General distribution and characteristics of active faults and folds in the Waimate District and Waitaki District, South Canterbury and North Otago

D. J. A. Barrell

GNS Science Consultancy Report 2015/166
Environment Canterbury Report R15/135
December 2016

GNS SCIENCE
TE PŪ AO

DISCLAIMER

BIBLIOGRAPHIC REFERENCE

Barrell, D.J.A. 2016. General distribution and characteristics of active faults and folds in the Waimate District and Waitaki District, South Canterbury and North Otago. *GNS Science Consultancy Report* 2015/166. 124 p.

ISBN 978-0-908316-65-6 (PRINT)
ISBN 978-0-908316-51-9 (WEB)

CONTENTS

FIGURES

TABLES

APPENDICES

APPENDIX FIGURES

EXECUTIVE SUMMARY

This report presents a general outline of the locations and character of active geological faults and folds in the Waimate and Waitaki districts. 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 commonly form above an underlying fault.

A fault or fold is termed 'active' where it has moved in the geologically–recent past, in particular where the movement has been sufficiently large to have emerged at the ground surface, forming offset and breakage of the ground (fault) or buckling or tilting of the ground (fold). Old landforms of uniform character, such as river terraces formed during the last ice age which ended about 18,000 years ago, are well suited for revealing the presence of active faults or folds, because they may be old enough to have experienced several rupture events and display large offsets or buckles. In areas of younger landforms, the land surface may be younger than the most recent fault or fold movements, and the presence and location of any active faults or folds may be 'concealed' from view. In this way, we can recognise active faults or folds in some places (e.g. where there are ice-age river terraces), but elsewhere we may be uncertain whether or not they are present (e.g. on young river floodplains).

Regional geological mapping has detected 29 areas of active or possibly active faults or folds at the ground surface in the Waimate and Waitaki districts. Because some of those areas contain multiple components, a total of 46 named faults or folds are identified in this report. This report is accompanied by Geographic Information System (GIS) datasets, showing the locations of the recognised active faults and folds. In some places, it is clear beyond doubt that a feature is an active fault or fold, but in others, the evidence is less certain or is doubtful. Levels of certainty in the recognition of active faults and folds are included in the datasets, as are estimates of average slip rates and recurrence intervals for each fault, in relation to Ministry for the Environment guidelines on planning for development of land on or close to active faults.

Hazards associated with active faults include: (i) strong ground shaking from locally-centred large earthquakes, and (ii) sudden ground surface offset or buckling at the fault which may result, for example, in the destruction or tilting of buildings in the immediate vicinity. No large earthquakes are known to have been centred within the Waimate or Waitaki districts since European settlement in the mid-1800s. However, the nature of hazards posed by active faults was demonstrated recently during the 2010 Darfield Earthquake that resulted in ground-surface rupture, and sideways land shift, on the Greendale Fault on the Canterbury Plains, and severe ground shaking across a wide area. The landform record shows evidence for prehistoric deformation at several locations in the Waimate and Waitaki districts, and highlights that these active fault or fold features should be treated as potential hazards.

The active faults and folds of the Waimate and Waitaki districts have been mapped at a regional scale. Information in this report and in the accompanying GIS layers highlights areas potentially affected by active fault or fold hazards, and may help to target locations for any further 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 Waimate and Waitaki districts. It is intended to create general awareness of the existence of the potential hazards, but is not in itself sufficient for specific zoning to avoid fault hazards.

1.0 INTRODUCTION

1.1 BACKGROUND

The geologically-active nature of New Zealand reflects our position astride the active boundary between two large slabs (plates) of the Earth's crust (Figure 1.1). The forces involved in plate movement 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 in the South Island is marked, at the ground surface, by a series of major faults that extend from Marlborough through North Canterbury, and then merge onto a single major feature, the Alpine Fault, which runs along the western margin of the Southern Alps to the Fiordland region.

In the central South Island from about Arthur's Pass south to Fiordland, most of the plate movement is concentrated on the Alpine Fault. The movement 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 central eastern South Island, including the Waimate and Waitaki districts, a relatively small proportion of the plate movement is distributed on a series of faults east of the Alpine Fault.

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 Earthquake provided a good example of the nature and effects of a large, ground-surface-rupturing earthquake on a geological fault (e.g., Barrell et al. 2011; Villamor et al. 2011) (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 (Figure 1.2 & Figure 1.3). This practical 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).

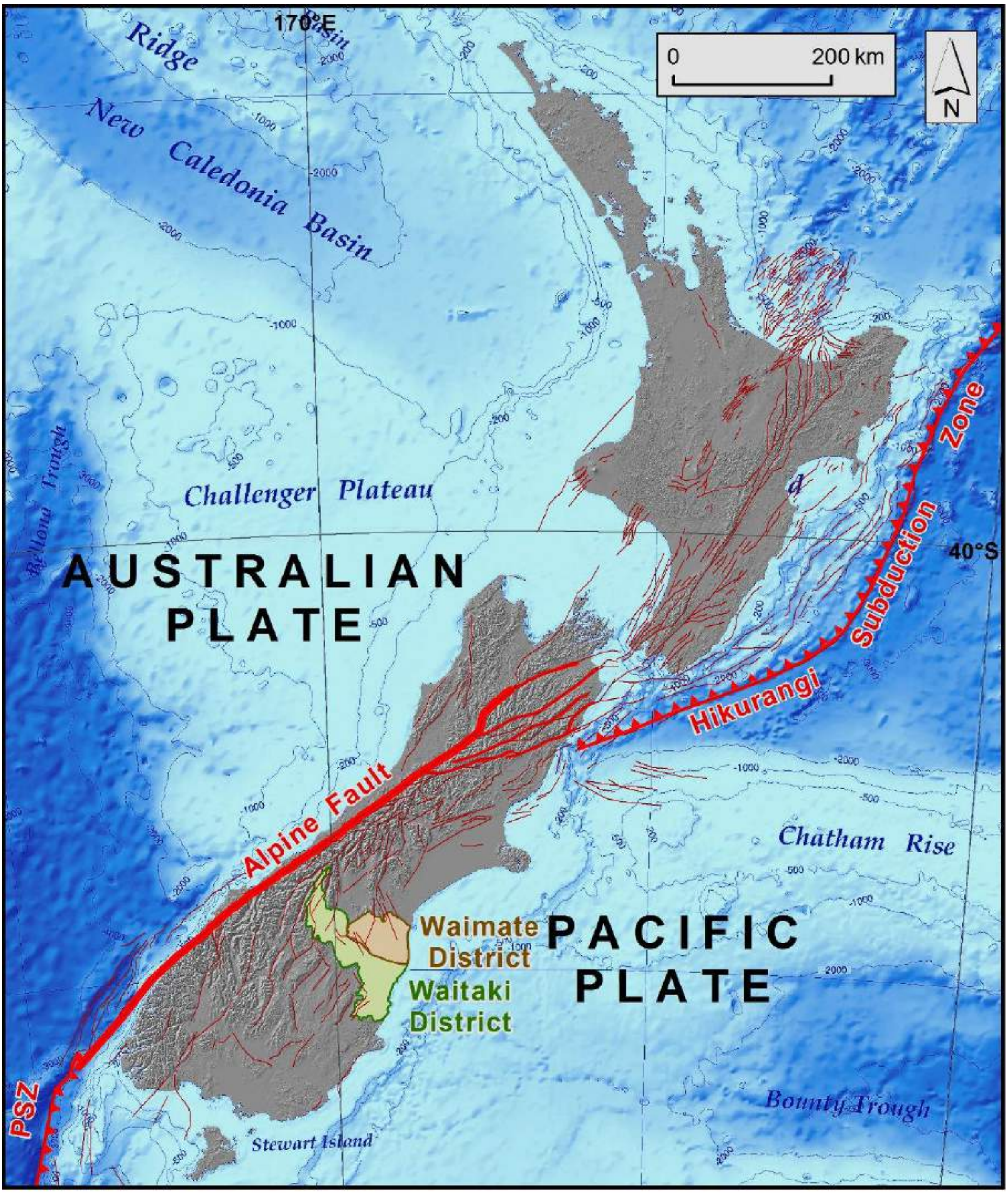

Figure 1.1 The tectonic setting of the Waimate and Waitaki districts. The junction between the Australian and Pacific plates of the Earth's crust passes through New Zealand, with the Pacific Plate pushing westward against the Australian Plate. At the Hikurangi Subduction Zone, the rocks of the Pacific Plate slide west under the North Island, while at the Puysegur Subduction Zone (PSZ), the rocks of the Tasman sea floor slide east under the southwestern South Island. In between is a sideways tear, the Alpine Fault (thick red line) and in the northern South Island, a companion set of tears, the Marlborough Fault System (medium thickness red lines), on which motion is transferred between the subduction zones. Although much of the plate movement is concentrated at the subduction zones and the Alpine Fault, there is a wider zone of deformation. The Waimate and Waitaki districts lie within this wider zone of tectonic deformation. Other active faults, taken from Litchfield et al. (2014), are shown by thin dark red lines. 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.

Figure 1.2 Illustrations of historical fault offsets of the ground surface in the Canterbury region. **A**: A fence offset sideways by ~2.4 m of strike-slip rupture on the Hope Fault west of Hanmer Springs during the 1888 North Canterbury Earthquake (Photo: A. McKay, GNS Science CN4852). **B**: A fence offset sideways by ~4.5 m of strike-slip rupture on the Greendale Fault during the 2010 Darfield Earthquake (Photo: N. J. Litchfield). Half-arrows either side of the fault indicate the direction of movement. In both cases, the movement is 'right-lateral', sometimes called 'dextral'. This means that to an observer, the ground on the far side of the fault has shifted sideways to the right. The effect is the same regardless of which side of the fault the observer is standing. The other type of strike-slip movement is 'left-lateral', sometimes called 'sinistral', but is not common in New Zealand.

There are many active geological faults and folds recognised in the Canterbury region. As part of ongoing improvements in the recognition and mitigation of natural hazards, Environment Canterbury and Otago Regional Council engaged the Institute of Geological and Nuclear Sciences Limited (GNS Science) to summarise the state of knowledge regarding active geological faults and folds in the Waimate and Waitaki districts (see Figure 3.2). This report presents that summary, and forms a companion to similar reports commissioned for the

Ashburton District (Barrell & Strong 2009), Mackenzie District (Barrell & Strong 2010), Hurunui District (Barrell & Townsend 2012), Selwyn District (Barrell 2013), Waimakariri District (Barrell & Begg 2013), Kaikoura District (Barrell 2015) and Timaru District (Barrell 2016).

Figure 1.3 A northward oblique aerial view of the Ostler Fault Zone, 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, that was sourced from the Lake Ohau area. Lake Ohau Road is at lower left, and State Highway 8 is in lower right. At the lower left, the fault scarp (in shadow) is sharply defined. Heading towards the photo centre, the fault scarp evolves into a broad fold which peters out near the photo centre. At that point, another fault strand and associated fold has emerged 200 m or so in front of it (right) and, in somewhat serrated from, curves broadly to the left towards the shadow of a high uplifted terrace (Table Hill), and then curves along the foot of the hill (in shadow) to the upper right corner. Right of centre and right of the fault scarp, the three darker lines are the channels of spring-fed streams that emanate from the foot of the fault scarp. This view shows an array of 'definite' faults and folds which all form part of a single entity, the Ostler Fault Zone. In the generalised dataset accompanying this report, the Ostler Fault Zone at this location is represented by a single mapped fault line, and the folds and numerous small subsidiary fault strands are not differentiated in this regional-scale dataset. In contrast to the strike-slip faults shown in **Figure 1.2**, the Ostler Fault Zone is a dip-slip fault with a reverse sense of movement (see **Figure 3.1** for diagrammatic representations of these two different styles of fault movement). Photo: D.L. Homer, GNS Science CN576/B; 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 Waimate and Waitaki districts. The principal information source is the GNS Science's 1:250,000 scale QMAP geological database, supplemented by information from the New Zealand Active Faults Database, the Environment Canterbury Active Faults Database, and any other relevant and accessible sources. The main product is a GIS map dataset that includes the following information: (i) whether a feature is a fault or a fold; (ii) the level of the certainty with which each feature is recognized (definite, likely or possible), and; (iii) an interpretation of how well expressed each feature is on the ground surface (well-expressed, moderately expressed, not expressed, unknown).

This report presents the GIS dataset, and includes tabulated information on estimated average slip rates and recurrence intervals for each fault/fold system, where known. Also indicated are relationships between information in this dataset and the Ministry for the Environment (2003) 'Planning for Development of Land on or Close to Active Faults' guidelines 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 Waimate and Waitaki districts where active faulting may be a hazard to look for. The information in this report is intended to assist local authorities in delineating the general areas of the Waimate and Waitaki districts that are potentially subject to active fault and fold hazards, particularly those hazards related to ground-surface fault rupture and ground deformation.

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

2.0 INFORMATION SOURCES

This report draws largely upon regional-scale geological mapping, compiled in digital format as part of the GNS Science 1:250,000 scale QMAP (Quarter-million scale MAP) project, represented in the Waimate and Waitaki districts by the Waitaki map (Forsyth 2001), and in the far northwestern part of the Waitaki District by the Aoraki map (Cox & Barrell 2007), Haast map (Rattenbury et al. 2010) and Wakatipu map (Turnbull 2000). Some more detailed studies have contributed to the generalised information shown on these maps and their underlying Geographic Information System (GIS) databases. Those studies and other more recent studies, where relevant, are identified in Table 5.2 of this report. Additional information on active faults is contained in the New Zealand Active Faults Database (NZAFD – see reference list and also Langridge et al. 2016), and in publications by Stirling et al. (2012) and Litchfield et al. (2014).

This report comprises an office-based review of existing information. Although the scope of work did not include site investigations or field inspections, the writer has extensive experience of the assessment area, on account of previous geological investigations and inspections over the past 20 years. Appendix 1 presents a brief description of the GIS datasets that form a companion to this report. Appendix 2 provides commentary on aspects of the existing information, as well as explanations of the interpretations adopted in this report for each active fault or fold. The fault and fold GIS map accompanying this report is derived from the QMAP digital dataset, with additions and refinements, as outlined in Section 5.0 of this report.

3.0 GEOLOGICAL OVERVIEW

3.1 ROCKS AND LANDFORMS

In the central eastern South Island, including the Waimate and Waitaki districts, the oldest underlying rock (basement rock) consists mainly of hard sandstones ('greywacke') and flaky mudstones ('argillite'). 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, marine mudstones, limestones and gravelly conglomerates, and some volcanic rocks, ranging in age from Late Cretaceous (~85 million years ago) 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 the Southern Alps, and in hill to mountain terrain of central to eastern South Canterbury and Otago, uplift and erosion has stripped away much 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 sides of major faults. The cover rocks are more widely preserved close to the coast.

The youngest deposits of the district are unconsolidated sediments whose nature and distribution is primarily a consequence of tectonic uplift and erosion of the mountain ranges and fluctuating climatic conditions during the latter half of the Quaternary Period (from about 1 million years ago to the present day). Uplift and erosion produced voluminous sediment that has been laid down in the basins, valleys and plains on top of the basement or cover rocks. A major feature of the Quaternary Period has been a cycle of large-scale natural shifts in global climate, with periods of generally cool conditions (glaciations, or 'ice ages') separated by periods of warmer climate ('interglaciations'), such as that existing today. In the last 500,000 years or so, an ice age has happened, on average, at least once every 100,000 years. During an ice age, ice was not everywhere, but rather the climate cooled enough to allow glaciers to form, or expand greatly, in some of the cooler and wetter places, such as in the Southern Alps. Sea level is linked to glaciation/interglaciation cycles. During ice ages, so much water became locked up in ice sheets that formed on Europe and North America that the level of the sea dropped. At the peak of the most recent ice age, about 20,000 years ago, sea level was at least 120 m lower than it is now. As Northern Hemisphere ice sheets melted, sea level rose, stabilizing at its present level about 7000 years ago. The last time the sea was as high as it is now was during the warmest part of the last interglacial period, about 125,000 years ago.

In the Waitaki District, the most recent glaciation generated sizeable glaciers in the Lake Ohau and Ahuriri River catchments. The Ohau Glacier flowed into the Lake Ohau basin, and meltwater rivers built extensive gravel plains downstream to the Waitaki River valley. The Ahuriri Glacier terminated in the middle reaches of the upper Ahuriri valley, with meltwater gravel plains extending down into the Omarama area, and on down to the Waitaki valley. Localised glaciers also formed on the highest parts of the tallest ranges of the Waimate and Waitaki districts, namely the Ohau Range, St Bathans Range, Hawkdun Range, St Marys Range, Benmore Range, Mt Sutton and the Kirkliston Range, but other parts of the districts remained ice-free (Barrell 2011). However, in the ice-free areas, erosion and deposition was greatly influenced by episodes of glacial climate. During glaciations, snowlines and treelines were many hundreds of metres lower than they are today (or were, prior to human-induced deforestation). The lack of trees aided erosion in the hills and mountains, and promoted build-up of river and stream sediments within valleys and on plains. Ice-age environmental conditions in the Waimate and Waitaki districts would have been harsh, with the lowlands dominated by exposed, dusty windswept river plains with few trees and patches of grassland. River silt picked up from floodplains by the wind formed accumulations of yellow-brown silt deposits, known as loess, that are common on stable terraces or rolling hill country, such as in the Waimate and Oamaru areas. The last ice age ended about 18,000 years ago (e.g. Barrell et al. 2013), and was followed by warming climate, retreat of glaciers from the mountain catchments, the spread of woody vegetation, and the stabilisation of hill slopes. As a result of the improved stability and reduced sediment supply, the rivers have become confined to narrower courses in their valleys and across the plains. A consequence of the stabilisation of these ice-age river plains, and glacially-sculpted landforms in the Ohau and Ahuriri catchments, is the preservation of locally extensive areas of ice-age land surfaces in parts of the Waimate and Waitaki districts. These ice-age landforms, although youthful in a geological sense, are old enough to have been affected by some of the most recent active fault and fold movements. Areas of younger landforms or deposits, such as steep, eroding mountain or hill slopes, young river terraces and floodplains and accumulating fans of stream sediment at the mouths of valleys and gullies, are commonly younger than the most recent fault movements or fold growth. Thus, they 'conceal' the locations of faults or folds.

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. As long as factors such as landsliding can be ruled out, these topographic features may confidently be attributed to fault or fold movements (e.g. Figure 1.2, Figure 1.3 & Figure 3.1).

In this report, and the accompanying GIS datasets, a distinction is made between the style of active deformation, whether predominantly by **fault** offset of the ground (fault scarp), or whether 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).

Two end-members of fault movement type are shown in Figure 3.1; a dip-slip fault which has up-down movement, and a strike-slip fault which has horizontal (sideways) movement. In practice it is not uncommon for a fault to display a combination of both types of movement; such faults are called 'oblique-slip', and have movement that is partly up-down and partly sideways. Most dip-slip faults 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 full range of variations and complexity that may exist (for example, see Figure 1.3). Indeed, 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 some impression of the bulldozer effect.

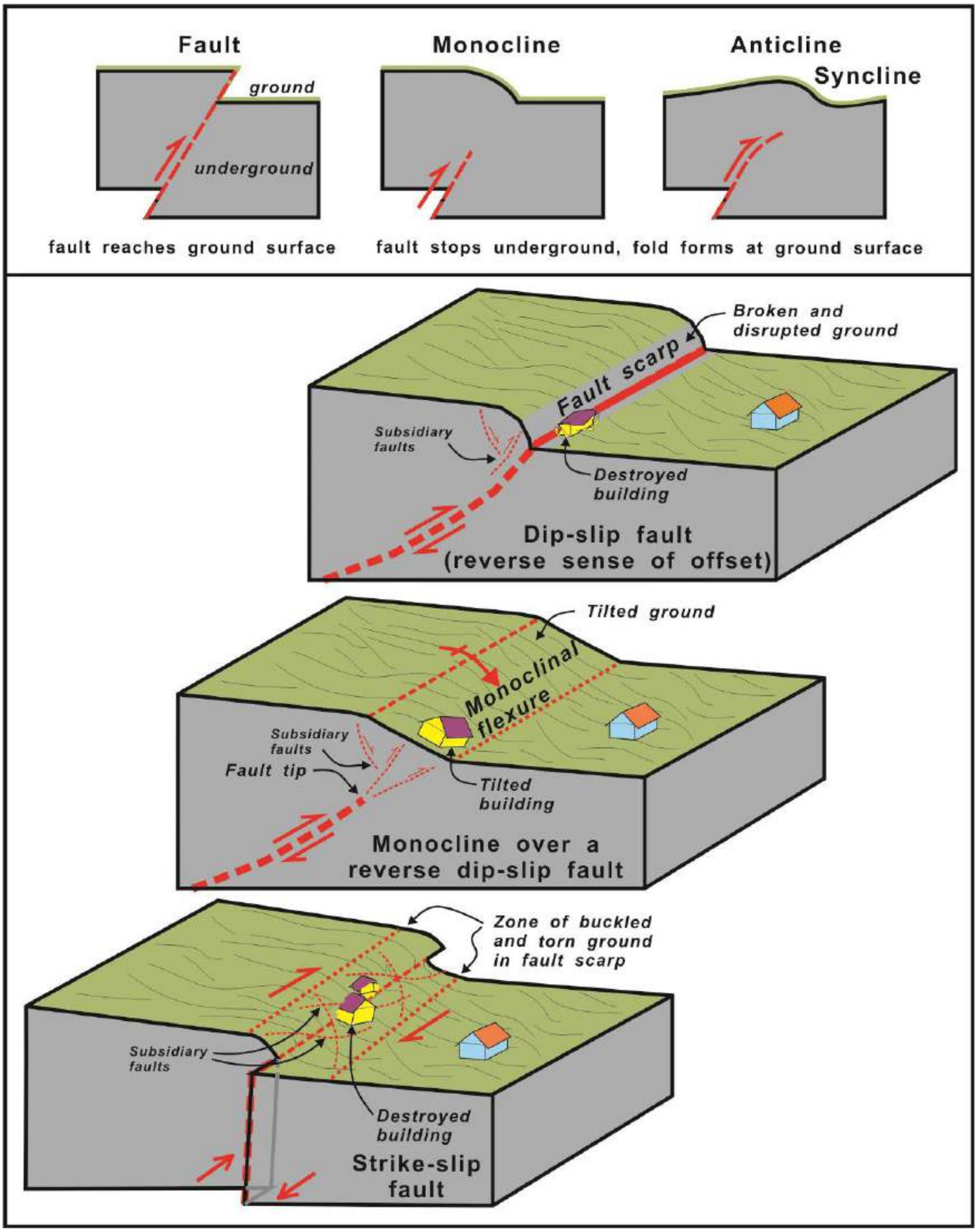

Figure 3.1 Diagrams illustrating styles of active faults and folds. The diagrams illustrate general concepts rather than actual details, and are not drawn to an exact scale. Upper panel: Cross-section (vertical slice) diagrams illustrating an active fault, active monocline and active anticline and syncline.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

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 in the vicinity of 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 (e.g. Kelson et al. 2001). The important message is that on any active fault or fold, there commonly are elements of both faulting and folding close to the ground surface (Figure 3.2). The amount of deformation due to faulting, relative to the amount expressed as folding, may vary over short distances.

