Highland Fault is identified primarily from a series of sharply defined north-south trending fault scarps across hillsides in the Fern Burn catchment on the western side of the Mt Cardrona to Mt Alpha range (see Figure 5.7 in the body of the report). Most of the scarps are up to the west. In QMAP the fault is extrapolated southwest of the prominent scarps to the west side of Middle Peak. That sector of the mapped fault is identified as a 'possible' active fault, but in this dataset, the most recent activity is extrapolated southward through a series of prominent fault scarps east of Middle Peak, into the Back Creek catchment. 'Likely' connectors are drawn between the 'definite' fault scarps in this area. Elsewhere in the Fern Burn catchment, connectors between 'definite', 'well expressed' scarps are classified as 'definite', 'not expressed'. The sharpness of the scarps indicates the most recent rupture(s) occurred sometime after the last glaciation ended ~18,000 years ago.

As the fault is relatively short (~12 km), it is tentatively interpreted as some sort of a splay off the Motatapu Fault, rather than a fault that ruptures on its own. It is provisionally assigned the same slip rate and recurrence interval (~6,500 years) as the Motatapu Fault, noting that these are maximum values for the Highland Fault, because it may not necessarily always rupture in unison with the Motatapu Fault.

A2.20 Home Hills fault zone (feature 26; Figure 5.3)

Between two and three parallel, east-southeast striking, fault strands extend from the St Bathans area towards the Naseby area. They have variously been referred to as the Blue Lake Fault Zone (Henne et al. 2011), Stranraer Fault (Madin 1988) and Waihemo Fault System (Forsyth 2001). In this dataset, these fault strands are referred to as the Home Hills fault zone, to minimise confusion with those other named faults. Exposures along the Manuherikia River show that the Home Hills fault strands are associated with east-northeast dipping fault deformation zones, across which basement rock of lesser metamorphic grade lies north of each fault (Henne et al. 2011). This indicates that they were initiated as normal faults in the Cretaceous, downthrown to the east-northeast. All now have basement rock upthrown to the east-northeast against Miocene-age cover strata, demonstrating Late Cenozoic reversal of throw.

Late Cenozoic offset of the peneplain is about 300 m across the fault zone, comprising about 50 m offset on the southwestern strand and as much as ~250 m on the north-eastern strand. All of the anticlines associated with the northeast-striking reverse faults extend across the Home Hills fault zone. These anticlines include the Raggedy Range – Blackstone Hill – Home Hills ridge on the upthrown side of the Blackstone Fault, the North Rough Ridge – Seagull Hill – Idaburn Hills ridge on the upthrown side of the Garibaldi Fault, and the Woodney Hill ridge associated with the Gimmerburn Fault Zone. This indicates that those faults have propagated northeast across the Home Hills fault zone, presumably cutting it off at depth.

Although Bishop (1979) and Forsyth (2001) mapped the southwestern strand of the fault zone as crossing the crest of Seagull Hill, the fault strand is repositioned in this dataset to curve around the southern margin of the hill, in better accord with the location of the peneplain offset.

There is no indication of any displaced landforms across the Home Hills fault zone, although the fault zone does have topographic prominence, due to basement rock, topped by the peneplain surface, having been upthrown northeast across the fault zone. The interpretation made here that the Home Hills fault zone was, like the Blue Lake Fault, active in the mid-Miocene, and more recent tectonic deformation has focused on the northeast-striking faults. Secondary slippage on the Home Hills fault zone during rupture of the northeast-striking faults is a possibility.

The Home Hills fault zone is not recognised here as an independently rupturing active fault, because it appears to have been dislocated by northeast-striking faults, presumably in the latter part of the Late Cenozoic Era. However, it is classified here as ‘potentially active’, to acknowledge the possible issue of secondary slip. Because such an occurrence would relate to the activity of the various primary fault ruptures, it not meaningful to try and place specific estimates of slip rate or recurrence interval on the Home Hills fault zone. However, to place it into context with the other faults assessed in this report, a nominal recurrence interval of greater than 20,000 years is assigned.

A2.21 Hunter Valley Fault (feature 14; Figure 5.1)

This north-northeast striking structure comes from the QMAP dataset, where it was named the Hunter Valley Fault, and classified as an active fault. This fault was suggested as ‘potentially active’ by Cox et al. (2012) and incorporated into the NZAFM under the name ‘Hunter’ fault zone, but no slip rate parameter was assigned in the NZAFM. It is not currently in the 2010 NSHM, but that sector on the Wakatipu QMAP sheet is included in the NZAFD.

The QMAP name Hunter Valley Fault is preferred here over the name Hunter that is used in the NZAFM, because the former has precedence and also confusion is minimized in relation to the Hunters Fault in South Canterbury (Barrell 2016). For most of its length, the Hunter Valley Fault is concealed under the water of Lake Hawea or the floodplain of the Hunter River. It is inferred to be the structure that separates differing grades of schist rock either side of the Hawea/Hunter valley, comprising semischist to the west and schistose greywacke to the east. Thus, it is likely that the fault originated during the Cretaceous Period.

On the eastern side of the Hunter valley, a semi-continuous topographic step tracks along the glacially-sculpted valley side for ~6.5 km. The step is down to the east, by several metres. It is inferred to be a scarp associated with past surface rupture of the Hunter Valley Fault, because it seems too long and too continuous to attribute to gravitational slope movement. It is classified as ‘well expressed’ and a certainty of ‘likely’ to acknowledge a possibility that it may conceivably be a result of gravitational slope movement on as pre-existing weakness in the rock, rather that fault rupture. The fault depicted under the valley floor in the QMAP dataset is also classified as ’likely’, for consistency with the ‘likely’ classification applied to the surface scarp. The Hunter Valley Fault is characterised in this report as a ‘likely’ active reverse fault dipping 60° to the west-northwest and extending 55 km north-northeast from an assumed ‘triple junction’ with the Grandview Fault and the Cardrona–Hawea fault. For estimating slip rate, the ‘likely’ fault scarp on the valley side is inferred to be 5 m high, and affecting a glacial landform assumed to be 18,000 years old. Taking account of the adopted fault dip and assuming pure dip slip motion, a net slip rate of 0.32 mm/year is obtained, and a recurrence interval of ~12,000 years is calculated using 2010 NSHM methodology.

A2.22 Hyde Fault (feature 39; Figure 5.3)

The northeast-striking Hyde Fault is a prominent geological feature of the Middlemarch and Strath Taieri areas, in the Dunedin City district, but only the northernmost 5 km of the fault is mapped as extending into the Central Otago District. The Hyde Fault is interpreted as a major northwest-dipping reverse fault that has elevated the Rock and Pillar Range. Deformation of geologically-young landforms is evident on the line of the fault in the Middlemarch area, but it is not yet clear whether such movements have extended as far as the Central Otago District. Accordingly, the fault there is classified as 'likely', 'not expressed'. It is expected that the Hyde Fault will be discussed more fully in an anticipated future report on the active faults of the Dunedin City district.

The Hyde Fault is included in both the 2010 NSHM and NZAFM, which assigned a fault dip of 45° and slip rates of 0.25 and 0.71 mm/yr respectively. A more sophisticated analysis by Villamor et al. (2018) considered a range of possible slip rates between ~0.7 and 0.02 mm/yr, which returned recurrence intervals in the range of ~6,000 years to ~200,000 years. The slip rate in the NZAFM takes account of geological dating by the optically stimulated luminescence method in proximity to the Hyde Fault (Norris and Nicolls 2004) that I suspect is incompatibly young in relation to the character of deformed landforms across the fault. For the present dataset the 2010 NSHM values of slip rate and recurrence interval (12,800 years, rounded up here to ~13,000 years) are used, pending further research.

A2.23 Lake Onslow fault (feature 42; Figure 5.3)

The north striking Lake Onslow fault is a newly recognised feature on the eastern flank of the Lake Onslow and upper Manor Burn basins, with an indicated a vertical separation of the peneplain of as much as ~100 m, up to the west. The feature as defined here is not included in the QMAP, NZAFD, NZAFM or 2010 NSHM datasets.

It is an inferred fault, because there are no known recorded geological field observations of fault outcrop and the fault is positioned along the foot of the topographic escarpment. It is assumed to be a west-dipping reverse fault. There are no discernible offsets of geologically young landform features and the Lake Onslow fault is classified here as a 'potentially active' fault. For the estimation of activity parameters, the Lake Onslow fault is assigned a dip of 60°, length of 22 km and a nominal slip rate of 0.05 mm/year. Using the 2010 NSHM methodology, a recurrence interval of ~30,000 years is calculated.

A2.24 Launceston Fault (feature 35a; Figure 5.3)

Named in the QMAP fault dataset after Launceston farm in the Hog Burn valley, the fault is identified from a discontinuous array of fault scarps, up to the west, across stream terrace and hillslope terrain. The scarps begin ~4 km southeast of Ranfurly township and extend north-northeast for at least ~10 km. One example is a broad scarp that is crossed by SH 85, 0.7 km east of the Bypass Road intersection. The scarp is between 5 and 10 m high on very old down-land terrain, but no more than 1 or 2 m high on inset valley floors to the northeast and southwest. This indicates that the fault has experienced repeated Quaternary movements. This fault has notably straight and sharply expressed 'definite' scarps. In particular, near Launceston homestead, the fault has a sharp, straight, uphill-facing scarp that appears to extend across gully floors. This indicates that the fault has moved probably within the last few thousand years, and certainly more recently than the last ice age. The straightness of the fault scarp across terrain indicates a near-vertical dip.

In order to place the fault in a hazard perspective, an indicative average slip rate of 0.1 mm/yr is inferred, based on a scarp height of ~10 m relative to an assumed age of ~100,000 years for the down-lands. The freshness of the Launceston Fault scarps is comparable to those of the Ranfurly Fault Zone, suggesting that the most recent surface rupture of the Launceston Fault may possibly have also involved the Ranfurly Fault Zone. Because their relatively short individual overall lengths, the Launceston Fault and Ranfurly Fault Zone are inferred to represent a single active fault feature, and following the NZAFM and 2010 NSHM, referred to here as the Ranfurly Fault Zone.

A2.25 Lindis Pass Fault Zone (feature 21; Figures 5.1–5.3)

This broad zone of overall north-striking faults extends from the Waitaki District into the Central Otago District. It is discussed in detail in the Waitaki District active faults report (Barrell 2016), and people should refer to that report for in-depth information. In summary, geologically recent activity is seen on parts of two named fault strands, the Longslip Fault and Dalrachney Fault. Towards the southwest in the Central Otago District, the most recent fault scarps step progressively to the southeast off the mapped line of the Longslip Fault, into the Dunstan Creek catchment. The Longslip Fault is a major fault in bedrock and continues south-southeast to the Dunstan Fault. Although the most recent ruptures have stepped off the Longslip Fault, the Longslip Fault is marked by a prominent topographic escarpment, although quite dissected by erosion, up to the northeast. Although the peneplain remnants are patchily preserved, there is estimated to be vertical separation of several hundred metres on the peneplain across the Longslip Fault. The Longslip Fault escarpment appears to have been folded across the Dunstan anticline, suggesting that most of the Late Cenozoic deformation on the Longslip Fault occurred before that of the Dunstan Fault. Nevertheless, because of proximity to the Dunstan Fault, and because the Cluden Fault Zone and Goodger Fault appear to end against the Longslip Fault, the fault overall is identified as a 'possible' active fault. This acknowledges that ruptures on those adjacent faults could potentially extend at least partly onto the Longslip Fault. There are several small fault-bounded blocks in the intersection zone between the Longslip Fault and the Cluden Fault Zone. The block-boundary faults are denoted as 'potentially active' in view of there being some, but small, possibility of secondary slip being transferred from the main faults.

Another strand of the Lindis Pass Fault Zone is evident north of Lindis Pass, here-named the Pavilion fault, after Pavilion Peak, one of the highest points on its upthrown side. A north-northwest striking fault in bedrock displays a several-hundred-metre vertical separation of the peneplain, up to the east-northeast. There are scattered remnants of 'likely' fault scarps along the line of the fault, and 'likely' connectors are drawn between scarps. The bedrock fault, where no scarps are evident, is classified as 'possible'. With an indicated fault length of only 16 km, it is interpreted to be a strand within the wider Lindis Pass Fault Zone rather than an independent active fault.

The current parameterisation of the Lindis Pass Fault Zone in the NZAFM and 2010 NSHM appears to be appropriate for encompassing the most recent movements of the fault zone that have extended into the Central Otago District. The 2010 NSHM assigns a slip rate of 0.47 mm/year, a dip of 75°, a length of 38 km and calculates a recurrence interval of ~5600 years.

A2.26 Lindis River Fault (feature 17; Figures 5.1–5.2)

The east- to northeast-striking Lindis River Fault is called the 'Lindis Fault' in the QMAP dataset, but the name Lindis River is applied here, to minimise the potential for confusion with another nearby fault system, the Lindis Pass Fault Zone. The fault is downthrown to the northwest, with Cenozoic strata preserved locally at the foot of the fault angle, and patchy remnants of the peneplain either side of the fault. The Lindis River has cut a narrow gorge across the uplifted block, and SH 8 follows the gorge. The fault is not included in NZAFM or 2010 NSHM datasets.

The QMAP dataset shows the north-eastern half of the fault as downthrown to the southeast, but it is considered here that a case can be made for an alternative view, based on interpreted peneplain offset, and that the Late Cenozoic downthrow is the northwest for the full length of the fault.

