General distribution and characteristics of active faults and folds in the Clutha and Dunedin City districts, Otago

DJA Barrell

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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 Clutha and Dunedin City 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 interpretations and geographic positionings of the fault and folds were 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 (within the past few tens of thousands of years), 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 that 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 26 named active, possibly active or potentially active faults have been delineated at the ground surface in the Clutha and Dunedin City 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 that may result in, for example, 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 Clutha or Dunedin City 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 Clutha and Dunedin City 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 Clutha and Dunedin City 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 Clutha and Dunedin City 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.

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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 Clutha and Dunedin City 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 southeastern South Island, including the Clutha and Dunedin City 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, which 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).

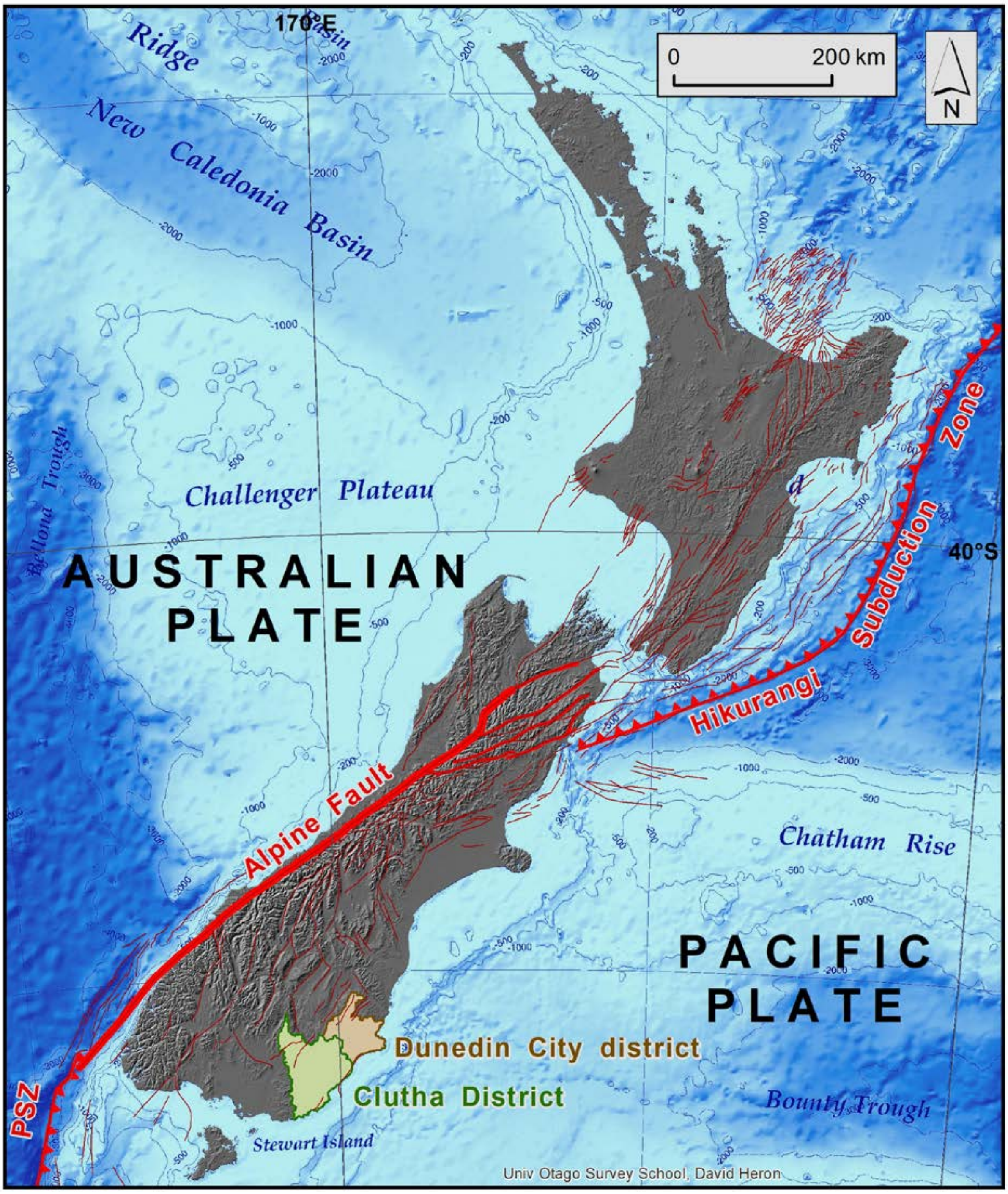

Figure 1.1 The tectonic setting of the Clutha and Dunedin City districts. The junction between the Australian and Pacific plates of the Earth's crust passes through New Zealand. The Pacific Plate pushes westward against, and under, the Australian Plate at the Hikurangi Subduction Zone while, at the Puysegur 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 southeastern 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).

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 Clutha and Dunedin City districts. This report presents that summary and is a companion to a similar report that addresses the Waitaki District (Barrell 2016) and the Queenstown Lakes and Central Otago districts (Barrell 2019).

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 and also several metres of sideways shift to the left, as indicated by the red half-arrow. Photo: GNS Science, VML ID: 210453; DB 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. The white lines indicate the amount of uplift, and the red arrow shows the breadth and curvature of the monocline. Photo: GNS Science; DJA 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; NJ Litchfield. The red half-arrow shows the amount of relative displacement, which here involved a shift to the right.

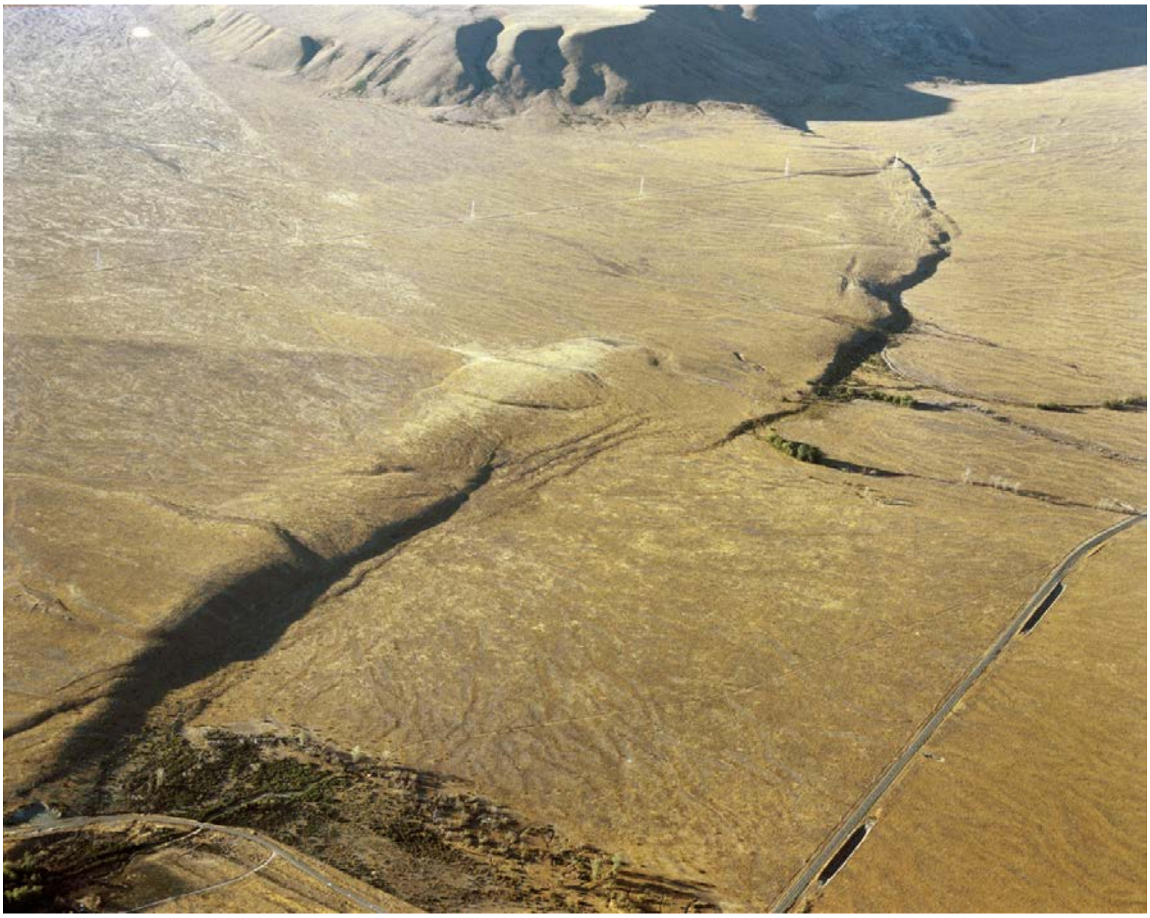

Figure 1.3 A northward oblique aerial view of ground-surface deformation across the Ostler Fault Zone, in the Waitaki District in the Canterbury region, about 12 km southwest of Twizel. The fault zone runs from lower left to upper right and has offset and buckled a ~22,000-year-old glacial meltwater outwash plain with well-preserved relict braided channels. 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 of 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. DL 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 Clutha and Dunedin City 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 Clutha and Dunedin City 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 Clutha and Dunedin City 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 enable the identification of 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 2018), 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 past active fault surface deformation at a nominal scale of 1:250,000 and indicates the general degree of fault activity. In the southeastern 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. At the time of writing, a comprehensive revision of the NSHM is underway (Van Dissen et al. 2021). A fifth type of active fault dataset comprises information of district or regional extent held by territorial or regional governmental authorities; for example, as described by Barrell et al. (2015). The active fault dataset described in this 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. The purpose of the dataset described here is to assist local authorities in land-use and development planning and provide an indication of areas where site-specific hazard assessments may be desirable.

The project described here used the QMAP dataset as a primary information source because it encompasses active faults and folds, whereas the NZAFD dataset is confined to active faults. The QMAP digital dataset (Heron 2018) is derived from a sheet-by-sheet series of published geological maps, represented in the Clutha and Dunedin City districts by the Dunedin map (Bishop and Turnbull 1996; southeastern parts of both districts), Murihiku map (Turnbull and Allibone 2003; southwestern Clutha District) and the Waitaki map (Forsyth 2001; northern and western parts of the Dunedin City district). 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 was 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 southeastern South Island, including the Clutha and Dunedin City 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 inland 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. In the Catlins area, there is a general accordance of summit elevations that appear to be the remnants of an ancient erosion surface, but it is not known whether it is the same as the Otago peneplain. In this report, it is referred to as the Catlins erosion surface.

Across the region, in many cases it is not clear when fault movement began, but there is evidence that uplift and erosion was underway by the Middle Miocene epoch, sometime between 11 and 19 million years ago, as illustrated in the area west of Dunedin where Dunedin Volcanic Group strata overlie an erosion surface cut across older cover rocks and, locally, the schist basement rock (Bishop and Turnbull 1996). As another example, uplift and exhumation of the peneplain had occurred on the northeast side of the Waihemo Fault System (Waitaki District) 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, as 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 inland 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 one 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 formed in the Southern Alps but did not reach into the Dunedin or Clutha districts. However, the near-coastal reaches of rivers and streams were affected by variations in global sea level that accompanied the expansion and recession of Northern Hemisphere ice sheets.

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 and 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 that has up-down movement and a strike-slip fault that 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 are commonly 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).

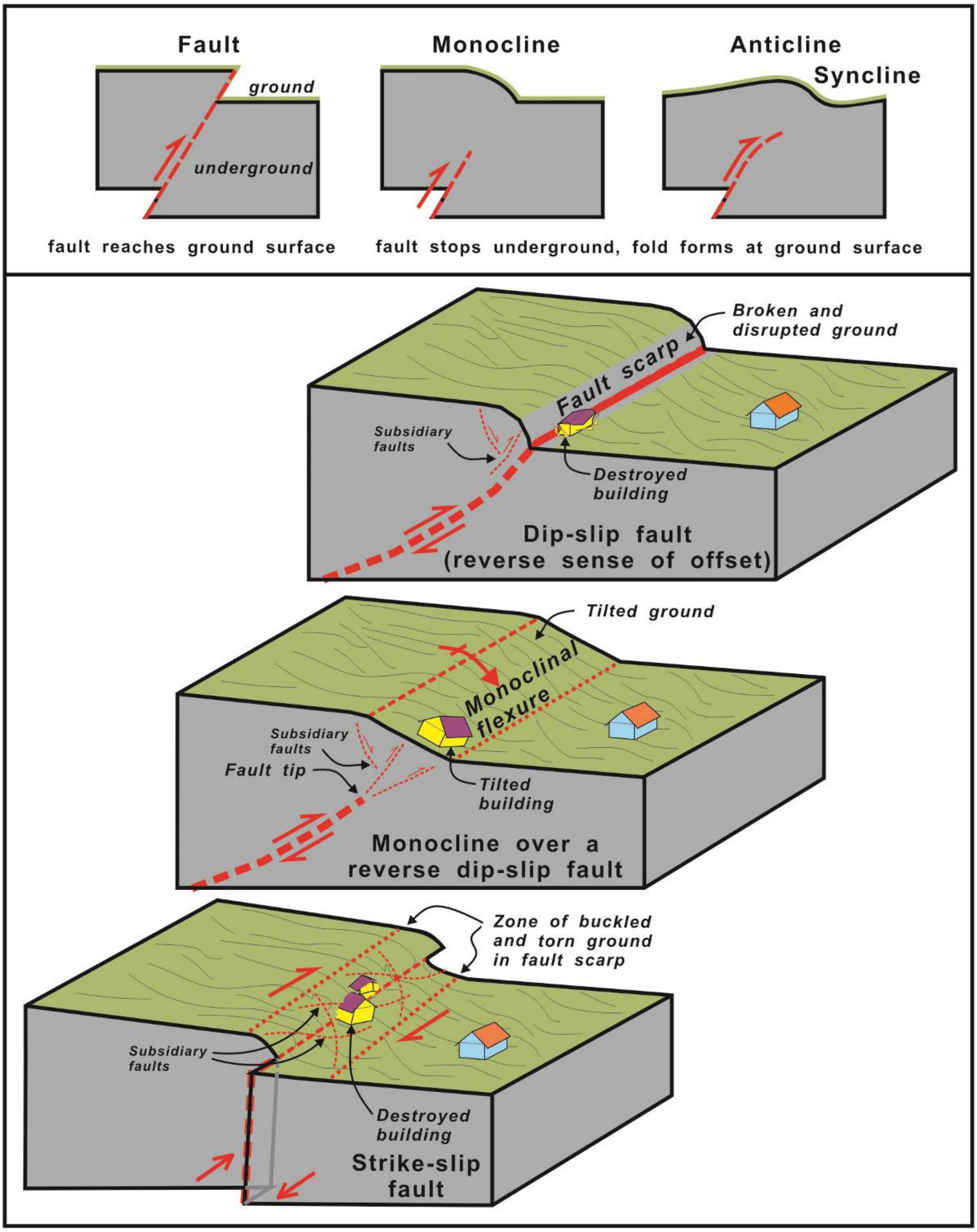

Figure 3.1 Diagrams illustrating styles of active faults and folds. The diagrams show general concepts rather than actual details and are not drawn to an exact scale. Upper panel: Cross-section (vertical slice) diagrams illustrating an active fault, active monocline and active anticline and syncline. 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.

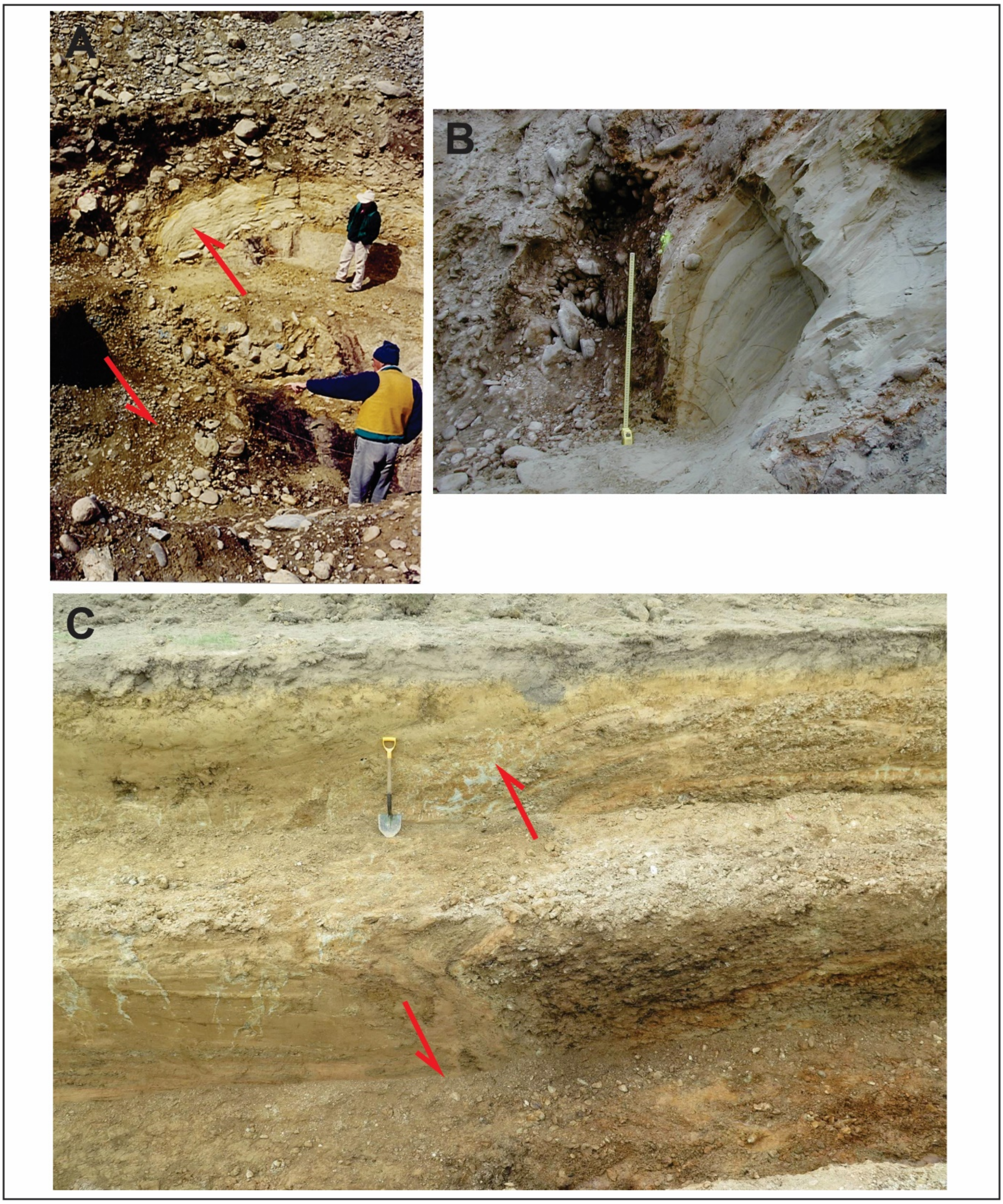

Figure 3.2 Illustrations of faults exposed in investigation trenches. Red half-arrows indicate the relative sense of fault displacement. A and B: The Waitangi Fault exposed in 1999 in a trench 700 m downstream of Aviemore Dam, Waitaki District of Canterbury (Barrell et al. 2009). A: the fault runs upper 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, DJA 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, which 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 riverbeds 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 that 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.

The local-magnitude 5.0 Dunedin Earthquake on 9th April 1974[1] was the largest earthquake reported for the Dunedin City or Clutha districts since European settlement. The epicentre was assessed as being offshore, about 10 km south of central Dunedin, with a suspected focal depth of 20 km (Adams and Kean 1974). Damage to masonry, particularly chimneys, resulted in 3000 claims to the Earthquake Commission, totalling $250,000 (Bishop 1974). The Dunedin Earthquake highlights that, despite the low historical seismicity, Otago is undoubtedly subject to earthquake activity.

1 The Richter, or local, magnitude (ML) 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. A more commonly used measure of earthquake size is the moment magnitude (MW), which is a measure of the total seismic energy released in an earthquake and is usually calculated from low-frequency waveforms recorded on seismographs.

4.0 CLASSIFICATION OF ACTIVE FAULTS AND FOLDS

4.1 Descriptive Classification

The original information on the active faults and folds of the Clutha and Dunedin City districts was extracted from the QMAP digital dataset (Heron 2018). 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 the surface expression of the mapped feature is; 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 recognised 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 or potentially 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. Otanomomo fault). For previously published names, a capital ‘F’ is used. The basis of all new names is explained in Appendix 2. 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’ 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 Clutha and Dunedin City 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. Clutha and Dunedin City 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. The estimated age of a landform or geological deposit, together with the amounts that the landform or deposit has or has not been offset, are used to calculate 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, which 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, and one recently completed for the Central Otago and Queenstown Lakes districts (Barrell 2019), 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 recurrence-interval 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 with 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 differs from the fault classification approach used for the Waitaki District (Barrell 2016), which 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, as 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; thus, they 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 August 2020, 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.

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 Clutha and Dunedin City 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).

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 fault ruptures had estimated magnitudes of 6.4 and 6.3, respectively, and did not cause surface rupture but produced 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.

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 Clutha and Dunedin City districts is presented in Figures 5.1 and 5.2, which collectively provide 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 5.1–5.2 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 26 active faults (comprising a total of 34 named fault features in Figures 5.1–5.2) identified in the Clutha and Dunedin City districts, nine are classified as comprising ‘definite’ or ‘likely’ components and can be regarded, respectively, as known or suspected active faults. Of the remaining faults, three are classed as ‘possible’ active faults and another 14 are classified as ‘potentially active’. The classification of ‘possible’ indicates that there is reason to think of those faults as having a greater likelihood of future activity than faults classified as ‘potentially active’.