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

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

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

Figure 3.2 Illustrations of faults exposed in investigation trenches. Dashed red lines indicate the position of the fault in each photo. A & B: The Waitangi Fault (feature 12f – see Appendix 2) exposed in 1999 in a trench 700 m downstream of Aviemore Dam. 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 trench excavated across the Kirkliston Fault Zone (feature 13 - see Appendix 2) in 2007, 14 km northeast of Kurow. The fault contact is beside the two people deep in the trench. Greenish-grey claystone overlain by yellow-brown stream gravel (left of centre) has been thrust up and buckled over against yellow-brown silt (loess) to the right. Detailed examination and mapping of the materials showed evidence for at least two separate rupture events. The blue-painted squares mark samples that were collected for luminescence dating to obtain age control on the rupture events. The dating showed that the most recent rupture most likely occurred between 12,900 and 22,000 years ago, and the recurrence interval for surface rupture is between 23,000 and 39,000 years. Photos A & B: D.J.A. Barrell; Photo C: S.A.L. Read.

4.0 CLASSIFICATION OF ACTIVE FAULTS AND FOLDS

4.1 DESCRIPTIVE CLASSIFICATION

The original information on the active faults and folds of the Waimate and Waitaki districts is extracted from the QMAP dataset (Forsyth 2001; Cox & Barrell 2007; Rattenbury et al. 2010; Turnbull 2000), as compiled in 'seamless' form by Heron (2014). These maps were 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. New features in the dataset can be identified by an absence of most of the data attributes in the QMAP database fields, which have been retained in these GIS layers (Appendix 1). Additional commentary on the mapping of several of the fault/fold systems, especially where the mapping and interpretations presented here differ notably from previous mapping or interpretations, is provided in Appendix 2.

Three data fields (also known as 'attribute' fields) have been added to the digital datasets (see Appendix 1). The names of these fields are:

- WMWK_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 (how well defined is the surface expression of the mapped feature; see below)

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. By and large the names correspond to those in the New Zealand Active Faults Database (NZAFD; Langridge et al., 2016), which in the Waimate and Waitaki districts is closely related to the QMAP dataset. In places where no name has previously been given to an active fault/fold feature, a representative name has been taken from a nearby named topographic feature or locality. Where names are informal, fault or fold are in lower case type (e.g. Falstone fault), while for previously published names, a capital 'F' is used. All new names are explained in the Appendix 2 discussion of each named fault/fold entity.

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 faulting or folding. Features designated as '**likely**' are most probably due to faulting or folding, 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 or fold, 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**'. Features identified as 'possible' should not be treated as delineated active faults or folds unless further positive information is obtained. They are identified to highlight areas that are worth a closer look with regard to the possible existence of active faults or folds.

Several of the active faults of the Waimate and Waitaki districts have been subject to close examination in the field, whereas other faults or folds 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 and folds 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 these features is likely to be, were they 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**' are not expected to have any 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/fold 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 a greater degree of precision, than are features identified as 'moderately expressed'.

4.2 ACTIVITY CLASSIFICATION

Two common ways of expressing the degree of activity of a fault or fold are average slip rate and average recurrence interval. Either of these parameters provides a way to compare the levels of activity of faults and folds across a wide area (e.g. Waimate and Waitaki districts). The behaviour of any particular active fault or fold 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. The amount of fault offset of a geological deposit or a land surface feature, such as a river plain, divided by the age of the deposit or the land surface feature (e.g. river plain), provides an average **slip rate**, usually expressed in mm per year. 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 large (high) slip rate (e.g. 2 mm/yr) generally indicates that a fault experiences a ground-surface rupture event more frequently than does a fault with a small (low) slip rate (e.g. 0.2 mm/yr).

Average **recurrence interval (RI)** is the average length of time that elapses between ground-surface rupturing events, and is a more explicit measure of how frequently surface-rupture events occur. However, RI is more difficult to estimate. Defining a RI depends on having an estimate of the amount of offset that occurs in a single surface rupture event (**single-event displacement, or SED**), having a geological feature (landform or sediment layer) that has been offset by at least two rupture events, and having an estimate of the age of that offset geological feature. More commonly, a minimum value for the RI of a fault can be inferred from the estimated age of geological features that have not been offset or otherwise deformed across a fault. Despite the challenges involved in its estimation, RI is an important quantity because it forms the basis for risk-based evaluation of ground-surface fault rupture hazard in relation to Ministry for the Environment guidelines that aim to minimise the risks of building across active faults. Because RIs range from being as short as a few hundred years for the most active faults, and as much as many thousands of years for other faults, the historically-documented record of earthquakes is too short to be of use. Instead, the geological record of deformation of young deposits and landforms is the main source of evidence for defining a RI for a particular fault.

Determining accurate values for slip rates and RIs usually requires detailed and expensive geological investigations. Commonly, the exact ages of landforms are not known, and geologists usually have to rely upon provisional age estimates based on regional geological knowledge. It is important to appreciate that the vertical component of offset is relatively easy to measure using geological features, such as the height of a fault scarp on a near-horizontal, near-planar, river terrace. Estimates of vertical offset can be made quickly by field inspection, examination of aerial photos or use of topographic map contours. Therefore, the values presented in this report focus on vertical slip rate and vertical component of single-event displacement. Sideways movements, or oblique movements that are partly up-down and partly sideways, are harder to measure, simply because there are hardly any near-vertical, near-planar landforms in the natural environment that would clearly show a relatively small sideways offset (e.g. several metres). A good illustration of this point is that, without fences and roads, the 2010 Greendale Fault horizontal offsets (Figure 1.2) would have been more difficult to recognise and measure accurately (Quigley et al. 2012). Where predominantly sideways-moving faults cross landforms that are sufficiently old to have experienced several rupture events, the cumulative offset is easier to recognise and measure.

Where detailed geological investigations have been undertaken on a fault, the findings usually include observation-based estimates of SED, and those estimates are used directly in this report. For faults lacking investigation data, SEDs have to be estimated. The method used in the National Seismic Hazard Model (NSHM; Stirling et al. 2012) calculates SED from estimates of fault length, fault dip and slip rate, and those estimates are generally determined by an expert panel of scientists. Instead, a simpler indicative method was developed for use in the active fault reviews in Canterbury, of which this report forms part. For faults lacking detailed investigation data, but for which there are identified landform offsets and presumed dominant dip-slip sense of displacement, an arbitrary SED value of 2 m for the vertical component of displacement is used. It is unlikely that the approximation for SED of 2 m for a dip-slip fault will be a good representation for all faults in the region, but it does at least enable comparative assessments of active fault and fold hazards, pending better-constrained site-specific data on faults and folds. The SED value, expressed in mm, is then divided by the estimated vertical slip rate, in mm per year, to obtain RI, which is the same method that is used in the NSHM to calculate RI. As an integral part of the method used for active fault reviews in Canterbury, a nominal +/- 67% uncertainty is applied to the RI estimates (see Table 5.2). However, it is useful to note that the ’2 m SED’ method has been used for only 7 of the total of 46 named fault/fold entities discussed in this report, and for the other faults, there are either more specific investigation data, or more extended discussion of RI.

An important point is that, except in the case of the few faults that have been investigated in detail and useful results obtained, the slip rate and RI estimates should be regarded as provisional, pending information from detailed site-specific investigations, which are necessary for earthquake geology and paleoseismology assessments. The estimates in this report merely indicate a provisional range of recurrence intervals that may be expected for these faults/folds and allow them to be placed into general context with the Kerr et al. (2003) guidelines. A key consideration is that for practical purposes, the shorter bound of the RI range listed in Table 5.2 should be used for evaluating the potential risks posed by a particular fault/fold, until such time as robust fault-specific data are obtained for that fault/fold.

The information on degree of 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 2015. The information in this report also builds on and refines information presented by Pettinga et al. (2001), Van Dissen et al. (2003), Stirling et al. (2008, 2012) and Litchfield et al. (2013, 2014) and references therein.

4.3 AS-YET UNDETECTED ACTIVE FAULTS AND FOLDS

The Canterbury earthquake sequence of 2010-2011 occurred on a series of previously unknown faults. These faults were not known about because of two key factors; first, that those faults have a low rate of activity (the average time between rupture events is many thousands of years), and second, that the Canterbury Plains consist of relatively young deposits and landforms, which mask most of the underlying geology, including faults. Rather different circumstances prevail in South Canterbury and North 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. There are, however, many unknowns and uncertainties concerning the extents of and inter-relationships between some faults in the Waimate and Waitaki districts.

The active faults and folds of the Waimate and Waitaki districts, that have a preserved record of previous ground-surface deformation of young deposits or landforms, are a minimum representation of the active faults and folds of the districts. Because we know about those faults and folds, they 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. A final consideration is that any as-yet unknown active fault will have relatively infrequent activity, otherwise its presence would be more evident in the landscape.

4.4 EARTHQUAKE MAGNITUDES

An active fault that is recognisable at the ground surface is testament to the past occurrence of ruptures large enough to have broken through to the ground surface. It is generally thought, for the types of faults that occur in the eastern South Island, that the amount of slip required for a fault to rupture the ground surface would generate a large earthquake, of magnitude (M) somewhere between the high sixes and mid-sevens (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 M 7.0, while the subsurface but still ground-deforming Charing Cross and Hororata movements had estimated magnitudes of M 6.4 and M 6.3 respectively (Beavan et al. 2012).

It is important to note that 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 fault and fold features identified in this report should be assumed to be capable of generating earthquakes with magnitudes between the high sixes to high 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 AND FOLDS

A regional-scale map of the active faults and folds identified so far in the Waimate and Waitaki districts is presented in Figure 5.1 and Figure 5.2, which collectively provide three overlapping panels of the mapped area. The wide extent of the assessment area is such that the fault and fold information would be illegible if presented on a single map within this report. In addition, a more detailed map of the faults of the Waitaki valley ('Waitaki Fault System') is presented as two overlapping panels in Figure 5.3, because the detail cannot be rendered satisfactorily at the scale used in Figure 5.1 and Figure 5.2.

Descriptions of the representative characteristics of active faults and folds and syntheses of the mapping categories used in this report, as well as preliminary correlations to the fault complexity classification of Kerr et al. (2003), are presented in Table 5.1. Table 5.2 summarises the main features of the identified active faults or folds in the Waimate and Waitaki districts, including estimates of the degree of activity of the faults and folds, based on estimated amounts of deformation of landform features of specific age or from other sources as listed in Table 5.2. Extended discussion of the mapping and interpretations is provided in Appendix 2.

For the purposes of illustration and discussion, in places where several active fault or fold features lie close to one another, they have been grouped together under one name, in places accompanied by a coloured area ('general fault area') to highlight this grouping (Figure 5.1). A more restricted coloured area is used to help in highlighting particular fault entities in Figure 5.3. A total of 29 individual or grouped fault or fold features are identified, and within the grouped components, 17 individual named fault or fold entities are differentiated. In total, 46 named active fault or fold features are discussed in this report (see Appendix 2).

There are many faults and folds identified in the Waimate and Waitaki districts, but only 19 out of the 46 named entities are classified as 'definite' or 'likely' active features. Three newly identified active faults are included in this compilation, the Omarama Saddle fault (feature 7 of Figure 5.1), the Longden fault (feature 15 of Figure 5.1) and the Maungati Fault (feature 22 of Figure 5.1). The majority of the faults/folds (27 out of 46) are assigned an activity classification of 'possible'. Most of the faults in the Waimate and Waitaki districts are thought likely to be dip-slip faults with a reverse sense of displacement, possibly with a lesser component of strike-slip movement. For the few faults for which a geologically young offset has been examined in natural or human-made exposures, the Ostler Fault Zone (feature 6 of Figure 5.1), Kirkliston Fault Zone (feature 13 of Figure 5.1), Stonewall Fault (feature 12l of Figure 5.3), and the Waihemo Fault System (feature 26 of Figure 5.2) are confirmed as having a pure, or dominant, reverse sense of movement. The Waitangi Fault (feature 12f of Figure 5.3) has been shown to have had an earlier history as a dip-slip fault with a significant normal component, and a more recent history as a reverse fault with a component of right-lateral movement. The Fern Gully Fault (feature 12e of Figure 5.3) has a dominantly left-lateral strike-slip sense of displacement, and is one of the few left-lateral strike-slip faults identified so far in New Zealand.

The most active fault delineated in this assessment is the Oster Fault Zone, in the Waitaki District (feature 6 of Figure 5.1), with a RI of between 2,000 and 3,500 years. The Ostler Fault Zone, in its central section near the Ohau River, has produced a vertical offset of about 20 m on 18,000 year old landforms. There are several faults that display definite or likely evidence for offsets of the order of 5 m or more of landforms judged to be no more than about 18,000 years old (Watson fault, Snowy Gorge fault, Timaru Creek Fault, Lindis Pass Fault Zone, and Omarama Saddle fault; see Figure 5.1, left panel). Because little else is known about these faults, and they have not been investigated in the field, each of those faults has been assigned a wide range of RI values of 1,200 to 6,000 years (Watson fault), 1,600 to 8,000 years (Lindis Pass Fault Zone) and 2,400 to 12,000 years for the other faults. There are two faults that show definite evidence for small offset (3 m or less) of landforms estimated to be no more than 18,000 years old (Middle Range Fault (feature 12a of Figure 5.3) and Longden fault (feature 15 of Figure 5.1) and these are assigned a wide-ranging RI of between 4,000 and 20,000 years. Three faults in the Lake Aviemore area (Waitangi Fault, Fern Gully Fault, Awahokomo Fault; see Figure 5.3) have been investigated in detail and evidence found for repeated ruptures in the last 25,000 years or so, and RIs of between 6,000 and 12,000 years. Nearby to the east, three faults have been investigated and have been shown to have notably long RIs (Dryburgh Fault >62,000 years; Stonewall Fault >16,000 years; Kirkliston Fault Zone ~25,000 years; see Figure 5.3).

There is reasonable confidence that none of the ‘possible’ active faults has moved within the last 10,000 years or so, and the RI for each is assessed as being at least 10,000 years. This means that in relation to Ministry for the Environment planning guidelines (Kerr et al. 2003), these ‘possible’ features should pose no impediment to planning for residential developments, for example, and only would be relevant to consider for higher-importance structures (such as a dam). As a consequence of the hydro-electric development in the Waitaki valley, considerable effort has gone into investigating several low-activity faults in the area, and this has been able to show that RIs in the vicinity of 25,000 years or more characterise some faults.

A point to note is that for most of the faults discussed in this report, it is not known when the most recent ruptures occurred, and this means that there is little or no information on where the present-day sits in regard to their rupture cycles. There is some information on the Ostler Fault Zone, and several components of the Waitaki Fault System. The weight of evidence suggests that the Ostler Fault Zone last ruptured about 3,500 years ago, and it has an assigned RI range of 2,000 to 3,500 years. What is not known is how much variability there may be in its rupture recurrence. Because of this, it would be an overstatement to suggest that a rupture is ‘overdue’, but by the same token it provides no room for complacency about the possibility of a large surface-rupturing earthquake on the Ostler Fault Zone in the foreseeable future. The Waitangi Fault, Fern Gully Fault, and Awahokomo Fault all experienced their most recent rupture(s) many thousands of years ago, and with RIs estimated to be in the range of 6,000 to 12,000 years, it also would be prudent to avoid any complacency about their possible future activity. The Waitangi Fault passes beneath Aviemore Dam, and the dam safety has been thoroughly evaluated in relation to fault rupture hazard, as summarised by Barrell et al. (2009). The dam has been assessed as being able to withstand a rupture of the Waitangi Fault without uncontrolled failure, and a number of engineering measures have been emplaced to improve the dam’s seismic performance.

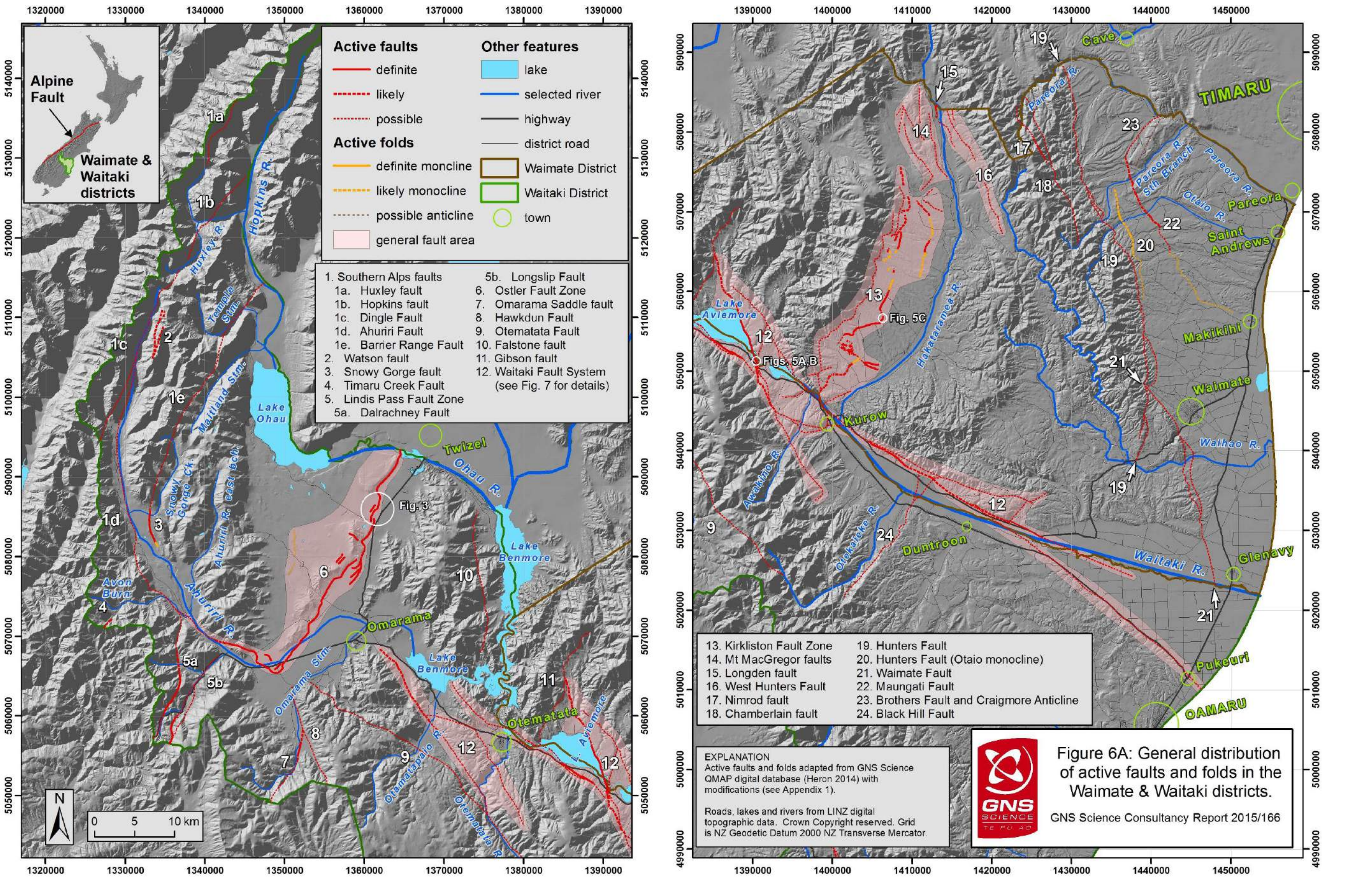

Figure 5.1 General distribution of active faults and folds in the Waimate and Waitaki districts (northwestern and northeastern overlapping panels). The pink areas indicate groupings of faults or folds that collectively form part of a single numbered entity. The pink areas are purely illustrative and do not imply anything about the location or extent of fault-related ground deformation. The southern overlapping panel is presented in Figure 5.2.