The peneplain shows as much as 300 m vertical separation, up to the southeast, across the fault and there is no known evidence for geologically young landform displacement across the fault. The fault position is adopted from the QMAP dataset without modification, which shows the fault as extending from close to the Grandview Fault, northeast to an intersection with the Johns Creek Fault in the northeast.

In this dataset the Lindis River Fault is classified as ‘potentially active’. In order to estimate recurrence interval using 2010 NSHM methodology, fault length of 35 km and dip of 60° southeast are adopted. Applying a nominal slip rate of 0.05 mm/year, a recurrence interval of ~50,000 years is calculated.

A2.27 Little Valley fault zone (feature 30; Figures 5.2–5.3)

This comprises an array of north-northeast striking array of faults, upthrown to the southeast. The array includes individually-named faults identified in the QMAP dataset as ‘Crawford Hills’, ‘Little Valley’ and ‘East Roxburgh’. The individual faults are no more than 3 km apart and are interpreted here to be splays of a single fault zone at depth. Collectively, the faults are referred to here as the ‘Little Valley fault zone’, named after the most prominent strand.

All the faults are defined by offset of Otago peneplain, which is extensively preserved on the upthrown side of each fault block, and in places Cenozoic cover strata are preserved on top of the peneplain on the downthrown side. Vertical separation across each fault is between a few tens of metres to as much as 300 m or so. Aggregate vertical separation of the peneplain across the fault zone is typically about 300 m.

The mapping is adopted from QMAP with some minor positional refinements based on high-resolution colour aerial imagery. One northerly-striking strand has been added in the Knobby Range area, based on indicated offset of the peneplain. No offset of geologically young landforms or deposits has previously been reported for any of the components of the Little Valley fault zone, and these faults are not currently included in the NZAFD, NZAFM or 2010 NSHM.

Because other similarly orientated faults in the surrounding regions show evidence of geologically recent activity, the Little Valley fault zone is classified in this dataset as ‘potentially active’, ‘not expressed’. For the purpose of estimating activity characteristics, a length of 42 km and nominal slip rate of 0.05 mm/year are assigned. Using 2010 NSHM methodology, a recurrence interval of ~60,000 years is calculated.

A2.28 Livingstone Fault (feature 1; Figure 5.1)

The approximately north-striking Livingstone Fault crosses the western edge of the Queenstown Lakes District, and a ~6.5 km length of the fault lies in the district. It is a geologically major fault which originated during the Mesozoic Era, and separates basement rocks of the Dun Mountain-Maitai Terrane to the west from rocks of the Caples Terrane to the east (Mortimer et al. 2014). There is evidence in places for geologically young reactivation of sectors of the fault. Its northern sector, including that portion in the Queenstown Lakes District, is classed as an active fault earthquake source in the 2010 NSHM and referred to as the Hollyford Fault. This same fault is identified in the NZAFM as the Livingstone-Key Summit Fault Zone. In the 2010 NSHM, the fault source is assigned a net slip rate of 1 mm/year and a recurrence interval of ~6400 years is calculated.

The fault is classified here as ‘likely’ active, because it is possible that the topographic steps (identified in this dataset as ‘moderately expressed’) that are suspected to be an expression of fault rupture could have other origins, such as stream erosion, or slope movement. The Greenstone Track and Caples Track both cross the mapped line of the Livingstone Fault beside Lake McKellar, just inside the limits of Fiordland National Park.

A2.29 Logan Burn fault (feature 48; Figure 5.3)

A northeast-striking fault, upthrown to the southeast, has long been mapped along the foot of the steep edge of the Rock and Pillar Range, on the southeast margin of the Serpentine basin in the upper Taieri catchment (Mutch 1963; Forsyth 2001). It is expressed as vertical separation of the peneplain of as much as ~350 m, up to the southeast. It is presumably a southeast-dipping reverse fault. A name has not previously been applied to the fault on those published geological maps.

Although originally drawn as being continuous with other similar faults farther northeast (Mutch 1963), there was later recognition of a lack of continuity of peneplain deformation between the two structural areas, as illustrated in the mapping by Forsyth (2001). That later depiction showed a ~22 km long inactive, un-named, fault adjacent to Serpentine Flat, separated by ~7 km from other un-named faults of similar character farther northeast.

The digital version of the NZAFD shows the inactive fault from QMAP as an active fault and applies a name ‘Logan Burn Fault’. The origin of that interpretation, and the naming, appears not to have been documented. The NZAFM and 2010 NSHM approximate this fault, and other similar faults farther north, including the QMAP-named Waipiata Fault, as a single, ~65 km long, feature referred to as the Waipiata fault zone (NZAFM) or active fault earthquake source (2010 NSHM). The interpretation in the NZAFM and 2010 NSHM more closely approximates the earlier Mutch (1963) depiction of a contiguous fault, than the later QMAP interpretation of separated faults (Forsyth 2001).

Overall, the geological evidence favours the existence of separate faults rather than a continuous structure. The step is taken here of including the QMAP-defined fault in this dataset, under the name Logan Burn fault, taken from a large stream that crosses the fault escarpment, and recognising the NZAFD’s existing use of that name. The fault escarpment can be traced farther southwest than shown by QMAP and, as mentioned in the Riddles fault section, appears to cross the Riddles fault and die out south-westward approaching the Beaumont River fault.

There are no discernible offsets of geologically young landform features anywhere along the Logan Burn fault, and it is classified here as 'potentially active'. For the estimation of activity parameters, the Logan Burn fault is assigned a dip of 60°, length of 42 km and a nominal slip rate of 0.05 mm/year. Using the 2010 NSHM methodology, a recurrence interval of ~60,000 years is calculated. By this interpretation, the Logan Burn fault becomes separate from the Waipiata fault zone depicted in the NZAFM and 2010 NSHM, and the need for revision of the latter is discussed in a separate section.

A2.30 Long Valley Fault (feature 43; Figure 5.3)

This northeast striking fault forms a prominent escarpment, upthrown to the southeast, in the upper catchment of Pool Burn. The fault is included in the NZAFD, 2010 NSHM and NZAFM. The fault escarpment has a clearly expressed length of ~21 km, and vertical separation of as much as 200 to 300 m of the peneplain across the fault. There are geologically young offsets of alluvial fans along the foot of the escarpment, with heights of as much as 8 m (GNS Science, unpublished data 2000). It is classified here as a 'definite' active fault.

There is currently no good context for assessing the age of the offset fans. A slip rate of 0.5 mm/year was assigned in the 2010 NSHM and NZAFM. However, if the rate were that large, a different morphology would be expected, with a flight of offset fans along the foot of the range-front. Rather, it seems more likely that the fans are older than previously thought. In order to refine the seismic hazard assessment, it is suggested that an age of ~50,000 years is a more realistic estimate for the offset fan surfaces. A scarp height of 8 m on a landform of that age indicates a vertical slip rate of 0.16 mm/year. Resolved on a 60° dipping fault, a net slip rate of 0.18 mm/year is obtained and a recurrence interval of ~7900 years is calculated using 2010 NSHM methodology.

Between 2 and 4 km southeast of the Long Valley Fault is a ~13 km long fault that offsets the peneplain by as much as ~80 m, up to the southeast. Because of its relatively short length, proximity to the Long Valley Fault and having the same sense of throw, it is interpreted here to be a break-out from the Long Valley Fault at depth. It is identified in this dataset as the 'Long Valley Fault - southeast strand'. It is regarded here as part of the surface expression of the Long Valley Fault, rather than an independently rupturing fault. A lack of indication in high-resolution aerial imagery of any geologically young landform offsets along this strand suggests that it has not experienced the most recent surface ruptures of the main strand of the Long Valley Fault. It is classified here as a 'possible' active fault.

A2.31 Moonlight Fault Zone (features 3 and 4; Figures 5.1–5.2)

Detailed studies of this major northeast-striking fault zone have been documented by Turnbull et al. (1975) and Norris et al. (1978). Its wider tectonic significance was discussed by Kamp (1986). Existing interpretations place it as part of an Eocene to Oligocene continental rift system, whose opening allowed incursion of the sea from the Tuatapere area (Southland) north into what is now part of the Shotover River catchment (all of this 30 million years ago, long before the modern topography developed). Distinctive marine sedimentary rocks, including sandstones, mudstones and limestones, known in the Queenstown area as the Bobs Cove Beds, were deposited in the rift. Development of the present plate boundary, and the Alpine Fault, in the earliest Miocene (~22 million years ago) led to closure of the rift and eventually produced the present mountains. These considerations are important because they have bearing on how the recent activity of the fault zone has been interpreted.

Two geologically recent fault scarps near the Mount Nicholas homestead, on glacially-sculpted bedrock and post-glacial lake beaches, are upthrown to the east and have been attributed to movement on the Moonlight Fault (Turnbull et al. 1975; Turnbull 2000). However, both are aligned north-south, rather than on the north-easterly strike of the Moonlight Fault Zone. Also in that area, the only preserved remnants of the Bobs Cove Beds are associated with a north-striking fault, the Home Creek Fault (Turnbull et al., 1975), which is upthrown to the east.

The 1975 interpretation was that Late Cenozoic movement of the Moonlight Fault ‘scissored’ across Lake Wakatipu, with the northwest side upthrown north of the lake, and the southeast side upthrown to the south of the lake. Kinematically, this is challenging if the Late Cenozoic motion is correctly interpreted as reversal of mid-Cenozoic normal faults of a rift zone, because the fault would need opposing dip directions either side of the lake.

The two scarps near Mount Nicholas are the only demonstrated Late Quaternary offsets in proximity to the Moonlight Fault Zone in the Queenstown Lakes District. About 70 km southwest of Lake Wakatipu, in the Southland Region, there is a prominent fault scarp at the northern foot of the Takitimu Mountains close to the mapped line of the Moonlight Fault at Elmwood. This north-northeast trending scarp is upthrown to the west-northwest on an alluvial fan inferred to be ~250,000 years old (Turnbull 2000). From examination of aerial photos, I estimate the height of the scarp to be as much as 15 m. A notable point is that the westerly sense of upthrow is opposite to the easterly sense of upthrow expected for the Moonlight Fault Zone southwest of Lake Wakatipu (Turnbull et al. 1975; Norris et al. 1978). Another important observation is that 45 km to the southwest of Lake Wakatipu, the Moonlight Fault Zone is mapped as ‘concealed’ beneath glacial moraine and outwash deposits inferred to be ~250,000 years old (Turnbull 2000). This indicates the fault in that area has not experienced discernible surface rupture since at least that time. Furthermore, on the line of the fault zone across the Lake Wakatipu trough, there is no discernible offset of post-glacial lake beaches or glacial-age landforms. Farther northeast along the line of the fault zone, which is mostly in rugged mountainous topography, there are no discernible fault-related offset on landform surfaces, notably including the glacially-smoothed valley sides of the Matukituki River west of Lake Wanaka. In that area there are some topographic steps on or close to the line of the fault, but all are down to the northwest, in opposition to the expected sense of throw on the fault and can satisfactorily be attributed to gravitational slope movement.

On balance, it seems more likely that the fault scarp at Elmwood is associated with a fault other than the Moonlight Fault. Otherwise there ought to be more indication of landform offsets elsewhere along the Moonlight Fault Zone. A more likely association for the Elmwood fault scarp is the arrays of northerly-striking contractional Late Cenozoic faults that mark the eastern margin of the Te Anau-Waiau tectonic basin (Turnbull 2000; Turnbull and Allibone 2003).

The following working interpretation for the Moonlight Fault Zone is adopted in this report. The Moonlight Fault northeast of Lake Wakatipu has been reactivated as a reverse fault in the Late Cenozoic, with slivers of Bobs Cove Beds caught up along the fault. Throw diminishes to the southwest approaching Lake Wakatipu, and the most extensive remnants of the Bobs Cove Beds are alongside the eastern shore of Lake Wakatipu, close to the inferred southwestern end of the reverse fault. The more extensive preservation of these strata here may indicate that the amount of Late Cenozoic contraction is much less than farther northeast. Southwest of Lake Wakatipu, the relatively high elevation of the Eyre Mountains southeast of the fault zone may simply reflect the original structural relief of rift-related normal movement on the fault zone, for at least ~50 km southwest to the Mararoa River valley, and one possibility is that sector of the fault has not reactivated in the Late Cenozoic. Alternatively, it may have resulted from the reversal of a former, southeast-dipping, rift-related, normal fault, although on a different fault strand to that associated with Late Cenozoic movement on the northeastern sector of the Moonlight Fault Zone. The Late Quaternary scarps, and the Home Creek Fault of Turnbull et al. (1975) are interpreted here as being associated with a separate north striking, Late Cenozoic fault zone, upthrown to the east (see section on West Wakatipu Fault).