Only two faults are assessed as having an average recurrence interval of less than 10,000 years: the Akatore Fault and the Settlement Fault, with estimated recurrence intervals of ~1700 years and 1800 years, respectively. These estimates reflect that both faults have displayed evidence for episodes of greater and lesser activity. Definitely the Akatore Fault, and possibly the Settlement Fault, have had greater activity in the geologically recent past compared to their longer-term average, with at least two surface surface-rupturing earthquakes indicated as having occurred on each fault within the past few thousand years. It is considered prudent to assume that they remain in a heightened state of activity.

A further six faults are assessed as having an average recurrence interval of between 10,000 and 20,000 years, including the Blue Mountain, Hyde and Titri faults. For many of the active or potentially active faults identified 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.

In the active fault assessment for the Waitaki District (Barrell 2016), the focus was on faults designated as active in the NSHM and NZAFM. Subsequently, in the southern Waitaki District, Villamor et al. (2018) delineated several more faults assessed as potentially active. All extend into the Dunedin City district, and, in the dataset described in this report, the full extent of those faults across both districts is included. The additional faults are the Murphys Creek, the Dunback Hill and the Flat Stream – Glenpark faults (Figure 5.2).

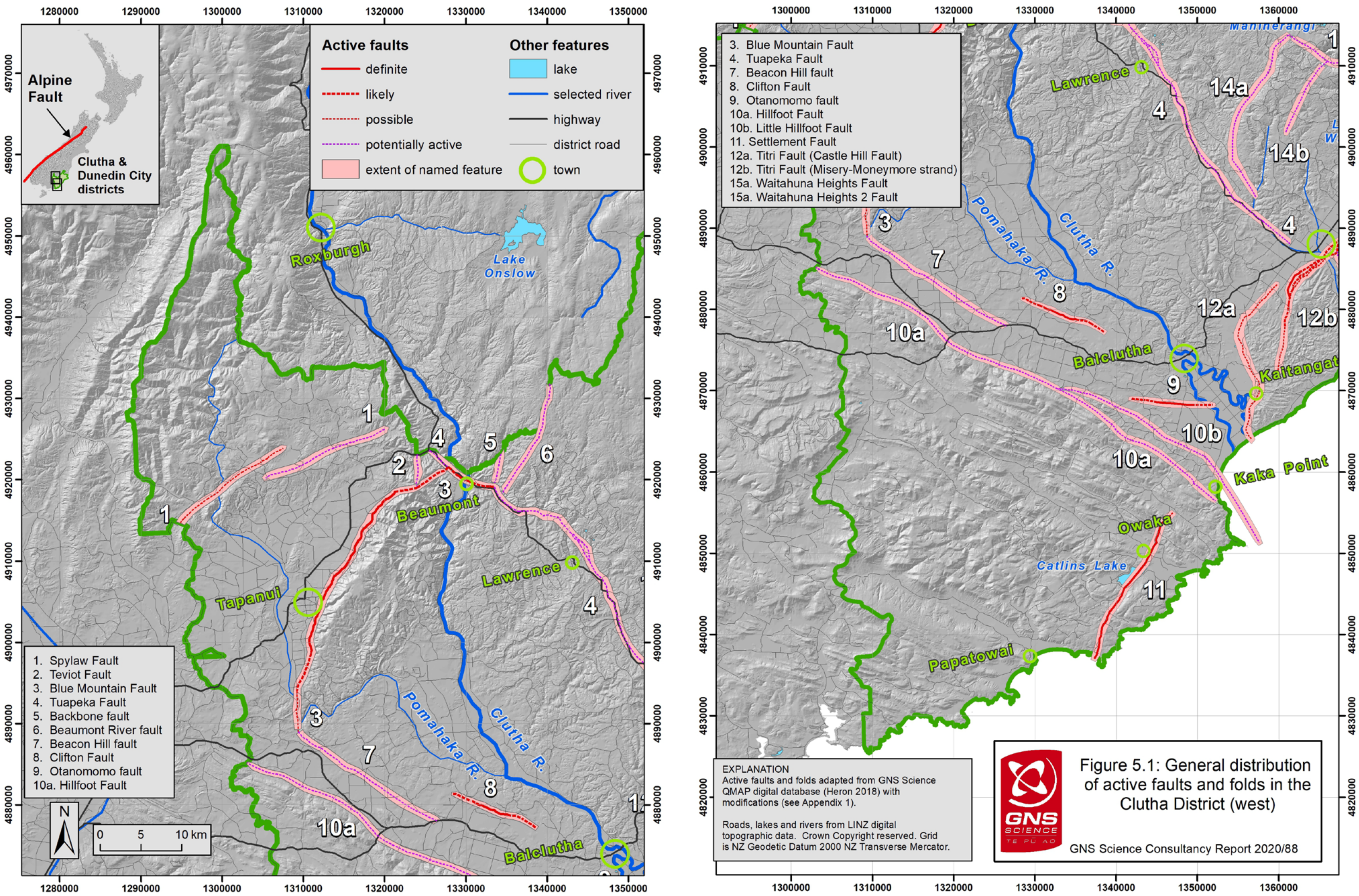

Figure 5.1 General distribution of active faults and folds in the western part of the Clutha District. The pink areas indicate groupings of fault or fold strands that collectively form part of a single numbered active fault. The pink areas are purely illustrative and do not imply anything about the location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

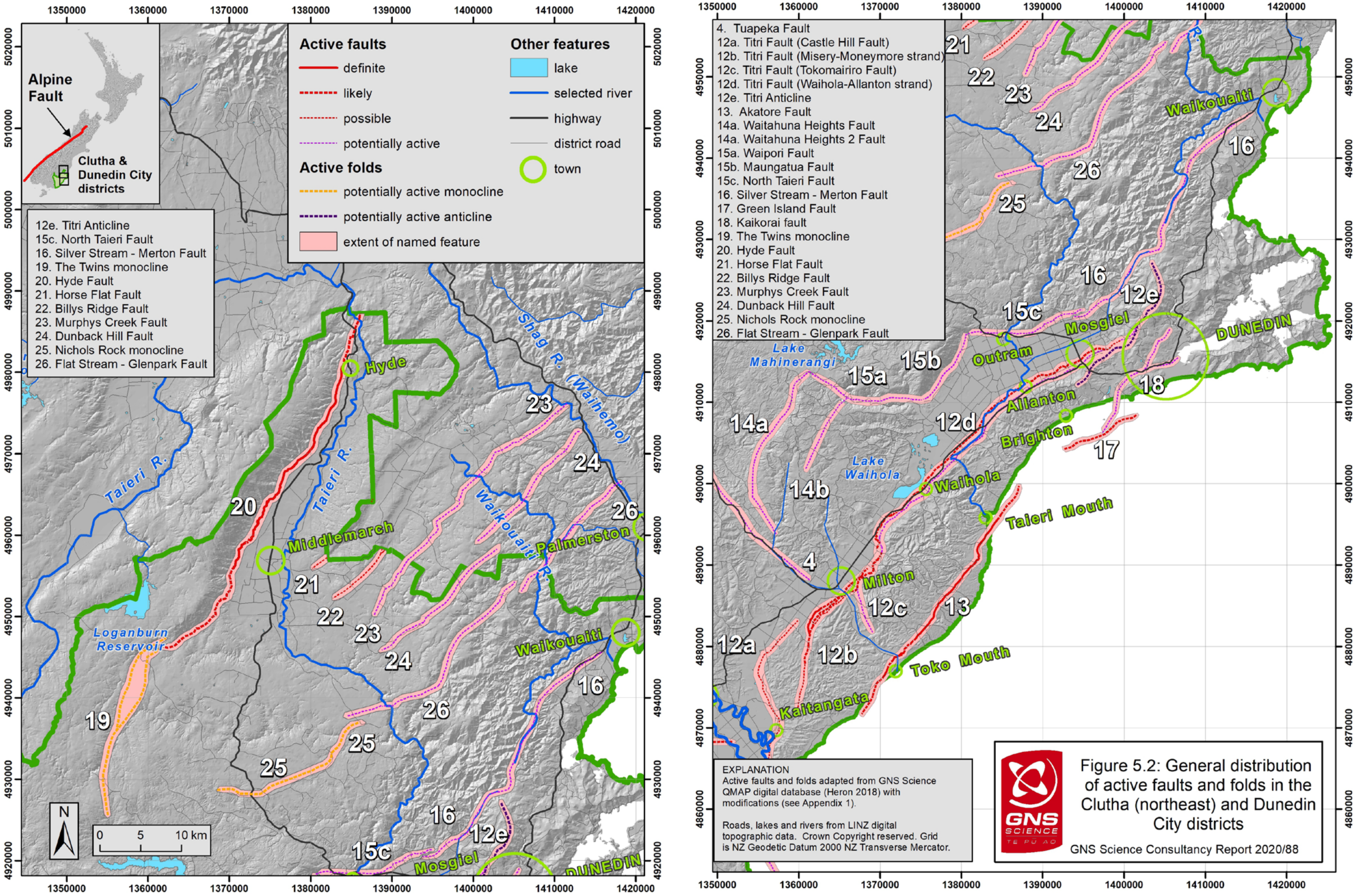

Figure 5.2 General distribution of active faults and folds in the eastern part of the Clutha District and the Dunedin City district. The pink areas indicate groupings of fault or fold strands that collectively form part of a single numbered active fault. The pink areas are purely illustrative and do 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 a neighbouring district. 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 Clutha and Dunedin City 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
		Potentially active	Not expressed	Little or no information from which to estimate the specific location of a potentially active fault.	No recognised deformation
Active monocline	Deformation in the form of one-sided tilting or buckling of the ground surface. Fold growth assumed to occur in sudden events accompanied by a large earthquake. May include some subsidiary fault offsets.	Potentially active	Moderately expressed	Coincides with a known or suspected monocline in bedrock or the peneplain surface, with no definitive evidence of geologically recent movement. The line marking the feature is positioned at the foot of the fold.	Uncertain deformation
Active anticline	Deformation in the form of broad up-doming of the ground surface. Fold growth assumed to occur in sudden events accompanied by a large earthquake. May include some subsidiary fault offsets.	Potentially active	Moderately expressed	Coincides with a known or suspected anticline in bedrock or the peneplain surface, with no definitive evidence of geologically recent movement. The line marking the feature is positioned along the axis (i.e. crest) at the foot of the fold.	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

Table 5.2 Summary of evidence and estimated deformation characteristics of active faults and folds recognised in the Clutha and Dunedin City 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, to the nearest thousand years for values <30,000 years and to the nearest 5000 years for longer RIs.

Name	**Observed Characteristics**	**References**	**Deformation Estimates**					
Name of feature (number in Figures 5.1–5.2)	*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)*	*Estimated recurrence interval (RI) – years*	*Comments*	*Indicated RI Class (following Kerr et al. [2003])*
Akatore Fault (13)	Fault in bedrock with offset of peneplain and offset of geologically young sediments and landforms	Taylor-Silva et al. (2020); this report	Air photo interpretation, field inspection and surveying, trenching and dating, LiDAR data, regional geologic mapping	Definite active fault	Between 0.3 and 6.0	1700	The fault displays episodic rupture recurrence and may be in a more active phase, which is why a relatively short RI is applied.	Class I (<2000 years)
Backbone fault (5)	Inferred fault zone(s) in bedrock, with indicated offset of peneplain	Barrell (2019)	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)
Beacon Hill fault (7)	Fault in bedrock, with indicated offset of peneplain	Turnbull and Allibone (2003); this report	Air photo interpretation, regional geologic mapping, geomorphologic interpretation	Potentially active fault	0.05	29,000	No known evidence for geologically young fault movement.	Class VI (>20,000 years)
Beaumont River fault (6)	Inferred fault zone(s) in bedrock, with indicated offset of peneplain	Barrell (2019)	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)
Billys Ridge Fault (22)	Fault in bedrock, with offset of peneplain	Litchfield et al. (2013); Villamor et al. (2018); Barrell (2016)	Air photo interpretation, regional geologic mapping, geomorphologic interpretation	Possible active fault	0.05	45,000	No known evidence for geologically young fault movement.	Class VI (>20,000 years)
Blue Mountain Fault (3)	Fault zone(s) in bedrock, with offset of peneplain and offset of geologically young landforms	Turnbull and Allibone (2003); Pace et al. (2005); this report	Air photo interpretation, regional geologic mapping, geomorphologic interpretation, geological dating	Definite, likely and possible active fault	0.22	11,000	-	Class V (>10,000 to ≤20,000 years)
Clifton Fault (8)	Inferred fault in bedrock, indicated offset of peneplain and offset of geologically young landforms	Turnbull and Allibone (2003); this report	Regional geologic mapping, LiDAR data, geomorphologic interpretation	Definite and likely active fault	0.09	20,000	Suspected to rupture together with Otanomomo fault. Activity estimates from Otanomomo fault.	Class V (>10,000 to ≤20,000 years)
Dunback Hill Fault (24)	Fault in bedrock, with offset of peneplain	Forsyth (2001); Villamor et al. (2018); this report	Air photo interpretation, regional geologic mapping, geomorphologic interpretation	Potentially active fault	0.05	50,000	No known evidence for geologically young fault movement.	Class VI (>20,000 years)
Flat Stream – Glenpark Fault (26)	Fault in bedrock, with offset of peneplain	Forsyth (2001); Villamor et al. (2018); this report	Air photo interpretation, regional geologic mapping, geomorphologic interpretation	Potentially active fault	0.05	65,000	No known evidence for geologically young fault movement.	Class VI (>20,000 years)
Green Island Fault (17)	Inferred fault zone(s) in bedrock, offshore of Kaikorai Estuary	Holt (2017); Villamor et al. (2018); this report	Offshore bathymetric and geophysical surveys	Likely active fault	0.05	22,000	Evidence for geologically young offset of the sea floor.	Class VI (>20,000 years)
Hillfoot Fault (10a, 10b)	Fault zone(s) mapped in bedrock, with indicated offset of peneplain	Bishop and Turnbull (1996); Turnbull and Allibone (2003); this report	Air photo interpretation, regional geologic mapping, geomorphologic interpretation	Potentially active fault	0.05	110,000	No known evidence for geologically young fault movement.	Class VI (>20,000 years)
Horse Flat Fault (21)	Fault in bedrock, with offset of peneplain	Forsyth (2001); Litchfield et al. (2013); Villamor et al. (2018); Barrell (2016)	Air photo interpretation, regional geologic mapping	Possible active fault	0.05	50,000	Also known as Taieri Ridge Fault. Equivocal evidence for geologically young fault movement.	Class VI (>20,000 years)
Hyde Fault (20)	Fault zone(s) in bedrock, with offset of peneplain and deformed geologically young sediments and landforms	Norris et al. (1994); Norris and Nicolls (2004); Litchfield et al. (2013); this report	Air photo interpretation, field inspection and surveying, trenching and dating, LiDAR data, regional geologic mapping	Definite, likely and possible active fault	0.25	14,200	Data from recent trenching and dating by University of Otago provided by M Stirling and J Griffin (personal communication) .	Class V (>10,000 to ≤20,000 years)
Kaikorai fault (18)	Inferred fault zone(s) in bedrock, with indicated offset of cover rock strata	Villamor et al. (2018); this report	Air photo interpretation, regional geologic mapping, geomorphologic interpretation	Potentially active fault	0.05	22,000	No evidence for geologically young fault movement.	Class VI (>20,000 years)

Name	**Observed Characteristics**	**References**	**Deformation Estimates**					
Name of feature (number in Figures 5.1–5.2)	*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)*	*Estimated recurrence interval (RI) – years*	*Comments*	*Indicated RI Class (following Kerr et al. [2003])*
Murphys Creek Fault (23)	Fault in bedrock, with offset of peneplain	Forsyth (2001); Villamor et al. (2018); this report	Air photo interpretation, regional geologic mapping, geomorphologic interpretation	Potentially active fault	0.05	50,000	No known evidence for geologically young fault movement.	Class VI (>20,000 years)
Nichols Rock monocline (25)	Inferred monoclinal fold in bedrock, with indicated deformation of peneplain	Villamor et al. (2018); this report	Air photo interpretation, regional geologic mapping, geomorphologic interpretation	Potentially active monocline	0.05	28,000	No known evidence for geologically young fault or fold movement.	Class VI (>20,000 years)
Otanomomo fault (9)	Inferred fault in bedrock, with offset of geologically young landforms	This report	Air photo interpretation, regional geologic mapping, LiDAR data, geomorphologic interpretation	Definite and likely active fault	0.09	20,000	Suspected to rupture together with the Clifton Fault.	Class V (>10,000 to ≤20,000 years)
Settlement Fault (11)	Fault zone in bedrock, with indicated offset of peneplain and offset of geologically young landforms	Bishop and Turnbull (1996); Turnbull and Allibone (2003); Litchfield et al. (2013); this report	Air photo interpretation, regional geologic mapping; geological dating, geomorphologic interpretation.	Definite active fault	Between 0.08 and 0.79	1800	May display episodic rupture recurrence and may be in a more active phase, which is why a relatively short RI is applied.	Class I (<2000 years)
Silver Stream – Merton Fault (16)	Fault zone(s) in bedrock, with indicated deformation of peneplain	Bishop and Turnbull (1996); Forsyth (2001); Villamor et al. (2018); this report	Air photo interpretation, regional geologic mapping, geomorphologic interpretation	Potentially active fault	0.05	50,000	No known evidence for geologically young fault movement.	Class VI (>20,000 years)
Spylaw Fault (1)	Fault in bedrock, with offset of peneplain and possible offset of geologically young landforms	Turnbull and Allibone (2003); Pace et al. (2005); Litchfield et al. (2013); this report	Air photo interpretation, regional geologic mapping, field inspection, geological dating, geomorphologic interpretation	Possible and potentially active fault	0.11	19,000	Evidence for geologically young fault movement is equivocal.	Class V (>10,000 to ≤20,000 years)
Teviot Fault (2)	Inferred fault zone in bedrock, with indicated offset of peneplain	Barrell (2019); 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)
The Twins monocline (19)	Monoclinal fold in bedrock, with deformation of peneplain	Bishop and Turnbull (1996); Forsyth (2001); Villamor et al. (2018); this report	Air photo interpretation, regional geologic mapping, geomorphologic interpretation	Potentially active monocline	0.13	13,000	No known evidence for geologically young fault or fold movement.	Class V (>10,000 to ≤20,000 years)
Titri Fault (12)	Fault zone in bedrock; offset of peneplain and offset of geologically young landforms and deposits	Litchfield (2001); Barrell et al. (2020); this report	Air photo interpretation, regional geologic mapping, field inspection and surveying, trenching and dating, LiDAR data	Definite, likely, possible faults; potentially active faults and anticline	Between 0.1 and 0.2	19,000	Possibility of episodic rupture recurrence and may be in a less active phase. A long-term average RI is applied.	Class V (>10,000 to ≤20,000 years)
Tuapeka Fault (4)	Fault zone in bedrock, with offset of geologically young landforms	Els et al. (2003); Villamor et al. (2018); this report	Air photo interpretation, regional geologic mapping, geomorphologic interpretation	Likely and potentially active fault	0.04	95,000	-	Class VI (>20,000 years)
Waipori – Maungatua – North Taieri Fault (15)	Faults in bedrock, with offset of peneplain	Bishop and Turnbull (1996); Barrell et al. (1998); this report	Air photo interpretation, regional geologic mapping, geomorphologic interpretation	Potentially active fault	0.05	50,000	No known evidence for geologically young fault movement.	Class VI (>20,000 years)
Waitahuna Heights Fault (14)	Faults in bedrock, with offset of peneplain	Villamor et al. (2018); 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)

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5.2 Comparison with Previous Assessments

The present project has delineated 26 active and potentially active faults thought to be potentially capable of generating ground-surface-rupturing earthquakes, noting that the total of 34 named fault features in Figures 5.1–5.2 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 seven active fault earthquake sources partly or entirely within the limits of the combined Clutha and Dunedin City districts, and the same seven active fault features are delineated in the NZAFM. The NZAFD, which in the assessment area 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 active fault dataset described in this report provides a full update of information on active faults in the combined Clutha and Dunedin City districts. The information on active faults in this report is more comprehensive than the current version (August 2020) of the NZAFD.

Most of the additional faults identified in the dataset described in this report were included in the assessment by Villamor et al. (2018) as potential active fault earthquake sources. The dataset described here provides more detailed delineations of the fault features identified by Villamor et al. (2018).

5.3 Assessment of Fault Activity Estimates

The delineation of many more faults in the dataset described here, compared to previous assessments, presents an issue 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 of 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.

Mirroring the approach used by Barrell (2019), this issue is considered for the new fault dataset described 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. In the southeastern 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 foothill terrain, on the upthrown side of the line of the fault, for example, the Titri Fault (Barrell et al. 2020). 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 new 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 the 2010 NSHM, the summed slip rate is ~3.1 mm/yr. The NZAFM assigns each modelled fault three slip rate estimates: a minimum, maximum and most likely (‘best’) value. The NZAFM summed slip rates have a range of 1.5 to 7.6 mm/yr (minimum to maximum) and 4.2 mm/yr ‘best’ estimate. The summed slip rate for the 26 faults in the new dataset is ~2.7 mm/yr. If the nominal 0.05 mm/yr slip rate were increased to 0.07 mm/yr, the summed slip rate would be ~3.0 mm/yr, equivalent to the 2010 NSHM value. Both sum estimates lie within the range from the NZAFM and indicates that the slip rates applied in the new dataset are broadly in overall accord with those of the 2010 NSHM and NZAFM datasets.