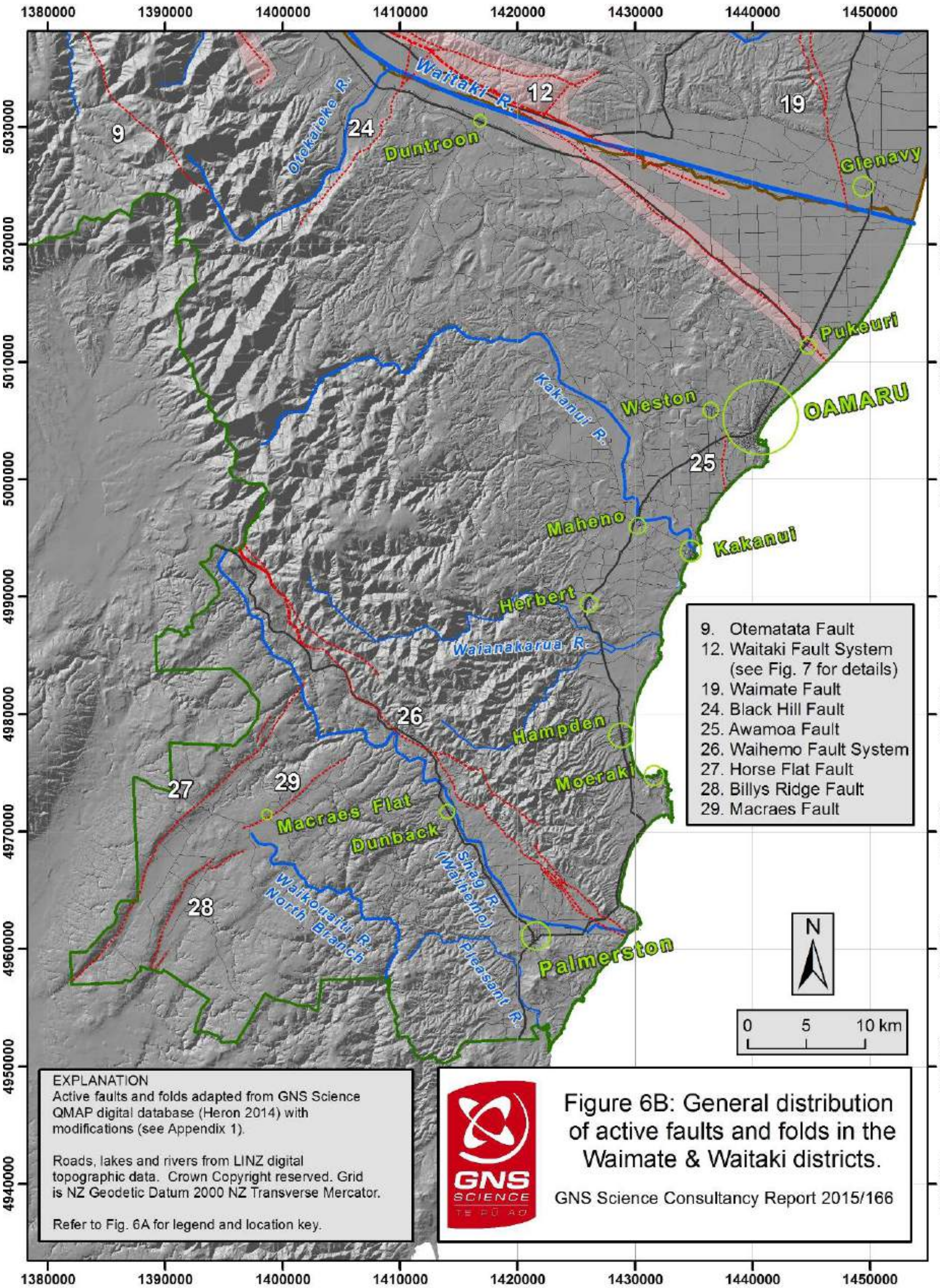

Figure 5.2 General distribution of active faults and folds in the Waimate and Waitaki districts (southern overlapping panel). The pink areas indicate groupings of faults or folds that collectively form part of a single numbered entity. The pink areas are purely illustrative and do not imply anything about the location or extent of fault-related ground deformation. The northwestern and northeastern overlapping panels are presented in Figure 5.1.

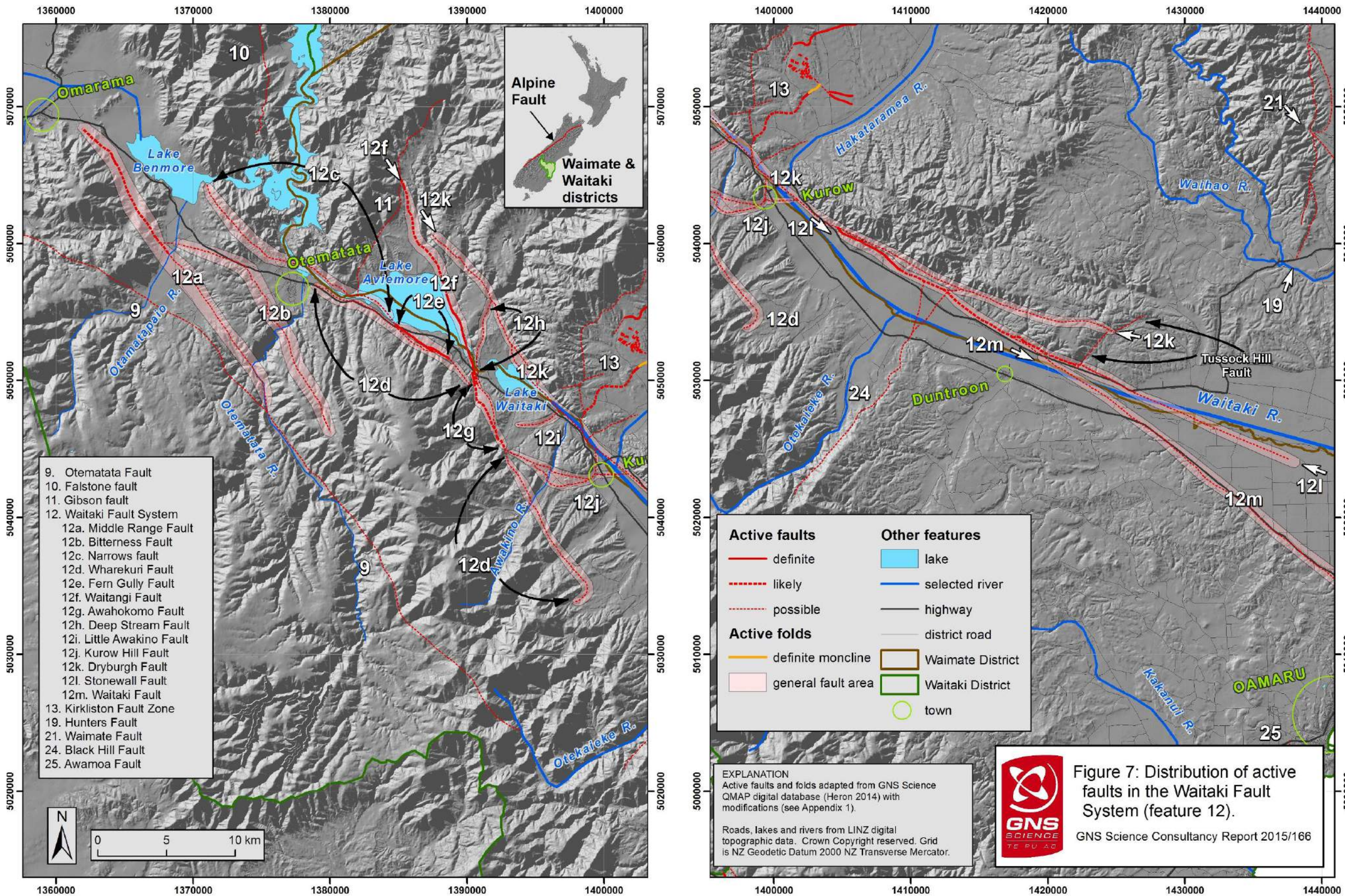

Figure 5.3 Distribution of active faults in the Waitaki Fault System (feature 12). The pink areas indicate groupings of faults or folds that collectively form part of a single numbered entity. The pink areas are purely illustrative and do not imply anything about the location or extent of fault-related ground deformation. The wider distribution of faults and folds in the Waimate and Waitaki districts is shown in Figure 5.1and Figure 5.2.

Table 5.1 Categories and terms used in this report to describe active faults and folds in the Waimate and Waitaki districts.

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

Definite = clear evidence for the existence of an active fault or fold
Likely = good reason to suspect the existence of an active fault or fold
Possible = some reason to suspect the existence of an active fault or fold

Well expressed = likely to be able to be located to better than +/- 50 m in site-specific investigations
Moderately expressed = likely to be able to be located to better than +/- 100 m in site-specific investigations
Not expressed = able to be located only by large-scale subsurface site-specific investigations
Unknown = probable that evidence for or against an active feature would be found in targeted site-specific investigations

Table 5.2 Summary of evidence and estimated deformation characteristics of active faults and folds recognised in the Waimate and Waitaki districts (see text and appendices for explanation).

Name	Observed characteristics	References	Deformation estimates						
Lower case last term (e.g. fault) = informal name. Upper case (e.g. Fault) = name previously published	*Geologic evidence*	*Most comprehensive published information on fault/fold activity*	*Basis of estimates*	*Estimated age of deformed landform* (years before present)	*Estimated vertical deformation of landform* (m)	*Calculated average vertical slip rate* (mm/yr)	*Implied long-term average recurrence interval (RI - years) of deformation event, assuming 2 m vertical deformation per event** (see notes on last page of table)	*Nominal 67% uncertainty in RI (years)*** (see notes on last page of table)	*Implied range of RI values / RI Classes* (following Kerr *et al.* 2003)
1. Southern Alps faults									
1a. Huxley fault	Fault zone(s) mapped in bedrock, considered to possibly be active.	Cox et al. (2012); Litchfield et al. (2014); this report.	geodynamic modelling; airphoto interpretation.	There appear to be no offsets of glacial landforms of assumed age ~18,000 years. A recurrence interval of more than 10,000 years is adopted in this report.					>10,000 years / Class V or greater
1b. Hopkins fault	Fault zone(s) mapped in bedrock, considered to possibly be active.	Cox et al. (2012); Litchfield et al. (2014); this report.	geodynamic modelling; airphoto interpretation.	There appear to be no offsets of glacial landforms of assumed age ~18,000 years. A recurrence interval of more than 10,000 years is adopted in this report.					>10,000 years / Class V or greater
1c. Dingle Fault	Fault zone(s) mapped in bedrock, considered to possibly be active.	Cox et al. (2012); Litchfield et al. (2014); this report.	geodynamic modelling; airphoto interpretation.	There appear to be no offsets of glacial landforms of assumed age ~18,000 years. A recurrence interval of more than 10,000 years is adopted in this report.					>10,000 years / Class V or greater
1d. Ahuriri Fault	Fault zone(s) mapped in bedrock, considered to possibly be active.	Cox et al. (2012); Litchfield et al. (2014); this report.	geodynamic modelling; airphoto interpretation.	There appear to be no offsets of glacial landforms of assumed age ~18,000 years. A recurrence interval of more than 10,000 years is adopted in this report.					>10,000 years / Class V or greater
1e. Barrier Range Fault	Fault zone(s) mapped in bedrock, considered to possibly be active.	Cox et al. (2012); Litchfield et al. (2014); this report.	geodynamic modelling; airphoto interpretation.	There appear to be no offsets of glacial landforms of assumed age ~18,000 years. A recurrence interval of more than 10,000 years is adopted in this report.					>10,000 years / Class V or greater
2. Watson fault	Likely active fault.	Rattenbury et al. (2010); Cox et al. (2012); this report.	airphoto interpretation; regional geologic mapping.	18,000	10	0.6	3,600	2,412	1,200 to 6,000 years / Classes I to IV
3. Snowy Gorge fault	Definite active fault and monocline.	Turnbull (2000); this report.	airphoto interpretation; regional geologic mapping.	18,000	5	0.3	7,200	4,824	2,400 to 12,000 years / Classes II to V
4. Timaru Creek Fault	Likely active fault.	Turnbull (2000); this report.	airphoto interpretation; regional geologic mapping.	18,000	5	0.3	7,200	4,824	2,400 to 12,000 years / Classes II to V
5. Lindis Pass Fault Zone; 5a. Dalrachney Fault; 5b. Longslip Fault	Definite, likely and possible active faults.	Turnbull (2000); this report.	airphoto interpretation; regional geologic mapping.	12,000	5	0.4	4,800	3,216	1,600 to 8,000 years / Classes I to IV
6. Ostler Fault Zone	Definite, likely and possible active faults and monoclines.	Van Dissen et al. (1993); Amos et al. (2007, 2010, 2011); this report.	airphoto interpretation; field inspection & surveying; trenching & dating; regional geologic mapping.	From a range of geological observations and dating results, a recurrence interval of in the range of 2,000 to 3,500 years is adopted. Vertical deformation rate is ~0.9 mm/yr, movement is likely to be pure reverse, and estimated net slip rate lies in the range of 0.70 to 2.41 mm/yr, depending on the assumed dip range of the fault (range 30 to 60°), with a preferred value of 1.27 mm/yr (Litchfield et al. 2013, 2014). Stirling et al. (2012) calculated a net single-event displacement of 4.7 m and RI of 3310 years.					2,000 to 3,500 years / Class II
7. Omarama Saddle fault	Definite, likely and possible active fault.	This report.	airphoto interpretation; regional geologic mapping.	18,000	5	0.3	7,200	4,824	2,400 to 12,000 years / Classes II to V
8. Hawkdun Fault	Possible active fault.	Forsyth (2001); this report.	airphoto interpretation; regional geologic mapping.	There appear to be no offsets of landforms of assumed age ~18,000 years. A recurrence interval of more than 10,000 years is adopted in this report.					>10,000 years / Class V or greater
9. Otematata Fault	Possible active fault.	Forsyth (2001); Litchfield et al. (2013); this report.	airphoto interpretation; regional geologic mapping.	There appear to be no offsets of landforms of assumed age ~18,000 years. A recurrence interval of more than 10,000 years is adopted in this report.					>10,000 years / Class V or greater
10. Falstone fault	Possible active fault.	Forsyth (2001); this report.	field inspection; airphoto interpretation; regional geologic mapping	There appear to be no offsets of landforms of assumed age ~18,000 years. A recurrence interval of more than 10,000 years is adopted in this report.					>10,000 years / Class V or greater

Name	Observed characteristics	References	Deformation estimates						
Lower case last term (e.g. fault) = informal name. Upper case (e.g. Fault) = name previously published	*Geologic evidence*	*Most comprehensive published information on fault/fold activity*	*Basis of estimates*	*Estimated age of deformed landform* (years before present)	*Estimated vertical deformation of landform* (m)	*Calculated average vertical slip rate* (mm/yr)	*Implied long-term average recurrence interval (RI - years) of deformation event, assuming 2 m vertical deformation per event** (see notes on last page of table)	*Nominal 67% uncertainty in RI (years)*** (see notes on last page of table)	*Implied range of RI values / RI Classes* (following Kerr *et al.* 2003)
11. Gibson fault	Possible active fault.	Forsyth (2001); this report.	field inspection; airphoto interpretation; regional geologic mapping	There appear to be no offsets of landforms of assumed age ~18,000 years. A recurrence interval of more than 10,000 years is adopted in this report.					>10,000 years / Class V or greater
12. Waitaki Fault System									
12a. Middle Range Fault	Definite, likely and possible active fault.	Wood et al. (1998); Forsyth (2001); this report.	field inspection; trenching & dating; airphoto interpretation; regional geologic mapping.	18,000	3	0.2	12,000	8,040	4,000 to 20,000 years / Classes III to VI
12b. Bitterness Fault	Possible active fault.	Forsyth (2001); this report.	airphoto interpretation; visual inspection; regional geologic mapping.	It has been suggested that movement on the Fern Gully Fault may have extended along parts of the Bitterness Fault (Litchfield et al. 2013, 2014; Stirling et al. 2012). The slip rate and recurrence interval of the Fern Gully Fault are tentatively applied to the Bitterness Fault (slip rate range 0.4 to 0.7 mm/yr; RI range 6,000 to 10,000 years - Barrell et al. 2002).					6,000 to 10,000 years / Class IV
12c. Narrows fault	Possible active fault.	Forsyth (2001); this report.	airphoto interpretation; field inspection; regional geologic mapping.	It has been suggested that movement on the Fern Gully Fault may have extended along parts of the Narrows fault (Litchfield et al. 2013, 2014; Stirling et al. 2012). The slip rate and recurrence interval of the Fern Gully Fault are tentatively applied to the Narrows fault (slip rate range 0.4 to 0.7 mm/yr; RI range 6,000 to 10,000 years - Barrell et al. 2002).					6,000 to 10,000 years / Class IV
12d. Wharekuri Fault	Possible active fault.	Forsyth (2001); Barrell et al. (2002); this report.	airphoto interpretation; field inspection; regional geologic mapping.	Activity that had previously been ascribed to the Wharekuri Fault (e.g. Gair & Gregg 1960) has subsequently been attributed to other named fault entities (Fern Gully Fault and Awahokomo Fault (Barrell et al. 2002; Litchfield et al. 2013, 2014). There appear to be no offsets of landforms of assumed age ~18,000 years across the Wharekuri Fault. A recurrence interval of more than 10,000 years is adopted in this report.					>10,000 years / Class V or greater
12e. Fern Gully Fault	Definite active fault.	Forsyth (2001); Barrell et al. (2002); this report.	airphoto interpretation; field inspection & surveying; trenching & dating.	Detailed investigations and dating (Barrell et al. 2002) have determined that at least three surface ruptures have occurred in the past ~23,000 years, with the most recent event sometime between 3,000 and 14,000 years ago. The most likely estimate of net slip rate lies in the range of 0.4 to 0.7 mm/yr, comprising predominantly left-lateral strike slip, and RI most likely in the range of 6,000 to 10,000 years.					6,000 to 10,000 years / Class IV
12f. Waitangi Fault	Definite, likely and possible active fault.	Forsyth (2001); Barrell et al. (2002, 2009); this report.	airphoto interpretation; field inspection & surveying; trenching & dating; regional geologic mapping.	Detailed investigations and dating (Barrell et al. 2002) have determined that at least two and possibly three surface ruptures have occurred in the past ~23,000 years, with the most recent surface rupture most likely having occurred between 13,000 and 14,000 years ago. The most recent surface rupture had a vertical component of displacement of between 1 and 2 m. The most likely estimate of net slip rate lies in the range of 0.1 to 0.3 mm/yr, comprising oblique reverse/right-lateral slip, and RI most likely in the range of 6,000 to 12,000 years.					6,000 to 12,000 years / Classes IV to V
12g. Awahokomo Fault	Definite and likely faults.	Forsyth (2001); Barrell et al. (2002); this report.	airphoto interpretation; field inspection & surveying; trenching & dating; regional geologic mapping.	Investigations and dating (Barrell et al. 2002) have determined that the most recent surface rupture occurred between 3,000 and 10,700 years ago, and taking account of both definite and likely deformation, the vertical slip rate lies in the range of 0.2 to 0.4 mm/yr. It is not known whether or not there is a strike-slip component of movement. In absence of any direct information on recurrence, the RI range for the Fern Gully Fault is adopted; 6,000 to 10,000 years.					6,000 to 10,000 years / Class IV
12h. Deep Stream Fault	Possible active fault.	Forsyth (2001); this report.	airphoto interpretation; regional geologic mapping.	The relative shortness of this fault, and proximity to larger active faults (Waitangi Fault, Awahokomo Fault) raises the possibility of interlinked or secondary slip due to those faults. There is no direct evidence of offset of geologically young landforms across the Deep Stream Fault, and a recurrence interval of more than 10,000 years is adopted in this report.					>10,000 years / Class V or greater
12i. Little Awakino Fault; 12j. Kurow Hill Fault	Possible active faults.	Forsyth (2001); Barrell & Van Dissen (2003); this report.	airphoto interpretation; regional geologic mapping.	The relative shortness of these faults, and proximity to larger faults (Awahokomo Fault, Dryburgh Fault) raises the possibility of interlinked or secondary slip due to rupture on those faults. There is no direct evidence of offset of geologically young landforms across the Little Awakino or Kurow Hill faults, and recurrence intervals of more than 10,000 years are adopted in this report.					>10,000 years / Class V or greater
12k. Dryburgh Fault	Possible active fault.	Forsyth (2001); Barrell & Van Dissen (2003); Barrell et al. (2005); this report.	airphoto interpretation; field inspection & surveying; drilling, trenching & dating; regional geologic mapping.	Investigations and dating (Barrell et al. 2005) have not been able to identify any direct evidence for offset of geologically young deposits or landforms. They determined that there has been no surface rupture within the past ~38,000 years, and probably not within the past 62,000 years. This points towards a geologically-defined recurrence interval of >62,000 years. A net slip rate value in the range of 0.001 to 0.026 mm/yr, with a preferred value of 0.006 mm/yr was assigned by Litchfield et al. (2013, 2014), while Stirling et al. (2012) calculated a net single-event displacement of 2.0 m and RI of 325,000 years.					>62,000 years / Class VI or inactive.