In the 2010 NSHM and NZAFM, the Moonlight Fault Zone is interpreted as having a vertical dip and is divided into two sections, named Moonlight North and Moonlight South, separated at the Von River/Oreti River drainage divide, ~20 km southwest of Lake Wakatipu (outside the Otago Region). Both sections were assigned a slip rate of 1 mm/year in the 2010 NSHM, with respective fault lengths of 88 and 100 km applied to the north and south sections, from which respective recurrence intervals of ~6100 and ~7000 years were calculated. The basis for estimating the slip rate was not stated in the NZAFM documentation, other than the value having been assigned by an expert panel. As far as I am aware, the only previous suggestion of a slip rate of that order comes from a tentative estimation of an uplift rate for the Takitimu Mountains, contained in a report by Carter and Norris (2005). They highlighted an altitudinal sequence of fluvial or glacial terraces, and gently sloping benches, of inferred glacial erosion origin, on bedrock forming the lower hillslopes of the Te Anau basin margin. Assuming that the height differences reflect progressive uplift over time, they used the heights to infer ages for the landforms, based on 'counting-back' correlation to Quaternary glacial cycles. They then used the height differences and inferred ages to calculate a long-term uplift rate. They concluded that the Takitimu Mountains, on the eastern side of the basin and on the presumed upthrown side of the Moonlight Fault Zone, have been rising at ~1 mm/year over the past 750,000 years or so. They also concluded that the Fiordland mountains, on the upthrown side of the faulted western margin of the basin, have also been rising at the same rate. This analysis implies that the basin is not being uplifted, or if so at a lesser rate. Arguable deficiencies with the analysis include: (1) there is no direct dating of the landforms; (2) if the bedrock benches really are glacial erosion features, their height cannot be meaningfully compared to fluvial terraces, because depending on ice-mass thicknesses in the valley, benches could be scoured by ice some distance above the bedrock floor of the basin, and; (3) there are other ways to create an altitudinal flight of glacial/fluvial landforms, such as by progressive erosional deepening of the valley, or by regional uplift unrelated to the faulted margins of the basin. In sum, the inferred 1 mm/year uplift rate, which could be taken to approximate a slip rate on the southern section of the Moonlight Fault Zone, is of questionable merit and should be set aside, especially when other landform evidence points towards a much lesser degree of fault activity.

A slip rate of 1 mm/year implies that an offset of the order of 20 m would be expected on landforms dating from the retreat of ice-age glaciers (~18,000 years ago), but there is no discernible offset of landforms of that age across the Moonlight Fault Zone in either the Lake Wakatipu valley or the Matukituki valley. For the purpose of this report and associated dataset, a nominal slip rate of 0.05 mm/year is assigned to each section of the Moonlight Fault Zone. The north section is interpreted here as extending northeast from Lake Wakatipu to the northern extent of the fault zone as shown in QMAP, at about the northern boundary of the Otago region, some 30 km farther northeast than depicted in the 2010 NSHM and NZAFM. This gives the revised Moonlight North active fault earthquake source a length of 100 km which, using 2010 NSHM methodology in conjunction with a slip rate of 0.05 mm/year, yields a recurrence interval of ~140,000 years. The Moonlight South fault source is repositioned as extending southwest from Lake Wakatipu for ~85 km to the Waiau River in the Manapouri area. Recalculation of its recurrence interval using the revised fault length and slip rate estimate returns a value of ~120,000 years.

A reality check on these estimates is provided here by assuming hypothetically that the offset alluvial fan at Elmwood, mentioned earlier, is related to surface rupture of the Moonlight Fault. The ~15 m offset of the inferred ~250,000-year-old fan surface returns an average slip rate of 0.06 mm/year, and would imply a recurrence interval of the order of 100,000 years. The absence of offset of landforms at Lake Wakatipu formed following the retreat of ice ~18,000 years ago, on the line of the Moonlight Fault, provides another check, by implying a maximum recurrence interval of more than 18,000 years. Together with the absence of indicated offset of ~250,000-year-old landforms across the Moonlight Fault Zone ~45 km southwest of Lake Wakatipu mentioned earlier, these checks illustrate that the nominal 0.05 mm/year slip rate adopted here is a reasonable value for estimating the activity of the Moonlight Fault Zone, based on overall weight of evidence.

The various strands of the Moonlight Fault are classified here as ‘potentially active’, except for a ~10 km long sector of the fault, classed as ‘likely’, that extends from the easternmost ‘definite’ scarp of the West Wakatipu Fault southwest to ~4 km beyond where the Home Creek Fault meets the Moonlight Fault. The reasoning is that rupture on the West Wakatipu Fault extending so close to the Moonlight Fault Zone may trigger localised slip on the Moonlight Fault Zone.

A2.32 Motatapu Fault (feature 5; Figures 5.1–5.2)

This northeast-striking fault was included and named in the QMAP dataset. QMAP shows this fault as ~20 km long, extending along the north-western foot of the Mt Cardrona - Mt Alpha range to abut the Wanaka Fault. High-resolution aerial imagery reveals a very well expressed, northeast trending, topographic step, up to the southeast, on ice-smoothed rock terrain on the eastern end of Roys Peninsula, and a similar step across comparable terrain north of Stevensons Arm. The step is estimated to be ~5 m high and is clearly due to ground movement. However, in this setting, it is difficult to rule out the possibility of stress-release relaxation of the rock mass following ice retreat from the Wanaka basin. For that reason, the steps are classified as ‘likely’ rather than ‘definite’ fault scarps.

The preliminary interpretation made here is that the Motatapu Fault is a ‘likely’ active reverse fault. Assuming a dip to the southeast of 60° and pure reverse motion, the inferred 5 m vertical scarp on landforms of an estimated age of 18,000 years indicates a net slip rate of 0.32 mm/year. Using 2010 NSHM methodology with a nominal fault length of 30 km, a recurrence interval of ~6,500 years is calculated.

A2.33 Nevis Fault Zone (feature 7; Figures 5.1–5.2)

This major northeast-striking fault runs along the north-western side of the Nevis valley, and forms the southwestern part of a major geological structure, named the Nevis-Cardrona Fault System by Beanland and Barrow-Hurlbert (1988). A notable feature of this fault system is that to its northwest, the terrain is generally mountainous, whereas to the southeast, the terrain comprises well-defined ranges and basins across which the Otago peneplain, in places still buried by Cenozoic sedimentary strata, is extensively preserved (Turnbull 2000). The other main component of the Nevis-Cardrona Fault System, the NW Cardrona Fault, is described in a separate section.

The Nevis Fault Zone has been responsible for uplift, on its north-western side, of the Hector Mountains, and their northernmost component, the Remarkables, relative to the Nevis valley. Although usually just called the Nevis Fault, it does include some individually-named components, such as the Schoolhouse Fault, and the word ‘Zone’ has been added here, for clarity. The southwestern part of the fault zone extends into the Southland region.

The mapping in this dataset here is taken directly from QMAP, without refinement. The reasons for this are three-fold. There is no lidar coverage, and there is a general lack of high-resolution aerial imagery for most of the length of the fault zone, even within Google Earth. This means that the QMAP work, compiled on a 1:50,000 scale topographic map base, cannot be improved upon without new fieldwork. Third, the area is remote and largely unpopulated, and there is currently no impetus there for detailed fault mapping.

Offset of geologically young landforms across the Nevis Fault Zone has been documented at selected sites in the Nevis valley by Beanland and Barrow-Hurlbert (1988), including some geological investigation trenches that confirmed a fault origin for several suspected fault scarps, but it was not possible to date any deformation events. Generally speaking, alluvial fan landforms assessed as having formed near the end of the last glaciation (~18,000 years ago) show fault deformation of the order of 2 m, whereas equivalent-age landforms along the NW Cardrona Fault typically have fault deformation of about 5 m. Progressive deformation of a flight of terrace surfaces at Drummond Creek, on the southwestern part of the fault zone ~35 km southwest of the Kawarau valley, indicate at least 4 surface rupture events on the Nevis Fault Zone in the past 18,000 years, but each with uplift of less than 0.5 m (Beanland and Barrow-Hurlbert 1988). This however may not be the only active strand of the fault at that location.

Fault scarps associated with the Nevis Fault Zone are classified here as ‘definite’, with differentiation of ‘well- expressed’ or ‘moderately expressed’ as appropriate based on what can be gleaned of their prominence in Google Earth, with ‘not expressed’ connections between them. Sectors at either end of the Nevis Fault Zone lacking any known preservation of deformed geologically young landforms are designated ‘likely’. This included the ‘Western Boundary Fault’ of Beanland and Barrow-Hurlbert (1988) mapped along the base of the range-front.

In the 2010 NSHM, the Nevis Fault Zone is modelled as a single rupture segment, extending for 69 km from the Kawarau River southwest to the Mataura River, with a net slip rate of 0.4 mm/year and a fault plane inferred to dip northwest at 45°. Calculated single-event displacement is about 5 m, and recurrence interval of ~12,000 years. This appears incompatible with the indication of at least 4 ruptures in the past ~18,000 years, and single-event displacements more of the order of 1 m. Those data suggest that the fault likely has rupture segmentation, with at least two separate segments. This warrants an expert panel review beyond the scope of this project. For present purposes, the only amendment made is to reduce the fault length, to accommodate the southern end of the NW Cardrona Fault having been shifted to Doolans Saddle. The new length for the Nevis Fault Zone is 52 km, from which a revised recurrence interval of 9000 years is calculated using 2010 NSHM methodology, and is used for the purposes of the present assessment.

A2.34 NW Cardrona Fault (feature 6, Figures 5.1–5.2)

This major northeast-striking fault runs along the north-western side of the Cardrona valley. The NW Cardrona Fault forms the north-eastern part of a major geological structure, named the Nevis-Cardrona Fault System by Beanland and Barrow-Hurlbert (1988). A notable feature of this fault system is that to its northwest, the terrain is generally mountainous, whereas to the southeast, the terrain comprises well-defined ranges and basins across which the Otago peneplain, in places still buried by Cenozoic sedimentary strata, is extensively preserved (Turnbull 2000). The other main component of the Nevis-Cardrona Fault System, the Nevis Fault Zone, is described in a separate section.

The NW Cardrona Fault has been responsible for uplift, on its north-western side, of the Mt Cardrona to Mt Alpha range, relative to the Cardrona valley. To the southwest, the fault is extrapolated through the Crown Range saddle to the southwestern side of the Kawarau valley. To the northeast of Wanaka, the NW Cardrona Fault has been previously extrapolated to the Lake Hawea area. As explained later in this section, a different name (Cardrona-Hawea fault) has been applied here to the sector of the fault northeast from Wanaka township area, and it is described in a separate section.

Offset of geologically young landforms across the NW Cardrona Fault has been documented in the Kawarau valley floor and in various places along the north-western side of the Cardrona valley (Beanland and Barrow-Hurlbert 1988) as far northeast as Branch Burn, about 15 km southwest of Wanaka township. No fault offset of geologically young landforms has previously been identified farther northeast towards Wanaka township. Features of the mapping, interpretation and classification of the NW Cardrona Fault are discussed below, starting in the southwest area and working northeast.

A2.34.1 Gibbston Area

A north-trending fault scarp runs across a river terrace on the Kawarau valley floor near Gibbston (Beanland and Barrow-Hurlbert 1988). The scarp (referred to here as the Kawarau valley scarp) is about 5 m high, up to the west, and is clearly visible running at a right angle to the trend of the valley, on the river-side of SH 6 about 0.5 km east of the Kawarau Bridge bungy jump carpark. It is illustrated in Figure 5.4 in the body of the report.

In 1984, a geological investigation trench was excavated across the Kawarau valley scarp, described in detail by Beanland and Barrow-Hurlbert (1988) and on which the following summary is based (see Figure 5.4 in the body of the report). The trench revealed a reverse-sense offset, involving schist bedrock overlain by ~4 m of river sediments, thrust eastwards over river and windblown silt sediments. The fault dip at the base of the trench is 44° west but flattens upwards through the sediment sequence. Geological relationships in the trench exposure indicate that the offset of the terrace deposits accrued from at least 3 surface rupture events, with an average uplift of 1.1 m per event. Taking into account the fault dip, this indicates an average net (i.e. dip-slip) single-event displacement of ~2 m (to the nearest metre). Deposit stratigraphy in conjunction with radiocarbon dating of offset buried soils indicates that at least one rupture occurred before 20,500 ± 1150 radiocarbon years BP, at least two events occurred after that date, and that the most recent event was younger than 9760 ± 560 radiocarbon years BP (Beanland and Barrow-Hurlbert 1988). Using the SHCal curve in the 'Calib' radiocarbon calibration programme, publicly available online at www. http://calib.org/calib/, these ages convert to calibrated calendar-year ages of 24,300 ± 3300 years BP and 11,200 ± 1500 years BP (rounded to the nearest century). This means that the fault, at this location, has experienced at least two surface ruptures during the past ~21,000 years (taking the younger bound of the older age), which together with an aggregate ~4 m dip-slip for two events, indicates a maximum dip-slip rate of ~0.2 mm/year at this site.

The Kawarau valley scarp is classified here as 'definite', 'well expressed'. In the QMAP dataset, this scarp was drawn as a short entity, not connected to the main mapped line of the Nevis-Cardrona Fault System, which was positioned ~0.5 km farther down-valley. In the QMAP dataset, the NW Cardrona Fault is interpreted as stopping on the northern margin of the Kawarau valley. Southwest from there, the main line of faulting was identified as the Nevis Fault, approximating the way the two faults were originally depicted by Beanland and Barrow-Hurlburt (1988). However, there is considerable geological continuity of the fault system either side of the Kawarau valley. On the eastern, downthrown, side of the fault, for ~10 km to the north and ~15 km to the south of the Kawarau valley, remnants of the Otago Peneplain dip west towards the fault at between 10° and 15°, with isolated slivers of Cenozoic strata preserved adjacent to the fault plane. The Kawarau valley scarp is of similar height to other geologically young scarps of the NW Cardrona Fault in the Cardrona valley (described in the following sub-sections). In contrast, the Nevis Fault only shows offset of notably older landforms, while landforms produced near the end of the last glaciation appear to show no deformation. In addition, the Nevis Fault in the Nevis valley shows structural complexity, commonly with two of more parallel strands, whereas the NW Cardrona Fault is typically a more discrete geological structure. In this dataset, the NW Cardrona Fault is extended as an entity to just south to Doolans Saddle, about 15 km south of the Kawarau River. South from there, the zone of more complex, multi-strand faulting is assigned here to the Nevis Fault Zone.