5.4 Discussion of Fault Activity Close to Population Centres

5.4.1 Southwestern Otago

In southwestern Otago (Figure 5.1), the two faults assessed as being most active in this area are the Blue Mountain Fault, about 1 km southeast of Tapanui, and the Settlement Fault, within ~1 km of Owaka. The Blue Mountain Fault is assessed as having a recurrence interval of ~11,000 years, similar to the value in the 2010 NSHM (Stirling et al. 2012), though it is not known when it last moved. There is some evidence to indicate that the Settlement Fault has experienced greater activity over the past few thousand years than in the preceding ~125,000 years or so. As discussed in Appendix 2, there is clear evidence for a surface-rupturing earthquake having occurred ~3600 years ago, with possibly another one ~1000 years ago. Based on the assumption that the fault has recently entered a more active phase, its recurrence interval is assessed at ~1800 years, somewhat shorter than the 4000 years given in the 2010 NSHM (Stirling et al. 2012).

There is evidence for past rupture on the Tuapeka Fault, which passes under Beaumont village and lies ~1.5 km northeast of Lawrence. Based on landform interpretation, the most recent rupture(s) are assessed as having occurred sometime between 20,000 and 65,000 years ago, and its recurrence interval is assessed as being ~95,000 years, making it a very low activity fault.

The recognition of several potentially active faults only minimally increases the chance of fault rupture and related hazards occurring due to a local-source earthquake in southwestern Otago, because their rates of activity (if any) are very low. The villages of Clinton and Kaka Point lie within a kilometre or so of the Hillfoot Fault, but there is no landform evidence of the fault having moved in geologically recent times (e.g. several tens of thousands of years) and its recurrence interval is assessed as being well in excess of 20,000 years.

5.4.2 Northern Dunedin City District

In the northern part of the Dunedin City district (Figure 5.2; left panel), the small population centres of Middlemarch and Hyde lie within 4 km and 1 km, respectively, of the Hyde Fault. The Hyde Fault has an estimated recurrence interval of ~14,000 years, with the most recent surface rupture ~10,000 years ago. Similarly to southwestern Otago, the recognition of several potentially active faults only minimally increases the chance of fault rupture and related hazards occurring due to a local-source earthquake in the northern part of the Dunedin City district, because their rates of activity (if any) are very low.

5.4.3 Coastal Hills and Basins North of Clutha River

The Tokomairaro and Taieri basins, and the coastal range of hills, are occupied by the main population centres of the assessment area (Figure 5.2; right panel). The most prominent feature is the Titri Fault, whose movement over time has been responsible for uplift that has raised the coastal hills. The fault has complexity of surface expressions, with step-overs from one fault strand to another and, in places, curved to sinuous surface break-up scarps (Figures 5.3–5.5). In several places, notably near Milton, Henley and Mosgiel, the exact location of the most recent fault break-outs are uncertain because stream action has removed or buried the fault-diagnostic landforms. In the south, there is a good geological and topographic basis for positioning the Titri Fault (Castle Hill Fault component) along the foot of the hills on the eastern edge of Kaitangata township, rather than farther west under the Inch Clutha plain as previously mapped. Further north, Milton lies about 2 km northwest of the Titri Fault, which is mapped as passing along the foot of higher ground immediately southeast of its Tokoiti suburb.

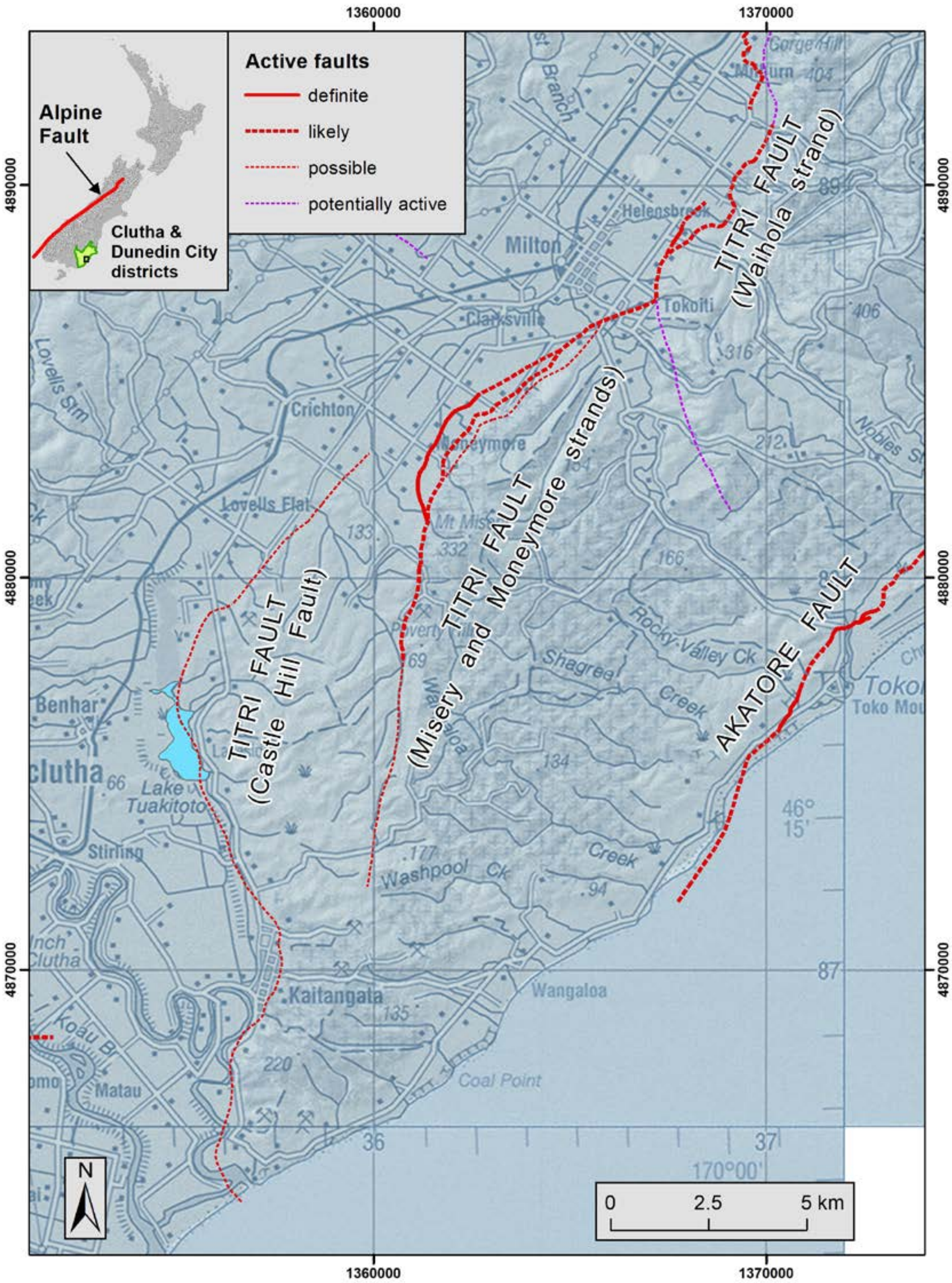

Figure 5.3 Active faults in the southwestern sector of the coastal hills. The background is the Topo 250 topographic map draped transparently over a hillshade digital elevation model. The location of the map panel is shown in the inset at top left.

The village of Waihola is built on low, hilly, terrain immediately on the southeastern, uplifted, side of the Titri Fault, with the fault inferred to lie approximately beneath the position of the railway line. Similarly, the villages of Allanton and East Taieri are on low, hilly, terrain immediately on the southeastern, uplifted, side of the fault. Through Mosgiel, the fault is inferred to lie approximately beneath the railway line and on the eastern side of Mosgiel, approximately along the course of Owhiro Stream. Near Wingatui, the fault is inferred to divert eastward through the village to join the position of the fault as mapped on bedrock relations north of the Chain Hills. For the most part, there are very few houses built directly on the inferred position of the fault, and the main infrastructure close to the line of the fault between Clarendon and Mosgiel are the railway line and State Highway 1. The Titri Fault has an estimated recurrence interval of ~19,000 years and, at least near Milton, last ruptured more than 18,000 years ago. However, it is not known whether the fault ruptures with a regular frequency or in bursts separated by periods of inactivity.

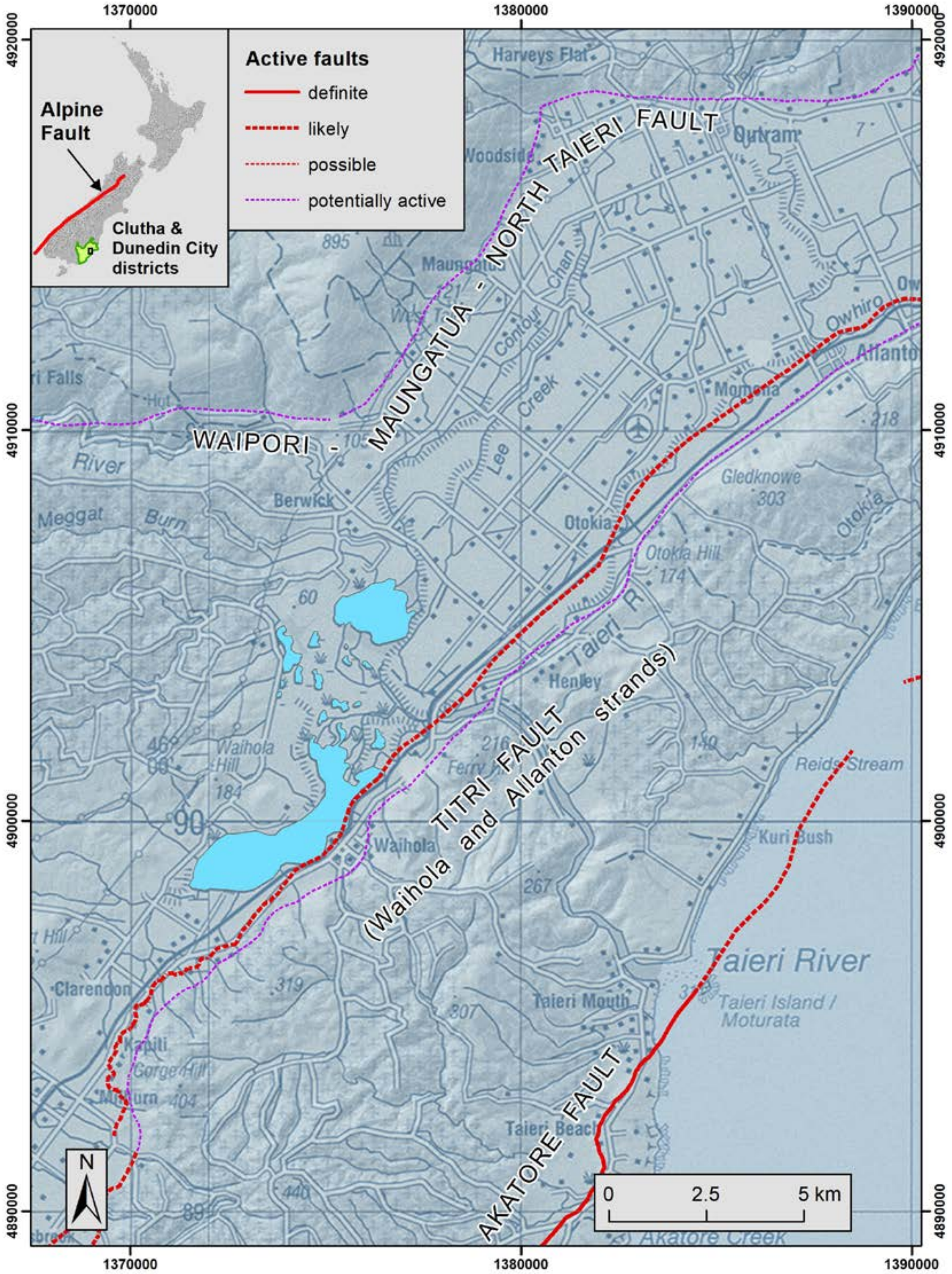

Figure 5.4 Active faults in the central sector of the coastal hills and the Taieri Plain. The background is the Topo 250 topographic map draped transparently over a hillshade digital elevation model. The location of the map panel is shown in the inset at top left.

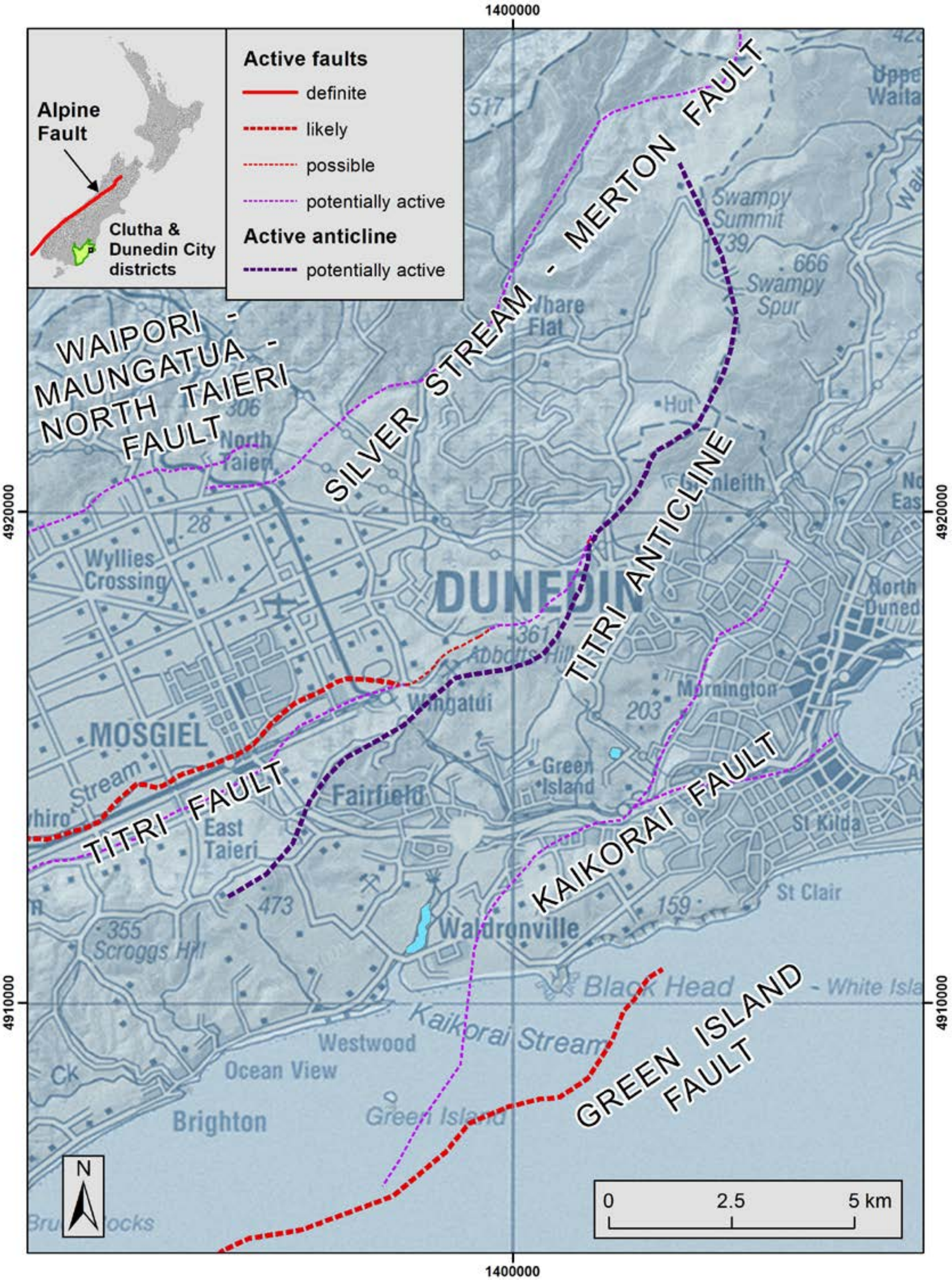

Figure 5.5 Active faults in the northern sectors of the coastal hills and Taieri Plain. The background is the Topo 250 topographic map draped transparently over a hillshade digital elevation model. The location of the map panel is shown in the inset at top left.

The northwestern side of the Taieri Plain is marked by the Waipori – Maungatua – North Taieri Fault, which has, over time, uplifted the hills on that side of the plains (Figures 5.4–5.5). The village of Outram lies within ~1 km southeast of the inferred mapped line of the fault, but none of the built-up area lies directly on the mapped position. Previously, sections of the fault had been interpreted as having had geologically recent activity, based on landform evidence. However, as part of the present assessment, that interpretation has been revised, and those landform features are now interpreted as being unrelated to fault activity. This fault is interpreted as potentially active with an assessed recurrence interval of ~50,000 years. It is not known when it last ruptured.

The Akatore Fault runs close to the coast and has, over time, uplifted a prominent ridge on its southeastern side. It is regarded as likely being in a state of heightened activity, has ruptured twice in the past ~1300 years and is assigned a recurrence interval of ~1700 years. The small village of Toko Mouth lies about 1 km southeast of the fault, on its uplifted side, while, where the fault goes offshore to the northeast, the village of Taieri Beach is within 1 km of the fault on its northwestern side.

The Kaikorai fault is an inferred potentially active fault that is mapped, on the basis of indicative geological relationships, from the coast near Waldronville along the eastern side of the Kaikorai valley floor and the western side of the Roslyn to Maori Hill ridge. A branch of the fault is inferred to extend through Lookout Point and down Caversham Valley into South Dunedin (Figure 5.5). The fault, if its existence as drawn is correctly diagnosed, is upthrown to the southeast and there is no evidence for geologically recent offset of the ground surface. The fault's exact location is mostly uncertain, and it is drawn in the best estimated position from sparse geological outcrop information and topographic considerations. As positioned in this dataset, the fault passes under the eastern fringe of Waldronville and through the eastern part of the Green Island suburb. From Burnside, the fault is drawn under the Kaikorai valley floor at approximately the location of Kaikorai Valley Road and/or Kaikorai Stream. The only significant fix on its location is ~100 m southeast of the Kaikorai Valley Road / Brockville Road intersection, where Benson's (1968) geological map explicitly shows a fault upthrown to the southeast, at the foot of the hill. Northeast of there, the fault is positioned along the axis of the broad valley through the Balmacewan area.

The possible branch of the fault extending east across the Lookout Point saddle has several likely position fixes. As far as is known, it is not crossed by the railway tunnels (the original tunnel north of the motorway through Caversham valley, or the new one south of the motorway), and it is not on the northern side of the Lookout Point motorway overbridge. Saturated very weak materials possibly associated with the geological boundary between Caversham Sandstone and Dunedin Volcanics were exposed in the motorway foundations east of Barnes Drive and south of the overbridge at the Glen, and it is inferred that the possible fault lies close by to the south. East from there, the fault is extrapolated through South Dunedin to the margin of the Otago Harbour.

5.4.4 Tsunami Generation

Several of the more active faults extend offshore, such as the southern end of the Settlement Fault, both ends of the Akatore Fault, the southern end of the Titri Fault and the entirely offshore Green Island Fault. Uplift of the sea floor associated with the rupture of any of those faults would likely generate a local-source tsunami, affecting nearby coasts and estuaries within a matter of minutes. Lowest-lying parts of the settlements at Pounawea, Kaka Point, Toko Mouth, Taieri Mouth and Brighton may be particularly exposed to such a hazard.

6.0 IMPLICATIONS FOR HAZARDS

Since European settlement in the Clutha and Dunedin City districts, there have been no known ground-surface fault rupture events. The geological record and landforms show clear evidence for zones of geologically recent (though pre-dating European settlement) fault deformation of the ground surface. This highlights that it would be prudent to treat the active fault or fold features of the Clutha and Dunedin City 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 only two of the faults in the Clutha and Dunedin City districts have a recurrence interval of less than 5000 years, and all of the rest have assessed 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 Clutha and Dunedin City districts, notably the Akatore Fault, Blue Mountain Fault, Hyde Fault, Settlement Fault and Titri Fault, 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 Clutha and Dunedin City 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. In addition, the issue of local-sourced tsunami is raised as a matter that may warrant consideration.

7.0 CONCLUSIONS

1. Regional geological mapping has identified a number of active fault and fold features in the Clutha and Dunedin City districts. In total, 26 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 and potentially 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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9.0 REFERENCES

Adams RD, Kean RJ. 1974. The Dunedin earthquake, 9 April 1974. Part 1: seismological studies. *Bulletin of the New Zealand Society for Earthquake Engineering*. 7(3):115–122.

Barrell DJA. 2016. General distribution and characteristics of active faults and folds in the Waimate District and Waitaki District, South Canterbury and North Otago. Dunedin (NZ): GNS Science. 124 p. + 1 DVD. Consultancy Report 2015/166. Prepared for Canterbury Regional Council (Environment Canterbury); Otago Regional Council.

Barrell DJA. 2019. General distribution and characteristics of active faults and folds in the Queenstown Lakes and Central Otago districts, Otago. Dunedin (NZ): GNS Science. 99 p. Consultancy Report 2018/207. Prepared for Otago Regional Council.

Barrell DJA, Jack H, Gadsby M. 2015. Guidelines for using regional-scale earthquake fault information in Canterbury. Dunedin (NZ): GNS Science. 30 p. Consultancy Report 2014/211. Prepared for Canterbury Regional Council (Environment Canterbury).

Barrell DJA, Litchfield NJ, Townsend DB, Quigley M, Van Dissen RJ, Cosgrove R, Cox SC, Furlong K, Villamor P, Begg JG, et al. 2011. Strike-slip ground–surface rupture (Greendale Fault) associated with the 4 September 2010 Darfield Earthquake, Canterbury, New Zealand. *Quarterly Journal of Engineering Geology and Hydrogeology*. 44(3):283–291. doi:10.1144/1470-9236/11-034.

Barrell DJA, Litchfield NJ, Van Dissen RJ, Wang N, Taylor-Silva BI, Hornblow S, Stirling MW. 2020. Investigation of past earthquakes on the Titri Fault, coastal Otago, New Zealand. Lower Hutt (NZ): GNS Science. 66 p. (GNS Science report; 2017/35).