Name	Observed characteristics	References	Deformation estimates						
Lower case last term (e.g. fault) = informal name. Upper case (e.g. Fault) = name previously published	*Geologic evidence*	*Most comprehensive published information on fault/fold activity*	*Basis of estimates*	*Estimated age of deformed landform* (years before present)	*Estimated vertical deformation of landform* (m)	*Calculated average vertical slip rate* (mm/yr)	*Implied long-term average recurrence interval (RI - years) of deformation event, assuming 2 m vertical deformation per event** (see notes on last page of table)	*Nominal 67% uncertainty in RI (years)*** (see notes on last page of table)	*Implied range of RI values / RI Classes* (following Kerr *et al.* 2003)
12l. Stonewall Fault	Definite, likely and possible active fault.	Forsyth (2001); Barrell & Van Dissen (2003); Barrell et al. (2004); this report.	airphoto interpretation; field inspection & surveying; trenching & dating; regional geologic mapping.	Investigations and dating (Barrell et al. 2004) have documented the occurrence of at least one surface rupture, with vertical single-event displacement (reverse) in the range of 0.9 to 2.4 m, between 15,700 and 46,000 years ago. This indicates vertical slip rate in the range of 0.002 to 0.15 mm/yr. As only one rupture event has been definitively identified, RI cannot be constrained, but for the purposes of this report, a RI of >16,000 years is inferred. It is not known whether or not there is any component of strike-slip motion. Stirling et al. (2012) characterised the fault as 20 km long, applied a slip rate of 0.07 mm/yr, and calculated single-event displacement of 1.4 m and RI of 21,430 years.					>16,000 years / Class V or greater
12m. Waitaki Fault	Possible active fault.	Forsyth (2001); Barrell & Van Dissen (2003); this report.	airphoto interpretation; field inspection; regional geologic mapping.	There appear to be no offsets of landforms of assumed age ~18,000 years. A recurrence interval of more than 10,000 years is adopted in this report.					>10,000 years / Class V or greater
13. Kirkliston Fault Zone	Definite, likely and possible active faults and monoclines.	Forsyth (2001); Barrell et al. (2008); this report.	airphoto interpretation; field inspection & surveying; trenching & dating; regional geologic mapping.	Investigations and dating (Barrell et al. 2008) on the central sector of the fault system documented the occurrence of at least two surface ruptures, on a 40° northwest-dipping reverse fault, with vertical single-event displacements of 3.25 ± 0.25 m, and vertical slip rate in the range of 0.08 to 0.11 mm/yr. The most recent rupture most likely occurred between 12,900 and 22,000 years ago, and the penultimate rupture between ~18,000 and 77,000 years ago, with a most likely estimate of ~50,000 years ago. RI is in the range of 23,000 to 39,000 years, with 25,000 years the preferred estimate. Vertical slip rate on the southwestern sector of the fault system is no more than ~0.05 mm/yr. No investigations have been done on the northeastern sector of the fault system. For the fault system as a whole, investigations and airphoto interpretation show that only landforms with loess cover show evidence for deformation, indicating that nowhere on the fault system has there been surface rupture more recently than ~18,000 years ago.					~25,000 years / Class VI
14. Mt MacGregor faults	Possible active faults.	Forsyth (2001); this report.	airphoto interpretation; regional geologic mapping.	There appear to be no offsets of landforms of assumed age ~18,000 years. A recurrence interval of more than 10,000 years is adopted in this report.					>10,000 years / Class V or greater
15. Longden fault	Definite active fault.	This report.	airphoto interpretation; field inspection.	18,000	2	0.1	18,000	12,060	4,000 to 20,000 years / Classes III to VI
16. West Hunters Fault	Possible active faults.	Forsyth (2001); this report.	airphoto interpretation; regional geologic mapping.	There appear to be no offsets of landforms of assumed age ~18,000 years. A recurrence interval of more than 10,000 years is adopted in this report.					>10,000 years / Class V or greater
17. Nimrod fault	Likely and possible active fault.	Forsyth (2001); this report.	airphoto interpretation; regional geologic mapping.	The straightness of this feature across mountainous terrain, and varying amounts of sense of throw suggest a near-vertical fault with a component of left-lateral strike slip motion. Based on the visual prominence of the lineament across steep terrain, a surface rupture during the past few thousand years is inferred, and a recurrence interval of between 5,000 and >10,000 years is tentatively adopted in this report.					5,000 to >10,000 years / Classes IV to V or greater
18. Chamberlain fault	Possible active fault.	Cox & Barrell (2007); Forsyth (2001); this report.	airphoto interpretation; regional geologic mapping.	Fault with a prominent reverse component of throw, approximated in other datasets as the 'Opawa Fault' (Stirling et al. 2012; Litchfield et al. 2014), but in need of renaming/re-evaluation because the Opawa Fault is a different, nearby active fault. There appear to be no offsets of landforms of assumed age ~18,000 years. A recurrence interval of more than 10,000 years is adopted in this report.					>10,000 years / Class V or greater
19. Hunters Fault	Possible active faults.	Forsyth (2001); Yetton (2008); this report.	airphoto interpretation; field inspection; regional geologic mapping.	There appear to be no offsets of landforms of assumed age ~18,000 years. Suggestions of offsets of older landforms (Yetton 2008) are not conclusive. Undoubted surface deformation east of the Hunters Fault is identified as a separate entity (Hunters Fault (Otaio monocline)). Because no conclusive Quaternary offsets have been identified on the Hunters Fault, the age of the most recent movement is not known. A recurrence interval for the Hunters Fault of more than 10,000 years is adopted in this report.					>10,000 years / Class V or greater
20. Hunters Fault (Otaio monocline)	Definite, likely and possible active monocline.	Forsyth (2001); Yetton (2008); this report.	airphoto interpretation; field inspection; regional geologic mapping.	There appear to be no offsets of landforms of assumed age ~18,000 years, but undoubted surface deformation of somewhat older landforms. It is likely that the most recent surface deformation has occurred within the past few tens of thousands of years. A recurrence interval of more than 10,000 years is adopted in this report.					>10,000 years / Class V or greater
21. Waimate Fault	Possible active fault.	Forsyth (2001); Barrell & Van Dissen (2003); Yetton (2008); this report.	airphoto interpretation; field inspection; regional geologic mapping.	There appear to be no offsets of landforms of assumed age ~18,000 years, but some indications of deformation of older Quaternary deposits (Yetton 2008). There appears to be no deformation of older terraces (Middle Quaternary age) of the Waitaki valley. A recurrence interval of more than 10,000 years is adopted in this report.					>10,000 years / Class V or greater

Name	Observed characteristics	References	Deformation estimates						
Lower case last term (e.g. fault) = informal name. Upper case (e.g. Fault) = name previously published	*Geologic evidence*	*Most comprehensive published information on fault/fold activity*	*Basis of estimates*	*Estimated age of deformed landform* (years before present)	*Estimated vertical deformation of landform* (m)	*Calculated average vertical slip rate* (mm/yr)	*Implied long-term average recurrence interval (RI - years) of deformation event, assuming 2 m vertical deformation per event** (see notes on last page of table)	*Nominal 67% uncertainty in RI (years)*** (see notes on last page of table)	*Implied range of RI values / RI Classes* (following Kerr *et al.* 2003)
22. Maungati Fault	Definite, likely and possible active fault and monocline.	Forsyth (2001); Yetton (2008); this report.	airphoto interpretation; regional geologic mapping.	There appear to be no offsets of landforms of assumed age ~18,000 years, but undoubted surface deformation of somewhat older landforms, with estimated vertical components of offset of 5 m and 10 m of progressively higher terraces. It is likely that the most recent surface deformation occurred more than 18,000 years ago, but within the past few tens of thousands of years. Assuming a minimum age of ~140,000 years for the terrace that exhibits a vertical offset of ~10 m implies a maximum average vertical slip rate of 0.07 mm/yr. A recurrence interval of more than 10,000 years is adopted in this report.					>10,000 years / Class V or greater
23. Brothers Fault and Craigmore Anticline	Possible active fault and active anticline.	Forsyth (2001); Cox & Barrell (2007); Barrell & Strong 2012; Litchfield et al. (2014); Barrell (2016); this report.	airphoto interpretation; regional geologic mapping.	The Brothers Fault is characterised by Stirling et al. (2012) and Litchfield et al. (2014) as a 35 km long reverse fault dipping east at 60°, with a net slip rate in the range of 0.01 to 0.13 mm/yr, and preferred estimate of 0.06 mm/yr., and calculated net single event displacement of 2.4 m and recurrence interval of 37,500 years. There appear to be no offsets or deformation of landforms of assumed age ~18,000 years. A recurrence interval of more than 10,000 years for fault rupture or anticline growth events is adopted in this report.					>10,000 years / Class V or greater
24. Black Hill Fault	Possible active fault.	Macfarlane (1988, 1989); Forsyth (2001); Barrell & Van Dissen (2003); this report.	airphoto interpretation; drilling; field examination; regional geologic mapping.	There appear to be no offsets of landforms and deposits assessed as being ~20,000 years old (Barrell & Van Dissen 2003). There is equivocal evidence from drilling for offset of fluvial gravels more than ~35,000 years old beneath the Waitaki valley (Macfarlane 1988, 1989; Barrell & Van Dissen 2003). A recurrence interval of more than 10,000 years is adopted in this report.					>10,000 years / Class V or greater
25. Awamoa Fault	Possible active fault.	Gage (1957); this report.	airphoto interpretation; field examination; regional geologic mapping.	A ~7 m height change of a coastal marine terrace may indicate movement on the Awamoa Fault, although other explanations are possible. If due to faulting, and assuming a terrace age of ~125,000 years, a vertical slip rate of 0.06 mm/yr is implied. Assuming 2 m vertical offset per surface rupture implies a recurrence interval of ~25,000 years. The fault is classed as possibly active, and a recurrence interval of ~25,000 years is tentatively adopted in this report.					~25,000 years / Class VI
26. Waihemo Fault System	Definite, likely and possible active faults.	Forsyth (2001); Curran & Norris 2009; Curran et al. (2011); this report.	airphoto interpretation; field inspection & dating; regional geologic mapping.	There appear to be no offsets of landforms assessed as being ~18,000 years old. An exposed offset on a northeast-dipping reverse fault had a vertical component of at least 1 m and occurred sometime between 12,800 and 71,100 years ago (Curran & Norris 2009). The most recent rupture is assumed to have occurred more than ~18,000 years ago, and a recurrence interval of more than 10,000 years is adopted in this report.					>10,000 years / Class V or greater
27. Horse Flat Fault / Taieri Ridge Fault	Possible active fault.	Forsyth (2001); Norris & Nicolls (2004); Litchfield et al. (2005, 2013); this report.	airphoto interpretation; field inspection & dating; regional geologic mapping.	[Horse Flat Fault is the preferred name]. There appear to be no convincing offsets of geological young landforms across the fault, and estimates of the age and deformation of geologically young sediments (Norris & Nicolls 2004) are considered equivocal (this report). A recurrence interval of more than 10,000 years is tentatively adopted in this report.					>10,000 years / Class V or greater
28. Billys Ridge Fault	Possible active fault.	Forsyth (2001); Litchfield et al. (2005, 2013); this report.	airphoto interpretation; field inspection; regional geologic mapping.	It has been inferred that the fault is active (Litchfield et al. 2005, 2013, 2014; Stirling et al. 2012), but there are no demonstrated offsets of any geologically young landforms, and thus no direct evidence that the fault is active. A recurrence interval of more than 10,000 years is tentatively adopted in this report.					>10,000 years / Class V or greater
29. Macraes Fault	Possible active fault.	Forsyth (2001); Litchfield et al. (2005, 2013); Barrell & Van Dissen (2011); this report.	airphoto interpretation; field inspection; trenching; regional geologic mapping.	It has been inferred that the fault is active (Litchfield et al. 2005, 2014; Stirling et al. 2012), and may be an extension of the Billys Ridge Fault, but there are no demonstrated offsets of any geologically young landforms, and thus no direct evidence that the fault is active. There is some evidence suggesting that it is inactive. Based on trenching investigations and geological inference, the most recent surface rupture occurred more than 11,500 years ago, and that value also represents a minimum recurrence interval.					>11,500 years / Class V or greater

NOTES

* Deformation of 2 m per event is arbitrarily assumed, for the purpose of placing these features in the context of the Kerr et al. (2003) RI classification. See text for further discussion

** In order to highlight the arbitrarily assumed deformation value, a nominal error of plus/minus two-thirds of the RI value (~67%) is applied

RI Class definitions

I ≤2,000 years
II >2,000 years to ≤3.500 years
III >3,500 years to ≤5,000 years
IV >5,000 years to ≤10,000 years
V >10,000 years to ≤20,000 years
VI >20,000 years to ≤125,000 years

6.0 IMPLICATIONS FOR HAZARDS

Since European settlement in the Waimate and Waitaki district, there have been no known ground-surface fault rupture events in the district. The only large historic earthquakes to have been felt strongly in the districts were the 1876 Oamaru Earthquakes (Downes 1999, Litchfield & Berryman 2012) which comprised two earthquakes on 25th February and another on 11th April of that year, all of which are estimated retrospectively as being about Magnitude 5.75. Newspaper reports highlight that the earthquakes were felt most strongly in the general area of Oamaru, with widespread damage to chimneys and some buildings. No epicentre can be defined from the historical records, mainly because its location close to the coast prevents a determination as to whether they were centred onland or offshore (where no records exist). The Awamoa Fault, just southwest of Oamaru is identified in this dataset as a possible active fault, but there is no reason to suspect it as the source of the earthquakes. That said, the occurrence of the 1876 earthquakes illustrates the existence of contemporary tectonic activity at depth beneath the general vicinity of Oamaru, and highlights that residents of the Waimate and Waitaki districts should avoid any complacency about earthquakes.

The geological record and landforms show clear evidence for many zones of geologically-recent (though pre-dating European settlement) fault and fold deformation of the ground surface. This highlights that it would be prudent to treat the active fault or fold features of the Waimate and Waitaki districts as potentially hazardous. Figure 1.2, Figure 1.3 and Figure 6.1 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. In general, faults and monoclines present the most focused forms of ground deformation, in regard to direct rupture or significant tilting of the ground surface. Such effects may occur in a sudden event. Active anticlines or synclines are likely to present a much lesser level of ground surface deformation hazard with regard to buildings, but may pose relevant hazards to developments such as canals or power stations (e.g. by tilting the ground). Furthermore, the presence of active folds suggests that there may be an underlying active fault at depth that may potentially generate a local, large, shallow earthquake, were it to rupture.

The geological estimates presented in this report indicate that relatively few of the faults in the Waimate and Waitaki districts have RIs of less than 5,000 years, and many are considered to have RIs of more than 10,000 years. For several of those inferred low-activity faults, there is uncertainty as to whether they should in fact be considered active. Nonetheless, there are several undoubtedly active faults in the Waimate and Waitaki districts and every reason for authorities and residents to be prepared for the occurrence of ground-surface rupturing fault movements, and resulting large, locally damaging earthquakes, over future decades to centuries (Stirling et al., 2008). It is important to appreciate that the mapped delineation of the active faults and folds of the Waimate and Waitaki 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 faults or folds. 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.

Figure 6.1 Fault scarp formed on the Chelungpu Fault during the magnitude 7.6 Chi-Chi Earthquake, Taiwan, 1999. The disrupted running track shows damage typical of a reverse fault ground-surface rupture, which is well expressed on the brittle surface (note the smoother rupture across grass behind). This location lies on a stream terrace that is younger than the previous rupture event on the fault, so that there was no scarp here before the earthquake. This example illustrates the sorts of effects that can be expected across fault scarps in the Waimate District or Waitaki District the next time any particular fault experiences a surface rupture earthquake. Photo from Kelson et al. (2001).

Following are some general comments and recommendations in relation to active fault ground-deformation hazards in the Waimate and Waitaki districts:

Many of the active faults are in remote locations, far from any existing or likely future developments. Accordingly, in regard to ground-surface fault rupture hazard, they are of minimal consequence. However, they do represent potential sources of major earthquakes that would be accompanied by widespread strong ground shaking, possibly along with localised earthquake-triggered landslides in hilly terrain and liquefaction in any localised low-lying areas, such as close to modern river beds, and the coastal fringe, for example between the Otaio and Waihao rivers, and in the Kakanui, Waianakarua and Shag (Waihemo) river estuary areas.

There are no definitely or likely active faults passing beneath any existing towns or villages in the Waimate or Waitaki districts. The Waimate Fault lies on the western side of Waimate township, but it is questionable as to whether or not it should be classified as an active fault. There is also a question-mark in regard to Otematata, because it is thought likely that movement associated with the Fern Gully Fault has likely extended into the Otematata basin, and Stirling et al. (2012) and Litchfield et al. (2013, 2014) show the Fern Gully Fault, in highly generalised form, as passing within ~1 km of Otematata. However, as delineated in the datasets accompanying this report, possible continuations of Fern Gully Fault activity is identified on the Narrows fault, and the Bitterness Fault, both of which lie at least 2 km from

Otematata. The matter could be investigated further, should there ever be a need to know more about the movement histories, and possible interconnections between, those faults.

Another feature of note identified in this report is the possibility of activity on the Awamoa Fault, which lies on the western fringe of Oamaru township. If it is an active fault, it likely has a low rate of activity, with a provisional estimate of RI of ~25,000 years.

For the more active faults in these districts, which pose the greatest risk of future rupture, a potential hazard to road serviceability, and any road-side utility corridors such as power or telephone lines, is posed by the Oster Fault Zone (Lake Ohau Road and State Highway 8 northwest of Otematata), and the Waitangi-Fern Gully-Awahokomo faults (State Highway 83 near Lake Aviemore and Te Akatarawa Road). A rupture of those latter faults, especially the Waitangi Fault, is likely to pose a tsunami and seiche hazard around the Lake Aviemore shoreline. A rupture of the Ostler Fault Zone is likely to create a tsunami on Lake Ruataniwha.

.

7.0 CONCLUSIONS

1. Regional geological mapping has identified a number of active faults and folds (monoclines, synclines and anticlines) in the Waimate and Waitaki districts. In total, 29 areas of known, suspected or possible active faults and/or folds are delineated, within which a total of 46 individual fault or fold entities are identified. Most of these were already known about, and are documented for example on published geological maps.
2. A GIS dataset of information on the active faults and folds accompanies this report. For each mapped fault and fold, an attribute of 'certainty' indicates the level of confidence in the mapping of the feature, whether 'definite', 'likely' or 'possible'. Also included is a classification of 'surface form', whether 'well expressed', 'moderately expressed', 'not expressed' or 'unknown'. The surface form classification provides a provisional estimate of how easy it would be to pinpoint the location of the particular fault or fold feature on the ground.
3. Table 5.2 summarises what exists in the way of geological evidence for the degree of activity of each feature. Average slip rate is a common way to compare the level of activity of a fault or fold. This can also be expressed as an average recurrence interval for deformation events, aided by some assumptions. The recurrence interval estimates provide a linkage to Ministry for the Environment active fault planning guidelines.
4. The information presented here is not sufficiently precise for site-specific hazard assessment. Instead, the information is intended to highlight those areas which, at the current state of knowledge, are potentially affected by active fault or fold hazards. The information may help to target site-specific investigations that may be desirable, or required, prior to development, and allow identification of lifeline vulnerabilities and emergency management response plans.

8.0 ACKNOWLEDGEMENTS

I thank Helen Jack and Marion Gadsby (Environment Canterbury) for technical discussions and development of the project brief. The report has benefited from reviews by Russ Van Dissen and Rob Langridge (GNS Science).

9.0 REFERENCES

Barrell, D.J.A. 2011. Quaternary Glaciers of New Zealand. In Quaternary Glaciations – Extent and Chronology: a closer look: Ehlers, J.; Gibbard, P.L.; Hughes, P.D., Eds). Developments in Quaternary Science 15: 1047–1064. Elsevier, Amsterdam.

Barrell, D.J.A. 2013. General distribution and characteristics of active faults and folds in the Selwyn District, North Canterbury. GNS Science Consultancy Report 2012/325, Environment Canterbury Report R13/27. 53 p.

Barrell, D.J.A. 2015. General distribution and characteristics of active faults and folds in the Kaikoura District, North Canterbury. GNS Science Consultancy Report 2014/210, Environment Canterbury Report No. R15/23. 59 p.

Barrell, D.J.A. 2016. General distribution and characteristics of active faults and folds in the Timaru District, South Canterbury. GNS Science Consultancy Report 2014/308, Environment Canterbury Report No. R15/112. 49 p.

Barrell, D.J.A.; Begg, J.G. 2013. General distribution and characteristics of active faults and folds in the Waimakariri District, North Canterbury. GNS Science Consultancy Report 2012/326, Environment Canterbury Report R13/28. 52 p.

Barrell, D.J.A.; Strong, D.T. 2009. General distribution and characteristics of active faults and folds in the Ashburton District, mid-Canterbury. GNS Science Consultancy Report 2009/227, Environment Canterbury Report R09/72. 17 p.

Barrell, D.J.A.; Strong, D.T. 2010. General distribution and characteristics of active faults and folds in the Mackenzie District, South Canterbury. GNS Science Consultancy Report 2010/147, Environment Canterbury Report R10/44. 22 p.

Barrell, D.J.A.; Strong, D.T. 2012. Geological contours for groundwater modelling, South Canterbury. GNS Science Consultancy Report 2012/245. 11 p, 6 Figures + 2 Appendices.

Barrell, D.J.A.; Townsend, D.B. 2012. General distribution and characteristics of active faults and folds in the Hurunui District, North Canterbury. GNS Science Consultancy Report 2012/113, Environment Canterbury Report. R12/39. 30 p.

Barrell, D.J.A.; Van Dissen, R.J. 2003. Project Aqua Geotechnical Investigations: Activity of geological faults in the lower Waitaki Valley. Institute of Geological & Nuclear Sciences Client Report 2003/107. Prepared for URS (NZ) Limited. 43 p.

Barrell, D.J.A.; Van Dissen, R.J. 2011. Review of Golder Associates (NZ) Ltd Report 1078301051: “Top Tipperary TSF: Active fault hazard assessment”. Electronic file: 1078301051-R100E.pdf, supplied by Golder Associates, 21 February 2011. GNS Science Consultancy Report 2011/04LR. Prepared for Oceana Gold (New Zealand) Limited. 2 p.