In the interpretation adopted for this dataset, the Kawarau valley scarp is regarded as lying on the main line of the NW Cardrona Fault, and a 'likely', 'not expressed' connector line has been drawn from the scarp to the main mapped lines of the fault to the north, across extensive landslide terrain on the northern side of the valley, to the saddle on the Crown Range Road, which is interpreted to mark a remnant of the Otago Peneplain on the immediate eastern (downthrown) side of the fault.

A long-standing puzzle concerns the location of a southern continuation of fault-related deformation expressed on the Kawarau valley scarp. In the area south of the Kawarau valley, there are flights of old alluvial fan terraces, the higher levels of which are undoubtedly older than the river terrace that is offset in the Kawarau valley. The considerable size of the single-event displacements (~2 m) identified in the investigation of the Kawarau valley scarp makes it very unlikely that the surface rupture deformation stopped at the south side of the Kawarau valley. Rather, the surface rupture deformation almost certainly continued for some distance farther in a general southerly direction. Lidar coverage now extends through part of that area, and profiling of the lidar, along with examination of archival air photos, reveals a broad step, several metres high and up to the west, sidling across a minor alluvial fan surface about 1 km south-southeast of the Kawarau valley scarp. Beyond there, ~2 km south-southeast of the Kawarau valley scarp, an ~2 m high broad step sidles across an inset low-level terrace of Toms Creek. On the presumption that surface rupture of the NW Cardrona Fault must have crossed this area, these two features are classified as 'likely', 'moderately expressed'. Intervening terrain comprises eroded valley-side or hill terrain, across which 'likely', 'not expressed' connector lines are drawn. A connector line is extrapolated around the northern foot of Camp Hill, to join a sector of the fault that is well established by geological relationships, by way of a sliver of Cenozoic strata preserved along the downthrown side of the fault for ~3 km from the floor of Camp Creek southeast to Coal Pit Saddle. The terrain from here through to the edge of the broad Nevis valley is mountainous, with extensive landslide terrain, and no geologically young surface fault-deformation has been identified. This sector of the fault is identified as 'likely', 'not expressed'.

While these interpretations of the NW Cardrona Fault south of the Kawarau valley are tentative, they are considered to provide the best accommodation of available geological information, notably the relatively discrete fault geometry extending south from the Cardrona valley to just beyond Doolans Saddle, the similarly of geologically young scarp heights in the Cardrona valley and Kawarau valley, and the likelihood that recent surface fault ruptures has extended south of the Kawarau valley.

A2.34.2 Cardrona Valley Southern Sector

For about 10 km north-northeast from the Crown Range Road saddle to Blackmans Creek, the NW Cardrona Fault is positioned at the western edge of a series of topographic benches along the foot of the Crown Range. These benches are interpreted to be remnants of the Otago Peneplain, a relationship confirmed by the presence of Cenozoic strata preserved on a bench at Coal Creek. The eastern face of the Crown Range is largely landslide terrain, and the location of the fault is largely obscured, or masked by recent gravitational mass movement. Geologically recent fault offsets have been identified across valley-floor alluvial-fan terraces in two locations, Maori Gully and Blackmans Creek.

The Maori Gully fault scarp lies about 6.5 km north of the Crown Range Road summit. It is described by Beanland and Barrow-Hurlbert (1988) as a ~4 m high topographic step, up to the west. The presence of fault offset was confirmed by geological investigation trench across the scarp, which exposed a northwest-dipping reverse fault, but the number of displacements could not be determined (Beanland and Barrow-Hurlbert 1988). The scarp is classified as ‘definite’, ‘Immediately to the northeast, there is a topographic step, up to the west, across landslide terrain, that Beanland and Barrow-Hurlbert (1988) interpreted as a fault offset. However, it is possible that it is a gravitational scarp within the landslide that just happens to align with the adjacent fault scarp. It is classified as ‘likely’, ‘moderately expressed’.

The Blackmans Creek fault scarp is about 10 km north-northeast of the Crown Range Road summit, and about 3.5 km southwest of the Cardrona Hotel. The feature was described by Beanland and Barrow-Hurlbert (1988) as a fault scarp, about 7 m high and up to the northwest, across an alluvial fan. This feature lies close to the Cardrona River, and the question arises as to whether the step, and the lower terrace at its base, are products of river erosion rather than fault movement. If that were the case, the ground on the lower side of the step would be a Cardrona river terrace, rather than a Blackmans Creek alluvial fan, and the terrace would slope down the Cardrona valley at the same gradient as the river. However, lidar shows that the ground on both sides of the topographic step slopes towards the Cardrona valley axis, showing that the feature is a faulted alluvial fan. The lower side of the step can be seen in Street View from Cardrona Valley Road; and the entire tread of the fan is visible from the road. Were it a river terrace, only the road-ward edge of the terrace would be visible, and not its full extent. This provides further illustration that the feature is a faulted alluvial fan surface.

It has been proposed that at this site there is ~10 m right-lateral offset of a stream-cut channel-edge feature on the Blackmans Creek fan surface (Beanland 1984; Beanland and Barrow-Hurlbert 1988). Close examination of lidar information for the purpose of this report shows that the fault scarp here has a plan-view width of 15 to 20 m, while the channel edge feature is 7 to 8 m wide in plan view. A slight change in trend of the channel edge in the area where the fault scarp now is could satisfactorily account for the positions of the channel-edge feature either side of the fault scarp. While it is possible that there has been lateral offset of the amount suggested, the uncertainties mean that the interpretation should be regarded as tentative without additional field evidence. Instead, the view provisionally preferred here is that the channel patterns on the fan can be accounted for adequately without lateral displacement, and a working interpretation is adopted that there is no confirmed discernible component of lateral offset.

About 0.5 km southwest of Blackmans Creek, a step about 1 m high on a low-level fan terrace was interpreted as a fault scarp by Beanland and Barrow-Hurlbert (1988). It is not well resolved in the lidar, and is classified here as ‘likely’, ‘moderately expressed’. The height of this relatively small scarp, assuming it is a fault scarp and not of some other origin, provides a maximum constraint on the vertical component of a single-event displacement at this location.

For about 300 m southwest of Blackmans Creek, there is a marked rise from the valley floor up onto higher fan surface remnants. The interpretation is made here that this step approximates the position of a former fault scarp, now somewhat eroded by the Cardrona River. For that reason, this section of the fault is classified as ‘likely’, ‘moderately expressed’.

From Blackmans Creek north for about 4 km to the Cardrona village area, there is no sign of fault deformation on the slopes and terraces on the northern side of the valley, and it is assumed that the fault is concealed beneath the young river flood-plain landforms of the Cardrona valley, or possibly by landslide debris on the lower flanks of the valley west of the river. This, and all other parts of the fault in this section of the Cardrona valley not mentioned above are classified as ‘likely’, ‘not expressed’. While there is no doubt that the active NW Cardrona Fault runs through this section of the valley, uncertainty about the fault’s location may in places be as much as several hundred metres. The designation of ‘likely’ is thought the best way to highlight that uncertainty.

A2.34.3 Cardrona Valley Northern Sector

Immediately north from Cardrona village, the general line of the fault curves northward and a conspicuous scarp, up to the west, crosses old fans in the Pringles Creek area. As revealed by lidar, the scarp is as much as 20 m high on the oldest landforms and the smallest scarp, in the incised Pringles Creek valley floor, is about 2 m high. That provides a maximum value for the vertical amount of single-event surface rupture displacement on the fault strand at this location. This fault scarp approaches the foot of the range at Boundary Creek. Northeast from there, discontinuous topographic steps, up to the northwest, are present along the foot range in the Macdonalds Creek catchment, about 5 km north-northeast of Cardrona village. These are interpreted to be fault scarps and are classified as ‘likely’, ‘moderately expressed’. The lower slopes of the range have been extensively affected by landslide movement, and this is probably why there is little landform evidence for recent fault offset. A line classified as ‘likely’, ‘not expressed’ is interpolated along the foot of the range between the ‘moderately expressed’ features.

For a distance of about 8.5 km between Boundary Creek and the south side of the Spotts Creek catchment, discontinuous northeast-trending fault scarps, up to the southeast by as much as several metres, lie parallel to, but about 0.5 km southeast of, the range-front fault. In this dataset, they are assumed to be the expression of a single active fault strand, named in this dataset as the ‘NW Cardrona Fault – backfault’. In 1984, a geological investigation trench was excavated across a ~4 m high ‘definite’, north-trending, scarp on a terrace of Macdonalds Creek (Beanland 1984; Beanland and Barrow-Hurlbert 1988; ‘Branch Creek Road trace’). The trench exposure showed a steeply southeast-dipping fault plane within similarly orientated Cenozoic strata bedrock, overlain by relatively thin alluvial sediments. The stratigraphic relationships were interpreted to indicate a net overall reverse offset of ~5 m, up to the east, on the fault plane, probably accrued in three rupture events. This implies an average slip of ~1.7 m per event. An image accessible in Google Earth, dated 22 December 2012, shows the stream channelling on the faulted terrace surface in fine detail, and there is no discernible lateral component of offset of the channel features. The terrace deposits could not be dated but are inferred to be about 18,000 years old (Beanland and Barrow-Hurlbert 1988). The well-expressed channel morphology on the terrace makes it unlikely that the terrace surface could be much older than that, because if it were it would likely carry a cover of windblown loess that was widely deposited during the last glaciation. The estimate of 18,000 years is considered here to be a working estimate for the age of the terrace surface. Assuming that an aggregate 5 m of net slip has occurred at the Macdonalds Creek trench site since 18,000 years ago, implies a net dip-slip rate of 0.3 mm/year (to the nearest decimetre) at this location.

The NW Cardrona Fault – backfault has similarity in form and setting with backfaults (referred to structurally as 'antithetic faults') associated with some other Central Otago fault systems such as the Dunstan Fault Zone and the Pisa Fault Zone (Beanland et al. 1986; Beanland and Berryman 1989). However, in the Cardrona valley there is no evidence for an underlying 'synthetic' fault breaking out farther east, as would be necessary to support the antithetic fault interpretation. Instead, Beanland and Barrow-Hurlbert (1988) hypothesized that the fault referred to here as the NW Cardrona Fault – backfault may be a bedding-plane slip fault associated with deformation in the steeply dipping Cenozoic strata underlying this part of the Cardrona valley.

An alternative possibility is suggested by geological relationships at the northern end of the NW Cardrona Fault – backfault, on the south side of the Spotts Creek catchment. There, the easterly-upthrown backfault disappears at about the same place where a westerly-upthrown southeastern strand of the NW Cardrona Fault at Spotts Creek (mentioned below) appears. The interpretation proposed here is that the NW Cardrona Fault – backfault represents a type of 'pop-up' developed over a section where the south-eastern strand of the NW Cardrona Fault has not broken out to the ground surface but instead terminates underground. By this reasoning the backfault's position would approximate the location of the blind, subsurface, tip of the south-eastern strand of the NW Cardrona Fault. If correct, this interpretation implies that surface rupture of the backfault is directly linked to large ruptures of the NW Cardrona Fault. In that case, the paleoseismic information from the Macdonalds Creek trench will provide an approximation of the timing and size of near-surface rupture events of the south-eastern strand of the NW Cardrona Fault. Overall, because there is interpreted to be another strand of the NW Cardrona Fault at the foot of the range, the slip rate estimated at the Macdonalds Creek trench site will be a minimum for the NW Cardrona Fault structure as a whole, because it does not account for any as-yet undocumented slip on the range-foot strand of the fault, or any folding and distributed minor faulting not clearly evident at the ground surface.

In the Spotts Creek valley, about 13 km northeast of Cardrona village, a topographic step, several metres high and up to the west, sidles across alluvial fan terraces, evident in high-resolution aerial imagery (it is outside of lidar coverage). Identical stream channel patterns can be seen either side of the step, and it is classified here as a 'definite', 'well expressed' fault scarp. It has not previously been identified. Northeast from Spotts Creek, a 'likely', 'not expressed' fault is extrapolated for a further 4 km along the foot of the range, through extensive landslide terrain (Figure A2.2).

Starting from the south side of the Spotts Creek catchment, lidar reveals another line of fault scarps, up to the northwest, diverging northeast from the foot of the range. The scarps are evident on fan terraces and some hillslopes and are classified as 'likely', 'moderately expressed', with 'not expressed' connectors in between. A ~2 m high scarp crosses the main terrace on the northern side of Spotts Creek, about 1 km upstream from the Cardrona Valley Road bridge. A fault-origin of this scarp is more certain, but the landform here is complicated by small alluvial fans built out across the terrace from the valley side, and a classification of 'likely' is preferred here, pending future field investigation. On the same line, 1.5 km northeast of Spotts Creek, a fault scarp classed as 'definite' crosses the floor of an un-named gully. Lidar shows it to be ~3 m high, up to the northwest.