Barrell DJA, Read SAL, Van Dissen RJ, Macfarlane DF, Walker J, Rieser U. 2009. Aviemore: a dam of two halves. In: Turnbull IM, editor. *Geological Society of New Zealand & New Zealand Geophysical Society Joint Annual Conference, Oamaru, 23–27 November 2009: field trip guides*. Wellington (NZ): Geological Society of New Zealand. 30 p.

Beanland S, Berryman KR. 1989. Style and episodicity of late Quaternary activity on the Pisa–Grandview Fault Zone, Central Otago, New Zealand. *New Zealand Journal of Geology and Geophysics*. 32(4):451–461. doi:10.1080/00288306.1989.10427553.

Beavan J, Motagh M, Fielding EJ, Donnelly N, Collett D. 2012. Fault slip models of the 2010–2011 Canterbury, New Zealand, earthquakes from geodetic data and observations of postseismic ground deformation. *New Zealand Journal of Geology and Geophysics*. 55(3):207–221. doi:10.1080/00288306.2012.697472.

Benson WN. 1968. The W.N. Benson geological map of Dunedin district [map]. Wellington (NZ): Department of Scientific and Industrial Research. 1 folded map + 1 booklet, scale 1:50,000. (New Zealand Geological Survey miscellaneous series map; 1).

Bishop DG. 1974. The Dunedin earthquake, 9 April 1974. Part 2: local effects. *Bulletin of the New Zealand National Society for Earthquake Engineering*. 7(3):123–129.

Bishop DG, Turnbull IM. 1996. Geology of the Dunedin area [map]. Lower Hutt (NZ): Institute of Geological & Nuclear Sciences. 1 folded map + 52 p., scale 1:250,000. (Institute of Geological & Nuclear Sciences 1:250,000 geological map; 21).

Coombs DS, Adams CJ, Roser BP, Reay A. 2008. Geochronology and geochemistry of the Dunedin Volcanic Group, eastern Otago, New Zealand. *New Zealand Journal of Geology and Geophysics*. 51(3):195–218. doi:10.1080/00288300809509860.

Els BG, Youngson JH, Craw D. 2003. Blue Spur Conglomerate: auriferous Late Cretaceous fluvial channel deposits adjacent to normal fault scarps, southeast Otago, New Zealand. *New Zealand Journal of Geology and Geophysics*. 46(1):123–139. doi:10.1080/00288306.2003.9515000.

Forsyth PJ. 2001. Geology of the Waitaki area [map]. Lower Hutt (NZ): Institute of Geological & Nuclear Sciences Limited. 1 folded map + 64 p., scale 1:250,000. (Institute of Geological & Nuclear Sciences 1:250,000 geological map; 19).

GNS Science. c2020. New Zealand Active Faults Database: surface traces of onshore active faults at a scale of 1:250,000. Lower Hutt (NZ): GNS Science; [updated 2020 Aug 3; accessed 2020 Oct]. http://data.gns.cri.nz/af/

Heron DW, custodian. 2018. Geological map of New Zealand 1:250,000. 2nd ed. Lower Hutt (NZ): GNS Science. 1 USB. (GNS Science geological map; 1).

Holt A. 2017. Acoustic investigations of geologic hazards and seismic processing off the coast of Otago, New Zealand [MSc thesis]. Dunedin (NZ): University of Otago. 205 p.

Hornblow S, Quigley M, Nicol A, Van Dissen R, Wang N. 2014. Paleoseismology of the 2010 M_W 7.1 Darfield (Canterbury) earthquake source, Greendale Fault, New Zealand. *Tectonophysics*. 637:178–190. doi:10.1016/j.tecto.2014.10.004.

Kerr J, Nathan S, Van Dissen R, Webb P, Brunsdon D, King A. 2003. Planning for development of land on or close to active faults: a guideline to assist resource management planners in New Zealand. Wellington (NZ): Ministry for the Environment. 67 p.

Landis CA, Campbell HJ, Begg JG, Mildenhall DC, Paterson AM, Trewick SA. 2008. The Waipounamu erosion surface: questioning the antiquity of the New Zealand land surface and terrestrial fauna and flora. *Geological Magazine*. 145(2):173–197. doi:10.1017/s0016756807004268.

Langridge RM, Ries WF, Litchfield NJ, Villamor P, Van Dissen RJ, Barrell DJA, Rattenbury MS, Heron DW, Haubrock S, Townsend DB, et al. 2016. The New Zealand Active Faults Database. *New Zealand Journal of Geology and Geophysics*. 59(1):86–96. doi:10.1080/00288306.2015.1112818.

Litchfield NJ. 2001. The Titri Fault System: Quaternary-active faults near the leading edge of the Otago reverse fault province. *New Zealand Journal of Geology and Geophysics*. 44(4):517–534. doi:10.1080/00288306.2001.9514953.

Litchfield NJ, Norris RJ. 2000. Holocene motion on the Akatore Fault, south Otago coast, New Zealand. *New Zealand Journal of Geology and Geophysics*. 43(3):405–418. doi:10.1080/00288306.2000.9514897.

Litchfield NJ, Van Dissen RJ, Sutherland R, Barnes PM, Cox SC, Norris RJ, Beavan RJ, Langridge RM, Villamor P, Berryman KR, et al. 2013. A model of active faulting in New Zealand: fault zone parameter descriptions. Lower Hutt (NZ): GNS Science. 120 p. (GNS Science report; 2012/19).

Litchfield NJ, Van Dissen RJ, Sutherland R, Barnes PM, Cox SC, Norris R, Beavan RJ, Langridge RM, Villamor P, Berryman KR, et al. 2014. A model of active faulting in New Zealand. *New Zealand Journal of Geology and Geophysics*. 57(1):32–56. doi:10.1080/00288306.2013.854256.

Litchfield NJ, Villamor P, Van Dissen RJ, Nicol A, Barnes PM, Barrell DJA, Pettinga JR, Langridge RM, Little TA, Mountjoy JJ, et al. 2018. Surface rupture of multiple crustal faults in the 2016 M_W 7.8 Kaikōura, New Zealand, earthquake. *Bulletin of the Seismological Society of America*. 108(3B):1496–1520. doi:10.1785/0120170300.

Nicol A, Van Dissen RJ, Stirling MW, Gerstenberger MC. 2016. Completeness of the paleoseismic active-fault record in New Zealand. *Seismological Research Letters*. 87(6):1299–1310. doi:10.1785/0220160088.

Norris RJ, Koons PO, Landis CA. 1994. Seismotectonic evaluation of fault structures in East Otago. Dunedin (NZ): University of Otago. 1 vol. EQC Funded Report 91/53.

Norris RJ, Nicolls R. 2004. Strain accumulation and episodicity of fault movements in Otago. Wellington (NZ): Earthquake Commission. 146 p. EQC Research Report 01/445.

Pace B, Stirling MW, Litchfield NJ, Rieser U. 2005. New active fault data and seismic hazard estimates for west Otago, New Zealand. *New Zealand Journal of Geology and Geophysics*. 48(1):75–83. doi:10.1080/00288306.2005.9515099.

Pettinga JR, Yetton MD, Dissen RJ, Downes G. 2001. Earthquake source identification and characterisation for the Canterbury Region, South Island, New Zealand. *Bulletin of the New Zealand Society for Earthquake Engineering*. 34(4):282–317. doi:10.5459/bnzsee.34.4.282-317.

Stirling M, McVerry G, Gerstenberger M, Litchfield N, Dissen R, Berryman K, Barnes P, Wallace L, Villamor P, Langridge R, et al. 2012. National Seismic Hazard Model for New Zealand: 2010 update. *Bulletin of the Seismological Society of America*. 102(4):1514–1542. doi:10.1785/0120110170.

Taylor-Silva BI, Stirling MW, Litchfield NJ, Griffin JD, van den Berg EJ, Wang N. 2020. Paleoseismology of the Akatore Fault, Otago, New Zealand. *New Zealand Journal of Geology and Geophysics*. 63(2):151–167. doi:10.1080/00288306.2019.1645706.

Turnbull IM, Allibone AH. 2003. Geology of the Murihiku area [map]. Lower Hutt (NZ): Institute of Geological & Nuclear Sciences. 1 folded map + 74 p., scale 1:250,000. (Institute of Geological & Nuclear Sciences 1:250,000 geological map; 20).

Van Dissen RJ, Berryman KR, Webb TH, Stirling MW, Villamor P, Wood PR, Nathan S, Nicol A, Begg JG, Barrell DJA, et al. 2003. An interim classification of New Zealand's active faults for the mitigation of surface rupture hazard. In: *Proceedings of the 2003 Pacific Conference on Earthquake Engineering*. 2003 Feb 13–15; Christchurch, New Zealand. Wellington (NZ): New Zealand Society for Earthquake Engineering. 8 p. Paper 155.

Van Dissen R, Seebeck H, Litchfield N, Nicol A, Barnes P, Langridge R, Villamor P, Barrell D, Ellis S, Rattenbury M, et al. Forthcoming 2021. Development of the New Zealand Community Fault Model – version 1.0. In: *2021 NZSEE Conference – The Christchurch earthquake 10th anniversary: turning challenges into positive legacies*; 2021 Apr 14–16; Christchurch, New Zealand.

Villamor P, Barrell DJA, Gorman A, Davy BW, Hreinsdottir S, Hamling IJ, Stirling MW, Cox SC, Litchfield NJ, Holt A, et al. 2018. Unknown faults under cities. Lower Hutt (NZ): GNS Science. 71 p. (GNS Science miscellaneous series; 124).

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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:

- Clutha_Dunedin_active_faults_September2020
- Clutha_Dunedin_active_folds_September2020
- Clutha_Dunedin_fault_entity_area_September2020

The original attribute fields for the first two feature classes were extracted from the QMAP (Quarter-Million-scale geological mAP) 'seamless' dataset (Heron 2018), sourced from map data represented in the Clutha and Dunedin City districts by the Dunedin map (Bishop and Turnbull 1996; southeastern parts of both districts), Murihiku map (Turnbull and Allibone 2003; southwestern Clutha District) and the Waitaki map (Forsyth 2001; northern and western parts of the Dunedin City district).

In the active faults feature class of the dataset prepared as part of this project, the 'DOWN_QUAD' attribute field of the QMAP dataset is retained, and, for the folds feature class, the QMAP fields of 'TYPE' and 'FACING' are retained.

For this project, three new attribute fields are added:

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

Unless indicated otherwise, all of 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 2018) online at GNS Science, www.gns.cri.nz, search term < QMAP digital data webmap >.

The dataset is based largely on broad-scale inferences and should not be used in isolation for any purposes requiring site-specific information. The main purpose of the dataset is to delineate areas where active or potentially active fault features may warrant further scrutiny for future planning and development activities.

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, Google Maps 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 Clutha and Dunedin City districts are encompassed by three published map sheets, with accompanying descriptive booklets, by the Dunedin map (Bishop and Turnbull 1996; southeastern parts of both districts), Murihiku map (Turnbull and Allibone 2003; southwestern Clutha District) and the Waitaki map (Forsyth 2001; northern and western parts of the Dunedin City district). Subsequently, all of the digital datasets from which these maps were generated were compiled into a nationwide 'seamless' dataset, published in digital form (Heron 2018). The subsets of 1:250,000-scale faults and folds that form the Clutha and Dunedin City district dataset presented in this report were extracted from the Heron (2018) 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 sections of the fault, were attributed as 'active', whereas other, more distant, sections of the same geological fault were attributed as 'inactive'. While the subdivision of a fault into active and inactive sections is somewhat artificial (a fault structure is commonly regarded as active or inactive), 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).

A 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 re-interpreted, 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 southeastern 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). An extensive erosion surface in the Catlins area, of uncertain affinity to the Otago peneplain, is referred to here as the Catlins erosion surface.

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 Akatore Fault (feature 13, Figure 5.2)

This northeast-striking fault, upthrown to the southeast, lies onland from near Toko Mouth in the southwest to Taieri Mouth in the northeast. It has offset the peneplain by as much as ~100 m, with the offset greatest midway along the fault at Big Creek, with offset diminishing both northeast and southwest. Conspicuous geologically young landform offsets have long been recognised near Taieri Beach and the Tokomairaro River valley.

To the southwest and northeast, the fault goes offshore, creating uncertainty as to how far it extends. A previous interpretation extrapolated the fault as much as ~30 km to the northeast, inferring that it comes back onland near Waldronville, and continues to South Dunedin (Bishop and Turnbull 1996). Villamor et al. (2018) noted that, near Taieri Mouth, the offset on the peneplain is diminishing northeastward. Offshore seismic reflection surveys indicate that the fault continues for ~6.5 km northeast of Taieri Island / Moturata before transitioning into an anticlinal fold (Holt 2017). That interpretation is adopted in this report, confining the offshore mapping to the fault as interpreted by Holt (2017).

To the southwest, previous maps have shown the fault going directly offshore, but, in this dataset, the fault is drawn along the beach zone for ~1.4 km before diverting offshore near Measly Beach along a sharp landward margin of two offshore reefs. This interpretation raises the possibility of a fault-related origin for the surprising course of the coastal reach of Shagree Creek, whose channel extends southwest for several hundred metres behind the dune barrier. Northeastward diversion of near-shore reaches of streams is more common, in keeping with the prevailing direction of longshore drift. It is possible, though, that the course of Shagree Creek is a quirk of coastal processes rather than being fault-related.

As mapped in this dataset, the Akatore Fault has an onland length of ~23 km, with likely offshore extensions of at least ~5 km to the southwest and ~9 km to the northeast, giving an indicative length of ~37 km. A trenching investigation at Big Creek (Taylor-Silva et al. 2020) exposed the fault, showing evidence for at least three surface rupture events with total vertical offset of between ~4 and ~5 m. The investigation also showed that the near-surface fault dip is between ~30 and ~50° SE. Previous estimates of overall dip for the fault structure of 45° and 55° given by Stirling et al. (2012) and Litchfield et al. (2014) are compatible with the new data.

The Taylor-Silva et al. (2020) investigation has shown that the Akatore Fault has experienced at least three surface ruptures since ~15,000 years ago, with total net slip in the range of 4.8 to 7.4 m. Before that, no surface ruptures had occurred since at least ~125,000 years ago, which indicates that the Akatore Fault experiences episodic rupture behaviour. This implies an indicative long-term slip rate of ~0.05 mm/year. The two most recent ruptures have occurred since ~1300 years ago. From the investigation data for the recent episode of activity, Taylor-Silva et al. (2020) calculated a recent slip rate in the range of 0.3 to 6.0 mm/year and recurrence interval in the range of 450 to ~5100 years, noting that the larger slip rate and shorter recurrence interval are extreme values.

Two additional considerations can be used to refine the Taylor-Silva et al. (2020) estimates. One is that, on the coast near the mouth of Big Creek, there is an uplifted Holocene sea cliff, with the base of the cliff and adjoining uplifted shore platform standing at ~4 to ~5 m above sea level. This is approximately the same as the vertical component of throw at the Big Creek trench and indicates that the last three ruptures recorded in the Big Creek trench must all have all occurred after the culmination of the post-glacial sea-level rise ~7000 years ago (Clement et al. 2016). Following the culmination of sea-level rise, sufficient time must have elapsed for coastal erosion to have cut a shore platform and sea-cliff in the schist bedrock along the coast, prior to the uplift events. A nominal estimate for the duration for the pre-uplift erosion of ~2000 years is assumed here. Taking an age of ~5000 years and dividing it by three rupture events that occurred since that time gives an indicative average recurrence interval of 1700 years (rounded to the nearest hundred years). That value is adopted for the purposes of this report.

A2.3 **Backbone fault** (feature 5, Figure 5.1)

The north-striking Backbone fault lies mostly in the Central Otago District and was identified and described by Barrell (2019). A summary description of the fault from the appendix of that report is presented below.

The Backbone fault is identified from an indicated up-to-the-west vertical separation of the peneplain of between ~100 and 200 m and is assumed to be a west-dipping reverse fault. There is no known geological exposure of the fault, and the line denoting its position is drawn along the foot of the topographic escarpment. It is assumed to be a west-dipping reverse fault. Only the southern 3.5 km of the fault lies in the Clutha District, and the fault is mapped as stopping at the Tuapeka Fault.

There are no known offsets of geologically young landform features, and the Backbone fault is classified as 'potentially active'. For the estimation of activity parameters, Barrell (2019) assigned a dip of 60°, length of 24 km and a nominal slip rate of 0.05 mm/year, from which a recurrence interval of ~35,000 years was calculated using the 2010 NSHM methodology.

A2.4 Beacon Hill fault (feature 9, Figure 5.1)

The northwest-striking Beacon Hill fault is from the QMAP dataset, where it is an unnamed fault within the Livingstone Fault System. This fault system is interpreted to be a major geological feature of New Zealand, separating different types (terranes) of basement rock, and has an overall steep dip to the northeast (e.g. Cawood 1987; Mortimer et al. 2002; Tarling et at al. 2019).

The Beacon Hill fault coincides with a notable topographic escarpment in the peneplain surface, up to the northeast, and is named here after a hill on its upthrown side. At the south end of the Blue Mountains range, the escarpment is ~150 m high but progressively diminishes southeastward to a few tens of metres high. It is up to the northwest. Because its northwestern end coincides with the end of the Blue Mountain Fault, the Beacon Hill fault is interpreted in this dataset as 'potentially active' and could possibly pick up slip transfer from the Blue Mountain Fault. Also a factor in this interpretation is that the Beacon Hill fault is nearby, and approximately parallel, to the Clifton and Otanomomo faults, which have experienced definite geologically young surface rupture.

There are no known offsets of geologically young landform features on the Beacon Hill fault. For the estimation of activity parameters, a dip of 70°, length of 21 km and a nominal slip rate of 0.05 mm/year were applied, from which a recurrence interval of ~29,000 years was calculated using the 2010 NSHM methodology.

A2.5 Beaumont River fault (feature 6, Figure 5.1)

The north-striking Beaumont River fault extends from the Central Otago District into the Clutha District and was identified and described by Barrell (2019). A summary description of the fault from the appendix of that report is presented below.

The Beaumont River fault is identified from an indicated up-to-the-east vertical separation of the peneplain of between ~100 and 200 m and is assumed to be an east-dipping reverse fault. There is no known geological exposure of the fault, and the line denoting its position is drawn along the foot of the topographic escarpment. It is assumed to be a west-dipping reverse fault. The southern ~15 km of the fault lies in the Clutha District, and the fault is mapped as stopping at the Tuapeka Fault.

There are no known offsets of geologically young landform features and the Beaumont River fault is classified as 'potentially active'. For the estimation of activity parameters, Barrell (2019) assigned a dip of 60°, length of 36 km and a nominal slip rate of 0.05 mm/year, from which a recurrence interval of ~50,000 years was calculated using the 2010 NSHM methodology.

A2.6 Billys Ridge Fault (feature 22, Figure 5.2)

This northeast-striking fault is ~35 km long and upthrown to the northwest, with vertical separation of the peneplain of as much as ~250 m but more commonly between ~50 and 100 m. In detail, it comprises two strands, the north-eastern one identified as the Macraes Fault and the southwestern one as the Billys Ridge Fault (Barrell 2016). The Macraes Fault is known to be a northwest-dipping reverse fault, and the Billys Ridge Fault is inferred to also be a northwest-dipping contractional fault. Only the southwestern ~9 km of the Billys Ridge Fault lies in the Dunedin district; the remainder is in the Waitaki District fault dataset, described by Barrell (2016).

Although not classified as active in the original QMAP dataset (Forsyth 2001), it has been reclassified as active in the QMAP database (Heron 2018). It is included in the NZAFD, NZAFM and NSHM (Litchfield et al. 2013). Previous estimates of fault activity parameters are discussed by Barrell (2016).

There are no known offsets of geologically young landforms or deposits. The fault is classified as a possible active fault in this dataset, following the reasoning presented by Barrell (2016). Villamor et al. (2018) identified it as an earthquake source. They considered various estimates for slip rate, ranging from 0.12 to 0.003 mm/year, and calculated corresponding average recurrence intervals in the range of ~18,000 years to more than 600,000 years. For the estimation of activity parameters for this report, a dip of 45°, a length of 34 km and nominal net slip rate of 0.05 mm/year were applied and a recurrence interval of ~47,000 years was calculated using the 2010 NSHM methodology.

A2.7 Blue Mountain Fault (feature 3, Figure 5.1)

The northeast-striking Blue Mountain Fault is one of the most topographically prominent faults of the Clutha District, with the Blue Mountains range having been uplifted on the southeast side of the fault. The vertical separation of the peneplain is as much as ~700 to ~800 m at the highest part of the range, east of Tapanui.

The fault is drawn along the foot of the range. There are no known exposures of the fault plane, but it is assumed to be a southeast-dipping reverse fault. At the north-eastern end of the fault, the fault has previously been interpreted as breaking into two strands, the main strand (Blue Mountain No. 1 Fault) and an east-northeast-striking short strand to the east (Blue Mountain No. 2 Fault) (e.g. Beanland and Berryman 1986; Turnbull and Allibone 2003). The 'No. 1' strand, classified as 'active' by Turnbull and Allibone (2003) has been depicted as terminating northeast against the Teviot Fault, while the Teviot Fault is depicted as terminating southward against the 'No. 2' strand (this strand was classified as 'inactive' by Turnbull and Allibone [2003]). That interpretation is regarded here as being unlikely kinematically.

There is no known geologically young offsets of landforms at the north-eastern end of the Blue Mountain Fault 'No. 1' strand (Pace et al. 2005). The likely reason that Turnbull and Allibone (2003) classified this strand as 'active' was because the main strand of the fault farther south is identified as the 'No. 1' strand. However, the main topographic expression of the Blue Mountain Fault (i.e. peneplain offset) follows the 'No. 2' strand, and that strand is regarded here as the main strand. From the point that the 'No. 1' and 'No. 2' strands diverge, ~16 km northeast of Tapanui, the ~3.5 km extension of the 'No. 1' strand is deleted and the 'No. 2' strand is retained. In the dataset, no distinction is made between the 'No. 1' and 'No. 2' strands, and the name 'Blue Mountain Fault' is applied collectively.