Barrell, D.J.A.; Van Dissen, R.J.; Berryman, K.R.; Read, S.A.L.; Wood, P.R.; Zachariasen, J.; Lukovic, B.; Nicol, A.; Litchfield, N.J. 2002. Seismic loads on dams - Waitaki system: Aviemore Power Station - Geological investigations for fault displacement characterisation. Institute of Geological & Nuclear Sciences Client Report 2001/125. Prepared for URS (NZ) Limited. 2 volumes. v.1: 99 p. + Figure and photos; v.2: appendices A-E.

Barrell, D.J.A.; Langridge, R.M.; Berryman, K.R.; Lukovic, B. 2004. Seismic loads on dams - Waitaki system: Dryburgh - Stonewall fault displacement characterisation. Institute of Geological & Nuclear Sciences Client Report 2004/56. Prepared for URS (NZ) Limited. 47 p. + maps and figures.

Barrell, D.J.A.; Langridge, R.M.; Litchfield, N.J.; Fraser, H.L.; Lukovic, B. 2005. Seismic loads on dams - Waitaki system: Dryburgh Fault displacement characterisation. Institute of Geological & Nuclear Sciences Client Report 2005/70. Prepared for URS (NZ) Limited. 64 p.

Barrell, D.J.A.; Berryman, K.R.; Mejia, L.; Macfarlane, D.F.; Read, S.A.L.; Van Dissen, R.J.; Walker, J. 2006. Fault displacement evaluation at Aviemore Dam, South Island, New Zealand. In: Proceedings New Zealand Geotechnical Society Symposium “Earthquakes and Urban Development”: 37-50.

Barrell, D.J.A.; Van Dissen, R.J.; Langridge, R.M.; Cox, S.C.; Wilson, K.J.; Rieser, U.; Lukovic, B. 2008. Seismic loads on dams - Waitaki system: Kirkliston Fault displacement characterisation. GNS Science Consultancy Report 2007/146. Prepared for URS (NZ) Limited. 26 p. + photos, Figure, and appendices.

Barrell, D.J.A.; Read, S.A.L.; Van Dissen, R.J.; Macfarlane, D.F.; Walker, J.; Rieser, U. 2009. Aviemore – a dam of two halves. Field Trip 6 In Geological Society of New Zealand and Geophysical Society of New Zealand Joint Annual Conference 2009: Field Trip Guides. Geological Society of New Zealand Miscellaneous Publication 128B. 30 p. Can be downloaded from www.gsnz.org.nz

Barrell, D.J.A.; Litchfield, N.J.; Townsend, D.B.; Quigley, M.; Van Dissen, R.J.; Cosgrove, R.; Cox, S.C.; Furlong, K.; Villamor, P.; Begg, J.G.; Hemmings-Sykes, S.; Jongens, R.; Mackenzie, H.; Noble, D.; Stahl, T.; Bilderback, E.; Duffy, B.; Henham, H.; Klahn, A.; Lang, E.M.W.; Moody, L.; Nicol, R.; Pedley, K.; Smith, A. 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: 283–291.

Barrell, D.J.A.; Almond, P.C.; Vandergoes, M.J.; Lowe, D.J.; Newnham, R.M. 2013. A composite pollen-based stratotype for inter-regional evaluation of climatic events in New Zealand over the past 30,000 years (NZ-INTIMATE project). Quaternary Science Reviews 74: 4–20.

Beavan, J.; Motagh, M.; Fielding, E.J.; 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: 207–221.

Cox, S.C.; Barrell, D.J.A. (compilers) 2007. Geology of the Aoraki area. Institute of Geological and Nuclear Sciences 1:250,000 Geological Map 15. 71 p. + 1 folded map.

Cox, S.C.; Stirling, M.W.; Herman, F.; Gerstenberger, M.; Ristau, J. 2012. Potentially active faults in the rapidly eroding landscape adjacent to the Alpine Fault, central Southern Alps, New Zealand. Tectonics, 31: TC2011. 24 p.

Curran, C.; Norris, R.J. 2009. The Waihemo Fault System, North Otago. In: Turnbull, I.M. (ed.). Field Trip Guides, Geosciences 09 Conference, Oamaru, New Zealand. Geological Society of New Zealand Miscellaneous Publication 128B. 27 p. Can be downloaded from www.gsnz.org.nz

Curran, C.; Norris, R.; Rieser, U. 2011. The Waihemo Fault of north Otago: constraints on late Quaternary activity. In: Litchfield, N.J.; Clark, K. (eds). Abstract volume, Geosciences 2011 Conference, Nelson, New Zealand. Geoscience Society of New Zealand Miscellaneous Publication 130A, p. 29.

Downes, G.L. 1995 Atlas of isoseismal maps of New Zealand earthquakes. Lower Hutt, Institute of Geological & Nuclear Sciences. Institute of Geological & Nuclear Sciences Monograph 11. 304 p.

Forsyth, P.J. (compiler) 2001. Geology of the Waitaki area. Institute of Geological and Nuclear Sciences 1:250 000 Geological Map 19. 64 p. + 1 folded map.

Gage, M. 1957: The Geology of the Waitaki Subdivision. New Zealand Geological Survey Bulletin 55. Wellington, Department of Scientific and Industrial Research.

Gair, H.S. 1967. Sheet 20 - Mt Cook. Geological Map of New Zealand 1:250 000. Wellington, Department of Scientific and Industrial Research. Map and notes (1 sheet).

Heron, D.W. (custodian) 2014. Geological map of New Zealand 1:250,000. GNS Science Geological Map 1. 1 CD

Kelson, K.I.; Kang, K.H.; Page, W.D.; Lee, C-T.; Cluff, L.S. 2001. Representative styles of deformation along the Chelungpu Fault from the 1999 Chi-Chi (Taiwan) earthquake: geomorphic characteristics and responses of man-made structures. Bulletin of the Seismological Society of America 91: 930–952.

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. Ministry for the Environment, July 2003. ME Number: 483; also identified as Institute of Geological and Nuclear Sciences Client Report 2002/124. Available for download at www.mfe.govt.nz.

Langridge, R.M.; Reis, W.; Litchfield, N.J.; Villamor, P.; Van Dissen, R.J.; Barrell, D.J.A.; Rattenbury, M.S.; Heron, D.W.; Haubrock, S.; Townsend, D.B.; Lee, J.M.; Berryman, K.R.; Nicol, A.; Cox, S.C.; Stirling, M.W. 2016. The New Zealand Active Faults Database. New Zealand Journal of Geology and Geophysics 59: 86-96.

Litchfield, N.J.; Berryman, K.R. 2013. Times and distances between events from selected global earthquake sequences; comparison with the 2010-2012 Canterbury earthquake sequence. Lower Hutt, GNS Science. GNS Science Report 2012/43. 20 p.

Litchfield, N.J.; McVerry, G.H.; Smith, W.D.; Berryman, K.R.; Stirling, M.W. 2005. Seismic hazard study for tailings embankments at Macraes gold project. Institute of Geological & Nuclear Sciences Client Report 2005/135. Prepared for Oceana Gold Limited. 75 p.

Litchfield, N.J.; Van Dissen, R.J.; Sutherland, R.; Barnes, P.M.; Cox, S.C.; Norris, R.J.; Beavan, R.J.; Langridge, R.M.; Villamor, P.; Berryman, K.R.; Stirling, M.W.; Nicol, A.; Nodder, S.D.; Lamarche, G.; Barrell, D.J.A.; Pettinga, J.R.; Little, T.A.; Pondard, N.; Clark, K.J. 2013. A model of active faulting in New Zealand: fault zone parameter descriptions. GNS Science Report 2012/19. 120 p.

Litchfield, N.J.; Van Dissen, R.J.; Sutherland, R.; Barnes, P.M.; Cox, S.C.; Norris, R.; Beavan, R.J.; Langridge, R.M.; Villamor, P.; Berryman, K.R.; Stirling, M.W.; Nicol, A.; Nodder, S.; Lamarche, G.; Barrell, D.J.A.; Pettinga, J.R.; Little, T.; Pondard, N.; Mountjoy, J.J.; Clark, K.J. 2014. A model of active faulting in New Zealand. New Zealand Journal of Geology and Geophysics 57: 32–56.

Norris, R.J.; Nicolls, R. 2004. Strain accumulation and episodicity of fault movement in Otago. EQC Research Report 01/445, also identified as EQC Research Paper 3710 (downloadable from www.eqc.govt.nz). 146 p.

NZAFD. New Zealand Active Faults Database, maintained by GNS Science. Accessible at the GNS Science website < www.gns.cri.nz >; search term < Active Faults Database >

Pettinga, J.R.; Yetton, M.D.; Van Dissen, R.J.; Downes, G.L. 2001.Earthquake source identification and characterisation for the Canterbury region, South Island, New Zealand. Bulletin of the New Zealand Society for Earthquake Engineering 34: 282–317.

Quigley, M.; Van Dissen, R.; Litchfield, N.; Villamor, P.; Duffy, B.; Barrell, D; Furlong, K.; Stahl, T.; Bilderback, E.; Noble, D. 2012. Surface rupture during the 2010 Mw 7.1 Darfield (Canterbury) earthquake: implications for fault rupture dynamics and seismic-hazard analysis. Geology 40: 55-58.

Rattenbury, M.S.; Jongens, R.; Cox, S.C. (compilers) 2010. Geology of the Haast area. Institute of Geological and Nuclear Sciences 1:250,000 Geological Map 14. 58 p. + 1 folded map.

Stirling, M.; Gerstenberger, M.; Litchfield, N.; McVerry, G.; Smith, W.; Pettinga, J.; Barnes, P. 2008. Seismic hazard of the Canterbury Region, New Zealand: new earthquake source model and methodology. Bulletin of the New Zealand Society for Earthquake Engineering 41: 51–67.

Stirling, M.; McVerry, G.; Gerstenberger, M.; Litchfield, N.; Van Dissen, R.; Berryman, K.; Barnes, P.; Wallace, L.; Bradley, B.; Villamor, P.; Langridge, R.; Lamarche, G.; Nodder, S.; Reyners, M.; Rhoades, D.; Smith, W.; Nicol, A.; Pettinga, J.; Clark, K.; Jacobs, K. 2012. National seismic hazard model for New Zealand: 2010 update. Bulletin of the Seismological Society of America 102: 1514–1542.

Turnbull, I.M. (compiler) 2000. Geology of the Wakatipu area. Institute of Geological and Nuclear Sciences 1:250,000 Geological Map 18. 72 p. + 1 folded map.

Van Dissen, R.J.; Berryman, K.R.; Webb, T.H.; Stirling, M.W.; Villamor, P.; Wood, P.R.; Nathan, S.; Nicol, A.; Begg, J.G.; Barrell, D.J.A.; McVerry, G.H.; Langridge, R.M.; Litchfield, N.J.; Pace, B. 2003. An interim classification of New Zealand's active faults for the mitigation of surface rupture hazard. Paper 155, Proceedings of the 2003 Pacific Conference on Earthquake Engineering, Christchurch, NZ. New Zealand Society for Earthquake Engineering. Available for download at www.nzsee.org.nz.

Villamor, P.; Barrell, D.J.A.; Litchfield, N.J.; Van Dissen, R.J.; Hornblow, S.; Levick, S.R. 2011. Greendale Fault: investigation of surface rupture characteristics for fault avoidance zonation. GNS Science Consultancy Report 2011/121; Environment Canterbury Report R11/25. 52 p. + 1 CD.

Wood, P.R.; Barrell, D.J.A.; Read, S.A.L. 1998. Mid-Waitaki power stations: characteristics of active faults for refining earthquake hazards. Institute of Geological & Nuclear Sciences client report 44780B.10. Prepared for Electricity Corporation of New Zealand. 121 p. + 5 appendices.

Yetton, M.D. 2008. Hunters Hills Fault Zone Study - Earthquake Hazard Assessment. Environment Canterbury Report: UO8/27.

APPENDICES

A1.0 APPENDIX 1: GIS LAYERS

The GIS layers referred to in this report and contained on the computer disk that is a companion to this report, consist of the following shapefiles:

- WMWK_faults.shp
- WMWK_folds.shp

The original attribute fields for active faults and folds are extracted from the QMAP (Quarter-Million-scale geological mAP) 'seamless' dataset (Heron, 2014), sourced from map data represented in the Waimate and Waitaki districts by the Waitaki map (Forsyth 2001), and in the far northwestern part of the Waitaki District by the Aoraki map (Cox & Barrell 2007), Haast map (Rattenbury et al. 2010) and Wakatipu map (Turnbull 2000). In order to make clear the linkage between the QMAP dataset and the amended dataset prepared as part of this project, all the attributes of the QMAP dataset are retained, without modification, in these shapefiles. For this report, all amendments are contained within three additional data fields:

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

The newly added faults and folds mapped as part of the work described in this report are identifiable by the lack of any QMAP attributes, other than sense of displacement and direction of downthrow. All the data have been compiled at a regional scale (1:250,000) and the locations of active faults and folds should be regarded as having a general accuracy of ± 250 m, and at best, ± 100 m. The geographic coordinate system for the data is New Zealand Map Grid 1949.

Note that some apparent inconsistencies exist between the QMAP 'Activity' field and the 'Certainty' field defined in this report. For the purposes of this data set, the 'Certainty' field supersedes the QMAP 'Activity' field.

Interested readers can examine and query the QMAP digital database (Heron, 2014) online at GNS Science, www.gns.cri.nz, search term < QMAP digital data webmap >. Note that this is best viewed using Google Chrome or Firefox browsers rather than Internet Explorer.

A2.0 APPENDIX 2: COMMENTARY ON THE MAPPING OF ACTIVE FAULT/FOLD FEATURES IN THE WAIMATE AND WAITAKI DISTRICTS

A2.1 BACKGROUND INFORMATION

The information in this Appendix is largely of a technical nature, and is intended primarily to aid future geo-scientific enquiry, although some aspects may well be of interest to lay people. In some instances, location co-ordinates are given for topographic features that can be viewed in, for example, Google Earth. The coordinates are in latitude/longitude, expressed in degrees/decimal minutes format. Readers of this Appendix may find it of benefit to refer to Google Earth, and topographic maps, such as may be accessed from www.topomap.co.nz.

The source of information on active faults and folds described in this report is from the 1:250,000-scale Geological Map of New Zealand, dubbed ‘QMAP’ because it is presented 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 Waimate and Waitaki districts are encompassed by four published map sheets, with accompanying descriptive booklets, comprising the Wakatipu map (Turnbull 2000; northwestern sector of Waitaki District), Haast map (Rattenbury et al. 2010; northern part of the Ahuriri catchment), Aoraki map (Cox & Barrell 2007; Ohau catchment) and the Waitaki map (Forsyth 2001; covering the bulk of the Waimate and Waitaki districts). Subsequently, all of the digital datasets from which these maps were generated were compiled into a nationwide ‘seamless’ dataset, published in digital form on DVD (Heron 2014). The subset of 1:250,000 scale faults and folds that form the Waimate and Waitaki district dataset presented in this report were extracted from the Heron (2014) seamless QMAP dataset.

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

Subsequently, a more conceptual interpretation of fault activity in the Southern Alps was published by Cox et al. (2012), which identifies several of what are called ‘potentially active’ faults. A generalised interpretation of active faults, encompassing all of New Zealand (the New Zealand Active Fault Model – NZAFM), was published by Litchfield et al. (2013, 2014). In the onshore parts of the South Island, the information in the NZAFM was largely compiled from expert panel workshops involving geological scientists between 2005-2008, as described in Litchfield et al. 2013, 2014) The NZAFM and Cox et al. (2012) 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. Many of the generalised faults depicted by Litchfield et al. (2013, 2014) are of identical location and extent to lines representing earthquake sources (i.e. active faults) in the National Seismic Hazard Model (NSHM; Stirling et al. 2012). The NSHM dataset focuses on delineating locations, in highly generalised form, of faults that are considered to be potential sources of large earthquakes. The NSHM dataset is used primarily to generate probabilistic and deterministic estimates of the intensities of earthquake ground motions at any specified location in New Zealand, over specified time ranges (e.g. 500 years, 2500 years).

This appendix includes discussion of faults identified in the Cox et al. (2012), Litchfield et al. (2013, 2014) and Stirling et al. (2012) datasets, and where judged appropriate elements of those interpretations are incorporated into the present dataset, but this dataset remains based on the 1:250,000-scale QMAP fault and fold dataset, unless indicated otherwise. The main areas of amendment from the QMAP dataset are in the Waitaki valley, where a substantial body of geological fault investigation work was carried out from the late 1990s to the late 2000s by GNS Science on behalf of Meridian Energy Limited (MEL), the owner of the hydroelectric power stations in the valley. The work is documented in a series of technical reports that are the property of MEL. However, main findings in regard to fault activity and characteristics are included in this report.

A2.2 SOUTHERN ALPS FAULTS (FEATURE 1)

The delineation of these faults has its origin in the work of Cox et al. (2012), who identified an array of what were described as ‘potentially active’ faults. Subsequently, these faults, more or less as delineated by Cox et al. (2012), were taken up in the NZAFM (Litchfield et al. 2013, 2014), who referred to each of them as a ‘representative active fault’. This can be taken to mean that active faults are thought likely to be present within the Southern Alps but their location and confirmatory evidence of their existence is thought to be lacking on account of the assumed rapid rates of erosion within the mountainous terrain. Because the identification of these faults is somewhere between conceptual and inferential, and not founded on direct geological evidence for recent movement, they are treated to some degree at arms’ length in the Litchfield et al. (2013, 2014) dataset, whereby no attempt was made to assign a slip rate. In the present dataset, they are treated in a similarly tentative way, by grouping them under a heading (feature 1; ‘Southern Alps faults’) that segregates them from other features whose activity is identified from more direct evidence.

A2.2.1 Huxley fault (feature 1a, Figure 5.1; see Figure A2.1)

This entity is identified in the NZAFM as a northwest-dipping reverse/right-lateral fault, based on geological map information from Cox & Barrell (2007) and interpretations of Cox et al. (2012). Although this fault zone is depicted as being about 30 km long by Litchfield et al. (2013, 2014), the mapped faults in the QMAP dataset at that location have a collective length of only about 20 km. These components from the QMAP dataset are identified in this report as the ‘Huxley fault’. There is no known evidence for landforms having been offset by those fault strands, and they are classified as ‘possible’, ‘not expressed’. No slip rate is assigned by Litchfield et al. (2013, 2014), and the fault is not included in the NSHM (Stirling et al. 2012). It remains to be established whether or not this entity is in fact an active fault. For the purposes of this report, a recurrence interval of >10,000 years is adopted.

A2.2.2 Hopkins fault (feature 1b, Figure 5.1; see Figure A2.1)

This entity is identified in the NZAFM as the ‘Ahuriri fault zone’. As with the Huxley fault, it is interpreted to be a northwest-dipping reverse/right-lateral fault, based on geological map information from Cox & Barrell (2007) and interpretations of Cox et al. (2012). A potential source of confusion is that this entity includes one strand at the northern end of the Ahuriri Fault, as named in the QMAP dataset, but the other fault strands comprising this entity are un-named in the QMAP dataset, other than being identified as components of the Main Divide Fault Zone. However, the remainder of the named Ahuriri Fault is approximated in both the NZAFM and NSHM datasets as the 'Ahuriri River Fault' (or 'fault zone'). It is unsatisfactory that the name of a fault in a less generalised database (Ahuriri Fault; QMAP) has been used for another, different, fault entity in highly generalised databases (NZAFM & NSHM). This has necessitated those databases then erecting a new term (Ahuriri River Fault) for the highly generalised depiction of the afore-mentioned named QMAP fault (Ahuriri Fault). The approach taken in this report is to assign an alternative name to the 'Ahuriri fault zone' of the NZAFM. The term 'Hopkins fault' is applied in this report, after the Hopkins River, in whose catchment most of the length of this inferred fault lies. It would be desirable for the name 'Hopkins fault' to be applied in future revisions of the NZAFM, if its existence as a named active fault entity is judged to be adequately supported by geological data (see below).

No slip rate is assigned by Litchfield et al. (2013, 2014), and this fault is not included in the NSHM (Stirling et al. 2012). There is no known evidence for landforms having been offset by this fault, and in this dataset it is classified as 'possible', 'not expressed'.

The northeastern continuation of this entity into the Mackenzie District approximately coincides with a feature identified by Barrell & Strong (2010) as the 'Neumann Range fault'. That feature includes 'likely' faults, and so provides a basis for identification of an active fault, approximated by the entity named the 'Ahuriri fault zone' in the NZAFM. However, it remains unclear whether or not the likely faults in the Mackenzie District referred to as the Neumann Range fault do in fact continue southwest along the 'Ahuriri fault zone' entity of the NZAFM. The line of this fault zone entity in the Waitaki District crosses areas of relict glacial landforms (approximately 18,000 years old) that show no indications of having been offset by fault movement. It should be noted that the Neumann Range fault was classified as 'likely' in the Mackenzie District dataset because it could not be ruled out that the topographic steps are simply a result of deep-seated gravitational movement associated with the steep mountain slopes, rather than tectonic fault rupture. Collectively, this means that the feature identified in the NZAFM as the 'Ahuriri fault zone', and renamed here the 'Hopkins fault', is of unclear validity as a representation of an active fault. For the purposes of this report, a recurrence interval of >10,000 years is adopted.

A2.2.3 Dingle Fault (feature 1c, Figure 5.1; see Figure A2.2)

This northeast-southwest striking fault is mapped in bedrock (Turnbull 2000; Rattenbury et al. 2010). Its existence is highlighted by a difference in basement rock type (schistose greywacke to the northwest, semischist to the southeast) either side of the fault. The QMAP digital dataset (Heron 2014) assigns the name 'Dingle Fault'. The digital data of Rattenbury et al. (2010), as incorporated in the Heron (2014) dataset, identifies an age of movement that includes "?Q1" (i.e. ?Holocene), whereas the Turnbull (2000) digital dataset assigned a movement age of undifferentiated Cenozoic (i.e. within the past 65 million years).