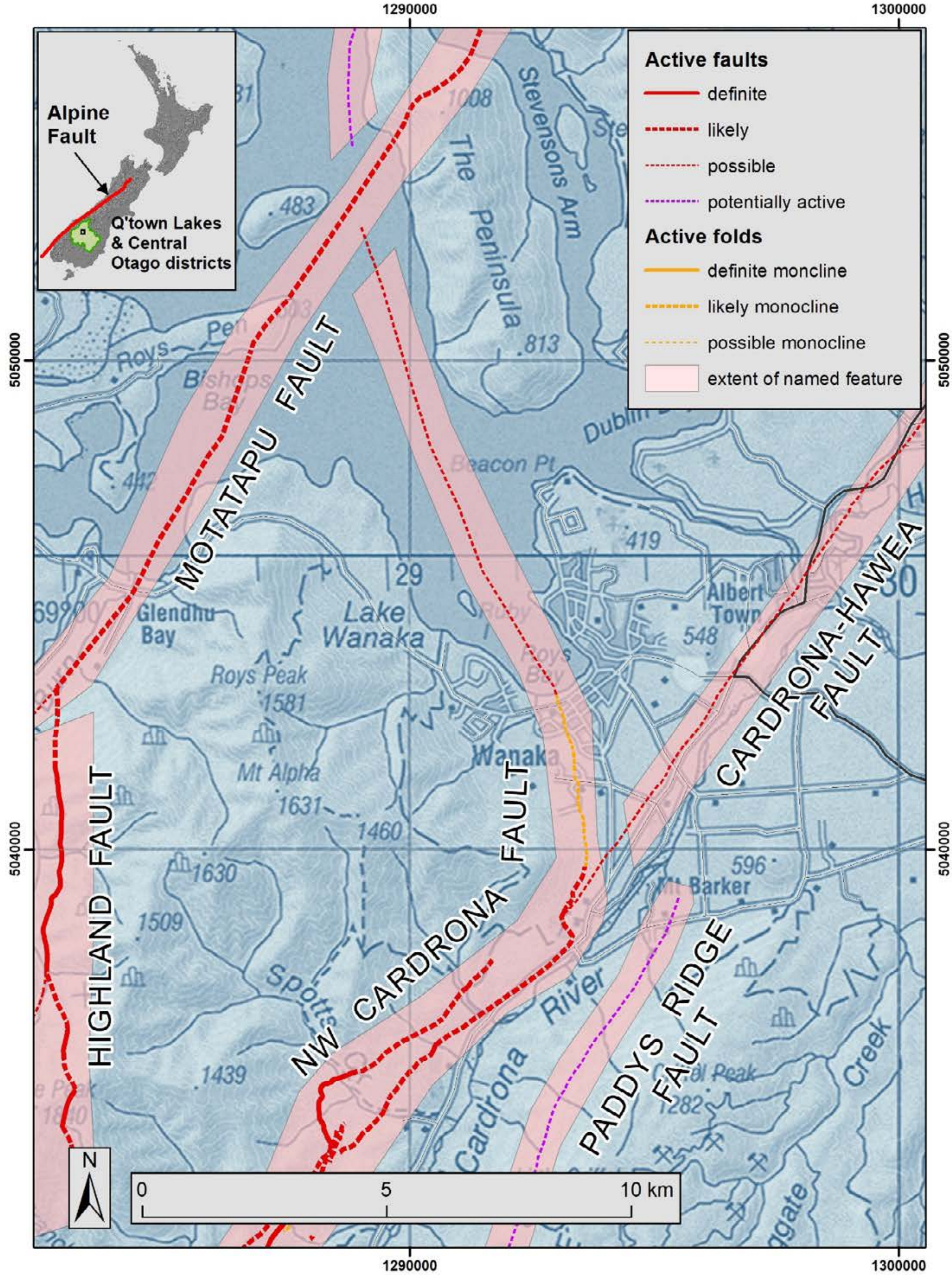

Figure A2.2 Map showing the interpretation and classification of active faults in the Wanaka area. The location of the map panel is shown by the black rectangle in the inset at top left.

Near where the Cardrona valley emerges into the Wanaka basin, an extensive terrace on the north-western side of valley stands about 100 m above the valley floor, west of the Hillend farm buildings. On the terrace, lidar reveals very well preserved glacial moraine and meltwater river plain landforms, formed at a time when ice filled the Wanaka basin during the ‘Luggate’ glacial advance, and meltwater spilled into the lower Cardrona valley. These landforms are likely to be at least 60,000 years old. There is no indication of fault deformation features crossing the terrace landforms. For that reason, the range-front (north-western) strand of the NW Cardrona Fault is stopped at the western side of this terrace. The south-eastern fault strand, described in the previous paragraph, is inferred to trend northeast beneath the young floor of the Cardrona valley, on the south-eastern side of the high terrace, before remerging across alluvial fan landforms at the foot of the range, northwest of the Hillend farm buildings, as described in the next subsection.

A2.34.4 Wanaka Area

Although previous work had not identified any fault offsets of landforms associated with the NW Cardrona Fault near Wanaka, lidar information and high-resolution aerial imagery has led to the recognition of suspected fault-related landforms in that area (Figure A2.2). Lidar information reveals a suspected fault scarp at the foot of the range on Hillend farm northwest of on the Cardrona Valley Road, about 5 km south-southwest of the Wanaka town centre. The feature is a northeast-trending topographic step, up to the northwest and 4 to 5 m high, running across alluvial fan landforms at the foot of the hillslope. An aspect suggestive of a fault origin for the step is that, in one place, the step peters out, and another step, partly overlapping, commences a few metres downslope and increases in height towards the northeast. However, because the step is very close to the Cardrona valley floor and its associated river terraces, it may be conceivable that the step is a river-cut feature, at the foot of which a sloping apron of material such as wind-blown river sand has accumulated, creating the appearance of an alluvial fan landform either side of the step. That possibility is acknowledged by classifying the step as ‘likely’, rather than ‘definite’. The step is identified as ‘well expressed’ due to its prominent form. Towards the north-northwest, the suspected fault scarp crosses alluvial fan terrain of more complicated geometry, and a classification of ‘moderately expressed’ is applied there.

About 600 m northwest of the intersection between Cardrona Valley Road and Riverbank Road, the discrete step becomes a broad rise that extends towards Wanaka township on a north to north-northwest trend. The rise is about 5 m high, between about 100 and 120 m wide and is interpreted to be a monoclinal fold developed over the top of the suspected fault. The line denoting the monocline position is placed along the centreline of the interpreted warped ground. The landform crossed by this sector of the suspected monocline is a composite array of alluvial fans which have built out eastward from small hillslope catchments on Mt Alpha. The fan complex, at its toe, has been cut by a glacial meltwater channel that emanates from the Wanaka terminal moraine belt, and the fan surface is somewhat dissected by gullies that drain into the meltwater channel. The fan complex is of composite age, with older parts formed during the last ice age when a glacier still occupied the Lake Wanaka basin, while the gullies are probably still actively evolving, through supply of floodwater and possibly sediment from the hillslope catchments.

On the outskirts of Wanaka near Studholme Road, about 2 km south-southwest of the town centre, lidar shows that the suspected monocline crosses the meltwater channel floor. The height of the broad topographic rise is about the same as to the south, 4 to 5 m, but over a distance of about 200 m, the rise broadens northward from about 120 m wide on the south side of the channel floor to about 180 m wide on the north side. This probably indicates an increasing depth of poorly consolidated subsurface sediments associated with the Wanaka glacial trough.

Within the southern sector of Wanaka township, the main landform feature is a belt of moraine and associated meltwater channels and terraces, formed at the terminus of the ice-age glacier that formerly occupied the Lake Wanaka basin. The moraine marks the rim of the Lake Wanaka glacial trough, and is probably about 18,000 years old, because that is the age of similar, lake-impounding, moraine belts at lakes Ohau and Pukaki in South Canterbury that have investigated using geological dating methods (Barrell et al. 2013; Putnam et al. 2013). Inside the Wanaka moraine belt is a flight of beach terraces, produced after the glacier retreated and the lake formed in the glacier trough. The lake initially stood about 20 m above its present level but progressively dropped as the Clutha River eroded more deeply into the lake outlet. The other main landscape element is a complex of alluvial fans in the southwest part of town that have built out from Mt Alpha, partially burying the moraine belt and beach terraces in that area.

The suspected monocline cannot be tracked across the moraine belt, because the highly irregular topography does not provide a uniform reference surface for its recognition, unlike the alluvial fans and meltwater channel farther south, which have uniform gradients, thereby allowing identification of anomalies in their gradients. North (lakeward) of the moraine belt, lidar reveals a well-defined gradient anomaly on the high beach terrace (see Figures 5.5–5.6 in the body of the report). The anomaly comprises a north trending, broad rise about 4 to 5 m high across a ~200 m wide zone. The beach terrace was originally flat, formed by wave action at the shoreline of Lake Wanaka when it was higher. The height change must reflect movement of the land after the lake dropped. The key diagnostic of this height change being due to land movement is that there are old beach ridges at right angles to the slope, such as can be seen trending east-northeast through Wanaka cemetery, about 1.3 km southwest of the town centre. The ground must have been tilted to account for their present arrangement.

A probable reason why this likely monocline on the Wanaka beach terrace has previously escaped notice is that this part of the township is long-established, and urban development has obstructed clear lines of sight across the full width of the rise. Also, by chance, there are no straight roads crossing the rise, which would have provided good lines of sight. With its presence revealed by lidar, it is now possible to see it on the ground, if looking in the right place. For example, it is evident looking east along Meadowstone Drive from the Willowridge intersection. A viewer there is standing beside houses, but the view in the distance overlooks the rooves of houses, even though they are on the same, originally flat, beach terrace.

Although detailed analysis has not been done for this report, lidar indicates that on the next lower beach terrace, on which most of the Wanaka Lakeview Holiday Park is situated, the rise is of similar width, but only about 2 m high. Closer to the lakeshore, the lidar suggests that the rise is present, but only about 1 m high. These are just preliminary interpretations, but they suggest that the rise, where 4 to 5 m high, has been produced in at least three growth events, while lower, younger, beach terraces have experienced fewer events. The ages of the beach terrace flight are as yet unknown, other than being younger than the 18,000-year-old glacial moraine belt. However, another possibility is that the deformation is rapidly dying out northward across the flight of beach terraces.

Although the topographic features described above between the mouth of the Cardrona valley and Lake Wanaka are considered very likely due to fault rupture of the ground surface, or in the case of the monocline, buckling of the ground above a subsurface fault rupture, they are classified here as ‘likely’ rather than ‘definite’. This allows for an outside chance that the steps or rises could have originated from river or stream-related processes, or in the case of the Wanaka beach terraces, differential ground subsidence due to melting of a large block of buried glacier ice. Proving through geological investigation trenching that one of the steps is a fault scarp may provide sufficient basis for elevating the status of all these features to ‘definite’.

The section of the suspected monocline across the Wanaka moraine belt is classified as ’not expressed’, because there is no basis on present information to confirm its location. The designation does not imply that the moraine area has not been affected by suspected monocline deformation.

North of the current lake shoreline, the inferred continuation of the deformation is marked as a 'likely' fault, 'not expressed' beneath Lake Wanaka. The position is that of the southern part of the inferred 'Wanaka Fault' in the QMAP dataset. Due to the changed interpretation of the NW Cardrona Fault in the Wanaka area, the southern sector of the previously mapped Wanaka Fault is included in this dataset as part of the NW Cardrona Fault. It is inferred to end as it approaches the Motatapu Fault. The previously mapped Wanaka Fault north of the Motatapu Fault is retained in this dataset as a potentially active fault under the name 'Wanaka Fault' (see separate section).

A2.34.5 Reassessment of NW Cardrona Fault Activity Characteristics

In summary, the suspected fault and fold features extending on a northerly trend from the Cardrona valley through to the Wanaka township area are attributed to post-glacial rupture(s) of the NW Cardrona Fault having transferred north towards the Lake Wanaka basin, rather than continuing northeast towards Lake Hawea as had previously been interpreted in the QMAP, 2010 NSHM and NZAFM datasets.

The recognition of 'likely' post-glacial scarps associated with the Motatapu Fault may indicate that post-glacial deformation on the NW Cardrona Fault has not extended north of the line of that fault.

In the 2010 NSHM, the NW Cardrona Fault is modelled as comprising two rupture segments, with the boundary between the northern and southern segments placed at Back Creek, about 14 km southwest of Wanaka, with respective lengths of 34 km and 28 km. A net slip rate of 0.38 mm/year was assigned to both segments in the 2010 NSHM, on a fault plane inferred to dip northwest at 60°. Calculated single-event displacements are about 2 m, noting that this is the displacement on the dipping fault plane, and would resolve as a vertical throw of a little less than 2 m. Calculated recurrence intervals are a little more than 5000 years, with specific values of ~6200 and 5100 years for the northern and southern segments respectively.

The 2010 NSHM assessment is aligned with field observations, including average dip-slip single-event displacements of about 2 m from Kawarau valley and Macdonalds Creek trench investigations, and smallest scarp heights at several locations of between 1 and 2 m, which represent maxima for single-event vertical displacement. Larger single-event scarps (e.g. 3 to 4 m) would be expected if the entire ~60 km length of the fault ruptured in a single earthquake. This provides ongoing justification for characterising the NW Cardrona Fault as comprising two rupture segments.

The recognition that post-glacial ruptures have passed northward to Wanaka, rather than continuing towards Hawea, has implications for the length of the northern segment of the fault. The interpretation suggested here is that the revised NW Cardrona Fault northern segment does not cross the Motatapu Fault, and presumably dies out approaching it. For the re-estimation of fault activity parameters, the northern end is placed 5 km southeast of the Motatapu Fault, passing under Wanaka and along the Cardrona valley to a southern end at Cardrona village, where the Paddys Ridge (aka SE Cardrona) and Roaring Meg (aka Gentle Annie) faults converge. The revised length is 30 km. That in turn affects the recurrence interval, recalculated using 2010 NSHM methodology, which is reduced to ~5500 years. The revised position of the NW Cardrona Fault southern segment extends from Cardrona village in the north, across the Kawarau valley to Doolans Saddle in the south, as discussed earlier. This provides a fault length of 30 km and thus has a ~5500-year recurrence interval, the same as obtained for the northern segment. It is not known when the most recent rupture of the northern segment occurred. For the southern segment, radiocarbon dating at the Kawarau valley scarp indicates that the most recent rupture there is younger than 11,200 ± 1500 years ago.