For a ~18 km section of the Blue Mountain Fault, between ~3.5 km south and ~15 km northeast from Tapanui, there are discontinuous steps at the front of medium- to high-level alluvial fan remnants along the foot of the range, and these have been interpreted as fault scarps (Beanland and Berryman 1986; Pace et al. 2005). In some cases, younger fan surfaces have been built out around the front of the steps, meaning that the surfaces either side of the scarp are not necessarily the same age. Stream drainage emerging from the range-front continues northwest away from the fault for as much as several kilometres. This means that the elevated steps at the foot of the range cannot be attributed to fluvial erosion but rather must have been elevated tectonically. For that reason, the fronts of the steps are identified as ‘definite’, ‘moderately expressed’ fault features, connected along strike by ‘definite’, ‘not expressed’ sections.

The section of the range-front with upfaulted alluvial fan remnants conforms with the interpretation of Pace et al. (2005), and stereoscopic examination of archival aerial photographs has been used to refine the position of the fault scarps compared to how the fault position was depicted in the QMAP.

Pace et al. (2005) report a luminescence age of 98,500 ± 10,300 years for the deposits of an alluvial fan, interpreted to have been offset ~20 m vertically across the Blue Mountain Fault. The typical scarp height on the old fans is between 10 and 20 m, and, for the purpose of this assessment, the mean age was taken as the time elapsed for an average of ~15 m vertical displacement. For the estimation of activity parameters, a dip of 45° and fault length of 35 km were assigned. This length value approximates the northeast-southwest length of the Blue Mountains range. The calculated vertical slip rate is ~0.15 mm/year. When resolved onto a 45° dipping fault plane with an inferred pure dip-slip motion, this equates to a net slip rate of 0.22 mm/year. From those values, a recurrence interval of ~11,300 years was calculated using the 2010 NSHM methodology. This is approximately the same as the recurrence interval of ~12,700 years calculated by Stirling et al. (2012) from the data provided by Pace et al. (2005). That value differed from the ‘best estimate’ of ~20,000 years determined by Pace et al. (2005). Balancing of slip rates across the wider region was a consideration in the Stirling et al. (2012) estimates but necessitated applying a fault length of 51 km, which is more than can be supported from geological data. In any case, all of the past estimates of recurrence interval indicate that Blue Mountain Fault has a relatively low level of activity, as assessed by recurrence interval.

The Blue Mountain Fault is mapped as ‘likely’ at its northeast end, close to its intersection with the Tuapeka Fault. Refer to the section on the Tuapeka Fault for discussion of possible transfer of slip from the Blue Mountain Fault to the Tuapeka Fault.

A2.8 Clifton Fault (feature 8, Figure 5.1)

This west-northwest-striking fault is identified solely on the basis of landform offsets. The fault has no general topographic expression across downlands terrain. It was first identified several decades ago and is named after the Clifton rural locality. In QMAP, it is identified as part of the Livingstone Fault System. This fault system is interpreted to be a major geological feature of New Zealand, separating different types (terranes) of basement rock, and has an overall steep dip to the northeast (e.g. Cawood 1987; Mortimer et al. 2002; Tarling et at al. 2019).

There is no LiDAR in the area of this fault, and its position and characteristics were reviewed using archival black and white aerial photos. The review found that the position of the fault was depicted in QMAP, and the NZAFD, with poor precision. As part of this project, it has been accurately repositioned, at ~1:10,000-scale, resulting in it being shifted as much as 400 m south of where it was previously shown.

Only the central ~4 km of the fault has a fairly continuous, undoubted fault scarp, up to several metres high, and is classed as ‘definite’. It appears to be quite a broad scarp in many places, so is classified as ‘moderately expressed’. The remainder is classified as ‘likely’.

With a total identified length of 11 km, the Clifton Fault is probably too short to account for the presence of several-metre-high surface offsets. This same problem exists for the Otanomomo fault, farther to the southeast, which has similar expression in the landscape to that of the Clifton Fault. For the estimation of activity parameters, the interpretation is made that those two faults are the surface expressions of the rupture of an unidentified fault at depth. The collective distance between the eastern end of the Otanomomo fault and the western end of the Clifton Fault is 27 km. Assuming both faults are reverse faults with dips of 70°, and pure dip-slip motion, the Otanomomo fault scarp height of 4 m with an adopted age of 45,000 years equates to a 0.09 mm/year net slip on the fault plane, and a recurrence interval of ~19,900 years was calculated using the 2010 NSHM methodology. These parameters are also applied to the Clifton Fault.

A2.9 Dunback Hill Fault (feature 24, Figure 5.2)

This northeast-striking fault is upthrown to the northwest, with vertical separation of the Otago peneplain of as much as ~150 m but mostly between ~50 and ~100 m. It is inferred to be contractional, with a dip to the northwest.

Similarly to the Flat Stream – Glenpark Fault, there is a step-over in central section of the Dunback Hill Fault, comprising a ~2 km step to the southeast. The north-eastern strand of the fault is named ‘Dunback Hill Fault’ in the QMAP, while the southwestern strand was un-named. The peneplain offset implies that the two faults are closely associated, and the name ‘Dunback Hill’ is applied to both strands in this dataset.

The fault strands were shown as inactive in the QMAP dataset, and are not in the NZAFD, NZAFM or NSHM. There are no known offsets of geologically young landforms or deposits, and the fault is classified in this dataset as potentially active. Villamor et al. (2018) identified what they called simply the Dunback Fault as a potential earthquake source. They considered various estimates for slip rate ranging from 0.07 to 0.002 mm/year and calculated corresponding average recurrence intervals in the range of ~34,000 years to more than 1 million years. For the estimation of activity parameters for this report, a dip of 45°, a length of 37 km and nominal net slip rate of 0.05 mm/year were applied, and a recurrence interval of ~52,000 years was calculated using the 2010 NSHM methodology.

A2.10 Flat Stream – Glenpark Fault (feature 26, Figure 5.2)

This northeast-striking structure, upthrown to the northwest, comprises the ~35 km long Flat Stream Fault in the southwest, which steps over to the ~20 km long Glenpark Fault in the northeast. At its southwest end on the Barewood plateau, the Flat Stream Fault has a ~10–20 m vertical separation of the peneplain (Villamor et al. 2018), which increases to as much as ~200 m before petering out towards Switchback Hill. At that location, the Glenpark fault becomes evident ~1.5 km southeast of the Flat Stream Fault. Vertical separation of the peneplain across the Glenpark fault is between ~50 and ~100 m. The Nichols Rock monocline (separate section) commences at the southwest end of the Flat Stream Fault.

The Flat Stream – Glenpark Fault is inferred to be contractional, with a dip to the northwest. The fault is shown as inactive in the QMAP dataset and is not in the NZAFD, NZAFM or NSHM. There are no known offsets of geologically young landforms or deposits, and the fault is classified in this dataset as potentially active. Villamor et al. (2018) identified the Flat Stream – Glenpark Fault as a potential earthquake source. They considered various estimates for slip rate ranging from 0.05 to 0.001 mm/year and calculated corresponding average recurrence intervals in the range of ~68,000 years to more than 2 million years. They also considered a scenario in which the Flat Stream – Glenpark Fault ruptures together with the fault underlying the Nichols Rock monocline, and that scenario has an average recurrence interval of more than 100,000 years. For the estimation of activity parameters for this report, a dip of 45°, a composite length of 45 km for the Flat Stream – Glenpark Fault and nominal net slip rate of 0.05 mm/year were applied, and a recurrence interval of ~63,000 years was calculated using the 2010 NSHM methodology.

A2.11 Green Island Fault (feature 17, Figure 5.2)

This northeast-striking fault is identified from offshore bathymetric and geophysical surveys (Holt 2017). Although it is wholly an offshore fault, it is included in this dataset because of a possible association with the onshore Kaikorai Fault interpreted by the writer in the Villamor et al. (2018) report. The writer now considers that there is a difficulty with that interpretation. There is evidence, afforded by what appears to be a fault scarp on the sea floor, that the Green Island Fault has experienced a geologically recent surface rupture, probably in the past few thousand years (Holt 2017). In contrast, there is no onland landform evidence for any fault scarp on the hill slope terrain on the line of the Kaikorai Fault, suggesting that it has not experienced a geologically recent surface rupture. It seems more likely that the indicated recent scarp on the Green Island Fault may be more closely associated with that of the Akatore Fault. For example, the Green Island Fault's most recent rupture(s) may have been triggered by geologically recent Akatore Fault rupture(s) or perhaps may have occurred independently in a similar time frame.

Offshore surveys indicate a length of ~16 km for the Green Island Fault. There is no information on the older geological history of movement of the Green Island Fault, for example, whether its rupture pattern is closely similar to that of the Akatore Fault. For the estimation of activity parameters for the Green Island Fault, a dip of 45° and slip rate of 0.05 mm/year (indicative long-term average rate for the Akatore Fault) are applied, from which a recurrence interval of ~22,000 years was calculated using the 2010 NSHM methodology.

A2.12 Hillfoot Fault (feature 10, Figure 5.1)

This west-northwest-striking fault is a major geological feature, separating two different types of basement rock (Mortimer et al. 2002) and is thought to have a near-vertical dip. The fault is marked by a prominent topographic step, up to the southwest. The vertical separation of the peneplain is typically as much as ~300 m. There are no known geologically young offsets of landform features along the fault in the Otago Region, and it is not in the NSHM or the NZAFD. The prominence of the topographic step, sometimes referred to as the Murihiku Escarpment, is the reason why it is included in this dataset as a potentially active fault. The fault continues into the Southland Region, and for the purpose of estimating potential seismic hazard, this part of the Hillfoot Fault is stopped at Gore, where there is a major cross-cutting fault that breaks the continuity of the escarpment. Farther northwest towards Lumsden, about 50 km west of the Otago region, Turnbull and Allibone (2003) did interpret a geologically young offset on a

~14 km long section of the Hillfoot Fault. This was an added factor in the decision made here to classify the Hillfoot Fault in Otago as potentially active.

Towards the southeastern coast, the Hillfoot Fault reduces in topographic prominence, and another strand, the Little Hillfoot Fault, is shown in QMAP as lying up to ~2.5 km northeast of the main strand. The topographic expression of the Little Hillfoot Fault is generally no more than 100 m or so, up to the southwest. It is mapped as extending offshore to about Nugget Point. In this dataset, both fault strands are classified as potentially active, and they are regarded as connected at depth.

For the estimation of activity parameters, a dip of 75°, length of 80 km and nominal slip rate of 0.05 mm/year are applied, from which a recurrence interval of ~110,000 years was calculated using the 2010 NSHM methodology.

A2.13 Horse Flat Fault (feature 21, Figure 5.2)

This northeast-striking fault is ~35 km long and upthrown to the northwest, with vertical separation of the peneplain of as much as ~200 m. The Horse Flat Fault (also known as the Taieri Ridge Fault) is inferred to be a northwest-dipping reverse fault. Only the southwestern ~2 km of the fault lies in the Dunedin district; the remainder is in the Waitaki District fault dataset, described by Barrell (2016).

Although not classified as active in the original QMAP dataset (Forsyth 2001); it has been reclassified as active in the QMAP database (Heron 2018). It is included in the NZAFD, NZAFM and NSHM (Litchfield et al. 2013). Previous estimates of fault activity parameters are discussed by Barrell (2016).

Interpretations have been made about possible deformation of geologically young landforms or deposits (Norris and Nicolls 2004), but these were regarded as equivocal by Barrell (2016). The fault is classified as a possible active fault in this dataset, following the reasoning presented by Barrell (2016). Villamor et al. (2018) identified it as a potential earthquake source. They considered various estimates for slip rate, ranging from 0.12 to 0.003 mm/year, and calculated corresponding average recurrence intervals in the range of ~17,000 years to more than 600,000 years. For the estimation of activity parameters for this report, a dip of 45°, a length of 35 km and a nominal net slip rate of 0.05 mm/year were applied, and a recurrence interval of ~49,000 years was calculated using the 2010 NSHM methodology.

A2.14 Hyde Fault (feature 20, Figure 5.2)

The northeast-striking Hyde Fault lies along the southeastern foot of the Rock and Pillar Range, which has been uplifted on the northwestern side of the fault. The vertical separation of the peneplain is as much as ~1200 m at the highest part of the range, northwest of Middlemarch. There is LiDAR coverage along most of the range-front. The following description progresses from northeast to southwest.

Northeast of Hyde village, the fault is classified as ‘likely, not expressed’, because its expression has involved an amount of folding. To the southwest, where the range becomes progressively higher, the fault is classified as ‘definite’, ‘not expressed’. At the Hyde gold diggings, the fault location in bedrock is well constrained (Norris et al. 1994) and is classified as ‘moderately expressed’. South of Heeney Creek, the position of the fault as located in the QMAP dataset has been refined with the aid of LiDAR. For about 15 km along the range-front, from Lug Creek in the north (~11 km north of Middlemarch) to the catchment of Doughboy

Creek in the south (~5 km west of Middlemarch), there are moderately to well-expressed fault scarps. The QMAP fault was shifted to accord to the fault scarp locations interpreted from LiDAR. Farther south along the range-front, the fault was repositioned to accord with the toes of landslide terrain at the foot of the slope. The reasoning for this is that the fault is inferred to lie at the foot of the range, that landslides are ubiquitous along this part of the range and that the toes of the landslides approximately define the foot of the range.

The topographic expression of the Hyde Fault diminishes southwest toward the headwaters of Sutton Stream, but thereafter an escarpment of tectonic origin becomes increasingly prominent towards the south (The Twins monocline; see separate section).

Recent geological investigations of the Hyde Fault, the data from which are still undergoing assessment, indicate that at least two ruptures, totalling about 4 m of uplift, have occurred in the past ~60,000 years (Jonathan Griffin, personal communication, July 2020). This implies a long-term vertical slip rate of ~0.07 mm/year. At that rate, it would have taken more than 10 million years to uplift the Rock and Pillar Range. There is also evidence from the geological investigations that the two most recent ruptures occurred in relatively quick succession, the earlier one ~23,000 years ago and the later one ~10,000 years ago. Taking the ~4 m uplift for those events and averaging it over ~23,000 years indicates a vertical uplift rate of 0.17 mm/year, at which rate the Rock and Pillar Range could have formed in the past ~5 million years. Either scenario for initiation of uplift is plausible. For the estimation of Hyde Fault activity parameters, an overall fault dip of 45° is assumed, and the faster vertical slip rate is preferred as it is more conservative from a ground surface tectonic deformation perspective. When the vertical slip rate is resolved onto a fault plane with an inferred pure dip-slip motion, this equates to a net slip rate of 0.25 mm/year. Taking the fault length as 50 km, an average recurrence interval of ~14,200 years was calculated using the 2010 NSHM methodology.

For comparison, Villamor et al. (2018) considered various estimates for slip rate ranging from 0.68 to 0.019 mm/year and calculated corresponding average recurrence intervals in the range of ~5600 to ~200,000 years. Stirling et al. (2012) applied a slip rate of 0.25 mm/year and calculated a recurrence interval of ~12,800 years. Overall, the Hyde Fault is assessed here as being a relatively low activity fault.

A2.15 Kaikorai fault (feature 18, Figure 5.2)

A2.15.1 Kaikorai valley

The existence of this northeast-striking fault is inferred from geological relationships (Villamor et al. 2018). There are differences in the elevations of the base of Dunedin Volcanic Group rocks either side of Kaikorai valley. Near the Southern Reservoir, on the west side of valley, the base of the volcanics is ~80 m asl (Glassey and Barrell 2000) but, on the ridge east of the valley, the base of the volcanics is ~140 m asl (McKellar 1990).

Farther up-valley, near the confluence of Frasers Gully and Kaikorai Stream, Benson's (1968) map shows a northeast-striking fault at the foot of the southeastern side of Kaikorai valley, with Caversham Sandstone up-faulted to the southeast against volcanics. The geological relationships depicted on Benson's map, when compared to the LiDAR elevation model, only require a throw of 35 m or so.

The southeastern side of Kaikorai valley is topographically prominent. Geologically, the southwestern side of Kaikorai valley comprises a general dip-slope of ~5° southeast off the crest of the Titri Anticline, approximating the base of Dunedin Volcanic Group. The underlying older geological strata dip a little steeper southeast (~10°), and progressively younger components of those strata are exposed approaching Kaikorai valley. In the Burnside – Green Island suburbs, Caversham Sandstone outcrops on the southeast side of the valley, forming a relatively steep 'scarp-slope' facing into the valley. This is a common landform associated with Caversham Sandstone outcrop in coastal Otago, because the sandstone is relatively stronger and more stable than the older formations. However, the topographic prominence of the southeastern side of Kaikorai valley continues to the northeast, beyond the Caversham Sandstone outcrop. At the head of Kaikorai valley, the prominent Maori Hill – Roslyn ridge is the continuation of this topographic promontory, but has volcanic rocks outcropping both sides of the topographic step. The height of the step decreases progressively northeast and dies out approaching the Leith valley. As the topographic step does not appear to be associated with a particular rock type, it lends weight to the interpretation that the step has a tectonic origin.

Towards the coast, between the Green Island and Waldronville suburbs, there is poor outcrop in the topographic escarpment. All previous geological maps (Ongley 1939; Benson 1968; McKellar 1990) show different outcrop patterns. A case could be developed for either no fault or for a fault with as much as ~100 m throw. If the outcrop pattern on McKellar's (1990) map is correct, it does highlight a difference in geological structure either side of Kaikorai valley. The outcrop pattern implies that, on the southeast side of the valley, the base of Caversham Sandstone has a gentle eastward dip of ~2 or 3°, and the base of Dunedin volcanics is near-flat near Kaikorai valley before developing a gentle eastward dip near St Clair. The contrasts in dip angle and dip direction either side of Kaikorai valley is the strongest evidence for the existence of the Kaikorai fault in the Green Island – Waldronville area.

Uncertainties of geological interpretation limit the confidence in mapping the position of the inferred Kaikorai fault. From the coast through Green Island suburb, the fault is drawn along a change from gentler slopes below to steeper slopes above. This position is compatible with stratigraphic exposure data shown on the Ongley (1939) and McKellar (1990) maps. Near the Burnside southbound off-ramp on the Southern Motorway, the fault is positioned as running out under the valley floor. It is drawn approximately along Kaikorai Valley Road until the Bradford suburb, where it is positioned along the southeastern margin of the valley floor. Near Brockville Road, the fault is drawn in the position of the fault shown on Benson's map. From there, it is continued along the broad valley on the northwestern margin of the Roslyn – Maori Hill ridge. The position there approximates the Kaikorai Stream channel, being as good a place as any to draw it. The fault is stopped at Balmacewan Road, where the ridge loses expression.

A2.15.2 Caversham valley and South Dunedin

Small fault offsets (centimetre to decimetre scale) were observed in the Lookout Point motorway overbridge excavation. They offset weathering colour-bands within highly weathered Caversham Sandstone, but the offsets do not extend up into the overlying loess, implying that the most recent movements occurred at least 100,000 years ago (Barrell and Litchfield 2013). Most of these faults have near-vertical dips, strike east-southeast and are downthrown to the north. There are also some shallow-dipping north-northeast-striking faults that dip gently east, with centimetre to decimetre scale displacements up to the west, implying a reverse component of movement. It was not possible to establish whether these faults are of tectonic origin or, alternatively, are related to slope movements. A subsequent inspection of a nearby deeper exposure found that the small-scale faults there do not extend down into the underlying less-weathered Caversham Sandstone. It was concluded that those small-scale faults were formed by gravitational movements within the highly weathered Caversham Sandstone rather than being fault-related phenomena (Barrell 2014). However, this does not preclude the possibility that a fault does pass through Lookout Point and, if so, most likely lies on the southeastern side of the overbridge (Ioannis Antonopoulos, Opus International Consultants, personal communication, 2013).

In Caversham valley, Caversham Sandstone is present on the southeast side of the valley, as seen in the railway tunnel portal, for example. In the Southern Motorway foundation excavation near the valley floor near Barnes Drive and at the Glen, saturated highly plastic clay was encountered that is suspected to mark the contact between Caversham Sandstone and overlying volcanic rock (personal observation of the writer). This provides a basis for tentatively inferring a fault, upthrown to the southeast by a few tens of metres, down the axis of Caversham valley and just south of the motorway through the Caversham suburb.

From there, the fault is extrapolated east, close to the position of the motorway and railway line, and on across South Dunedin to the margin of Otago Harbour.

A2.15.3 Overall Interpretation

The geological information is tentatively resolved to interpret the presence of a fault, upthrown to the southeast of as much as 50–100 m, along the eastern side of Kaikorai valley, with a splay extending east through Lookout Point and into South Dunedin, with perhaps a few tens of metres throw, up to the south. There are no known offsets or deformation of geologically young landform features or sedimentary deposits across the Kaikorai fault or its Caversham Valley splay.

For earthquake source modelling, Villamor et al. (2018) used a combined length of the Kaikorai fault and the offshore Green Island Fault. A problematic aspect of that approach is that the Green Island Fault is interpreted to have experienced a geologically young surface rupture, because a bathymetric step on the sea floor is interpreted to be a fault scarp (Holt 2017; Villamor et al. 2018). In contrast, there is no evidence for geologically young movement on the Kaikorai fault.