Subsequently, Cox et al. (2012) presented a highly generalised line depiction of the location and extent of this fault, which they identified as 'potentially active'. Litchfield et al. (2013, 2014) showed a similarly generalised depiction of this fault, but of slightly different location and extent to that of Cox et al. (2012), which was referred to as the 'Dingle Burn' fault zone in the Litchfield et al. (2014) digital dataset. There is a minor inconsistency in that this feature is identified as the 'Dingle fault zone' in descriptions and tables in Litchfield et al. (2013, 2014).

All this information is mentioned here so as to minimise any future misunderstandings. The term ‘Dingle Fault’ was first applied in 2000 and has precedence over more recent mentions of ‘Dingle Burn fault zone’ or similar. Therefore, the term Dingle Fault is used in the digital dataset accompanying this report.

The northern end of ‘Dingle fault zone’ entity is shown by Litchfield et al. (2013, 2014) as extending northeast from the mapped position of the ‘Dingle Fault’ as shown in the QMAP dataset, to underlie active fault traces shown by QMAP in the Barrier Range on the eastern side of the upper Ahuriri valley. It seems probable that these fault traces were taken as evidence in support of the activity of the ‘Dingle fault zone’ entity in the NZAFM. However, these ‘likely’ active fault traces are identified in the present report as feature 2 (Watson fault; see later section), and it is unknown as to whether or not they are associated with the ‘Dingle Fault’ as mapped in bedrock by QMAP. As there is no reported evidence for any landform offsets on the line of the Dingle Fault, as depicted in the QMAP dataset, it is classified here as ‘possible’, with a surface form attribute of ‘not expressed’. A recurrence interval of >10,000 years is assumed. Also see further discussion of the Dingle Fault in relation to feature 3 (Snowy Gorge fault).

A2.2.4 Ahuriri Fault (feature 1d, Figure 5.1; see Figure A2.2, Figure A2.3**)**

The entity identified in the NZAFM (Litchfield et al. 2013, 2014) and NSHM (Stirling et al. 2012) datasets as the ‘Ahuriri River fault zone’, or ‘Ahuriri River Fault’ respectively, corresponds closely to an entity within the QMAP dataset named the ‘Ahuriri Fault’. There is potential for confusion in respect of the separately-named ‘Ahuriri fault zone’ which is discussed in relation to the Hopkins fault (feature 1b above). In regard to the Ahuriri Fault as delineated in the QMAP dataset, this northerly-striking fault is identified from the juxtaposition of semischist (west) and greywacke (east) on the eastern side of Ben Avon peak (Turnbull 2000). The Turnbull (2000) map shows the interpretation that the Ahuriri Fault continues continue south beneath the floor of the Ahuriri valley, to a three-way inferred intersection with the Dalrachney Fault and the Ostler Fault. To the north, it is mapped as following the valley floor of the Ahuriri River, gradually curving towards the north-northeast (Rattenbury et al. 2010), to adjoin the Dingle Fault at an acute angle, and then continuing to curve north-northeastwards to adjoin a component of the Main Divide Fault Zone (Hopkins fault; feature 1b above).

Litchfield et al. (2013, 2014) assigned a slip rate in the range of 0.1 to 1 mm/yr, with a preferred value of 0.5 mm/yr (2014), explained as being based on the offset of till surfaces (2013). Although the Litchfield et al. (2013) report does not elaborate upon this, the observation presumably relates to the fault scarp referred to in this report as the Snowy Gorge fault (feature 3) and whose association with mapped bedrock fault structures remains unclear. Stirling et al. (2012) using a fault length value of 44 km, assigned a single-event displacement of 3.1 m and a recurrence interval of 6130 years. There are no identified landform offsets at locations where the mapped Ahuriri Fault crosses the location of older landforms (for example, immediately north of Avon Burn; Turnbull 2000), and so the question of whether the Ahuriri Fault, as positioned in the QMAP dataset and in the present report, is an active fault entity remains unclear.

A fault scarp, identified in this report as the Snowy Gorge Fault (feature 3), lies between 2 and 3 km east of the mapped position of the Ahuriri Fault. One possibility is that this scarp is an expression of movement along a strand of the Ahuriri Fault, but other possibilities exist, as discussed further in the section addressing the Snowy Gorge fault.

For the purposes of the present dataset, the Ahuriri River Fault is classified as 'possible', not expressed'. The slip rate and recurrence interval estimates provided by Litchfield et al. (2013, 2014) and Stirling et al. (2012) are here considered to be questionable because it is not clear that the geomorphic information relied upon for those estimates actually relates to movement on the Ahuriri Fault. Mindful of these uncertainties, the 'Ahuriri River Fault' as mapped in the NZAFM and NSHM is tentatively regarded in this report as having a recurrence interval of >10,000 years, with a proviso that if any further information is needed in respect of the Ahuriri Fault (QMAP definition), then focused field investigations would be necessary in order to advance the state of knowledge in regard to this fault.

A2.2.5 Barrier Range Fault (feature 1e, Figure 5.1; see Figure A2.2, Figure A2.3)

An entity called the Dobson Fault that is delineated in the Litchfield et al. (2014) digital dataset is derived from information in Cox et al. (2012). The Dobson Fault corresponds closely in location with a feature the QMAP digital dataset comprising a northeast-southwest striking fault within bedrock, named the Barrier Range Fault, that separates schistose greywacke to the northwest from greywacke to the southeast (Cox & Barrell 2007). Within the Waitaki District, the correspondence is sufficiently close that there seems little reason to erect a new name, the Dobson Fault. The QMAP fault is utilised in this dataset and the name Barrier Range Fault is used here. The reason for including it as an active fault in this dataset is that it was interpreted by Cox et al. (2012) and Litchfield et al. (2013, 2014) to be a 'potentially active' fault.

In the Ahuriri valley, at the southwestern end of the Barrier Range Fault, is a definite fault scarp that is identified as a separate entity within the present dataset (see Snowy Gorge Fault; feature 3, below). That fault decisively offsets of glacial landforms, but the Barrier Range Fault extends along the western flank of the Snowy Gorge Creek valley across some exceptionally well preserved glacially-smoothed terrain, of analogous age to the glacial landforms of the Ahuriri valley, without any discernible displacement of the landforms. Despite the proximity of the Barrier Range Fault and the fault scarp at its southwestern end, the lack of glacial landform offset across the Barrier Range Fault gives reason for caution in making an association between the two, hence the separation within this dataset. Due to an apparent absence of any deformation of glacial landforms across the Barrier Range Fault, it is identified in this dataset as 'possible', 'not expressed', and tentatively assigned a recurrence interval of >10,000 years. No slip rate is assigned to the 'Dobson Fault' by Litchfield et al. (2013, 2014), and neither that fault, nor the Barrier Range Fault, are included in the NSHM (Stirling et al. 2012).

A2.3 WATSON FAULT (FEATURE 2, FIGURE 5.1; SEE FIGURE A2.2)

Named after the nearby Watson Stream, this feature was originally delineated in the QMAP dataset (Rattenbury et al. 2010) and comprises several closely spaced topographic steps trending north-northeast on the eastern side of the upper Ahuriri River valley. Judging by what can be gleaned from aerial photographs, the steps are upthrown to the west by as much as perhaps 5 m. The question arises as to whether they are related to gravitational slope movement and associated deformation, or whether they are the expression of an active fault. The continuity of as much as 5 km over which these features can be traced along the valley side tends to favour the interpretation that they are due to faulting, but nonetheless the possibility of gravitational movement cannot be ruled out. For the present dataset they are judged as 'likely', and assuming a net vertical offset of about 10 m across these scarps, collectively, and inferring a land surface age of ~18,000 years, implies a vertical slip rate of about 0.6 mm/yr. If indeed it is a fault offset rather than a movement related to slope instability, it remains unknown as to whether the offset was the result of a single event or multiple events.

A2.4 SNOWY GORGE FAULT (FEATURE 3, FIGURE 5.1; SEE FIGURE A2.3)

First delineated on the geological map of Turnbull (2000), this north-trending definite fault scarp offsets glacial outwash gravel fans formed following the onset of deglaciation of the Ahuriri valley. The scarp is estimated from aerial photos to be about 5 m high in most places, but locally appears to be somewhat higher, perhaps 8 m or so, on the south side of Snowy Gorge Creek. The fault scarp is sharply expressed across those fans, but is much more difficult to trace across an intervening area of irregular moraine.

To the south, the scarp broadens into a distinct monoclinal flexure, before it trends into the young incised valley of the Ahuriri River, and there is no further sign of the fault/fold scarp in that direction. To the north, the fault scarp can be traced onto an alluvial fan on the north side of Snowy Gorge Creek, but thereafter there is no sign of it in the landscape.

Assuming a characteristic vertical offset of ~5 m on a ~18,000 year old landform implies a vertical slip rate of about 0.3 mm/yr. The length of the fault scarp plus monoclinal flexure is ~5 km, and this is unlikely to represent the full length of surface rupture(s) that formed the scarp/flexure. Thus, it is likely that the active fault continues along strike beyond the recognised ends of the mapped features, either in a northerly or southerly direction, or both.

The northern end of the mapped fault scarp is close to the approximate mapped location of the southwestern end of the Barrier Range Fault. However, as noted in relation to that fault (feature 1d), it passes through extensive areas of glacial landforms, and if the scarp in the Ahuriri valley were due to movement of that fault, it seems inescapable that a prominent scarp should be evident across that glacial terrain. For that reason, it seems unlikely that the fault scarp is associated with the Barrier Range Fault, hence the main reason for naming the Snowy Gorge fault as a stand-alone entity.

The size, trend and sense of upthrow of the scarp on the Snowy Gorge fault is similar to that of the scarps of the Watson fault (feature 2) about 20 km farther north. The Snowy Gorge fault scarp also has similar characteristics to those of the Lindis Pass Fault Zone (feature 5), some 17 to 25 km farther south. This invites two alternatives, one that the Snowy Gorge fault and Watson fault are discontinuous remnants of surface ruptures on an active fault at least 20 km long, approximately aligned with the Ahuriri Fault, but between 1 and 3 km east of it. An alternative is that the Snowy Gorge fault is a northern extension of the Lindis Pass Fault Zone. A third possibility, that the Snowy Gorge fault represents a northwestern extension of the Ostler Fault Zone (feature 6), whose northwesterly strand can be traced to about 18 km from the Snowy Gorge fault, is less compelling, because the senses of upthrow are different.

At face value, it seems that the generalised 'Ahuriri River Fault' of Stirling et al. (2012) gives appropriate recognition of the presence of at least one active fault in the middle reaches of the upper Ahuriri valley. The interpretation of Litchfield et al. (2013, 2014) comprising a shorter 'Ahuriri River fault zone' and their definition of the 'Dingle Burn' (aka 'Dingle'; see previous discussion of feature 1c) fault zone to encompass the feature identified in this report as the Watson fault, is but one possibility. The nature of active faults in the vicinity of the upper Ahuriri valley would benefit from further review and evaluation. The dataset accompanying the present report provides observation-based information that may aid that review.

A2.5 TIMARU CREEK FAULT (FEATURE 4, FIGURE 5.1; SEE FIGURE A2.3)

This feature is known from a definite, well expressed northeast-trending fault scarp that offsets a valley-floor alluvial plain, up to the southeast by several metres, in the Lindis River headwaters, in the Central Otago District, 2 km southwest of the Waitaki District boundary. The offset fluvial landform surface is judged to be no older than the end of the Last Glaciation (18,000 years), and may well be a little younger than that. The fault is shown on the geological map of Turnbull (2000), and its name comes from the QMAP digital dataset. It is included in the NZAFD, with linework adopted from QMAP, and is also depicted in generalised form in the Cox et al. (2012) dataset, but for unknown reasons is not included in the Litchfield et al. (2013, 2014) NZAFM dataset or the Stirling et al. (2012) NSHM dataset. It certainly warrants being included in future iterations of those datasets.

No scarp is evident on the ridgeline that marks the district boundary, or across slopes northeast towards the floor of the western branch of Avon Burn. It is judged likely, on account of the proximity of a definite fault scarp, that the active fault does extend into the Waitaki District but due to a lack of any as-yet identified surface evidence, its location or activity cannot be confirmed from existing information.

On account of being along strike from a definite fault scarp, the sector of this fault within the Waitaki District is classified as 'likely, 'not expressed'. For estimating slip rate and recurrence interval, the fault is inferred to have produced a vertical offset of 5 m on an 18,000 year old river plain (Lindis River headwaters). Whether this was a single event or the cumulative result of multiple events is unknown.

A2.6 LINDIS PASS FAULT ZONE (FEATURE 5, FIGURE 5.1)

This term was introduced by Litchfield et al. (2013, 2014) for northeast-southwest striking faults in the Lindis Pass area. The main entities are two named faults within the QMAP dataset, the Longslip Fault and the Dalrachney Fault. There is an additional un-named fault within the QMAP dataset, parallel to and southeast of the Longslip Fault, that is identified in this dataset as an un-named component of the Lindis Pass Fault Zone.

A2.6.1 Dalrachney Fault (feature 5a, Figure 5.1; see Figure A2.3, Figure A2.4)

This fault is mapped as an entity in bedrock from the southern boundary of the Waitaki District near Lindis Pass, northeastwards towards the upper Ahuriri valley (Turnbull 2000). There are no identifiable landform offsets until a point ~3.2 km northeast of Lindis Pass, where there is a relatively sharp, 'definite', fault scarp upthrown to the northwest. This prominent scarp continues, with minor discontinuities across landslide terrain, for ~5 km into the headwaters of an un-named northern branch of Longslip Creek. The northeastern end of the prominent scarp is at 44° 31.549'S, 169° 41.375'E, beyond which there is no convincing fault scarp, but at locations throughout the catchment of this un-named Longslip Creek tributary, on the mapped line of the fault, there are scattered topographic anomalies that could possibly be related to fault movement. This sector of the mapped fault is classified as 'likely', 'unknown', because field examination might conceivably identify evidence for fault expression. Northeast of the Longslip Creek catchment, the mapped fault is classed as 'possible', 'not expressed'. Activity estimates are included in Section A2.6.3 below.

A2.6.2 Longslip Fault (feature 5b, Figure 5.1; see Figure A2.3, Figure A2.4)

This northeast-southwest striking fault is identified from a prominent, ‘definite’, fault scarp, upthrown to the northwest, in the headwaters of Longslip Creek east of Lindis Pass. The somewhat sinuous fault scarp is at least 5 m high, with a very sharp expression, across relatively young alluvial fans. Its prominence is due to the topography mostly sloping to the west, and hence the downhill side is uplifted. It is clearly visible in Google Earth, especially in the headwaters of Dip Creek (a Lindis River tributary just south of the Waitaki District boundary), where small lakes have formed against the fault scarp at 44° 35.871'S, 169° 40.016'E, about 2.1 km southeast of the Lindis Pass summit. There is another prominent scarp visible in Google Earth at 44° 34.491'S, 169° 40.394'E, 2.8 km northeast of the Lindis Pass summit. Some of these scarps were depicted on the geological map of Mutch (1963), and mapped with greater continuity by Turnbull (2000), who applied the name Longslip Fault.

Judging from the clear expression of the fault scarp across virtually all land surfaces (alluvial and colluvial fans, and hill slopes), plus local ponding of water, I consider it highly likely that there has been at least one surface rupture within the Holocene, probably within the last few thousand years. In places, older degraded fan surfaces stand as much as 15-20 m high on the upthrown side of the fault, abutted by younger fans on the downthrown (upslope) side. This indicates strongly that that there has been a history of many surface ruptures during the Late Quaternary. The sectors of the fault represented by a surface scarp are classified as ‘definite’, ‘well expressed’.

About 400 m southwest of the Lindis Pass road (State Highway 8), the fault scarp loses all visible expression, and cannot be traced with any confidence northeast from that point. Beyond there, there are no convincing landform offsets on the projected continuation of the Longslip Fault, and it is classified as ‘possible’. Between 1.8 and 2.1 km northeast of where the Longslip Fault scarp disappears, the QMAP dataset shows a segment of the fault marked as ‘accurate’. It is at a location where the landforms are extremely young (active river bed and steep eroded cliff) and its mapping as ‘accurate’ is possibly because fault-crushed rock may be exposed in the steep cliff. Farther east, closer to the Ahuriri River, another section of the fault, attributed as ‘accurate’, corresponds with an exposure of fault-crushed rock. There is no direct evidence that the fault zones in these exposures have experienced recent movement. However, on the presumption that they do accurately mark the location of a fault, their surface expression is identified as ‘moderately expressed’, in unison with a certainty of ‘possible’.

The reason for classifying the active-fault-certainty of the northeastern sector of the Longslip Fault as ‘possible’ rather than ‘likely’, even though it adjoins a sector of the fault that is ‘definite’, is that to the northwest of the location where the Longslip Fault scarp loses expression, a fault scarp becomes evident on the Dalrachney Fault. That surface scarp extends to the northeast, with up-to-the-northwest throw, of similar size and expression to that represented by the Longslip Fault scarp. A tempting interpretation is that the most recent surface ruptures have transferred from the Longslip Fault to the Dalrachney Fault, and thus, at least for the recent geological past, they could tentatively be regarded as a single rupturing entity. This is in good accord with the step taken by Stirling et al. (2012) and Litchfield et al. (2013, 2014) of grouping these two faults as a single entity, the Lindis Pass Fault Zone.

An un-named component of the Lindis Pass Fault Zone is mapped by Turnbull (2000) as a northeast-southwest striking fault that branches east from the Longslip Fault, at a point ~2.5 km east of Lindis Pass, and meets the Longslip Fault again ~8 km north-northeast of Lindis Pass. As mapped, the un-named fault forms a boundary between semischist to the northwest and schistose greywacke to the southeast. There is a line of low knolls along a ~700 m sector of the mapped fault, which may possibly be dissected remnants on an old alluvial fan uplifted to the northwest along the fault. Alternatively the knolls may be of some other origin. This fault is classified as 'possible', 'not expressed', apart from the sector adjacent to these knolls which is classified as 'possible', 'moderately expressed'. There is certainly no fault scarp present with a sharp character like that seen on the Longslip Fault east of the Lindis Pass. The most recent ruptures on that sector of the Longslip Fault appear to have not extended onto this un-named fault.

A2.6.3 Lindis Pass Fault Zone activity

From the observations outlined in the preceding two sections, there is an estimated vertical component of offset of 5 m on landforms of assumed Holocene age (i.e. no older than ~12,000 years) on the Longslip Fault strand of the fault zone. This implies a vertical slip rate of at least 0.4 mm/yr. In the NZAFM (Litchfield et al. 2013, 2014) the Lindis Pass Fault Zone is characterised as a steeply westward-dipping reverse/right-lateral fault with a poorly-constrained net slip rate in the range of 0.1 to 1.31 mm/yr, and a preferred estimate of 0.47 mm/yr. The NSHM (Stirling et al. 2012) assigns a net slip rate of 0.5 mm/yr and length of 38 km, and calculates a net single-event displacement as 2.6 m and recurrence interval of 5,630 years. The values used in the NSHM are compatible with the observational evidence outlined in the preceding two subsections.

A2.7 OSTLER FAULT ZONE (FEATURE 6, FIGURE 5.1; SEE FIGURE A2.4, FIGURE A2.5)

This conspicuous northeast-southwest striking fault, upthrown to the northwest, is one of the best expressed active faults of New Zealand, because it crosses extensive tracts of old 'ice-age' landforms (see Figure 2 of main report). There is much complexity and variation in its surface scarps, with considerable amounts of folding as well as faulting. It has been studied extensively, initially in relation to the Upper Waitaki Hydro-electric Scheme (e.g. Read 1984; Beanland 1987; Blick et al. 1989; Read and Blick 1991), and subsequently as a focus of university research projects, the results of which have been published in a succession of journal articles (Davies et al. 2005; Ghisetti et al. 2007; McClymont et al. 2008; Amos et al. 2007, 2010, 2011; Campbell et al. 2010a, 2010b).

Detailed mapping of the fault zone in the Twizel area (Mackenzie District), and accompanying Fault Avoidance Zonation, is presented by Barrell (2010). No similarly detailed work has been undertaken for the Ostler Fault Zone in the Waitaki District, because the fault runs across farmland with little or no residential development pressure. The QMAP linework used in this report is very generalised and there are many more fault-related features (fault scarps and folds) in the general vicinity of the mapped line than are depicted in the dataset. The main strands of the Ostler Fault are named in the Waimate-Waitaki dataset as 'Ostler Fault Zone', while smaller fault traces off the line of the main strands are named 'Ostler Fault Zone - subsidiary faults'. A notable feature of the Ostler Fault Zone is 'the Knot', which refers to the location on the Ahuriri River plains where the fault trace takes a 90° change in strike and heads northwest towards the upper Ahuriri valley. In the hills to the northwest of 'the Knot', there is a change in basement rock type either side of the fault scarp, suggesting that this scarp is developed along a pre-existing fault within basement, whose earlier movement, probably during the Mesozoic, has brought two different types of basement rock into contact (semischist to the northeast, greywacke to the southwest). It therefore seems likely that rupture of the northeast striking Ostler Fault has, at its southwest end, transferred northwestwards onto a pre-existing northwest striking fault. It may, for example, be a continuation of the Hawkdun Fault which enters the Omarama basin from the southwest, and juxtaposes semischist to the northeast against greywacke to the southwest, the same relationship as exhibited on the northwest striking sector of the Ostler fault scarp. The northwest striking sector of the Ostler Fault may therefore represent a lateral tear fault. The fault scarp can be traced to the margin of the Ahuriri valley floor, about 16 km west of Omarama. Beyond there, the likely continuation of the bedrock fault, beneath the young landforms of the Ahuriri River valley floor, is classed as 'possible', 'not expressed'.