A2.35 Old Man Fault (feature 28; Figure 5.3)

The north-northwest-striking Old Man Fault is a major structure that has uplifted the Old Man Range, with the uplift equating to as much as ~1000 m vertical separation of the Otago peneplain, up to the west (Stirling 1990). The Old Man Fault is included in the NZAFD, NZAFM and the 2010 NSHM. However, there is no known evidence for geologically young landform displacement across the fault. It is interpreted that no surface rupture has occurred on the Old Man Fault since deposition of the 'Lindis' age outwash gravel (Hull and Stirling 1992), the age of which adopted here is ~330,000 years (see Grandview Fault section). However, more recent work has identified an exposure showing a ~5 m offset of those gravels (GNS Science, unpublished data 2000).

The mapped linework in the present dataset is adopted from QMAP without modification, and fault activity parameters are adopted from the 2010 NSHM, which include an assigned length of 52 km and a slip rate of 0.01 mm/year. The resulting calculated recurrence interval in 2010 NSHM is ~360,000 years. Notably, at that recurrence interval, it would have taken ~100 million years to uplift the Old Man Range. However, other geological considerations indicate that the range's uplift has probably occurred in no more than the past 15 million years or so. This indicates that the Old Man Fault has been become less active in the recent geological past. On account of the extremely long recurrence interval currently indicated, the Old Man Fault is classified in this dataset as 'potentially active'.

A2.36 Omarama Saddle fault (feature 24; Figures 5.2–5.3)

This approximately north-striking fault was included in the QMAP dataset with a classification of inactive (Forsyth 2001), but evidence for geologically recent activity was described by Barrell (2016), for that sector of the fault in the Waitaki District, north of Omarama Saddle. This fault is not in the NZAFD, NZAFM or 2010 NSHM.

For this project, mapping of the Omarama Saddle fault is extended into the Central Otago District based on inferred dislocation of as much as several hundred metres, up to the east, of inferred remnants of the Otago peneplain. Peneplain reconstruction in this area is difficult. The topographic evidence comprises narrow broad-crested ridgelines in basement rock, with intervening wide, deeply eroded, valleys. The ridges show elevation accordance, and are inferred to be peneplain remnants, but an absence of Cenozoic strata preserved on the ridges means that the inference is tentative. The Omarama Saddle fault is positioned along a change in the gradient of the inferred peneplain remnants. To the east of Omarama Saddle, the strike of the tilted peneplain is northeast and the dip is ~6° southeast. To the west, the reconstructed peneplain surface strikes north and has a dip between ~5 and ~8° to the east.

At Omarama Saddle, the indicated peneplain offset of ~400 m, up to the east, and decreases southwards due to convergence of the peneplain gradient trends. About 6 km from Omarama Saddle the indicated offset is no more than ~100 m, and that offset is maintained southwards to the western margin of the Manuherikia basin. Because it depends on a tentative reconstruction of the peneplain, defined from widely separated elevation-accordant ridges, this represents a modelled offset, rather than something that is obvious in the landscape. A crushed zone shown in QMAP on the lower flanks of the St Bathans Range about 8 km north-northeast of St Bathans village, is inferred to mark the Omarama Saddle fault. Across ridges and spurs north from the crushed zone towards Omarama Saddle, a persistent though only partly continuous topographic anomaly is visible in Google Earth imagery, at about the location of the peneplain-inferred fault. It appears to be a several-metre-high step, up to the east. It is classified as a 'likely', 'moderately expressed', fault scarp. Its recognition is regarded as tentative, pending a future ground inspection.

South from the crushed zone, the Omarama Saddle fault is extrapolated along the Isolated Spur Fault recognised by Madin (1988). This latter fault was not included in QMAP, but has a throw of ~100 m, up to the east, defined by offset of cover rock strata, and to the south ends at or close to the Stranraer Fault, according to Madin (1988). Note that this latter fault is referred to in this report as the Home Hills fault zone. The area close to the Home Hills fault zone just lies within the lidar coverage of the Manuherikia valley, and two en-echelon, broad, northeast-trending topographic steps, about 1 to 2 m high and down to the northwest, about 0.7 km east of the Loop Road/Hawkdun Runs Road intersection, are mapped as 'likely' monoclines associated with the Isolated Spur Fault. About 1 km to the north, at the southern end of Isolated Spur and just outside of lidar coverage, colour aerial imagery shows a 'definite' fault scarp, trending northeast and up to the southeast, offsetting a hillslope and the floors of gullies draining down the slope. This scarp is inferred to be on the Isolated Spur Fault section of the Omarama Saddle fault.

The tentative nature of the recognition of the Omarama Saddle fault for much of its length, based on modelled reconstruction of peneplain contours, suggests that 'possible' would be a preferred certainty to apply to this fault. There is however a need to define a plausible surface-rupturing fault to account for the 'definite' fault scarps at either end of the structure (Twinburn in the Waitaki District – see below; and Isolated Spur). Therefore, 'likely' is the default certainty adopted here for the fault. It should nonetheless be regarded as a provisional categorisation pending any investigatory field work that may be done in the future.

Using aerial photos, Barrell (2016) identified a landform offset of ~5 m on a river terrace of assumed age 18,000 years near Twinburn farm in the Waitaki District. A subsequent drive-by inspection by the writer indicated that the scarp height is closer to ~3 m. This scarp is up to the northwest, in opposing sense to the peneplain offset, and indicates some complexity of movement on the Omarama Saddle fault. For the purposes of this assessment, the vertical slip rate proposed by Barrell (2016) of 0.3 mm/year is revised to ~0.2 mm/year based on the revised scarp height. Adopting a length of ~32 km, extending from the Hawkdun Fault in the north to the Home Hills fault zone in the south, and assuming a dip of 60° to the east and pure dip-slip reverse motion, the recurrence interval is calculated to be ~12,000 years, using 2010 NSHM methodology.

A2.37 Paddys Ridge fault (feature 8; Figure 5.2)

This northeast-striking fault is mapped along the north-western flank of the Pisa Range, adjacent to the Cardrona valley. It has previously been referred to as the SE Cardrona Fault (e.g. Beanland and Barrow-Hurlbert 1988; Turnbull 2000; McDonnell and Craw 2003). There is a potential for confusing that name with the NW Cardrona Fault, and so a new name is applied here to the SE Cardrona Fault. The new name is taken from Paddys Ridge, shown on the 1:50,000-scale topographic map, which is traversed by the access road from the Cardrona valley to the Waiorau Snow Farm ski area. The mapped position of the fault is taken directly from QMAP, and it is not included in the NZAFM or the 2010 NSHM. The fault is identified on the basis of slivers of Cenozoic strata caught up along the fault, and the need to account for basement rock of the Pisa Range standing high about Cenozoic strata in the Cardrona valley. Upthrow is to the southeast and it is inferred that it is a southeast-dipping reverse fault. There has been substantial Late Cenozoic displacement, since the middle Miocene, but there is no evidence for or against Late Quaternary displacement. Beanland and Barrow-Hurlbert (1988) drew a 'possible' fault trace on an alluvial fan ~1 km northwest of the projected line of the Paddys Creek fault but noted that it "does not continue across adjacent fan surfaces, and its origin is doubtful". I agree with that assessment and consider it more likely to be a landform of erosional origin. Although this possible fault feature is included in the QMAP and NZAFD fault datasets, it is not included in the present active fault dataset.

The Paddys Ridge fault is identified here as a potentially active fault. A length of 22 km is assigned along with an assumed dip of 60° and nominal slip rate of 0.05 mm/year. Using 2010 NSHM methodology, a recurrence interval of ~30,000 years is calculated.

A2.38 Pisa Fault Zone (feature 21; Figures 5.2–5.3)

Movement on the northeast-striking Pisa Fault has been responsible for the uplift of the Pisa Range to the northwest. The Pisa Range is in part a fault block, but with a substantial component of anticlinal folding, seen in the attitude of foliation in the schist on the upthrown side of the fault, and in deformation of the Otago peneplain. To the southwest of the Kawarau River valley, the Carrick Range is a continuation of the Pisa Range uplifted/upfolded block. The Bannockburn to Cromwell basin comprises a prominent synclinal fold, that is paired with the Pisa Range anticline, and the Dunstan Mountains anticline to the southeast. The term 'Pisa Fault Zone' is used in this report to encompass the Pisa Fault as well as the Carrick and Bannockburn faults.

Previous workers have suggested that to the northeast, the Pisa Fault Zone continues along the foot (east side) of the Lindis Peak range / west side of the Tarras basin (Officers 1984; Halliday 1986; Beanland and Berryman 1989). I consider there are three difficulties with this interpretation. First, the amplitude of the Pisa Range anticline diminishes north-eastward, and swings northward to plunge into the Wanaka – Hawea basin (i.e. west of the Lindis Peak range). This implies that the range-bounding fault is petering out in that direction. Second, the Lindis Peak range is primarily associated with uplift by a fault (Goodger Fault) on its north-western side. If the Pisa Fault Zone did continue as a prominent feature on the southeast side of the range, the two faults would intersect at shallow depth. Third, at the north end of the Tarras basin there are three faults (Cluden Fault Zone), with up-to-the-northwest displacement of the peneplain. Their collective vertical separation of the peneplain is about 300 to 400 m, and they appear to terminate to the northeast against the Longslip Fault (Lindis Pass Fault Zone). In order to be sufficiently long to have produced the observed displacement, the Cluden Fault Zone must extend southwest to near the southern end of the Grandview Fault.

The interpretation adopted here is the Pisa Fault Zone as a ground-surface feature extends northeast to the Grandview Fault (which is upthrown to the east) but does not cross the Grandview Fault. What has previously been regarded as the northern part of the Pisa Fault Zone is renamed the Cluden fault zone (see separate section).

From Low Burn northeast to about 2 km beyond Lochar Burn, the Pisa Fault has a prominent expression on medium to high terraces. Investigations have shown it is predominantly a monocline rather than a fault break-out (Officers 1984), and in the dataset accompanying this report the feature is generalised as a single monocline, positioned at about the mid-point of the fold. The monocline has associated with a broad zone of surface buckling, locally some discrete back-faults just northwest of the monocline crest, and a broader zone of backtilt extending farther to the west. The most up-to-date information source is the Beanland and Berryman (1989) paper. For the present data set, the line denoting the monocline should be regarded as representing the centre of a 400-m wide deformation zone.

The prevailing assessment is that there has been no surface deformation associated with the Pisa Fault since the river terraces and alluvial fans of the “Albert Town” landform set were formed (Beanland and Berryman 1989). However, the age of these landforms is not well established. They were assessed as having formed in the early part of the last glaciation (~65,000 years go) on QMAP, although Barrell (2011) suggested they may be younger, dating from the latter part of the glaciation. The matter remains unresolved at present.

To the south, the Carrick Fault forms the structural continuation of the Pisa Fault, and comprises a zone of faults along the foot of the Carrick Range. There is no direct evidence for Quaternary-age offset, and the strands of the Carrick Fault are identified as ‘possible’ active faults.

The Bannockburn Fault is well defined near the Bannockburn inlet, where schist is faulted up to the west, with an asymmetric syncline in Manuherikia Group strata, locally overturned, to the east (feature 20a). Farther south, peneplain contours provide a basis, along with patchy remnants of Manuherikia Group Cenozoic strata, for correlating a series of mapped faults in bedrock with the Bannockburn Fault, through to the Fraser Dam area. There is a ~100 to 200 m vertical offset of the peneplain across the fault. The Bannockburn Fault is considered here to be a splay of the Carrick Fault, and is classified as possibly active. The Carrick Fault can be similarly traced to about the same southern extent. Beyond there, both meet the Old Man Fault. By the interpretation presented in this dataset, the Fish Creek Fault and Cairnmuir fault (features 22a, 22b) end south-westwards against the Bannockburn Fault.

Although the north-eastern extent of the Pisa Fault Zone has been reduced in the reinterpretation presented here, it is approximately balanced by the extension southwest along the Carrick and Bannockburn faults. No changes are suggested for the characterisation of the Pisa Fault Zone in the 2010 NSHM, which uses a length of 47 km, dip of 60° to the northwest, and slip rate of 0.1 mm/year. The calculated recurrence interval is ~31,000 years, generalised here as ~30,000 years.

A2.39 Pylep fault (feature 44; Figure 5.3)

The previously-unnamed Pylep fault comprises two northeast striking, partly overlapping, fault strands, well expressed on the peneplain surface, by upthrow of about 50 m to the southeast. In high-resolution aerial imagery, there are in places structural lineaments in rock outcrop and subcrop, presumably marking the fault crushed zone. The two strands are ~12 km (northern) and ~16 km (southern) long, and they overlap by about 3 km, separated by less than 2 km in the strike-normal direction. Both were included in the QMAP dataset, and also on the 1st generation 1:250,000-scale geological map (Mutch 1963). The name is taken from Pylep Creek on the upthrown side of the southern fault strand. Linework positions have been refined in the present dataset, because high-resolution colour aerial imagery allows for much more accurate mapping than was possible by QMAP methods. The features defined here are not included in the NZAFD, NZAFM or 2010 NSHM datasets.