A feature of note is that the Kaikorai fault is broadly parallel to and 4–5 km southeast of the Titri Fault and Titri Anticline. It is conceivable that the Kaikorai fault is a splay at depth off the Titri Fault. If that is the case, then one possibility is that the Kaikorai fault may potentially rupture together with the Titri Fault rather than being an independently rupturing fault. That then raises a question as to whether the Kaikorai fault relates to an earlier phase of Titri Fault development and may no longer be active. Conversely, it could be an ongoing component of Titri Fault evolution. These possibilities are raised here for completeness but cannot be resolved from present information. It is regarded as most prudent to regard the Kaikorai fault as an independent entity for the purposes of this assessment.

Villamor et al. (2018) considered various estimates for combined Green Island / Kaikorai fault slip rate ranging from 0.04 to 0.001 mm/year and calculated corresponding average recurrence intervals in the range of ~35,000 to more than ~1.3 million years. For the estimation of activity parameters for this report, a length of 16 km is applied to the Kaikorai fault by itself (including the Caversham valley splay). Adopting a dip of 45° and a nominal net slip rate of 0.05 mm/year return a recurrence interval of ~22,000 years using the 2010 NSHM methodology.

A2.16 Murphys Creek Fault (feature 23, Figure 5.2)

This northeast-striking fault is ~35 km long and upthrown to the northwest, with vertical separation of the peneplain of as much as ~100 m. It is inferred to be contractional, with a dip to the northwest.

The fault is shown as inactive in the QMAP dataset and is not in the NZAFD, NZAFM or NSHM. There are no known offsets of geologically young landforms or deposits, and the fault is classified in this dataset as potentially active. Villamor et al. (2018) identified it as a potential earthquake source. They considered various estimates for slip rate ranging from 0.05 to 0.001 mm/year and calculated corresponding average recurrence intervals in the range of ~46,000 years to more than 1 million years. For the estimation of activity parameters for this report, a dip of 45°, length of 37 km and nominal net slip rate of 0.05 mm/year were applied and a recurrence interval of ~52,000 years was calculated using the 2010 NSHM methodology.

A2.17 Nichols Rock monocline (feature 25, Figure 5.2)

This north-northeast-striking feature forms a subtle topographic step, up to the northwest. Because it is a broad rather than sharp step, it is assumed to be a monocline rather than a fault at the ground surface. Villamor et al. (2018) characterised this structure as a potentially active fault, on the presumption that the monocline is underlain by a fault whose subsurface rupture would generate an earthquake. This feature was referred to as the ‘Nichols Rock’ active fault earthquake source by Villamor et al. (2018), and the name ‘Nichols Rock monocline’ is applied here after Nichols Rock Road, which crosses the monocline escarpment just east of State Highway 87.

The vertical separation of the peneplain across the monocline is as much as ~60 m. The best evidence of tectonic origin is adjacent to State Highway 87 near ‘Abbotsford’ farm, where a remnant of quartz sandstone, overlain by volcanic rock, is preserved on the peneplain at the foot of the monocline. North from there, the highway ascends the ~800-m-wide monocline, with the schist plateau at the crest of the monocline standing ~55 m higher than it does at ‘Abbotsford’. To the northeast, the monocline’s expression dies out at about the location where the southwestern end of the Flat Stream Fault scarp becomes evident, ~1.5 km to the northeast. To the southwest, the expression of the monocline is lost in irregular dissected terrain of the Lee Stream valley. The line representing the monocline is positioned at the foot of the topographic step.

There are no known offsets or deformation of geologically young landform features. Villamor et al. (2018) considered various estimates for slip rate ranging from 0.04 to 0.001 mm/year and calculated corresponding average recurrence intervals in the range of ~35,000 to more than ~1.3 million years. For the estimation of activity parameters for this report, a dip of 45°, length of 21 km and a nominal net slip rate of 0.05 mm/year return a recurrence interval of ~28,000 years using the 2010 NSHM methodology.

A2.18 Otanomomo fault (feature 9, Figure 5.1)

This east-west-striking fault is identified solely on the basis of landform offsets. It is named after the nearby Otanomomo locality. The fault has no general topographic expression across downlands terrain to the west and runs across two northwest-striking faults in bedrock shown in QMAP as part of the Livingstone Fault System. The fault scarp is most prominent where it is crossed by the Owaka Highway ~2 km south of Finegand meatworks. Previously mapped as a step between a higher and lower river terrace by Barrell et al. (1998), the availability of LiDAR makes it clear that it is a definite fault scarp. The main terrace, previously thought to be two terraces, has an ~4-m-high scarp at the highway, up to the north. About a kilometre to the east, there is a remnant inset terrace about 4 m lower than the main terrace, and it has a ~1- to 2-m-high fault scarp across it. A luminescence age of 134,000 ± 18,000 years was obtained by Barrell et al. (1998) on beach sand underlying the main terrace, indicating it is of last interglacial age. They also obtained a date from the base of a ~3.2-m-thick loess layer overlying the sand of 38,000 ± 7600 years. As it is the terrace surfaces that offset, a reasonable interpretation seems to be that the fault offsets occurred after at least part, if not all, of the loess had accumulated. On that basis, the fault is interpreted to have ruptured at least twice since ~45,000 years (older bound of the loess age).

It is noted that the new information from LiDAR means that the geomorphological map of he Inch Clutha Plains (Figure 4 in Barrell et al. [1998]) is now not correct in the Telford-Otanomomo area due to the new interpretations of fault scarps.

With the aid of LiDAR and aerial photos, the fault can be tracked as a distinct step on the downlands terrain to the west. It is mapped as ‘definite’, and either ‘moderately expressed’ or ‘not expressed’, for 3 km west of the Owaka Highway. Beyond there, its expression is less clear cut and it is classified as ‘likely’ for a further 3 km, beyond which it cannot be discerned. Towards the east, it is extrapolated as ‘not expressed’ across the Clutha floodplain and stopped before it meets the mapped location of the Livingstone Fault, on the presumption is does not cross that major geological structure.

With a total identified length of 10 km, the Otanomomo fault is too short to account for the size of surface offsets of as much as 2 m per event. This same problem exists for the Clifton Fault, farther to the northwest, which has similar expression in the landscape to that of the Otanomomo fault. For the estimation of activity parameters, the interpretation is made that those two faults are the surface expressions of the rupture of an unidentified fault at depth. The collective distance between the eastern end of the Otanomomo fault and the western end of the Clifton Fault is 27 km. Assuming both faults are reverse faults with a dip of 70°, and pure dip-slip motion, the Otanomomo fault scarp height of 4 m with an adopted age of 45,000 years equates to a 0.09 mm/year net slip on the fault plane, and a recurrence interval of ~19,900 years was calculated using the 2010 NSHM methodology.

A2.19 Settlement Fault (feature 11, Figure 5.1)

The northeast-striking Settlement Fault displays a vertical separation of the Catlins erosion surface of the order of 100 m, up to the southeast. The fault has uplifted a Holocene sea cliff and adjoining shore platform on the eastern side of Catlins Lake, demonstrating at least one surface rupture since the present sea level was attained in the mid-Holocene, ~7000 years ago (Clement et al. 2016). The villages of Pounawea and at Jacks Bay are built on former shore platforms raised above sea level by recent movement(s) on the Settlement Fault.

A2.19.1 Geological Character

The fault was originally mapped from geological relationships in the Jurassic-age greywacke bedrock that underlies the area (Speden 1971). Those relationships indicate that the geological sense of bedrock offset across the Settlement Fault is down to the southeast, of opposite sense to the current topographic sense of offset.

According to Speden (1971), most of the northeast-striking faults in the north-eastern Catlins area have a 'normal' sense of geological throw, and on his map notes the amounts of offset of distinctive stratigraphic contacts, where present. There is only one recorded offset on the Settlement Fault, at Purakaunui valley, of 1200 feet (~370 m) vertical component of offset down to the southeast. The interpretation is made here that the Settlement Fault is a re-activated former normal fault that originally accumulated vertical downthrow of ~500 m to the southeast. Movement has subsequently reversed, with ~100 m of vertical upthrow to the southeast seen across the Catlins erosion surface, which has partly restored the original stratigraphic offset.

A2.19.2 Location and Expression of the Fault

In the southwest, a well-expressed fault scarp is preserved at the south coast on the eastern side of a pocket beach, on the west side of the Irihuka (Long Point) headland. There is an uplifted Holocene sea cliff and shore platform immediately east of the fault scarp, but not to the west. LiDAR analysis indicates the scarp is about 2 m high. This location lies ~4 km west of where the Settlement Fault was previously drawn at the coast, at the eastern end of Tahakopa Bay by Speden (1971) and Bishop and Turnbull (1996), with a north-easterly strike to the Purakaunui River valley. That mapping of the fault was based on bedrock geological relationships, but neither the topographic expression of the Catlins erosion surface offset or the geologically young surface fault scarp follow that trend. The topographic expression and surface fault scarp at the coast instead take a more northerly trend and meet the geologically mapped position of the fault at the Purakaunui River valley. Either the original mapping interpretation was incorrect or the more recent movement on the Settlement Fault near Catlins Lake has diverged southward off the original fault.

Northeast of the Purakaunui River valley, the fault underlies steep and irregular hill terrain on the northwest side of Hinahina Hill through to the southern margin of the Catlins Lake estuary. There are some topographic anomalies on spurs low on the slope that may mark the fault location, but there is much evidence of past landslide and hillslope erosion activity, that could also account for topographic anomalies. Accordingly, the fault through this area is classified as 'not expressed'.

At the southwestern shore of Catlins Lake, the position of the fault has been shifted about 150 m west of where it was shown by QMAP to place it west of the Holocene sea cliff. Under Catlins Lake, the exact position of the fault is not known, and it is interpolated between points of geomorphic constraint at the southwestern and northern shores.

On the northern shore of Catlins Lake, Hinahina Rd runs along the foot of the uplifted sea cliff, and the uplift ceases where Hinahina Rd heads inland northeast towards Owaka. At that location, a short segment of the fault is classified as 'well defined'.

The fault scarp extends past the eastern outskirts of Owaka as a broad topographic step, in a few places with a more distinct break in slope. There is no LiDAR coverage through this area, so high-resolution colour aerial photographs, aided by Street View from the sealed roads, were used to refine the position of the QMAP line representation of the fault to more closely accord with the topographic features. It is classified as 'moderately expressed'.

Across the Owaka River valley floor northeast of Owaka township, the Owaka Highway is constructed approximately along the crest of the fault scarp. This is evident at the Owaka River bridge, where the valley floor is a wide poorly drained floodplain west of the road, but, east of the road, the valley floor is a terrace, about 1 or 2 m higher than the floodplain to the west, into which the river channel is incised. Due to the good constraint on fault location in this area, it is classed as ‘well expressed’, even though its detail is obscured by the roading earthworks.

For about 1 km on the northeast side of the Owaka valley, the fault scarp is unusually sharply expressed as a several-metre-high step along the hill slope, parallel to and about 170 m east of the Owaka Highway. Farther northeast towards the saddle where Dans Peak Rd branches off the highway, an alignment of changes in slope near the foot of the hill east of the highway are inferred to mark the fault scarp, classed as ‘definite’, ‘moderately expressed’.

Along strike northeast of there, there is no indication of a fault scarp or notable topographic step. A short ‘possible’ extension is drawn out into the Ahuriri Flat valley. Whether the most recent deformation on the Settlement Fault stopped at the Ahuriri Flat valley, or stepped elsewhere, is unknown.

A2.19.3 Evidence for Fault Rupture Events / Uplift Events

Based on microfossil faunas from sediment cores, Hayward et al. (2007) reported evidence for three Holocene earthquake events on the Settlement Fault, based on subsidence or uplift either side of the fault (determined by changes in water depth). The indicated events were ~1000 calendar years ago (0.4 m of subsidence – downthrow or compaction – west of the fault), ~3600 calendar years ago (1.2 m uplift of an extensive terrace on the east side of the fault) and an earlier event ~5000–4500 calendar years ago (1 m of abrupt subsidence west of the fault). Figueira and Hayward (2014) subsequently re-interpreted the earlier event as non-tectonic, arising from erosion and reworking of microfossils. At least one, but not necessarily more, Holocene rupture accounts for the uplifted shore platform, with timing of uplift at ~3600 years ago fixed by radiocarbon dating of a cockle shell on the platform (Hayward et al. 2007).

From a landform perspective, in several places where the fault is ‘moderately expressed’ across hill or downland terrain, the overall topographic step is usually 5 to 10 m high, substantially more than the 1–2-m-high scarp that displaces Holocene shoreline features at Catlins Lake and the south coast. This indicates that previous surface ruptures are preserved in the landscape, but the ages of those hill or downland surfaces are unknown. There are no mapped remnants of previous interglacial marine terraces along the coast southeast of the Settlement Fault (Speden 1971; Bishop and Turnbull 1996). This likely reflects a combination of the highly exposed coast, with an active cliff-line usually several tens of metres high, and relatively slow rates of uplift that means that any previously formed shore platforms have been removed during the Holocene.

There is only one likely remnant of a previous interglacial terrace southeast of the fault, near Catlins Lake about 1 km southwest of the Hinahina Road bridge over the estuary. This terrace remnant is alongside the C7 radiocarbon dating site of Hayward et al. (2007) that furnished the ~3600-year age of the Holocene terrace uplift. The higher terrace remnant is illustrated in Figure 7 of that paper as a suspected last interglacial (~125,000 years old) terrace. This site is just within LiDAR coverage, and the LiDAR data are consistent with that interpretation. LiDAR shows that the ~400-m-long by 400-m-wide terrace remnant is nearly flat, with an elevation of between 10 and 15 m above sea level (asl). Its northern margin is the ~3600-year-old sea cliff at the back of the ~2-m-asl uplifted Holocene shore platform.

In regard to the nature of the 10 to 15 m asl terrace, Figure 77 of Speden (1971) is a detailed inset map of this locality, showing fossil collection sites and bedrock structural data. There is a bedrock fossil collection site at the western edge of this terrace remnant and a bedrock dip and strike measurement in the middle of the terrace remnant. This suggests that the terrace is largely an eroded bedrock platform with little sediment cover.

The last interglacial peak sea level is generally regarded as having been ~5 m higher than present. Assuming that this terrace is ~125,000 years old and stands ~5 to 10 m above its assumed altitude of formation, this implies that between 5 and 10 m of uplift has occurred over the past ~125,000 years.

A2.19.4 Long-Term Slip Rate and Activity Estimates

The nature and estimated age of the 10 to 15 m asl terrace remnant described above implies a long-term uplift rate (including the most recent uplift[s]) of between 0.04 and 0.08 mm/year. The average of the two rate calculations (0.06 mm/year) is therefore taken as a satisfactory long-term uplift estimate at this location.

A longer-term estimate of vertical displacement rate can be made by assuming that the ~100 m offset of the Catlins erosion surface across the Settlement Fault was achieved over the past ~2 million years – an indicative reference age used by Barrell (2019) to calculate nominal slip rates for some faults farther inland in Otago. This implies a net long-term vertical displacement rate of 0.05 mm/year.

Collectively, the generally subdued nature of the fault scarp in most places, and the lack of flights of fluvial or marine terraces on the uplifted side of the Settlement Fault, is consistent with it being a relatively low activity fault over the long-term, but one that has experienced a geologically young rupture or ruptures.

The collective distance over which the 'definite' geologically young displacement features are mapped on the Settlement Fault is 19 km, from the south coast to the southwestern margin of the Ahuriri Flat valley. Allowing for small extension of the fault offshore to the south, and into the Ahuriri Flat valley, an overall fault length of 23 km is adopted, the same length as assigned by Stirling et al. (2012).

For a long-term estimation of activity parameters using the 2010 NSHM methodology, a fault dip of 45°, length of 23 km and slip rate of 0.08 mm/year (0.06 mm/year uplift since ~125,000 years ago, resolved onto a 45° dipping fault plane with assumed pure dip slip motion) return a calculated recurrence interval of ~20,000 years.

A2.19.5 Short-Term Slip Rate and Activity Estimates

The activity estimates assigned by Stirling et al. (2012) emphasise the Holocene movement evidence from the data of Hayward et al. (2007). Using an assigned fault dip of 45° and slip rate of 0.4 mm/year, they calculated a recurrence interval of 4000 years. The work of Figueira and Hayward (2014) has discounted the earlier event ~5000–4500 years ago. The uplift event ~3600 years ago is well constrained by geomorphology (raised shore platform and cliff) and radiocarbon dating of a cockle shell on the uplifted shore platform. A subsequent rupture event ~1000 years ago, inferred by Hayward et al. (2007), is regarded here as more equivocal than the evidence of the conspicuously uplifted Holocene terrace. However, it remains possible that the uplifted terrace is the composite result of two recent fault ruptures, an earlier and larger rupture ~3600 years ago and a smaller later one ~1000 years ago. Assuming that an overall vertical separation across the fault of ~2 m has occurred in at least two ruptures since ~3600 years ago indicates an average vertical slip rate of 0.56 mm/year. Resolved onto a 45°-dipping fault plane with assumed pure dip-slip motion indicates a net slip rate of 0.79 mm/year, and, with 23 km fault length, a recurrence interval of 1800 years is calculated.

A2.19.6 Summary

This review of information highlights similarities between the Settlement Fault and the Akatore Fault. Both have a north-easterly strike, similar length and similar total offset of the peneplain, or peneplain-like, surface. The Akatore Fault has well-demonstrated slow long-term slip rate, but a more recent re-activation since ~15,300 years ago, with at least three surface ruptures since that time and the most recent between ~1000 and ~750 years ago (Taylor-Silva et al. 2020). For the current episode of greater fault activity since ~15,300 years ago, they calculated an Akatore Fault slip rate of between 0.3 and 6.0 mm/yr and corresponding recurrence interval range of between 450 and 5110 years. More investigation would be needed to determine whether or not the Settlement Fault Holocene activity involved more than one rupture.

The available evidence indicates that the Settlement Fault has experienced a recent re-activation, possibly involving more than one recent rupture in the late Holocene. If this is the case, the short-term recurrence interval (~1800 years) is much less than the estimated long-term recurrence interval (~20,000 years) and implies an episodicity of fault rupture and a possibility that the fault may currently be in a more active phase. It is therefore regarded here as prudent to adopt the short-term recurrence interval of ~1800 years as the best current working estimate of activity.

A2.20 Silver Stream – Merton Fault (feature 16, Figure 5.2)

This feature extends northeast from the Taieri Plain along the valleys of Silver Stream and Waikouaiti River South Branch and then along the northwestern side of the Merton valley. The terrain is heavily dissected by erosion, and recognition of the fault is based on offsets of geological strata at either end of the fault; mapping of fault crushed rock on the Silver Stream valley floor (GNS Science unpublished data); and tentative reconstruction of the peneplain surface, from summit and ridge height accordance (Villamor et al. 2018). The fault system is upthrown to the northwest and is assumed to have contractional reverse motion.

At the north-eastern end of the Taieri Plain, the fault has produced vertical separation of the peneplain and basal Cretaceous–Cenozoic strata of the order of a few tens of metres. In the Merton valley, the vertical separation is ~100 m, with uplift of the peneplain on the northwestern side of the fault diminishing northeast. The peneplain meets sea level on the western side of the Waikouaiti valley, near the presumed northern end of the fault.

Peneplain reconstruction indicates a maximum vertical separation of about 300 m, at a dome-like structure centred on the Silver Peaks. The picture is complicated by the presence of the Titri Anticline on the southeast side of the fault, which makes the apparent vertical separation across the fault less than would otherwise be the case. The Silver Peaks dome is about the same extent, and of similar height above sea level to the Maungatua dome. Remnants of the tilted peneplain are preserved locally on western parts of the dome at Mt John and Lamb Hill. The Silver Peaks dome has been heavily dissected by stream and gully erosion, giving it a different appearance to the largely undissected Maungatua dome.

The Silver Peaks lie adjacent to a north-northeast-striking section of the Silver Stream – Merton Fault, with lesser throw on northeast to east-northeast-striking sections of the fault. This is similar to the association of fault strike and throw seen on the Maungatua – North Taieri Fault (see separate section) and is suggestive of a component of oblique dextral motion on east-northeast-striking sections of the fault.

It is assumed that the Silver Stream – Merton Fault and the Maungatua – North Taieri Fault are adjacent structures, with one dying out where the other starts. It is also assumed that the fault underlying the Titri Anticline terminates against the Silver Stream – Merton Fault.

The Silver Stream – Merton Fault system is shown as inactive in the QMAP dataset (Bishop and Turnbull 1996) and is not included in the NZAFD, NZAFM or NSHM. There are no known geologically young offsets of deposits or landforms on the Silver Stream – Merton Fault, and in this dataset it is classified as 'potentially active'.

Villamor et al. (2018) identified the Silver Stream – Merton Fault as a potential earthquake source. They considered various estimates for slip rate ranging from 0.16 to 0.004 mm/year and calculated corresponding average recurrence intervals in the range of ~12,700 to more than ~400,000 years. For the estimation of activity parameters for this report, a dip of 45°, length of 35 km and nominal net slip rate of 0.05 mm/year were applied, and a recurrence interval of ~49,000 years was calculated using the 2010 NSHM methodology.

A2.21 Spylaw Fault (feature 1, Figure 5.1)

The northeast-striking Spylaw Fault has prominent topographic expression, having uplifted a peneplain remnant by as much as 200 m on its southeast side. It has long been regarded as an active fault (e.g. Beanland and Berryman 1986; Pace et al. 2005). It is included in the NZAFD, NZAFM and NSHM (Stirling et al. 2012; Litchfield et al. 2013).