There is much detail about the dating of the most recent movements of the Ostler Fault Zone in the publications listed above, along with interpretations of the geometry of faulted deposits at depth, and the evolution of the Ostler Fault Zone. In my opinion, much of the interpretation based on geophysical surveys in absence of observed data control (e.g. as could be obtained by drilling) is quite speculative (e.g. Ghisetti et al. 2007; McClymont et al. 2008; Campbell et al. 2010a,b; Wallace et al. 2010), and should be treated with caution. Studies involving age dating of strata or geometric interpretation of fault character at depth based on topographic information from buckled landforms (Davis et al. 2005; Amos et al. 2007, 2010, 2011), are more reliable, in my view.

Based on radiocarbon dating of deformed and undeformed sediments across the northern strand of the Ostler Fault Zone in the Twizel River headwaters (Mackenzie District), Van Dissen et al. (1993) estimated a recurrence interval for surface-rupturing earthquakes of ~3,000 ± ~1,000 years, and that the most recent surface rupture occurred ~3,500 years ago (Barrell (2010) provides a summary of those results). A recurrence interval range of between 2,000 and 3,500 years was assigned to the Ostler Fault Zone by Van Dissen et al. (2003), and was also applied by Barrell (2010). This finding is compatible with results obtained from trenching investigations and Optically Stimulated Luminescence (OSL) dating of sediments deformed by fault movement on a strand of the Ostler Fault northwest of Twizel, documented by Amos et al. (2011). That study obtained results of lesser completeness than those of Van Dissen et al. (1993), but they are nevertheless valuable because they are from a location on the fault many kilometres from the Van Dissen et al. investigation site, and the OSL results corroborate, or at least do not contradict, those of Van Dissen et al. (1993)

Detailed dating of the glacial moraine sequence of Lake Ohau by Putnam et al. (2013), which allows ages to be inferred for the associated meltwater outwash plains that cross the Ostler Fault Zone, has provided a solid framework for the estimation of ages of offsets across the fault adjacent to Lake Ohau. A strength of the Putnam et al. (2013) dataset is that it is based on numerous (typically more than 10) separate measurements within each moraine belt, thus providing a good level of replication. On the eastern side of the Ohau River valley (now Lake Ruataniwha), the 'Mt John' outwash surface emanates from moraines formed 22,510 ± 660 years ago, and the 'Tekapo' outwash surface extends from moraines formed 18,220 ± 500 years ago (Putman et al. 2013). Both outwash surfaces have identical amounts of deformation across the Ostler Fault Zone (Blick et al. 1989; Barrell 2010), comprising a vertical component of displacement of ~20 m. This means that no discernible ground-surface deformation occurred across the fault at that location between ~18,200 and ~22,500 years ago, but a total of ~20 m vertical deformation has accrued since ~18,200 years ago. This implies an average vertical slip rate of ~0.9 mm/yr at that location. The older and younger bounds of the age ranges of the Mt John and Tekapo moraine belts (Putnam et al. 2013) indicate that between 3130 and 5450 years elapsed between the formation of those outwash plains. There was no discernible surface rupture event on that strand of the Ostler Fault Zone (Ruataniwha Fault of Barrell 2010) during that time interval. This is compatible with a recurrence interval of the order of ~3,500 years.

The printed map of Forsyth (2001) showed three discontinuous, north-northeast striking active fault traces in the vicinity of Quail Burn, about 13 km northwest of Omarama. These were originally delineated by Barrell in the mid-1990s, while assisting with compilation of the Forsyth (2001) map; their mapping was undertaken using aerial photo interpretation, with the faults inferred from the presence of higher ground to the west, plus what may possibly be a warped glacial moraine bench on the west side of Quail Burn. These mapped active fault traces were not included in the QMAP digital dataset, either the sheet-specific dataset of Forsyth (2001) or the ‘seamless’ QMAP (Heron 2014). I acknowledge that the interpretation of these fault traces is tentative, but I do not recall whether there were any discussions leading to a decision to exclude them from the digital dataset. For completeness, I have represented them in the Waimate-Waitaki dataset as a monoclinal fold, which I have attributed as ‘possible’ and ‘moderately expressed’, and named it as a component of the ‘Ostler Fault Zone - subsidiary faults’. If these topographic features, comprising a rise in elevation up to the west, are of tectonic origin, they affect only relatively old moraines and outwash surfaces (MIS 4 and 6), and at the northern end there is no topographic disruption of the moraines and outwash plains dated as 32,520 ± 970 and 22,510 ± 660 years old (Barrell et al. 2011; Putnam et al. 2013). I consider that this feature is relatively unlikely to be tectonic, but if there is a need for more information at any future time, detailed field inspection may, in the first instance, help to discriminate whether or not the feature is of tectonic origin.

In the NZAFM dataset (Litchfield et al. 2013, 2014), a net slip rate in the range of 0.70 to 2.41 mm/yr is assigned to the Ostler Fault, with a preferred value of 1.27 mm/yr. The NSHM (Stirling et al. 2012) assigns a slip rate value of 1.43 mm/yr and a fault length of 68 km, and calculates a net single-event displacement of 4.7 m and recurrence interval of 3310 years. The net slip rates are on the plane of the fault, based on an inferred dip range for the fault plane of between 30° and 60°, and preferred dip value of 45°. The 0.9 mm/yr vertical slip rate estimated in this report equates to a 1.27 mm/yr net slip rate on a 45° dipping fault, thus coincides with the preferred net slip rate of Litchfield et al. (2013, 2014).

A2.8 OMARAMA SADDLE FAULT (FEATURE 7, FIGURE 5.1; SEE FIGURE A2.4)

A north-northeast-striking, unnamed, fault, classified as inactive, was shown on the map of Forsyth (2001) passing through Omarama Saddle. The fault accounts for localised minor differences in basement rock metamorphic grade either side of the Omarama Stream valley, but the fault’s recognition is based largely on an interpreted dislocation, of as much as several hundred metres, up to the southeast, of inferred remnants of the Otago Peneplain, represented by tilted low relief surfaces on the crests of the ranges and associated spurs (Figure 4 of Forsyth 2001). Near the confluence of Omarama Stream and Little Omarama Stream, examination by the writer of aerial photographs dating from 1959, several years ago as part of another project, revealed a previously unidentified fault scarp, up to the northwest, within about 300 m of the mapped position of the basement fault. The scarp is notably sinuous, with several possible parallel strands, and runs transversely across an alluvial fan, with prominent fluvial channelling, formed by Little Omarama Stream. The position and form of the fan suggests that it dates from late Last Glaciation, and I assume an age for the fan surface of about 18,000 years. In recent years, a large centre-pivot irrigator has been installed on this fan, and as a result the fluvial channelling and the fault scarp are now largely obscured, if examined in Google Earth. However, the sinuous fault scarp can still be discerned in Google Earth, albeit vaguely, between 44° 36.622'S, 169° 52.472'E and 44° 36.328'S, 169° 52.769'E. The main scarp lies between 600 m southeast and 1 km south of the Twinburn farm buildings. I assume that the scarp is as much as 5 m high. The sector of the mapped fault (as positioned in the QMAP dataset adjacent to the surface scarp) is classified as ‘definite’, ‘moderately expressed, while adjacent sectors are classed as ‘likely’, ‘not expressed’, and the remainder of the fault towards Omarama Saddle is classed as ‘possible’, ‘unknown’.

As this fault is newly identified as active, it is not included in current versions of the NSHM (Stirling et al. 2012) or the NZAFM (Litchfield et al. 2013, 2014). The wider context of this fault is unknown, because it approaches meets the Hawkdun Fault towards the north, and there are no known active fault features farther south along the Omarama Saddle fault.

A2.9 HAWKDUN FAULT (FEATURE 8, FIGURE 5.1; SEE FIGURE A2.4)

The Hawkdun Fault is mapped along the western foot of the Hawkdun Range, for a length of about 50 km from the southern edge of the Omarama basin to the Naseby area (outside the Waitaki District). Movement on this fault has, during the Late Cenozoic, elevated the Hawkdun Range by as much as 1 km or more relative to adjacent lower-lying areas to the west. There is however no reported offset of any distinct landform features anywhere along the fault, and the fault has long been regarded as inactive. However, for two reasons it is included in this dataset, and classified as ‘possible’, ‘unknown’. The first is that the ~90° swing in strike at the southern end of the Ostler Fault may be due to partial reactivation of a possible northern continuation of the Hawkdun Fault. The second reason is that the newly recognised fault scarp, identified as the Omarama Saddle fault, strikes towards, and is mapped as terminating against the Hawkdun Fault. Thus there may be potential for reactivation, or at least secondary slip on, the Hawkdun Fault, in relation to a rupture of the Omarama Saddle fault. Due to the apparent absence of any demonstrably offset landforms along the Hawkdun Fault, in particular alluvial fans whose surfaces probably date from the Last Glaciation, a recurrence interval of >10,000 years is inferred in this report.

This fault is not included in the NSHM (Stirling et al. 2012) or the NZAFM (Litchfield et al. 2013, 2014). Due to the current absence of identified Late Quaternary offset on the Hawkdun Fault, there is no compelling reason to include it within those data sets, unless new information is obtained to support its inclusion.

A2.10 OTEMATATA FAULT (FEATURE 9, FIGURE 5.1; SEE FIGURE A2.4, FIGURE A2.6)

This northwest striking fault has been mapped from near the Danseys Pass area for some 65 km northwest to the southwestern edge of the Omarama basin. It separates different types of basement rock (Forsyth 2001 and references therein), with semischist to the southwest and greywacke or schistose greywacke to the northeast. The fault appears to have deformed the peneplain surface by several hundred metres up to the northeast on the northwestern side of the St Cuthbert Range. The position of the fault is well expressed in the topography, such as can be seen in Google Earth, on account of prominently delineated outcrops of semischist rock southwest of the fault. The fault location is marked by topographic lineaments, of uncertain origin, in many places. There is no definitive evidence for a surface rupture fault scarp and so the fault is classified as ‘possible’, ‘not expressed’ across areas of Quaternary sediments, and ‘possible’, ‘moderately expressed’ across hill terrain. In the latter case, this assignation highlights that fault’s position is likely to be definable quite accurately on the ground due to its geological and topographic characteristics.

Because there are no indications of any surface offsets of Otamatapaio River plains or nearby alluvial fans, it is presumed that the most recent rupture of the Otematata Fault was more than 18,000 years ago. A recurrence interval of at least 10,000 years is provisionally assigned.

In the NSHM (Stirling et al. 2012) and NZAFM (Litchfield et al. 2013, 2014) datasets, the Otematata Fault is represented by a 17 km long line, centred on the Otamatapaio basin, that is characterised in the NHSM as a reverse/left-lateral fault dipping 70º northeast, with a net slip rate of 0.02 mm/yr, a net single-event displacement of 1.2, and recurrence interval of 49,330 years. In the NZAFM, the slip rate is characterised as a range of 0.005 to 0.082 mm/yr, with a preferred estimate of 0.024 mm/yr. The absence of any definitive field data on fault activity means that all these estimates should be treated with caution, especially as the modelled fault is much shorter than the geologically-mapped fault.

A2.11 FALSTONE FAULT (FEATURE 10, FIGURE 5.1; SEE FIGURE A2.5)

This north-south striking fault is mapped for 18 km along the eastern flank of the Benmore Range. Previously unnamed, the name applied in this dataset is taken from Falstone Creek, which crosses the line of the fault. The fault location is distinctive, on account of an alignment of knobs and saddles rising up on the eastern side of the fault on the flank of the range. On the line of this features are several prominent topographic steps, down to the west, that may possibly relate to Late Quaternary displacement. The writer carried out field reconnaissance there in 1996 as part of the compilation of the Forsyth (2001) map, and found several exposures of fault-crushed rock on the line of this feature, with a majority of the shears dipping steeply (60 to 80°) to the west. This reinforces the interpretation that this entity is a fault, and given that the topographic expression is up to the east, suggests that the most recent movements (if the topographic features are of tectonic origin) have had a significant component of normal displacement.

On account of the steep terrain, and the potential for these topographic features to represent gravitational movement (e.g. ridge rents) or differential erosion, the fault is classed as a ‘possible’ active fault, despite some temptation arising from the consistency of form of these steps to assign it as ‘likely’. Those sectors associated with topographic expression are classed as ‘moderately expressed’, with the remainder of the fault classified as ‘not expressed’.

At its northern end, the fault projects across the alluvial fan of a stream draining the Benmore Range (approximate location 44° 20.646'S, 170° 9.979'E). There is no indication of a fault scarp across the well-channelled surface of this fan. Of particular significance is that the toe of this fan was trimmed during formation of a glacial outwash surface, sourced from the Lake Ohau glacial valley, and the outwash surface abuts a river-cut riser at the fan toe. Dating of glacial moraines at Lake Ohau by Putnam et al. (2013) allows age constraint to be placed on the associated outwash plains. The outwash surface is interpreted to be of Mt John age (Barrell et al. 2011), and thus at least 20,000 years old. Even if this interpretation is incorrect, and the outwash plain is of Tekapo age (~18,000 years old), either of these ages provides a substantial minimum time elapsed since the most recent surface rupture at the northern end of the Falstone fault. Based on this information, a recurrence interval of >10,000 years is inferred for the Falstone fault.

This fault is not included in the NSHM (Stirling et al. 2012) or the NZAFM (Litchfield et al. 2013, 2014). Due to the current absence of identified Late Quaternary offset on the Falstone fault, there is no compelling reason to include it within those data sets, unless new information is obtained to support its inclusion.

A2.12 GIBSON FAULT (FEATURE 11, FIGURE 5.1; SEE FIGURE A2.6)

The existence of this northeast-striking fault is inferred from geological and topographic considerations. It forms the northwestern boundary of the Lake Aviemore basin, with a range formed in greywacke rock standing at elevations between 800 and 1400 m on the northwestern (upthrown) side and Cenozoic cover rocks preserved in the basin on the downthrown side. The presence of this fault was first indicated by Marwick (1935), whose Figure 7 shows this fault as forming the eastern margin of an uplifted block of basement rock that he referred to as the 'Hewlings Block'. The Gibson Fault is drawn as extending northeastwards from the Narrows fault (see separate section) for some 15 km to where it encounters higher ground in the form of an east-west trending mountain ridge that does not reveal any significant differential offset across the fault. The name Gibson fault is applied in this dataset, using a term introduced by Wood et al. (1998), after Gibson Stream, whose catchment is crossed by the fault.

There is nothing to suggest any landform offsets along the fault except for a location which is about 3 km north of Lake Aviemore, where there is a topographic step, up to the northwest, of as much as several tens of metres, on what may be an ancient alluvial fan. The area on the downthrown side of the fault appears to have a geological substrate of cover rocks that include relatively soft strata prone to landsliding but nearby to the southeast is a remnant of greywacke conglomerate of presumed Pliocene age with distinctive herringbone gully patterning. The location of the topographic step is at approximately 44° 34.630'S, 170° 16.504'E. The writer has examined it on the ground and while the fault-origin interpretation is somewhat compelling when viewed in aerial photography, this is by no means the only plausible explanation for this landform. It could for instance have resulted from slope instability movements that have evacuated material downslope of this step. For this reason the Gibson Fault is classed as 'possible'. The step mentioned above is classified as 'moderately expressed', while the remainder of the fault as mapped within the QMAP database is classified as 'not expressed'. A recurrence interval of >10,000 years is inferred.

This fault is not included in the NSHM (Stirling et al. 2012) or the NZAFM (Litchfield et al. 2013, 2014). Due to the current absence of confirmed Late Quaternary offset on the Gibson fault, there is no compelling reason to include it within those data sets, unless new information is obtained to support its inclusion.

A2.13 WAITAKI FAULT SYSTEM (FEATURE 12, FIGURE 5.1 & FIGURE 5.3)

This term first appeared on the map of Mortimer (1993) as the 'Waitaki fault zone' for an assemblage of fault strands that strike between west and north, and along which the Waitaki River valley is generally aligned. The slightly modified name 'Waitaki Fault System' was proposed by Wood et al. (1998), and is included in the QMAP digital dataset for this area (Forsyth 2001; Heron 2014). Individual names, some formally published, others unpublished, have been applied to the various components of the fault system.

Many aspects of the character and the inter-relationships, if any, of the components of this fault system are yet to be established. The recognition of this fault system is based largely on geographic grounds. The grouping of fault system components does not necessarily imply a genetic or kinematic connection between the individual components. Equally, it is not intended to imply an absence of genetic or kinematic interrelationships. For example, several of the mapped faults separate different metamorphic grades of basement rock. Those faults therefore originated, and much of the basement rock stratigraphic offset accumulated, not long after formation of the rocks during the Mesozoic Era, and prior to the deposition of the Late Cretaceous – Cenozoic cover rock sequence. Several of the faults (not necessarily the same ones) have accumulated substantial offsets (several hundred metres to as much as 2 km) that disrupt the Late Cretaceous – Cenozoic strata, and/or the prominent erosion surface

(Waipounamu Erosion Surface, also known locally as the Otago Peneplain; Landis et al. 2008) that marks the base of that stratigraphic sequence. Finally, several, but by no means all, of the component faults display evidence for landform offsets of Late Quaternary age.

Following the concepts that were developed by Wood et al. (1998), and incorporated into the QMAP dataset of Forsyth (2001; also Heron 2014), interpretations have been incorporated in other datasets. The NSHM (Stirling et al. 2012) categorises the Waitaki Fault System as four earthquake-source entities; the Fern Gully Fault, the Waitangi Fault, the Dryburgh Northwest fault and the Stonewall Fault. In the NZAFM (Litchfield et al. 2013, 2014), the southern third of the Fern Gully Fault is identified as a fifth entity, the Awahokomo Fault, and the Stonewall Fault is omitted from the NZAFM dataset, for reasons that are not explained. In both those datasets, attempts have been made to try and identify fault entities of sufficient length to be compatible with likely fault rupture dimensions. Against the backdrop of the model-based considerations that underlie those two datasets, in the present report, emphasis is placed on highlighting observed surface evidence for active faulting. The primary reason for this is to document information obtained during field investigations of the past two decades or so, much of which has not previously been published. Thus the emphasis of the present report is on describing the state of knowledge with respect to available evidence.

The components of the Waitaki Fault System are identified and described in the following sections, including the Middle Range Fault, the Bitterness Fault, the Narrows fault, the Wharekuri Fault, the Fern Gully Fault, the Waitangi Fault, the Awahokomo Fault, the Kurow Hill Fault, the Dryburgh Fault, the Stonewall Fault and the Waitaki Fault.

A2.13.1 Middle Range Fault (feature 12a, Figure 5.3; see Figure A2.5, Figure A2.6)

This fault was originally named by Retallack & Ryburn (1982) and its length was expanded by Forsyth (2001) to encompass a feature named the Otamatapaio Fault by Wood et al. (1998). The strongest indication of activity on the fault is an arcuate scarp as much as 3 m high trending northwest across an alluvial fan about 1.5 kilometres west of Lake Benmore Holiday Park on State Highway 83. The scarp is classed as definite because it is upthrown on the downhill side (i.e. northeast) of the fan, and runs transversely across a fairly steep fan surface, in a way that cannot be plausibly ascribed to stream flow. There is, however, no similar scarp preserved anywhere else along the mapped length of the fault. There are some indistinct topographic steps, in an area on the north bank of the Otamatapaio River between ~1 and ~1.5 km south of Otamatapaio homestead, and also near Omarama, several hundred metres south-southeast of the intersection between SH 83 and Prohibition Road, as reported by Wood et al. (1998). At the latter site a trench was excavated and found possible indications of fault-related disturbance of the alluvial fan sediments. A piece of charcoal from a sediment layer above the possibly disturbed strata yielded an age in radiocarbon years of 723 ± 66 years BP (NZA 8303). This provides a minimum age for the most recent fault rupture at the site, if the possible disturbance is indeed related to faulting (Wood et al. 1998). The definite scarp is classed as ‘well expressed‘ while the other topographic features described above are classed as ‘likely’, ‘moderately expressed‘ and intervening sectors of the fault are marked as ‘likely’, ‘not expressed’. That sector of the Middle Range Fault to the southwest of the Otamatapaio River is classed as ‘possible’, because there are no clearly evident fault scarps, except in an area of between 4.5 and 6 km southwest of the Otamatapaio River where there are some up-to-the-southwest topographic steps, evident in Google Earth (e.g. 44° 37.115'S, 170° 7.127'E) which may conceivably be a result of fault movement, although other explanations are plausible (e.g. slope instability, differential erosion within bedrock strata). That short sector of the fault is classed as ‘possible’, ‘moderately expressed‘.

A puzzling aspect of this fault is the very prominent scarp west of the Lake Benmore Holiday Park, and the absence of any similarly well preserved scarps elsewhere. In this general area there are very large accumulations of alluvial fan deposits brought down by streams draining St Cuthbert Range and thus there is presumably a large amount of time represented in the deposition of these alluvial fans. The only likely explanation is that in the area where the scarp is well preserved, there is a sector of relatively old land surface and elsewhere the fan surfaces are presumably younger than the most recent fault rupture. An age of 18,000 years is inferred for the faulted sector of the fan surface.