There are no discernible offsets of geologically young landform features, and the Pylep fault is classified here as ‘potentially active’. The two overlapping strands are regarded as the surface expression of a single fault at depth. For the estimation of activity parameters, the Pylep fault is assigned a dip of 60°, length of 23 km and a nominal slip rate of 0.05 mm/year. Using the 2010 NSHM methodology, a recurrence interval of ~30,000 years is calculated.

A2.40 Ranfurly Fault Zone (feature 35; Figure 5.3)

The Ranfurly Fault Zone comprises a remarkable array of en-echelon faults that is as much as 2 km across, aligned east-northeast – west-southwest across the Maniototo Plain. Most are up on the southeast side, but there are several with an opposing throw. Overall, the array has the appearance of a dilatational fault system. On the lower river terraces near Ranfurly, there are at least 5 scarps across the zone, each typically with no more than ~1 m offset. The scarps offset all but the lowest, freshest river plains, and it is also notable that the scarps are not much higher (no more than two or so metres) on high terraces or downland terrain, judged likely to be more than 100,000 years old. Overall identified map length of the 'definite' or 'likely' components of the fault zone is 9 km, extending southwest of the southern end of the Launceston Fault. Farther southwest for ~6 km are ill-defined topographic steps on high-level terraces that as classified as 'possible', 'moderately expressed', with 'not expressed' connector lines.

It is unclear from the reconnaissance-level desktop study that forms the basis of this report whether some fault strands affect a particular river terrace, but others do not. If this were shown to be the case, it might indicate different components of the array moved during different surface rupture events. A detailed mapping study of fault scarps and other landforms in the vicinity of the Ranfurly Fault Zone would be needed to address this question.

For the purpose of placing the fault zone in a hazard perspective, an indicative average slip rate of 0.1 mm/yr is inferred, by summing the heights of ~5 scarps across the zone (~10 m) relative to an assumed age of ~100,000 years for the higher terraces and downlands.

The Launceston Fault and Ranfurly Fault Zone each have a relatively short length, and their scarps have a similar freshness. They are inferred to represent a single active fault structure, collectively assessed as being 24 km long. This is markedly more than the 15 km length assigned in the 2010 NSHM (Stirling et al., 2012). Using the extended length, a revised recurrence interval of ~17,000 years is re-calculated using 2010 NSHM methodology. This substantially longer than the value of ~2,200 years in the 2010 NSHM. The longer value is more compatible with the overall landform expression of the Ranfurly Fault Zone.

A2.41 Riddles fault (feature 47; Figure 5.3)

The Riddles fault extends from the uppermost reaches of the Taieri River, north-northeast for ~21 km, and has produced ~100 m of vertical separation of the peneplain, up to the west. The fault forms part of the western margin of the Serpentine Flat basin. It is included in the QMAP dataset and is assumed here to be a west-dipping reverse fault. It is not named in the QMAP dataset, and the name assigned here is from Riddles Creek, which crosses the northern part of the fault escarpment. There are no discernible offsets of geologically young landform features.

The southern ~10 km of the Riddles fault is parallel to, and about 4 km east of, the Beaumont River fault. As the Beaumont River fault and Riddles fault are assumed to have opposing dips, they are interpreted as intersecting at moderate depth. The Beaumont River fault is longer and is therefore assumed to the larger structure. The interpretation is made here that the Riddles fault is an earlier-formed structure and has subsequently been cut off at depth by the Beaumont River fault. In addition, the escarpment of the Logan Burn fault crosses and appears to offset the Riddles fault escarpment, before rapidly petering out about 2 km east of the mapped position of the Beaumont River fault. This lends weight to the idea that the Beaumont River fault and Logan Burn fault have developed interactively, and both are younger than the Riddles fault.

For the current assessment, the Riddles fault is not regarded as an active, independently rupturing fault. It is conceivable however that it could experience secondary slip associated with rupture of the Logan Burn fault or the Beaumont River fault, and therefore in this dataset the Riddles fault is classed as ‘potentially active’, ‘not expressed’. No slip rate or specific recurrence interval are assigned to the Riddles fault in this report, other than identifying it as having a recurrence interval class of VI (greater than 20,000 years), compatible with both the Logan Burn and Beaumont River faults.

A2.42 Roaring Lion fault (feature 10; Figures 5.1–5.2)

This northeast-striking fault is mapped along the north-western foot of the Garvie Mountains at the south-eastern margin of Nevis valley. The mapped position of the fault is taken directly from QMAP, and it is not included in the NZAFM or the 2010 NSHM. It has not previously been named, and the applied here is from Roaring Lion Creek which drains from the Garvie Mountains across the fault escarpment. The fault is identified from schist basement rock faulted up to the southeast relative to Cenozoic strata, with an indicated vertical separation of the peneplain across the fault of as much as 600 m. It is inferred that it is a southeast-dipping reverse fault. There has been substantial Late Cenozoic displacement, but there is no evidence for or against Late Quaternary displacement.

This fault is identified as ‘potentially active’. A length of 46 km is assigned along with an assumed dip of 60° and nominal slip rate of 0.05 mm/year. Using 2010 NSHM methodology, a recurrence interval of ~65,000 years is calculated.

A2.43 Roaring Meg fault (feature 9; Figures 5.1–5.2)

The identification of this north-striking fault is based on the presence of peneplain remnants overlain by patches of Cenozoic strata in the headwaters of Roaring Meg and Gentle Annie Creek, sitting ~500 m below the elevation of schist rock forming the Mt Allan – Queensbury Hill ridge to the west. Unpublished mapping undertaken for Kawarau River proposed hydroelectric development in the 1980s shows numerous approximately north-striking fault zones crossing the Kawarau River east of the Gibbston basin. Beanland and Barrow-Hurlbert (1988) associated the peneplain displacement with the Gentle Annie Fault zone, which comprises a several-hundred-metre wide zone of steeply southeast-dipping shears in schist in the Kawarau River valley floor. This implies a normal sense of displacement to account for the Late Cenozoic geological relationships in the Roaring Meg/Gentle Annie catchments, and is difficult to reconcile with the indicated reverse nature of other peneplain-offsetting faults in the wider region. However, there are also bedrock faults dipping to the northwest, which could represent reverse faults more likely associated with the peneplain offset. The interpretation adopted in this dataset is that the fault(s) associated with the peneplain offset, referred to here as the Roaring Meg fault to avoid confusion with the southeast-dipping Gentle Annie Fault, extends south down Gentle Annie Creek, along the Kawarau River channel at the foot of Mt Difficulty, and then south up Slapjack Creek, and through Slapjack Saddle in the Carrick Range. South of Slapjack Saddle, the peneplain stands about 200 m higher than on adjacent parts of the Carrick Range. The fault is assumed to peter out south of there, as the peneplain dislocation diminishes in that direction. Doubtless other interpretations could be made, but this is considered to be the one that currently provides a satisfactory explanation of the indicated peneplain offset both north and south of the Kawarau River valley. By this interpretation, the Gentle Annie Fault zone described by Beanland and Barrow-Hurlbert (1988) has been truncated at depth by the Roaring Meg fault.

The Roaring Meg fault is regarded as part of the Nevis-Cardrona Fault System, following the reasoning of Beanland and Barrow-Hurlbert (1988) for including the Gentle Annie Fault in that system. It is approximately parallel to, and 5 to 6 km southeast of, the southern segment of the NW Cardrona Fault. As there is no indication of any offset of geologically young landforms, it is classified as 'potentially active', 'not expressed', on the presumption that the NW Cardona Fault has been accommodating strain in this general area in the recent geological past.

The Roaring Meg fault is characterised here as having an assumed dip of 60, a nominal slip rate of 0.05 mm/year and length of 28 km. Using NSHM methodology, a recurrence interval of ~40,000 years is calculated.

A2.44 Rocks Creek Fault Zone (feature 24a; Figure 5.3)

This encompasses an array of generally northeasterly-striking faults, downthrown to the southeast, along the western margin of the upper Manuherikia basin, as shown in QMAP and classified there as 'inactive'. This fault zone is not in the NZAFM or 2010 NSHM, although the Vulcan Fault and Tunnel Hill Fault components (see below) are included in the NZAFD.

The QMAP delineation is based largely on the interpretation of lignite exploration drillhole data by Bishop (1981), who applied the names 'St Bathans' to northeast-striking fault strands, and 'Manuherikia' to more easterly-striking fault strands. Each set of fault strands has displaced the peneplain by 100 m or so. Nowhere has a fault exposure been reported but they are assumed here to be northwest-dipping reverse faults. Between 1 and 2 km southeast of those faults are fault-deformed landform surfaces that were investigated by Beanland and Fellows (1985). They defined the 'Vulcan Fault' that deforms fans and river terraces on the west side of the Manuherikia River, and about 2 km to the southwest, the 'Tunnel Hill Fault' that affects middle-level fan terraces of Rocks Creek. A fault displacement origin for the Vulcan feature was confirmed by trenching of a scarp across the floor of a small un-named stream, about 1 km west-southwest of the Hawkdun Runs Road bridge over the Manuherikia River. The trench exposure showed gravels deformed by a reverse fault, dipping northwest at 40°. Using airphotos, I have expanded upon the mapping of Beanland and Fellows (1985) by differentiating front and back faults, or monoclines where the deformation zones are broad. Collective vertical deformation is as much as 20 m on river or fan landforms of assumed age ~130 000 years, as interpreted on QMAP. No deformation is evident on low-lying, probably Holocene age, terraces, apart from the Vulcan Fault excavation site. However, in absence of dating, the age estimates are tentative and of high uncertainty. Surface deformation of the Vulcan Fault and Tunnel Hill Fault can be traced for only about 3.5 km along strike.

Collectively, all these fault features are referred to here as the Rocks Creek Fault Zone, adopting a name used by Madin (1988). The Rocks Creek Fault Zone is classified as 'likely', apart from 'definite' sectors of the Vulcan and Tunnel Hill fault strands. The fault zone has a maximum strike length of only 16.5 km, between the Hawkdun Fault in the northeast and Omarama Saddle fault in the southwest. Due to its shortness, the Rocks Creek Fault Zone is not interpreted here as an independently rupturing active fault, but instead inferred to be a diffuse 'back-fault' break-out from the Omarama Saddle fault. The slip rate (0.2 mm/year) and recurrence interval (12,000 years) for the Omarama Saddle fault are adopted as maxima for the Rocks Creek Fault Zone. A cross-check exists via the estimated ~20 m vertical deformation on a landform of assumed age 130,000 years mentioned above, which implies a slip rate of ~0.15 mm/year. While the age estimate is of highly uncertain validity and should not be relied upon, the derived slip rate is compatible with the line of reasoning of an association between the Rocks Creek Fault Zone and the Omarama Saddle fault.

A2.45 Teviot Fault (feature 40; Figure 5.3)

The north-northwest striking Teviot Fault is approximately parallel to, and stepped as much as 4 km southeast from, the Old Man Fault. There is as much as ~300 m vertical separation of the peneplain across the Teviot Fault, up to the west, and no known evidence for geologically young landform displacement. The Teviot Fault is classified in this dataset as 'potentially active'. It is presumed to have a southern limit where it meets the projected positions of the Blue Mountain Fault and the Tuapeka Fault.

The Old Man Fault lies at the foot of the Old Man Range, which diminishes progressively in height south of Roxburgh, and peters out southwest of Ettrick. The Teviot Fault has uplifted an un-named range of low hills north of Raes Junction, and that range diminishes in height and peters out approaching Ettrick. Two possibilities are that the Teviot Fault is either a separate segment of the Old Man Fault, or is an individual fault, albeit similar to the Old Man Fault. The latter interpretation is provisionally adopted for this dataset. On account of the similarity between the two faults, the Teviot Fault is assigned the same slip rate as the Old Man Fault (0.01 mm/year) and a length of 32 km is adopted. Using 2010 NSHM methodology, a recurrence interval of ~225,000 years is calculated for the Teviot Fault.

A2.46 Timaru Creek Fault (feature 16; Figure 5.1)

This northeast-striking feature is known from a 'definite', 'well expressed' northeast-trending fault scarp that offsets a valley-floor alluvial plain, up to the southeast by several metres, in the Lindis River headwaters. The offset fluvial landform surface is judged to be no older than the end of the Last Glaciation (18,000 years) and may possibly be a little younger than that. The fault is shown on the geological map of Turnbull (2000), and its name comes from the QMAP digital dataset. It is included in the NZAFD, with linework adopted from QMAP, but not included in the NZAFM or the 2010 NSHM.

Northeast of the 'definite' scarp, the fault is classified as 'likely', 'not expressed', up to a saddle at the Central Otago/Waitaki district boundary, where it adjoins a similarly classified fault strand in the Waitaki District (Barrell 2016). For ~0.7 km southwest from the 'definite' fault scarp across the Lindis valley floor, a topographic anomaly extends along the slopes of a tributary valley, and is classified as a 'definite', 'moderately expressed' fault. In the QMAP dataset, the fault is extrapolated a further 8 km across mountainous terrain. There is no indication of any surface displacement features along that sector of the fault, and it is classified here as 'likely, 'not expressed'.

About 2 to 3 km southeast of the Timaru Creek Fault, another northeast-striking fault is mapped, named the Johns Creek Fault in the QMAP dataset. On that structure is a 'definite', 'well expressed' east-northeast-trending fault scarp that offsets hillslopes, and an alluvial fan, on the northern side of the Lindis River valley, up to the southeast. The alluvial fan offset is several metres, of similar size to that seen on the Timaru Creek Fault, and these two scarps are effectively en-echelon.