The main evidence for geologically recent activity on the Spylaw Fault is the presence of a prominent step on a terrace beside Spylaw Burn, illustrated in Figure 6 of Pace et al. (2005). This terrace is interpreted to have been offset with vertical separation of between 3 and 7 m. Pace et al. (2005) reported a luminescence age of 39,200 ± 3400 years for the interpreted uplifted terrace from near the base of a ~2.7-m-thick silt deposit, interpreted as loess, overlying the stream gravel of the terrace. The low, interpreted downthrown, side of the fault scarp is close to modern stream level. The ~2.7 m loess cover on uplifted side of the interpreted fault scarp implies the stream gravel stands only about half the terrace height above stream level, suggesting that the uplift would only be a little more than half the upthrown terrace height. In addition, loess accumulation requires a land-surface rather than a stream bed, so it is likely that the loess accumulation began after the terrace became elevated above stream level. If the terrace was elevated by faulting, the age for the basal loess may be a minimum age for that uplift. On balance, that is the interpretation preferred here for the data presented by Pace et al. (2005). Assuming a tectonic uplift of ~3.5 m of the stream gravel, and indicative age of ~40,000 years for that uplift, indicates a vertical slip rate of 0.09 mm/year. If resolved onto a fault plane dipping 45° with assumption of pure dip slip motion, this gives an average net slip rate of 0.11 mm/year, which equates to the minimum slip rate estimate provided by Litchfield et al. (2013).

Another possibility is that the elevated terrace at Spylaw Burn owes its origin to stream erosion (i.e. stream downcutting and lateral trimming) rather than fault uplift. Examination of archival air photos indicates that there is no comparable step on alluvial fan terrain to the northeast or southwest on the projected line of the fault. This terrain contains elements of likely similar age to the terrace beside Spylaw Burn, and evidence for a comparable fault scarp should be present across that terrain. There are scattered topographic features to the southwest along the line of the fault that, in isolation, resemble fault scarps. However, they lack continuity across adjacent landforms of similar age, indicating that they are more likely topographic steps formed by river or stream erosion, or in some cases, landslide movement. Most are topographic steps on dissected overlapping alluvial fans, where intersecting and merging stream channels can leave isolated step-like benches.

Overall, this review of information raises questions about the interpretation of landform features along the line of the Spylaw Fault thought to be related to geologically recent fault rupture. In addition, if these features are of fault origin, there are reasons to prefer a slip rate at the lower end of previous estimates.

Near Spylaw Burn, the offset of the peneplain diminishes rapidly in height north-eastwards, but, 2 km to the southeast, another fault offset of the peneplain commences, and the offset grows in size towards the northeast. This en-echelon relationship between the two faults is interpreted as them both being branches (splays) of a single fault at depth. Although the northeast splay fault is given a different name in QMAP (Turnbull and Allibone 2003; Heron 2018), the 'Park Hill – Dunrobin Fault', they are both called Spylaw Fault in this dataset. The north-eastern splay has no known indications of geologically young landform offsets (Pace et al. 2005). Both of these en-echelon strands are included in the Spylaw Fault entity as delineated in the NZAFM and NSHM, while only the western strand is included in the NZAFD.

Based on the considerations above, the western strand of the Spylaw Fault (proper) is classified as 'possible', the possible fault scarp at Spylaw Burn is classified as 'moderately expressed' and the remainder of the fault is classified as 'not expressed'. The eastern strand (Park Hill – Dunrobin Fault) is classified as 'potentially active', 'not expressed'.

In both the NSHM and NZAFM, the Spylaw Fault entity is given a length of ~50 km. This is achieved by extending the Spylaw Fault, as delineated in QMAP, southwest for ~20 km along mapped bedrock faults that have an opposite sense (upthrow to the northwest) to that of the Spylaw Fault. It is preferred in this report to restrict the Spylaw Fault to the geological structure that has upthrown the peneplain to the southwest, which has an overall length of ~30 km. For the estimation of activity parameters for this report, a dip of 45°, length of 30 km and re-estimated net slip rate of 0.11 mm/year were applied and a recurrence interval of ~19,000 years was calculated using the 2010 NSHM methodology. This is somewhat more than the ~12,400-year recurrence interval given in the NSHM (Stirling et al. 2012).

A2.22 Teviot Fault (feature 2, Figure 5.1)

The north-northwest-striking Teviot Fault lies mostly in the Central Otago District, with only the southern 3 km of the fault extending into the Clutha District. The fault characteristics were described by Barrell (2019), and a summary of the description of the fault from the appendix of that report is presented below.

The peneplain has an indicated up-to-the-west vertical separation of as much as ~300 m across the Teviot Fault. It is assumed to be a west-dipping reverse fault, with no known offsets of geologically young landform features, and is classified as 'potentially active'. Based on similarities to the nearby Old Man Fault, the Teviot Fault was assigned the same slip rate as the Old Man Fault (0.01 mm/year) and a length of 32 km, from which a recurrence interval of ~225,000 years was calculated using 2010 NSHM methodology.

The Teviot Fault is mapped here as ending southward at the Blue Mountain Fault. However, see the section on the Blue Mountain Fault for discussion of this interpretation.

A2.23 The Twins monocline (feature 19, Figure 5.2)

This north-northeast-striking feature forms a prominent topographic step, up to the west. It is shown in the QMAP dataset as a monocline that is expressed in the foliation (layering) in the schist rock. The vertical separation of the peneplain across the monocline is as much as ~400 m. The northern half of the structure comprises two parallel monocline strands. The western one was the one shown in QMAP, and the eastern one is inferred from topographic expression. Villamor et al. (2018) characterised the structure as a potentially active fault, on the presumption that the monocline is underlain by a fault whose subsurface rupture would generate an earthquake. In this dataset, the feature is represented as a monocline as befits its surface geological character. The lines representing the monocline are positioned at the foot of the topographic step. This feature was referred to as the 'Hyde South – The Twins' earthquake active fault source by Villamor et al. (2018). Here, the surface geological structure is referred to as 'The Twins monocline', after a peak on the elevated side named on the Topo 50 map.

There are no known offsets or deformation of geologically young landform features. Villamor et al. (2018) considered various estimates for slip rate ranging from 0.25 to 0.007 mm/year and calculated corresponding average recurrence intervals in the range of ~5900 to more than ~200,000 years. Because it is essentially contiguous with the Hyde Fault, but the topographic expression is only about half of that of the Hyde Fault, a net slip rate for The Twins monocline structure of 50% of that applied to the Hyde Fault (i.e. 0.125 mm/year) is inferred. For the estimation of activity parameters, a dip of 45°, length of 23 km and net slip rate of 0.125 mm/year return a recurrence interval of ~12,700 years using the 2010 NSHM methodology.

A2.24 Titri Fault (feature 12, Figure 5.2)

The Titri Fault is a major northeast-striking system of faults. Uplift on the southeastern side of the fault has elevated a range of coastal hills, which separates the low-lying Taieri and Tokomairaro plains from the coast. It is sometimes referred to as the Titri Fault System or Titri Fault Zone, but the simpler term 'Titri Fault' is preferred in this report.

The Titri Fault and geological relationships either side of it have been much studied since the 1950s, and the background is set out in the publicly available paper by Litchfield (2001) and report by Barrell et al. (2020), to which an interested reader should refer. In summary, the Titri Fault was originally a normal fault, with displacement down to the southeast during the mid- to late Cretaceous Period, ~100 million years ago. Contractional deformation in the Late Cenozoic (within the last ~20 million years) has re-activated the Titri Fault with reversal of movement that has uplifted the southeast side, forming the coastal hills.

In the southwest, the north-striking Castle Hill Fault was also a Cretaceous normal fault whose movement allowed a thick sequence of Taratu Formation coal measures to accumulate on the eastern, downthrown side of the fault at the Kaitangata Coalfield, with a much thinner sequence of Taratu Formation strata to the west (Harrington 1958). The Castle Hill Fault has also experienced reversal of movement in the Late Cenozoic and is regarded as a component of the re-activated Titri Fault (Litchfield 2001).

The dataset described in this report is based on the QMAP dataset. The original QMAP linework depicting the fault was compiled by Bishop and Turnbull (1996) from existing geological map information. Considerable refinements to the fault mapping and interpretation were made by Litchfield (2000, 2001). Those refinements were subsequently incorporated into the QMAP dataset (Heron 2018). In the late 2010s, further mapping, trenching and dating along the Titri Fault, aided greatly by the availability of LiDAR coverage, introduced further refinements to the mapping and interpretation (Barrell et al. 2020), which are compiled into the dataset described in this report.

The LiDAR, coupled with the identification of definite fault scarps from trenching, has provided a strong interpretive basis for focusing on topographic features in the mapping of the fault. The QMAP dataset placed more reliance on identifying fault locations from geological relationships, because few fault scarps were previously identified. The recent recognition of more scarps raises the confidence of placing faults along the foot of prominent topographic steps.

A2.24.1 Background on Fault Mapping and Interpretation

The terminology follows that provided by Litchfield (2001). In the north, the Titri Fault structure is characterised predominantly by a large anticline, the Titri Anticline, which is evident northwards from the Saddle Hill / Chain Hills area. The central section of the fault is characterised by what has been referred to as the ‘master fault’, at the foot of the main hills, and is regarded as the location where the bulk of previous fault movement has occurred and which, over long geological time (e.g. several million years), has elevated the coastal hills. At the northwestern foot of the main hills is a strip of low rounded hills and terraces. The northwest margin of that strip is regarded as the location where the most recent movements of the Titri Fault have broken out at the ground surface. That movement zone has been referred to as the ‘frontal strand’ of the fault. Geographically, the frontal strands are divided into three sections. From north to south, these are the Allanton section from about Three Mile Hill southwest to near Henley, the Waihola section from near Henley southwest to the Tokomairaro River (note recently gazetted revision of spelling) and the Misery section from the Tokomairaro River to the hill country north of Kaitangata. The Misery section has a parallel component to the northwest, approximated by the Castle Hill Fault, which lies along the southwestern margin of the coastal hills.

The Titri Fault had previously been extrapolated through the western side of the Dunedin urban area in the upper part of the Water of Leith catchment by Bishop and Turnbull (1996). The assessment by Villamor et al. (2018) found that the geological structure in the upper Leith catchment could not be reconciled by that model, as there was no clear indication of continuity between that structure and that of the Titri Fault to the southwest in the Taieri basin. Instead, they highlighted that the Titri Anticline structure is also evident in the geological structure of the Dunedin Volcanic Group rocks of the high ridge that includes the summits of Flagstaff and Swampy Summit, a point previously identified by Barrell (2002). That interpretation is adopted in this dataset.

A2.24.2 Commentary on Fault Mapping and Interpretation

This commentary on fault mapping and interpretation proceeds from southwest to northeast.

At Kaitangata township, two points of information bear upon the location of the Castle Hill Fault. A shaft at the former Castle Hill Mine, about 215 m east of the Eddystone Street / Bembridge Street intersection, according to location coordinates in Harrington (1958), encountered a major reverse fault at ~80 m depth, dipping 60° east (Castle Hill Reverse Fault, as named by Harrington [1958]), which has emplaced Taratu Formation coal measures up over younger marine strata of likely early Eocene age and correlated with the younger part of the Wangaloa Formation. At Kaitangata Mine, the main shaft (also known as Shore's Shaft), about 280 m east of the Selcombe Street / Start Street intersection, passed through at least 200 m of steeply west-dipping coal measures strata, presumably beneath which lies a major reverse fault. Its location approximates the edge of the uplifted coastal hills. It is classified as 'possible', 'not expressed'. The position of the fault through Kaitangata shown on Harrington's (1958) map does not accord with the location or information provided by Harrington for the Castle Hill Mine shaft. The fault has been repositioned along the foot of the hills at the eastern margin of Kaitangata township. There is no indication of offset of any geologically young landforms. Northeast from Lake Tuakitoto, the fault coincides with a topographic step of as much as a few tens of metres, up to the east. This is inferred to be fault-related topography, and the fault is classified as 'moderately expressed'.

East of the Castle Hill Fault, there is another prominent, up to the east, topographic step, extending through hill terrain from the southern end of the Tokomairaro basin south to near Kaitangata. It coincides with mapped faults and is referred to here as the 'Misery section' of the Titri Fault, after Mt Misery near Moneymore. It was referred to in part as the Hillfoot Fault by Litchfield (2001), but a more generic name is applied here to save any confusion with the previous nomenclature for specific faults in the Kaitangata Coalfield. The topographic step is as much as 200 m high in the north, decreasing to a few tens of metres in the south. In the north it is classified as 'likely', due to proximity of 'likely' and 'definite' fault scarps near Moneymore (Moneymore 1 and Moneymore 2 traces) and 'possible' farther south. Because the topographic step is not sharp and lies in terrain generally dissected by erosion, it is classed as 'not expressed'.

The Moneymore traces comprise two parallel scarps, one at the foot of the range (Moneymore 1), classed as 'likely', and one ~0.5 km to the northwest out in the basin (Moneymore 2), classed as 'definite'. In the Moneymore area, the master fault at the range-front is identified as the Misery section, with which it has continuity to the south. However, adjacent to the 'likely' and 'definite' Moneymore traces, the Misery section at the range-front is classed as 'possible', on the presumption that the geologically more recent activity has migrated to the Moneymore traces.

On the Waihola section, offsets of geologically young deposits due to rupture of the Titri Fault have been identified by trenching at two locations, one at Glenledi Road ~2 km east of Milton and the other at the Clarendon rural locality ~8 km northeast of Milton (Barrell et al. 2020). That information provides a basis for mapping the approximate position of the fault along the foot of topographic steps at the northwest margin of low hill terrain and terraces in a similar setting to that present near Moneymore. Only the locations where fault offsets have been demonstrated by trenching are identified as ‘definite’. Other locations where topography indicates the presence of the fault are classed as ‘likely’. Southwest of Lake Waihola, where the northwestern margin of the low hill and terrace terrain is generally continuous, the fault is classified as ‘moderately expressed’. Where the continuity is disrupted by stream valley erosion and adjacent to Lake Waihola and the Taieri-Waipori river plains, where erosion has trimmed the northwest edge of the low hill/terrace terrain, the fault is classed as ‘not expressed’. Throughout the area northeast of the Tokomairaro River, the master fault is classified as ‘potentially active’, on the presumption that the geologically more recent activity has been on the frontal topographic step.

At Tokomairaro River, there is an apparent discontinuity of the character of the range-front. It has been suggested that this represents a kinematic break in the Titri Fault, with those parts of the fault northeast and southwest of the Tokomairaro River rupturing independently, at least on some occasions (Villamor et al. 2018; Barrell et al. 2020). There is prominent topographic relief on the east side of the Tokomairiro Fault, which strikes south down the river valley, and it is classified as ‘potentially active’ in recognition that it could conceivably accommodate movement were the Titri Fault northeast of there to rupture independently of the Moneymore section.

On the Allanton section, Litchfield (2001) drew the frontal strand northeast of the lower Taieri gorge near Henley as merging with the master fault at the foot of the range. This dataset follows QMAP in drawing the fault as ‘not expressed’ ~0.5 km northwest of the foot of the range. The reasoning is that, near Waihola and between Allanton and Wingatui, the frontal strand is consistently about that distance out from the foot of the range. The interpretation is that, in the general area of Henley, erosion has removed the distinctive hill and terrace terrain that elsewhere lies southeast of the frontal strand of the fault.

From Allanton northeast to Wingatui, the northwest margin of the low hill and terrace terrain is partly continuous, broken by minor stream valleys draining northwest into the basin. Drainage of this sector of the Taieri Plain is to the southwest, creating potential for stream action to have eroded the margin of the terrain. However, the margin of the terrain shows a somewhat sinuous form, similar to that seen southwest of Lake Waihola where the fault escarpment is thought to have suffered little if any erosion. Therefore, the interpretation is made that the Allanton section frontal strand lies just northwest of the low hill and terrace terrain but is classified as ‘not expressed’ to signal some uncertainty regarding fault location. There is no evidence as to whether the most recent ruptures on the Waihola section extended along the Allanton section, but it is assumed that they did, and the Allanton section is classed as ‘likely’.

Northeast of Wingatui, the Titri Fault projects into hill terrain. Its position there is taken from geological mapping, and it is classified as a ‘possible’ active fault because it is not known whether the most recent surface ruptures have extended that far northeast along the fault. In this area, the Titri Anticline is the most prominent aspect of the Titri Fault structure, providing further reason to consider that past ruptures may not have reached the ground surface in this area. At Three Mile Hill Road, unpublished mapping by Liggett (1975) documents the character of the fault by the nature and attitude of bedding in the Dunedin Volcanic Group.

The mapping places the anticline axis ~0.5 km north of the intersection between Three Mile Hill Rd and Halfway Bush Rd. The anticline has a gentle southeast limb and a steep northwest limb. About 60 m northwest of the axis, the strata are overturned, and Liggett's (1975) cross-section interprets a fault at that location. This is included in the dataset as a 'possible' fault. Probably this is not the Titri Fault as a whole, but it could be regarded as a splay off of it. To indicate the probable association, a 'potentially active' connection is drawn between this fault and the end of the 'possible' Titri Fault ~3 km to the southwest near Abbotts Hill.

A2.25 Estimation of Titri Fault Activity

On the northern side of the mouth of the Clutha River / Matau Branch is an elevated flat bench, interpreted to be a marine terrace, near the locality of Summer Hill. A modern river-cut cliff at the terrace margin shows bedrock outcrop extending at least half to two-thirds of the height of the cliff (personal observation of the writer). The terrace surface is 30 m asl, based on LiDAR information. These general observations suggest the marine-erosion surface on bedrock is between ~15 and 20 m asl, and Bishop and Turnbull (1996) map it as being of last interglacial age (~125,000 years ago). It is generally regarded that, at the time, the sea level was ~5 m higher than today. That implies that the marine erosion surface has been uplifted by between 10 and 15 m, which equates to a long-term average uplift rate of ~0.1 mm/year. Because of the assumptions used, this should be seen as no more than an indicative estimate.

Data from the trenching and dating investigations on the Waihola section indicate that the Titri Fault has ruptured at least twice in the past ~38,000 years (Barrell et al. 2020). The earlier rupture occurred sometime between ~38,000 and ~28,000 years ago, followed by another one sometime before ~18,000 years ago. The collective vertical separation from those ruptures was ~3.5 m. Barrell et al. (2020) concluded that the Titri Fault has a slip rate in the range of 0.1–0.2 mm/yr and recurrence interval in the range of ~7000 to ~19,000 years, with a preference towards the longer end of that range.

The question remains as to whether the Titri Fault experiences episodicity of rupture activity similar to what has been shown for the Akatore Fault. The data from the Titri Fault are inconclusive in that regard. In combination with the tentative information from the uplifted terrace at the Clutha River mouth, the net fault slip over the past ~38,000 years from the Waihola section suggest the vertical component of movement (approximating uplift) from that time period is similar to the average uplift rate since ~125,000 years ago. This could be interpreted to mean that the Titri Fault ruptures are relatively regular, or that periods of quiescence are relatively shorter than the >100,000 years found for the Akatore Fault by Taylor-Silva et al. (2020).

Using data from the Titri Fault rupture history investigations reported by Barrell et al. (2020), Villamor et al. (2018) considered a range of fault segmentation scenarios and slip rates and calculated recurrence intervals in the range of ~5000 to more than ~40,000 years.

For the purpose of this assessment, an average slip rate of 0.15 mm/year and an indicative average recurrence interval of 19,000 years (based on two ruptures in the past ~38,000 years) are adopted for the Titri Fault.

A2.26 Tuapeka Fault (feature 4, Figure 5.1)

The northwest-striking Tuapeka Fault is a prominent geological feature of the Lawrence to Waitahuna areas. The Tuapeka Fault is a southwest-dipping normal fault of Cretaceous age (Els et al. 2003), mapped as extending from Raes Junction in the north for ~55 km southeast to near Milton. The crushed zone of the Tuapeka Fault is exposed on the western side of the Beaumont Highway (State Highway 8), about 3 km north of the Beaumont Hotel, marked by barriers to keep debris from falling onto the road. The plane of the Tuapeka Fault is extensively exposed in the Gabriels Gully historic gold mining area near Lawrence (Els et al. 2003), who found that the fault dip ranges from 26° to 60°.

A2.26.1 Evidence for and Interpretation of Geologically Young Fault Offsets

Near the northwestern end of the fault near Beaumont, ~0.8 km west of the Beaumont Hotel, there is a several-metre-high topographic step crossing remnants of medium- to high-level river terraces on the western side of the Clutha River valley. This suspected fault scarp is on the projected line of the Tuapeka Fault and is up to the southwest, indicating reversal of the original Cretaceous sense of fault movement. There are two closely spaced river terrace levels, and the scarp height is about the same on both terraces. On trend immediately to the northwest is a similar, though broader, step on the axis of a ridge separating a minor stream catchment from the Clutha valley. Nowhere else on the Tuapeka Fault is there any known evidence for geologically young offsets.

The Clutha River terraces west of Beaumont are fortuitously preserved remnants of old landforms, in a setting where they have largely escaped erosional modification. Elsewhere along the Tuapeka Fault, the terrain is mostly moderate to steep hill country, subject to much more recent, and ongoing, natural landscape evolution. It is therefore possible that only at Beaumont have the most recent movement(s) of the Tuapeka Fault been preserved. Another possibility is that the fault scarp at Beaumont is the result of slip having transferred onto part of the Tuapeka Fault during rupture(s) of another nearby active fault. The Blue Mountain Fault is the most likely contender, as it has experienced geologically recent ruptures, whereas no geologically recent activity is known on the Teviot Fault. This possibility contributes to the interpretation of fault activity below.