The total mapped length of the Timaru Creek Fault shown in QMAP, and collated into the NZAFD, is ~13 km. Only the central, ~6 km long, sector of the strand named Johns Creek Fault in QMAP, and included in the NZAFD, was identified as active in those datasets (feature 16a). Eastern and western parts of the Johns Creek Fault structure were classed as inactive. Individually, these lengths are too short to be independent, surface rupturing faults, and the interpretation is made here that the Timaru Creek Fault and Johns Creek Fault are connected at depth, and two parts of a single active fault referred to here as the Timaru Creek Fault, and that name is applied to all surface components of it, with the Johns Creek component identified in this dataset as the 'Johns Creek strand' of the Timaru Creek Fault. The composite mapped length of the Timaru Creek Fault and Johns Creek strand is ~28 km.

To the west of the 'definite' scarp, the Johns Creek strand is classified as 'likely', 'moderately expressed', across two prominent notched spurs, with two further sectors similarly classified farther west, one a topographic step across landslide terrain north of Little Breast Hill, and one along a hillslope in the northeastern headwaters of Breast Creek, to the west of Little Breast Hill. A classification of 'likely', 'not expressed' is applied to other parts of the fault strand, except that the westernmost sector is classed as 'possible', 'not expressed', on the presumption that surface rupture may peter out approaching the Grandview Fault.

The positions of the surface fault scarps ('well expressed' or 'moderately expressed') have been adjusted from their QMAP locations to confirm closely with the position of surface offsets which are clearly visible in aerial imagery.

For calculating slip rate, the 'definite' scarps are assumed to be about 5 m high and has offset fluvial landforms with an assumed age of 18,000 years. Whether this was a single event or multiple events is unknown. The composite Timaru Creek Fault is characterised here as a reverse fault dipping 60° to the southeast and extending for 28 km northeast from about the location of the Grandview Fault. Using 2010 NSHM methodology and taking account of the adopted fault dip and assuming pure dip slip motion, a net slip rate of 0.32 mm/year is obtained and a recurrence interval of ~6100 years is calculated.

A2.47 Tuapeka Fault (feature 41; Figure 5.3)

The northwest striking Tuapeka Fault is a prominent geological feature of the Lawrence to Waitahuna areas, in the Clutha District, but only the northernmost 1.5 km of the fault extends into the Central Otago District. The Tuapeka Fault is a southwest-dipping normal fault of Cretaceous age (Els et al. 2003), but on the projected line of the fault near Beaumont (Clutha District) there is a several-metre-high, suspected fault scarp crossing medium to high level terraces of the Clutha River. The scarp is upthrown to the southwest, indicating reversal of its original Cretaceous sense of movement.

A 4-km-long sector of the fault is shown as 'active' on QMAP (Turnbull and Allibone 2003) and that sector is included in the NZAFD. It is not included in either the NZAFM or 2010 NSHM.

The north-western-most end of the fault that passes into the Central Otago District is classed here as 'likely', 'not expressed'. It is expected that this fault will be discussed more fully in a future report on the active faults of the Clutha District. It is assigned a recurrence interval in the range of ~250,000 to ~680,000 years by Villamor et al. (2018). To avoid pre-empting future assessment of active faults of the Clutha District, no slip rate or specific recurrence interval are assigned in this report, other than identifying the Tuapeka Fault as having a recurrence interval class of VI (greater than 20,000 years).

A2.48 Waihemo Fault Zone (feature 37; Figure 5.3)

This major northwest-striking fault lies along the southwestern foot of the Kakanui Mountains. It mostly lies in the Waitaki District and is discussed in detail by Barrell (2016). The most recent information on geologically-young activity is by Curran and Norris (2009) and Curran et al. (2011), from work in the Waitaki District sector of the fault zone. Within the Central Otago District, a prominent topographic step, up to the northeast by as much as ~10–15 m, runs across a mid-level alluvial fan surface of Old Hut Creek, about 13 km east-southeast of Naseby, and is interpreted as a 'likely', 'moderately expressed' fault scarp. The caveat on interpretation is that in the general area, there are low-lying knobs of hillocks of bedrock at the foot of the range, and the topographic anomaly could possibly be due to such a hillock having been partly overridden by the alluvial fan. However, for 3 km to the northwest, and 7 km to the southeast, there are short, discontinuous sectors of similar topographic anomalies, and intervening zones where the topography is such that geologically-young fault deformation could be obscured. On balance, the features are interpreted as the 'likely' result of past rupture of the Waihemo Fault Zone.

Towards the Kye Burn valley, the bedrock fault zones of the Stranraer, Dansey Pass and Waihemo fault structures all converge. As noted earlier in relation to the Dansey Pass Fault, the Stranraer fault (feature 37a) has offset geologically young middle to high terraces of the Little Kye Burn valley (see Figure 5.9 in the body of the report). Due to a general similarity of height and likely age of that 'definite' scarp of the Stranraer Fault and the 'likely' fault scarps on the Waihemo Fault Zone to the southeast, an interpretation is made that they are part of the same active fault structure.

For the purposes of quantifying fault activity, the aggregate length of the Stranraer Fault and Waihemo Fault Zone, extending southeast to the coast, is 80 km. Assuming that the middle terrace of the Little Kye Burn valley is nominally 100,000 years old, and has a vertical component of fault offset of 10 m, on a fault plane dipping 60° and assuming pure dip-slip motion, implies a net slip rate of 0.12 mm/yr. Using 2010 NSHM methodology, a recurrence interval of ~50,000 years is calculated.

A2.49 Waipiata Fault Zone (feature 38; Figure 5.3)

The northeast-striking Waipiata Fault Zone includes a number of complicated elements. For the purposes of description, its components are grouped into three stands.

A2.49.1 Waipiata strand

The western strand extends along the eastern margin of the Maniototo basin, from Patearoa northeast through Waipiata, and along the western foot of the Camp Hill anticlinal ridge and is identified as the 'Waipiata Fault Zone – Waipiata strand'. In the northeast, Cenozoic strata dip west at a moderate angle into the basin, and whether it is a fault or a monocline limb is unclear. It is identified as a fault in QMAP, and classified as 'possible', 'not expressed' in this dataset. At its north-eastern end, near SH 85, it projects across a high terrace, and there is no hint of a topographic step. For that reason, the north-eastern limit of this strand of the Waipiata Fault Zone is positioned ~2 km southwest of SH85.

For ~5 km between the Taieri River and Pig Burn, there is a topographic step of as much as 10 or 20 m, up to the SE, at the mapped location of the Waipiata strand. However, aerial photos show the terrain on the higher ground comprises moderately northwest-dipping Cenozoic strata, and the step may simply be a dip slope on the strata, with the dip-slope buried to the northwest by fluvial sediments. In that area, high-resolution aerial imagery has been used to slightly reposition the QMAP line to accord more closely with the topographic step, and it is identified as ‘possible’, ‘moderately expressed’.

About 7 km southwest of Waipiata, there is a distinct topographic step trends across river terraces extending for 2 km southwest of Pig Burn. It is as much as several metres high and is classed as ’well expressed’. However, it is conceivable it is a river-cut step, trimmed by drainage down-plain from adjacent tributary fans to the southwest. The reason for suspecting a river-cut origin of this step is that, were it the product of fault rupture, it is surprising it is not clearly evident across higher terrain northeast or southwest, where it should be reasonably prominently expressed. However, on balance, the tectonic origin seems likely and the step is classified accordingly.

Southwest of Patearoa, there is a topographic step at the likely position of the fault, but it is not clear whether it may just mark the boundary where fluvial sediment has accumulated against the margin of the schist rock forming the foot of the range. The step is classified as ‘possible’, ‘moderately expressed’, for 2 km southwest of Patearoa. Beyond there, along the mapped line of the fault in the QMAP dataset, the landscape comprises old alluvial fans and schist bedrock terrain, well suited for identifying geologically recent fault scarps, but there is no sign of any. A mapped extrapolation of the ‘possible’ fault, classified as ‘not expressed’, is extrapolated a further 2.5 km southwest and terminated there.

A2.49.2 Clunie strand

The central strand extends along the eastern side of the Camp Hill anticlinal ridge and is identified as the ‘Waipiata Fault Zone – Clunie strand’, after nearby Clunie Road. Mid- to high level river terraces along the western side of the Kye Burn valley are not matched on the other side of the valley, and one possibility is that the terraces on the western side of the valley have been elevated by tectonic movement. Two en-echelon monoclines, up to the west, are inferred to account for the elevated terraces, each positioned at the foot of the riser up to the terraces. Features in support of this interpretation are that along the more southern monocline, the terrace riser is surprisingly gentle for a river-cut feature. A feature of the northern monocline is the presence of what appear to be discontinuous fault scarps, up to the southeast, along the crest of the rise. All features associated with this structure are identified as ‘likely’. This strand is presumed to be associated with an underlying reverse fault dipping northwest, and if so is presumably a back-fault from the Waipiata strand.

A2.49.3 Hamilton strand

Shown in QMAP is an array of northeast-striking faults partway up the lower flank of the Rock and Pillar Range, upthrown to the southeast. There is indicated vertical separation of as much as several hundred metres on the peneplain. Being only a few kilometres southeast of the Waipiata strand, this fault array is interpreted to be a strand of the Waipiata Fault Zone, and named after Hamilton Diggings, that lie close to the fault. There is no indication of offset of geologically-young landforms. It is presumed to be a less active, perhaps older, part of the Waipiata Fault Zone, and is classified as ‘potentially active’, ‘not expressed’.

A2.49.4 Re-assessment of Waipiata Fault Zone Activity

Overall, there are few good geomorphic indicators to aid the assessment of activity of the Waipiata Fault Zone. Collectively, the suspected monoclines of the Clunie strand are assessed as being about 10 m high, and a nominal age of 100,000 years is assigned to the landform on the inferred uplifted side. This is taken, within error, as an indicative slip rate of 0.1 mm/yr. In conjunction with inferred fault dip of 60° and overall length of 35 km, a recurrence interval of ~24,000 years is calculated using 2010 NSHM methodology.

A2.50 Wanaka Fault (feature 13; Figure 5.1)

This north-northeast striking structure includes the Castle Hill Fault from QMAP Haast, and the Wanaka Fault of QMAP Wakatipu (different names were applied to the same fault structure). It also equates to the Makarora Fault Zone of the NZAFM, which was one of the Southern Alps 'potentially active' faults proposed by Cox et al. (2012), and to which no slip rate was assigned in the NZAFM. The Wanaka Fault is not in the 2010 NSHM.

For most of its length, the Wanaka Fault is concealed under Lake Wanaka or the floodplain of the Makarora River. It is inferred to be the structure that separates differing types and/or metamorphic grades of schist rock either side of the Wanaka/Makarora valley. Thus, it is likely that the fault originated during the Mesozoic Era. The Wanaka Fault is depicted in the QMAP dataset as curving east-southeast beneath Roys Bay and Wanaka township to meet the line of the NW Cardrona Fault. However, in this dataset the Wanaka Fault is stopped at the line of the Motatapu Fault due to indications that post-glacial rupture of the Motatapu Fault may have extended across the line of the Wanaka Fault. There are no known offsets of geologically young landforms on the Wanaka Fault, and it is classified as 'potentially active'. Using 2010 NSHM methodology, the Wanaka Fault is assigned a length of 60 km, a dip of 60° east-southeast and a nominal slip rate of 0.05 mm/year. A recurrence interval of ~85,000 years is calculated from those values.

A2.51 West Wakatipu Fault (feature 2; Figure 5.1)

This north-northwest striking fault is depicted on QMAP as separating semischist basement rock, upthrown to the east, from schistose greywacke rock to the west. The fault is mapped along the western side of the upper Wakatipu valley for ~27 km from the Greenstone/Caples river mouth north to just beyond the Route Burn valley. To the south the fault presumably extends under the lake. While it is not known whether there may be other faults hidden under Lake Wakatipu, the tentative interpretation made in this report is to equate the previously identified West Wakatipu Fault with the similarly striking Home Creek Fault near Mt Nicholas, which has a similar sense of upthrown, at least in the Late Cenozoic. Although there is no reported post-glacial offset on the Home Creek Fault, there is higher ice-sculpted bedrock terrain near the lakeshore, up to the east, along the approximate line of the fault. A connection is inferred between the West Wakatipu Fault under Lake Wakatipu and the Home Creek Fault, positioned along the western margin of that slightly higher terrain, named 'Fern Hills' on the topographic map. The inference made here is that the two prominent fault scarps east of Mt Nicholas, previously attributed to the Moonlight Fault, are associated with post-glacial rupture(s) of the Home Creek Fault a.k.a. the West Wakatipu Fault. The latter name is preferred here because the name Home Creek Fault has been previously regarded as part of the Moonlight Fault Zone (Turnbull et al. 1975).

The two fault scarps near Mt Nicholas are classified here as 'definite' active faults, while the Home Creek Fault, the West Wakatipu Fault, and an inferred connection between the two under Lake Wakatipu, are classified as 'likely'. The heights of the post-glacial fault scarps near Mt Nicholas have not been reported, but using colour aerial imagery, each is estimated here to be ~1.5 m high. Using 2010 NSHM methodology, the aggregate ~3 m vertical offset of landforms assumed to be as old as ~18,000 years, on a fault plane of inferred dip 60° east with pure dip slip motion, returns a net slip rate of 0.19 mm/year. In conjunction with an adopted overall length of 55 km for the West Wakatipu Fault, from the Moonlight Fault Zone north to the Route Burn area, a recurrence interval of ~20,000 years is calculated. If further work were to be undertaken to determine whether there has been any post-glacial offset on the Home Creek strand of the fault, and some is found, that would increase the slip rate and decrease the recurrence interval.

A2.52 Appendix 2 References

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