A 4-km-long section of the fault is shown as 'active' on QMAP (Turnbull and Allibone 2003) and the remainder of the fault classified as 'inactive'. The 'active' section of the Tuapeka Fault is included in the NZAFD, but the Tuapeka Fault is not included in either the NZAFM or 2010 NSHM. In compiling the dataset described in this report, the line depicted in QMAP for the 'active' section of the fault has been refined in position to accord better with the fault-related landform features evident in high-resolution photographic resources (aerial imagery and Google Street View). The topographic step near Beaumont runs transverse to the Clutha River terrace features and affects several different-age landform features. However, there is a faint possibility that the topographic step could be due to some sort of slope instability, and so it is classified as 'likely' fault scarp, although it is close to qualifying as 'definite'. The classification of likely' is extended ~3.5 km east of Beaumont, with the fault classified as 'not expressed' under the low terraces of the Clutha River and the broad valley floor of its Low Burn tributary. From there, the fault takes a more southeasterly strike and is classified as 'potentially active', due to an absence of direct evidence for any geologically recent surface offsets of landforms. The reasoning is that slip transfer is unlikely to extend much beyond the uplifted Blue Mountains fault block, if there is validity to the possibility that the Blue Mountain Fault is the origin of the primary slip (see paragraph above). The section of the Tuapeka Fault north of the intersection with the Blue Mountain Fault is also classified as 'potentially active'.

A2.26.2 Estimation of Tuapeka Fault Activity

The lowest (i.e. youngest) terrace that displays the suspected fault scarp at Beaumont was interpreted to be of Penultimate Glaciation age (i.e. older than ~130,000 years) by Turnbull and Allibone (2003), and the adjacent next lowest terrace that is not displaced was assigned an age of Early Last Glaciation (~60,000 to 70,000 years). There is a view that the ages used in QMAP for the glacial moraines and meltwater outwash terraces of the upper Clutha valley have been overestimated (Barrell 2011), and the writer considers this is also the case in the Beaumont area. A key geomorphological consideration is the lowest river terrace of the Beaumont basin, which stands only a few metres above river level and to which QMAP assigned an age of Late Last Glaciation (~20,000 years). Sizeable tributary streams drain onto the western margin of this broad terrace surface but have constructed only small alluvial fans, much smaller than would be expected if the terrace were really that old. On that basis, the broad lowest terrace is interpreted here to be of post-glacial age, probably no older than ~10,000 years. The next higher terrace, on which the Beaumont Hotel is built, is not offset by the fault and is suggested here to be Late Last Glaciation (~20,000 years old). The lowest faulted terrace is suggested to be of Early Last Glaciation age (~65,000 years old). The adjacent ridge, whose crestline has what appears to be an offset of similar size to that on the next lower terrace, is indicated by Turnbull and Allibone (2003) to be a remnant of a much older river terrace. The ridge stands ~50 m above Clutha River level, and, based on information on terrace ages from the upper Clutha valley (Barrell 2011; GNS Science unpublished data), the writer estimates that ridge landform to be at least 200,000 years old.

Based on the inferences above, the Tuapeka Fault at Beaumont is estimated to have experienced at least one surface rupture between ~20,000 years ago and ~65,000 years ago but, before that, no surface rupture back to at least ~200,000 years ago. Taking the scarp height as a nominal ~5 m high, accrued since ~200,000 years ago, implies a long-term vertical slip rate of no more than 0.025 mm/year (rounded to 0.03 mm/year). In regard to the interpretation that the Tuapeka Fault offsets are due to slip transfer from another fault, likely the Blue Mountain Fault, which has a vertical slip rate of ~15 mm/year, it implies either a relatively small slip transfer onto the Tuapeka Fault, or that that transfer does not occur during every rupture.

The Tuapeka Fault was assigned a recurrence interval in the range of ~250,000 to ~680,000 years by Villamor et al. (2018) through the application of a slip rate of 0.01 mm/year. The slip rate estimated above for the Beaumont area can be considered a maximum for the Tuapeka Fault as a whole, if the slip transfer interpretation is correct. Assuming an average fault dip of 45° and pure dip-slip motion, a vertical slip of 0.03 mm/year translated to a net slip rate of 0.04 mm/year. In conjunction with a fault length of 55 km, a recurrence interval of ~95,000 years is obtained using the 2010 NSHM methodology.

A2.27 Waipori – Maungatua – North Taieri Fault (feature 15, Figure 5.2)

These faults form a prominent escarpment along the northern margin of the Taieri Plain. As defined in this dataset, this entity comprises three separately named components from the QMAP dataset, from west to east: the southeast- to east-striking Waipori Fault, the northeast-striking Maungatua Fault and the east-striking North Taieri Fault. Upthrow is to the northwest and north, respectively. Uplift reaches a maximum at Maungatua hill, where the peneplain has been up-domed to as much as ~900 m above sea level with uplift diminishing both to the east and west. At the eastern end, near North Taieri, uplift of the peneplain and locally preserved overlying Late Cretaceous to Cenozoic strata diminishes rapidly, with the peneplain surface descending to as little as 100 m above sea level. This is interpreted to mark the eastern limit of this fault structure. At about the same location, another fault structure, identified as the Silver Stream – Merton Fault, becomes evident and increases in throw northeastwards (see separate section).

This system of faults is inferred to be contractional, and the maximum uplift, being adjacent to the northeast-striking Maungatua Fault, raises the possibility that the east-striking Waipori and North Taieri faults may be oblique-slip with a component of right-lateral motion. Structurally, the western component, the Waipori Fault, is likely to accommodate any slip differential between the northwest-facing Waitahuna Heights Fault and the southeast-facing Maungatua Fault.

All these faults were shown as inactive in the original QMAP dataset (Bishop and Turnbull 1996). Using aerial photos, Barrell et al. (1998, 1999) interpreted discontinuous topographic steps along the southeastern foot of Maungatua hill, and on old alluvial fan terraces at the foot of the North Taieri Fault escarpment, as Late Quaternary fault scarps. These were subsequently incorporated into the QMAP digital dataset (Heron 2018) and the NZAFD.

However, recent field observations and examination of LiDAR datasets has led the writer to revise his previous interpretation that these features are fault scarps. There is insufficient lateral continuity across adjacent similar-age landforms to support a fault origin for these topographic steps. Instead, it is more likely that they are fluvial erosion features or, in some cases, possibly toe thrusts of landslides. An important consideration is that the Taieri River system has tended to erode down into its valley floor during episodes of glacial climate due to lowered sea level (Barrell et al. 1999), and its tributary streams would have responded similarly. This likely would have imparted a stronger southwesterly drainage grain down the Taieri Plain than prevails in today's regime of generally impeded drainage, as well as the building of broad alluvial fans out towards the axis of the plains. Under a glacial climate fluvial regime, the main tributaries of the north-eastern part of the Taieri Plain, Mill Stream and Silver Stream would likely have episodically eroded the foot of the North Taieri Fault escarpment, creating overlapped and terraced alluvial fans that have topographic anomalies superficially resembling fault scarps.

The writer considers that there is currently no convincing evidence for geologically young fault offsets of landforms along the Maungatua or North Taieri faults or along the Waipori Fault. This system of faults is therefore classified in this dataset as 'potentially active'. It remains a possibility that some evidence for fault activity may come to light in the future and so may warrant a change in classification.

Villamor et al. (2018) identified the Maungatua – North Taieri Fault (including the Waipori Fault) as a potential earthquake source. It has not previously been included in the NZAFM or NSHM, although the previously interpreted fault scarps (now interpreted otherwise) are included in the NZAFD. Villamor et al. (2018) considered various estimates for slip rate for the Maungatua – North Taieri Fault ranging from 0.39 to 0.01 mm/year and calculated corresponding average recurrence intervals in the range of ~5900 to more than ~200,000 years. For the estimation of activity parameters for this report, a dip of 45°, length of 35 km and nominal net slip rate of 0.05 mm/year were applied, and a recurrence interval of ~49,000 years was calculated using the 2010 NSHM methodology.

A2.28 **Waitahuna Heights Fault** (feature 14, Figure 5.2)

The north- to northeast-striking Waitahuna Heights Fault has produced an up-to-the-southeast vertical separation of the peneplain of as much as ~250 m. It is assumed to be a southeast-dipping reverse fault, with no known offsets of geologically young landform features, and is classified as 'potentially active'. The fault name comes from the QMAP dataset (Bishop and Turnbull 1996). Villamor et al. (2018) identified this fault as a potential earthquake source. It has not previously been included in the NZAFD, NZAFM or NSHM. About 4.5 km to the southeast, there is a shorter parallel fault with up to 50 m vertical separation of the peneplain, also up to the southeast. This fault was not shown in the QMAP dataset, but its topographic expression on the peneplain surface is strong evidence for its existence. This fault was referred to as the Waitahuna Heights 2 Fault by Villamor et al. (2018), who also identified it as a potential earthquake source. However, in this report, it is considered to be a splay at depth off the Waitahuna Heights Fault and not an independent fault structure.

As part of the Villamor et al. (2018) assessment, the writer used topographic considerations to interpret that the Waitahuna Heights Fault extends 4 km farther northeast than was shown on QMAP to the southwest margin of Lake Mahinerangi. As part of this review, and upon wider consideration of nearby faults, the writer now prefers the QMAP interpretation. Upon reconsideration, the topographic features used to reinterpret the fault extent can adequately be accounted for by erosional rather than tectonic processes. Further, it is easier to reconcile the kinematic relationships between the Waitahuna Heights Fault and the Maungatua – North Taieri Fault nearby to the east, the former upthrown to the southeast and the latter upthrown to the northwest, with the QMAP depiction of faults.

In this dataset, the Waitahuna Heights Fault extends north to northeast from near the Tuapeka Fault for 23 km to intersect the Waipori Fault at the southwest margin of the Waipori river valley (refer to Maungatua – North Taieri Fault section for information on the Waipori Fault). The Waitahuna Heights 2 Fault has a length of 10 km and is ended north-eastward at the Waipori Fault. There are no known offsets of geologically young landforms along either fault.

Villamor et al. (2018) considered various estimates for slip rate for the Waitahuna Heights Fault ranging from 0.14 to 0.004 mm/year and calculated corresponding average recurrence intervals in the range of ~11,300 to more than ~400,000 years. For the estimation of activity parameters for this report, a dip of 45°, length of 23 km and nominal net slip rate of 0.05 mm/year were applied, and a recurrence interval of ~32,000 years was calculated using the 2010 NSHM methodology.

A2.29 Appendix 2 References

Barrell DJA. 2002. Geological stability assessment of the Port Otago tide gauges, Otago Harbour, New Zealand. Lower Hutt (NZ): Institute of Geological & Nuclear Sciences. 19 p. (Institute of Geological & Nuclear Sciences science report; 2001/21).

Barrell DJA. 2011. Quaternary glaciers of New Zealand. In: Ehlers J, Gibbard PL, Hughes PD, editors. *Quaternary glaciations, extent and chronology: a closer look*. Amsterdam (NL): Elsevier. p. 1047–1064. (Developments in quaternary science; 15).

Barrell DJA. 2014. SH1 Caversham: investigation of displacement features, Lookout Point: addendum report on additional features examined on 9th & 11th December 2013. Dunedin (NZ): GNS Science. 8 p. Consultancy Report 2013/333LR. Prepared for: Opus International Consultants Ltd.

Barrell DJA. 2016. General distribution and characteristics of active faults and folds in the Waimate District and Waitaki District, South Canterbury and North Otago. Dunedin (NZ): GNS Science. 124 p. + 1 DVD. Consultancy Report 2015/166. Prepared for Canterbury Regional Council (Environment Canterbury); Otago Regional Council.

Barrell DJA. 2019. Assessment of liquefaction hazards in the Queenstown Lakes, Central Otago, Clutha and Waitaki districts of the Otago region. Dunedin (NZ): GNS Science. 99 p. Consultancy Report 2018/67. Prepared for: Otago Regional Council.

Barrell DJA, Forsyth PJ, Litchfield NJ, Brown LJ. 1999. Quaternary stratigraphy of the Lower Taieri Plain, Otago, New Zealand. Lower Hutt (NZ): Institute of Geological & Nuclear Sciences. 24 p. (Institute of Geological & Nuclear Sciences science report; 99/15).

Barrell DJA, Litchfield NJ. 2013. SH1 Caversham: investigation of displacement features, Lookout Point. Dunedin (NZ): GNS Science. 10 p. Consultancy Report 2013/312LR. Prepared for Opus International Consultants Ltd.

Barrell DJA, Litchfield NJ, Van Dissen RJ, Wang N, Taylor-Silva BI, Hornblow S, Stirling MW. 2020. Investigation of past earthquakes on the Titri Fault, coastal Otago, New Zealand. Lower Hutt (NZ): GNS Science. 66 p. (GNS Science report; 2017/35).

Barrell DJA, McIntosh PD, Forsyth PJ, Litchfield NJ, Eden DN, Glassey PJ, Brown LJ, Froggatt PC, Morrison B, Smith Lyttle B, et al. 1998. Quaternary fans and terraces of coastal Otago. Lower Hutt (NZ): Institute of Geological & Nuclear Sciences. 36 p. (Institute of Geological & Nuclear Sciences science report; 98/11).

Benson WN. 1968. The W.N. Benson geological map of Dunedin district [map]. Wellington (NZ): Department of Scientific and Industrial Research. 1 folded map + 1 booklet, scale 1:50,000. (New Zealand Geological Survey miscellaneous series map; 1).

Bishop DG, Turnbull IM. 1996. Geology of the Dunedin area [map]. Lower Hutt (NZ): Institute of Geological & Nuclear Sciences. 1 folded map + 52 p., scale 1:250,000. (Institute of Geological & Nuclear Sciences 1:250,000 geological map; 21).

Beanland S, Berryman KR. 1986. Seismotectonic hazard assessment for lower Clutha power development. Lower Hutt (NZ). New Zealand Geological Survey. 40 p. Report EDS 104.

Cawood PA. 1987. Stratigraphic and structural relations of strata enclosing the Dun Mountain Ophiolite Belt in the Arthurton–Clinton region, Southland, New Zealand. *New Zealand Journal of Geology and Geophysics*. 30(1):19–36. doi:10.1080/00288306.1987.10422191.

Clement AJH, Whitehouse PL, Sloss CR. 2016. An examination of spatial variability in the timing and magnitude of Holocene relative sea-level changes in the New Zealand archipelago. *Quaternary Science Reviews*. 131:73–101. doi:10.1016/j.quascirev.2015.09.025.

Els BG, Youngson JH, Craw D. 2003. Blue Spur Conglomerate: auriferous Late Cretaceous fluvial channel deposits adjacent to normal fault scarps, southeast Otago, New Zealand. *New Zealand Journal of Geology and Geophysics*. 46(1):123–139. doi:10.1080/00288306.2003.9515000.

Figueira B, Hayward BW. 2014. Impact of reworked foraminifera from an eroding salt marsh on sea-level studies, New Zealand. *New Zealand Journal of Geology and Geophysics*. 57(4):378–389. doi:10.1080/00288306.2014.924971.

Forsyth PJ. 2001. Geology of the Waitaki area [map]. Lower Hutt (NZ): Institute of Geological & Nuclear Sciences Limited. 1 folded map + 64 p., scale 1:250,000. (Institute of Geological & Nuclear Sciences 1:250,000 geological map; 19).

Glassey PJ, Barrell DJA. 2000. Southern water treatment station. Phase 3: detailed site assessment. Dunedin (NZ): Institute of Geological & Nuclear Sciences. 1 vol. Client Report 2000/33. Prepared for: Dunedin City Council.

Harrington HJ. 1958. Geology of Kaitangata Coalfield. Wellington (NZ): Department of Scientific and Industrial Research. 2 vol. (New Zealand Geological Survey bulletin; 59).

Hayward BW, Grenfell HR, Sabaa AT, Southall KE, Gehrels WR. 2007. Foraminiferal evidence of Holocene subsidence and fault displacements, coastal South Otago, New Zealand. *Journal of Foraminiferal Research*. 37(4):344–359. doi:10.2113/gsjfr.37.4.344.

Heron DW, custodian. 2018. Geological map of New Zealand 1:250,000. 2nd ed. Lower Hutt (NZ): GNS Science. 1 USB. (GNS Science geological map; 1).

Holt A. 2017. Acoustic investigations of geologic hazards and seismic processing off the coast of Otago, New Zealand [MSc thesis]. Dunedin (NZ): University of Otago. 205 p.

Landis CA, Campbell HJ, Begg JG, Mildenhall DC, Paterson AM, Trewick SA. 2008. The Waipounamu Erosion Surface: questioning the antiquity of the New Zealand land surface and terrestrial fauna and flora. *Geological Magazine*. 145(2):173–197. doi:10.1017/S0016756807004268.

Langridge RM, Ries WF, Litchfield NJ, Villamor P, Van Dissen RJ, Barrell DJA, Rattenbury MS, Heron DW, Haubrock S, Townsend DB, et al. 2016. The New Zealand Active Faults Database. *New Zealand Journal of Geology and Geophysics*. 59(1):86–96. doi:10.1080/00288306.2015.1112818.

Liggett KA. 1975. Three Mile Hill Road section. [14] p. Located at GNS Science, Dunedin, NZ; Mapping Techfile I44/71.

Litchfield NJ. 2000. Quaternary deformation at the leading edge of the Otago reverse fault province [PhD thesis]. Dunedin (NZ): University of Otago. 1 v.

Litchfield NJ. 2001. The Titri Fault System: Quaternary-active faults near the leading edge of the Otago reverse fault province. *New Zealand Journal of Geology and Geophysics*. 44(4):517–534. doi:10.1080/00288306.2001.9514953.

Litchfield NJ, Van Dissen RJ, Sutherland R, Barnes PM, Cox SC, Norris RJ, Beavan RJ, Langridge RM, Villamor P, Berryman KR, et al. 2013. A model of active faulting in New Zealand: fault zone parameter descriptions. Lower Hutt (NZ): GNS Science. 120 p. (GNS Science report; 2012/19).

Litchfield NJ, Van Dissen RJ, Sutherland R, Barnes PM, Cox SC, Norris R, Beavan RJ, Langridge RM, Villamor P, Berryman KR, et al. 2014. A model of active faulting in New Zealand. *New Zealand Journal of Geology and Geophysics*. 57(1):32–56. doi:10.1080/00288306.2013.854256.

McKellar IC. 1990. Southwest Dunedin urban area [map]. Lower Hutt (NZ): New Zealand Geological Survey. 1 fold. map + 1 booklet, scale 1:25,000. (New Zealand Geological Survey miscellaneous series map; 22).

Mortimer N, Davey FJ, Melhuish A, Yu J, Godfrey NJ. 2002. Geological interpretation of a deep seismic reflection profile across the Eastern Province and Median Batholith, New Zealand: crustal architecture of an extended Phanerozoic convergent orogen. *New Zealand Journal of Geology and Geophysics*. 45(3):349–363. doi:10.1080/00288306.2002.9514978.

Norris RJ, Koons PO, Landis CA. 1994. Seismotectonic evaluation of fault structures in East Otago. Dunedin (NZ): University of Otago. 1 vol. EQC Funded Report 91/53.

Norris RJ, Nicolls R. 2004. Strain accumulation and episodicity of fault movements in Otago. Wellington (NZ): Earthquake Commission. 146 p. EQC Research Report 01/445.

Ongley M. 1939. The geology of the Kaitangata-Green Island subdivision, eastern and central Otago divisions. Wellington (NZ): Department of Scientific and Industrial Research. 90 p. (New Zealand Geological Survey bulletin; 38).

Pace B, Stirling MW, Litchfield NJ, Rieser U. 2005. New active fault data and seismic hazard estimates for west Otago, New Zealand. *New Zealand Journal of Geology and Geophysics*. 48(1):75–83. doi:10.1080/00288306.2005.9515099.

Speden IG. 1971. Geology of Papatowai subdivision south-east Otago. [Wellington] (NZ): Department of Scientific and Industrial Research. 166 p. (New Zealand Geological Survey bulletin; 81).

Stirling M, McVerry G, Gerstenberger M, Litchfield N, Dissen R, Berryman K, Barnes P, Wallace L, Villamor P, Langridge R, et al. 2012. National Seismic Hazard Model for New Zealand: 2010 update. *Bulletin of the Seismological Society of America*. 102(4):1514–1542. doi:10.1785/0120110170.

Tarling MS, Smith SAF, Scott JM, Rooney JS, Viti C, Gordon KC. 2019. The internal structure and composition of a plate-boundary-scale serpentinite shear zone: the Livingstone Fault, New Zealand. *Solid Earth*. 10(4):1025–1047. doi:10.5194/se-10-1025-2019.

Taylor-Silva BI, Stirling MW, Litchfield NJ, Griffin JD, van den Berg EJ, Wang N. 2020. Paleoseismology of the Akatore Fault, Otago, New Zealand. *New Zealand Journal of Geology and Geophysics*. 63(2):151–167. doi:10.1080/00288306.2019.1645706.

Tonkin & Taylor Limited. 2008. Geotechnical investigations: Bunnings Warehouse, Dunedin. [Christchurch] (NZ): Tonkin & Taylor Ltd. Prepared for Alan Reay Consultants.

Turnbull IM, Allibone AH. 2003. Geology of the Murihiku area [map]. Lower Hutt (NZ): Institute of Geological & Nuclear Sciences. 1 folded map + 74 p., scale 1:250,000. (Institute of Geological & Nuclear Sciences 1:250,000 geological map; 20).

Villamor P, Barrell DJA, Gorman A, Davy BW, Hreinsdottir S, Hamling IJ, Stirling MW, Cox SC, Litchfield NJ, Holt A, et al. 2018. Unknown faults under cities. Lower Hutt (NZ): GNS Science. 71 p. (GNS Science miscellaneous series; 124).

www.gns.cri.nz

Principal Location

1 Fairway Drive, Avalon
Lower Hutt 5010
PO Box 30368
Lower Hutt 5040
New Zealand
T +64-4-570 1444
F +64-4-570 4600

Other Locations

Dunedin Research Centre
764 Cumberland Street
Private Bag 1930
Dunedin 9054
New Zealand
T +64-3-477 4050
F +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road
Private Bag 2000
Taupo 3352
New Zealand
T +64-7-374 8211
F +64-7-374 8199

National Isotope Centre
30 Gracefield Road
PO Box 30368
Lower Hutt 5040
New Zealand
T +64-4-570 1444
F +64-4-570 4657