A2.13.2 Bitterness Fault (feature 12b, Figure 5.3; see Figure A2.6)

This fault extends southeastwards from the Otamatapaio River along the western margin of the Otematata basin and into the St Marys Range (Mutch 1963; Bishop 1976: Forsyth 2001). The fault is upthrown to the west and adjacent to Otematata has elevated semischist to form a range of low hills adjacent to the Otematata basin which contains cover rock strata. In the area from Ahuriri Pass to near the Otematata River, there are some topographic anomalies across alluvial fans draining from the low hills into the basin. These anomalies take the form of steps up to the west and occur at the location of the mapped fault and as much as several hundred metres to the northeast of the mapped fault. One prominent topographic step, which is one of the more compelling in regard to a possible fault-related origin, is located at 44° 35.849'S, 170° 9.632'E, about 2.5 km west-northwest of Otematata. This step, up to the southwest, is between 5 and 10 m high and can be seen in Google Earth Street View at 44° 35.722'S, 170° 9.767'E, looking southwest, in the middle distance, beyond the second set of power lines.

The origin of these steps is unclear and some possibilities include offsets due to faulting, differential erosion of the underlying strata or perhaps slope instability. Another possibility is that they may in part relate to investigation earthworks in the search for materials for the construction of Benmore Dam between the mid-1950s and mid-1960s. The assessment of this possibility is difficult because the earliest aerial photos held in the GNS Science collection are from 1959, and they show a landscape at that location considerably modified by excavations and other earthworks activities related to the dam development. The sector of the mapped fault which displays the topographic anomalies is mapped as ‘possible’, ‘moderately expressed’, because I consider that there is not sufficient continuity and similarity between the topographic anomalies to justify the mapping of a ‘likely’ fault, based on present knowledge. Other sectors of the fault are mapped as ‘possible’, ‘not expressed‘. Up-to-the-west topographic relief continues across the Bitterness Fault as far southeast as Mt Weta in St Marys Range, and the sector of the Bitterness Fault that is classed as ‘possible’, ‘not expressed’ is extended that far. Although the Bitterness Fault continues farther southeast as a geological entity, it displays no differential topographic relief where it runs along the crest of the range. This implies that sector of the fault has experienced little if any Cenozoic movement and this provides a compelling basis for regarded it as inactive in that area.

Within the Stirling et al. (2012) and Litchfield et al. (2013, 2014) datasets, their modelled Fern Gully Fault passes through the Otematata basin broadly coincident with the general location of topographic anomalies in proximity to the westerly-striking, northern sector of the Bitterness Fault. Indeed, the presence of those topographic anomalies probably guided the interpretation of an extension of the Fern Gully Fault through that area. However, whether or not those anomalies are a result of fault movement is yet to be established. If there is any need, in the future, to establish whether or not the topographic anomalies close to the Bitterness Fault are the product of fault movement, then detailed field inspection perhaps accompanied by excavations across one or more of the topographic anomalies may provide useful information.

The absence of any confirmed Late Quaternary offset on most of the length of the Bitterness Fault provides good reason for not including the fault in future iterations of the NSHM (Stirling et al. 2012) or the NZAFM (Litchfield et al. 2013, 2014) datasets. The northern sector of the Bitterness Fault that is approximated in those datasets as a northwestern continuation of the Fern Gully Fault is worth further consideration as an interpretation, but note further discussion in the subsection on the Narrows fault (feature 12c).

A2.13.3 Narrows fault (feature 12c, Figure 5.3; see Figure A2.6)

This name was applied to the fault that forms the northeastern boundary of the Cenozoic cover strata in the Otematata basin. Greywacke basement rock is upthrown against cover rock strata near Rostreivor homestead, about 2 km north-northeast of Otematata township. This relationship was first depicted on the geological map of Mutch (1963), and the fault was mapped as continuing northwest up Big Gully and across the Pass Peak range of hills. However, the present writer made an error while assisting with the compilation of the Forsyth (2001) geological map, in which a round hill, approximately 1.8 km northwest of Otematata, at 44° 35.519'S, 170° 10.917'E, was incorrectly drawn as greywacke basement, whereas Mutch (1963) had shown it as Late Cenozoic greywacke conglomerate (i.e. Kowai Formation). Subsequent to the Forsyth (2001) map publication, I have inspected the hill on foot, and confirmed that weathered rounded greywacke pebbles are abundant in the soil, indicating that the Mutch (1963) interpretation is correct. As a result, a fault drawn southeast of the hill on the Forsyth (2001) map, in order to account for the juxtaposition of supposed greywacke in the hill and cover rock strata farther southwest within the Otematata basin, is no longer a justified interpretation. That fault has been deleted from the present dataset.

The term Narrows fault was proposed by Wood et al. (1998), after a local informal geographic term 'the Narrows' that pertains to the narrow upstream reach of Lake Aviemore upstream of Parsons Rock Creek. In this dataset, the name is applied to the fault near Rostreivor, and possible extensions to the northeast up Big Gully and to the southwest. The southwest extension is a fault on the north side of the Lake Aviemore 'Narrows', which was attributed as 'Wharekuri Fault' in the Forsyth (2001)/Heron (2014) digital dataset. That terminology came from the source paper (Hada & Landis 1995), which referred to the northwest-southeast striking fault along the northern bank of Lake Aviemore as 'Wharekuri Fault – branch'. However, the character of that fault is quite unlike that of the Wharekuri Fault. The Wharekuri Fault runs along the southwestern margin of a tectonic depression whose axis is now occupied by Lake Aviemore. The Wharekuri Fault (see next section) is a moderately to steeply southwest-dipping reverse fault that has uplifted schist and semischist on its southwestern side relative to the cover rocks preserved in the Aviemore depression. In contrast, the Narrows fault on the north side of Lake Aviemore has distinctive, locally-fossiliferous, greywacke rock on both sides of the fault. Although Hada & Landis (1995) did not report a dip angle for that fault, the disposition of greywacke bedding shown on their map either side of the fault is compatible with the fault having a steep dip.

It is not inconceivable that the Narrows fault has continuity with the Fern Gully Fault farther to the southeast, the latter being identified only from its Late Quaternary surface trace which shows it to be a steeply dipping or vertical fault with predominantly strike-slip (left-lateral) movement. Accordingly, beneath Lake Aviemore, an inferred extension of the Narrows fault has been drawn out beneath the now-drowned floor of the Waitaki valley, to approach the northwestern end of the Fern Gully Fault. The reason for this action is that closer to the valley margin, along State Highway 83, there is a complex of alluvial fans spanning a wide range of ages. Some of those fans are likely to be old enough to have been displaced by the Fern Gully Fault, if that fault were to continue northwestwards close to the valley margin. Therefore, if the Fern Gully Fault does extend northwest, as seems highly likely because the fault is prominent at its northwestern onland extent, it almost certainly lies beneath the valley floor, where the now-drowned landforms are relatively young. Beneath the lake, between Parsons Rock and the Rugged Ridges homestead, there is a now-drowned remnant of the 'Aviemore'-group river terrace set of the Waitaki valley (Read et al. 1998), and there is a linear feature on that submerged terrace, visible on pre-lakefill aerial photos, that could be a fault scarp, although other explanations are possible (e.g. a particularly straight fluvial channel). The inferred continuation of the Narrows fault is drawn through that linear feature, and the section of the fault corresponding to the now-submerged linear feature is classed as 'possible', 'moderately expressed'. The reason for identifying it as such in this dataset is to draw attention to its location should there be any future desire to investigate it, by way of high-resolution bathymetric surveying, for example.

A2.13.4 Wharekuri Fault (feature 12d, Figure 5.3; see Figure A2.6, Figure A2.7)

Movement on the northwest-striking Wharekuri Fault during the Late Cenozoic has elevated the St Marys Range relative to the Waitaki Valley. The fault is mapped confidently based on geological relationships from the Otiake River northwest for about 30 km to the narrows at the head of Lake Aviemore. To the southwest, schist has been upthrown relative to greywacke and overlying cover rock strata to the north-east. Total uplift is as much as ~2 km west of Kurow, and diminishes progressively to the northwest. It was originally named the Wharekuri-Otekaike Fault (Uttley 1920a,b; Marwick 1935), noting the spelling of Otekaike is the old name for that locality, prior to gazetting of its modern spelling 'Otekaieke' in 1953. Subsequent workers have simplified the name of this structure to Wharekuri Fault (e.g. Gair & Gregg 1960; Mutch 1963; Forsyth 2001).

The Wharekuri Fault became notable on account of the identification of a left-lateral strike-slip surface trace southwest of Aviemore Dam reported by Gair & Gregg (1960) and illustrated on the map of Mutch (1963). However, subsequent work undertaken in relation to the Waitaki hydroelectric dam system found difficulties with that interpretation. Investigations showed that the strike-slip fault evident at the ground surface was near-vertical, in contrast to the moderately dipping reverse fault plane of the Wharekuri Fault. This led to the strike slip fault being assigned a different name (Fern Gully Fault; see below). Two exposures of the Wharekuri fault plane have been described. In the north bank of Fern Gully Creek about 0.8 km upstream of State Highway 83 (44° 39.640'S, 170° 20.309'E), an exposure made using an excavator revealed a fault plane dipping 42° to the southwest with crushed schist bedrock thrust over sheared Miocene-age coal measures overlain by 8 m of unfaulted alluvial gravel (Wood et al. 1998; Barrell et al. 2002).

In Wharekuri Creek, between about 0.8 and 1.1 km upstream of the State Highway 83 bridge (approximate location 44° 40.694'S, 170° 21.460'E), there is patchy exposure of faulted rocks along the western bank of the creek. The information below is from the writer's own observations in the late 1990s, as documented in the report by Wood et al. (1998). The area of this exposure has been somewhat disturbed by slope instability and it is possible the fault exposures may have been disrupted or modified by landslide movements. Faults in the exposures show a reverse sense of movement with schist displaced up to the southwest over cover rock strata. One exposure shows 6 m of fault crush separating schist above from cover rocks below. A clay gouge within this zone strikes north-south and dips to the west at 60° implying a reverse sense of movement. Striations on the gouge indicate almost pure dip-slip displacement. At the northern end of this patchy exposure a fault separates schist above from cover rock strata below (conglomerates and mudstone), with the fault striking west-northwest and dipping 25° southwest. It is not clear from these exposures to whether the fault is better characterised as gently dipping or moderately to steeply dipping. Farther to the southeast the geomorphic expression of the fault in the landscape as revealed by the contrast in rock types either side of the fault suggests that the fault is more likely to have a moderate to steep dip overall.

Only in the area between Wharekuri Creek and the Awakino River valley are there any indications of Late Quaternary offsets in the vicinity of the Wharekuri Fault. For pragmatic reasons related to the quantification of fault rupture hazards in relation to Aviemore Dam, Barrell et al. (2002) introduced another name for these Late Quaternary fault scarps; the Awahokomo Fault (see below). The reason for this approach was that it seemed plausible, and perhaps likely, that the fault scarps in proximity to the Wharekuri Fault may be the result of distributed movement sourced from other faults nearby (e.g. Waitangi Fault or Fern Gully Fault), rather than independent rupture of the Wharekuri Fault itself.

In Awahokomo Creek, Marshall (1915) reported an exposure of the Wharekuri Fault, with the fault contact between schist and cover rocks dipping west-southwest at 73°. When inspected by the writer in the late 1990s, there was no exposure at the location of the fault.

From the Awakino River southeast, and Wharekuri Creek northwest, there are no compelling indications of any landform offsets across the Wharekuri Fault. Because of the activity of the Awahokomo Fault in proximity to the Wharekuri Fault, and because the relationship between the two is not well understood, the Wharekuri Fault is classed as ‘possible’, ‘not expressed’. A nominal recurrence interval for the Wharekuri Fault (excluding the Awahokomo Fault) of greater than 10,000 years is inferred, while acknowledging that the Wharekuri Fault may in fact not be a currently active fault. In this dataset, the Wharekuri Fault, as far southeast as Malcolms Creek, some 10 km south of Kurow, is classified as ‘possible’. Although inferred faults also identified as ‘Wharekuri Fault’ in the QMAP digital dataset continue farther southeast, the fault is drawn along a vague topographic step, with basement rock both sides of the inferred fault. There are no indications of landform offset, nor indeed any necessity that the fault actually exists. Those sectors of the mapped fault are excluded from this dataset.

A2.13.5 Fern Gully Fault (feature 12e, Figure 5.1; see Figure A2.6)

The Fern Gully Fault can be mapped as a distinct feature from the northern side of the Fern Gully Creek valley for about 5 km northwestwards to where it meets the shore of Lake Aviemore. Discussion of possible continuations to the northwest is given in the section on the Narrows fault component of the Waitaki Fault System (feature 12c). Continuation southeast of Fern Gully Creek is uncertain and the relationship of the Fern Gully Fault to the Waitangi Fault (feature 12f) and the Awahokomo Fault (feature 12g) is yet to be determined definitively (but also see discussion in the introductory text to the Waitaki Fault System).

The most prominent feature along this fault is a flight of alluvial fan terraces that are preserved on the northeastern side of a linear northwest-trending fault scarp on the northern side of Fern Gully Creek (44° 39.569'S, 170° 20.203'E), about 1 km southwest of State Highway 83. The fault has been investigated in considerable detail, by way of mapping, trenching and dating. A total of nine fault investigation trenches were excavated between

1988 and 1999 and dating of sediments from those trenches was undertaken in the late 1990s using luminescence methods (Barrell et al. 2002). Some of the dating results were variable in their consistency which has resulted in some large uncertainties in the characterisation of fault movement rates.

The Fern Gully Fault, as observed in trench exposures, has a dip ranging from vertical to 60° southwest. A trench near Fern Gully Creek showed that cover rock strata are present either side of the fault, suggesting that the Fern Gully Fault is distinctly different from the Wharekuri Fault which should have schist rock on its southwestern (upthrown) side. Movement on the Fern Gully Fault is predominantly left-lateral strike slip and, in detail, the fault has many characteristic strike-slip features including sidesteps and pull-aparts. As a result, the Fern Gully Fault has differing senses of upthrow from place to place. The fault is readily visible on alluvial fan terraces on the southeastern side of McRae Creek (44° 39.103'S, 170° 19.340'E), where net downthrow on the southwestern side has left a clear vegetation line on account of better soil moisture conditions on the downthrown side. The only location on the fault where there is a definitive measurable landform offset is on the northern side of Banks Stream, where the fault has offset a riser between two alluvial fan terraces (44° 38.362'S, 170° 17.720'E) by 8 ± 2 m horizontally, and about 1 m vertically. Trenching of the scarp on the lower (younger) terrace showed that the riser offset was the result of at least two fault ruptures. Based on this, the preferred estimate of single-event displacement on the Fern Gully Fault is between 2 m and 5 m, predominantly strike-slip. Dating from that trench indicates that at least two surface ruptures have occurred within the last c. 16,000 years. Dating from another trench southwest of McRae Creek (approximate location 44° 39.094'S, 170° 19.291'E) indicates that at least three surface ruptures have occurred within the past 23,000 years with the most recent rupture having occurred sometime between 3000 and about 14,000 years ago. Based on all of these data, the preferred estimate for recurrence interval is between 6000 and 10,000 years. The net slip rate (predominantly left-lateral) is constrained to lie in the range of 0.4 to 1.7 mm/yr, with a preferred estimate of 0.4 to 0.7 mm/yr (Barrell et al. 2002). For the NZAFM, Litchfield et al. (2013, 2014) adopted a preferred slip rate value of 0.61 mm/yr, and using that slip value along with an assigned length of 53 km, the NSHM (Stirling et al. 2012) calculated a preferred single-event displacement of 3.7 m and recurrence interval of 6,050 years. It is important to note that the representation of the Fern Gully Fault in the NSHM is an entity that includes parts of the Bitterness Fault, Middle Range Fault and Awahokomo Fault, as delineated in the present report.

A2.13.6 Waitangi Fault (feature 12f, Figure 5.1; see Figure A2.6)

This north-northwest-striking, west south-west dipping fault forms the northeastern margin of the Lake Aviemore basin. In its overall form, the fault has a net upthrow to the northeast with greywacke rock marking the upthrown side in a prominent topographic escarpment. Downthrown to the west are Cenozoic-age cover rocks. The fault has been investigated in considerable detail because it passes beneath the foundations for Aviemore Dam. Although the dam was constructed to accommodate the differing types of geological foundation either side of the fault, the fault was thought, at the time of dam design and construction, to be inactive. However, evidence for recent activity was found during geological investigations nearby in the mid-1990s and this led to an increasingly thorough investigation of the Waitangi Fault. In contrast to the overall disposition of the stratigraphic units either side of the fault which decisively show a net normal displacement over the Late Cenozoic, the Late Quaternary movement has been up to the west (see Figure 5 of the main report). This demonstrates that the most recent movements have had a reverse component of throw. The simplest explanation for this is that the fault during the early history had a normal sense of displacement while more recently the movement has reversed.

The investigation work is documented in detail by Barrell et al. (2002), and is publicly available in summary form in a Geological Society of New Zealand field trip guide (Barrell et al. 2009), and similarly documented in conference proceedings (e.g. Barrell et al. 2006). The key geological findings of the work are that the Waitangi Fault has an overall steep north-northwest dip (≥70°), the most recent surface ruptures have had a predominantly reverse with subordinate right-lateral strike-slip sense of displacement, and have occurred on, or within about 6 m northwest of the greywacke/cover rock fault contact. In addition, there is a zone of minor deformation including discrete small-scale Late Quaternary fault and fold deformation extending for as much 150 m northwest of the main fault. In regard to rupture history, the main fault has experienced at least two, and possibly three, surface ruptures within the past 23,000 years, with the most recent surface rupture definitely having occurred prior to 10,700 years ago, and most likely between 13,100 and 14,100 years ago (Barrell et al. 2009). Fortuitous constraint on single event displacements was obtained from the trenching investigations which found that, at one location, each of the two most recent ruptures had broken through on different slip planes a few metres apart, which allowed the displacement of each rupture to be measured with minimal ambiguity (illustrated and explained in Barrell et al. 2009). The penultimate rupture had a vertical component of about 0.5 m while the most recent rupture had a vertical displacement of between 1 m and 2 m. The overall net slip rate is estimated to lie in the range of 0.1 to 0.3 mm per year and the average recurrence interval lies in the range of 6,000 years to 12,000 years. The observation that the most recent surface rupture most likely occurred at least 13,100 years ago suggests that the inter-event times between individual surface ruptures have not been constant.

In the NZAFM, Litchfield et al. (2013, 2014) assigned a slip rate range of 0.1 to 0.31 mm/yr, and a 'best-estimate' slip rate of 0.17 mm/yr. In the NSHM, Stirling et al. (2012) assigned a length of 16 km and a slip rate of 0.18 mm/yr, and calculated an average single-event displacement of 1.1 m and recurrence interval of 6,190 years. These values are all derived from the investigation data in Barrell et al. (2002, 2009). In the event of any need arising to scrutinise these values, the field-derived estimates, with error ranges, from Barrell et al. (2002) should probably be accorded the greatest weight.

Interested readers should refer to Barrell et al. (2009) for a summary description of the engineering assessments and responses in regard to Aviemore Dam undertaken in light of the finding of the Waitangi Fault investigation.

Geological mapping has identified the location of the Waitangi Fault, as expressed by offset bedrock relationships, from the valley of Wharekuri Creek north-northwest for about 2.5 km to Aviemore Dam. Beyond that, the prominent greywacke escarpment on the east-northeast side of the fault closely approximates the limits of the location of the fault trace. Within this dataset, the fault at and immediately downstream of Aviemore Dam is marked as 'definite', 'well expressed', because it has been accurately located and mapped during the investigations described above, even though there is no well-defined fault scarp preserved. Farther to the south southeast towards Wharekuri Creek, the fault is classed as 'definite', 'moderately expressed. Towards the north-northwest, the fault is mapped as 'definite', 'not expressed' beneath Lake Aviemore, for a nominal 4.5 km upstream of the dam and as 'likely' north-northwest from there. The reasoning for this change is the increasing distance from the definitive observations of activity near Aviemore Dam. North of Lake Aviemore, the area on the downthrown side of the fault-line escarpment has been extensively affected by landslide movement, and the terrain is largely hummocky and irregular. However, over a sector about 1.3 km southeast of Sutton Stream, there are, along the foot of the escarpment, some depressions enclosed on the west-southwest side which could possibly reflect the most recent reverse-sense surface rupture displacements. These features were recognised prior to the main trenching investigations close to the dam but were considered likely to be inconclusive targets for further investigation because of the possibility that any displacements were found would be difficult to robustly interpret in regard to fault origin versus landslide origin. That 1.3 km long sector of the fault is classed as 'moderately expressed'. Although the fault-line escarpment continues prominently north-northwest of Sutton Stream, the fault is classed as 'likely', 'not expressed', because there are no suitable landform features for the recognition, or not, of fault deformation (e.g. the landforms are too young or too irregular). The Waitangi Fault escarpment dies out approaching the Gibson fault (feature 11).

A2.13.7 Awahokomo Fault (feature 12g, Figure 5.3; see Figure A2.6)

The Awahokomo Fault is mapped from the northern margin of the Wharekuri Creek valley, south-southeast for about 5.5 km to the southern side of the Awahokomo Creek valley. The definition of the Awahokomo Fault refers solely to known or suspected surface deformation features (i.e. fault scarps and/or monoclinal folds). The reason for this is that although the surface deformation features are very close to the Wharekuri Fault and, in the valley of Wharekuri Creek, the Waitangi Fault, it was not clear, in the early stages of the investigations described below, to which, if either, of those faults the surface deformation relates.

Alluvial fan terraces in the valley of Wharekuri Creek are crossed by two west-northwest trending, sub-parallel topographic steps, transverse to the fall-line of the valley floor, and both up to the west-southwest. The steps are about 250 m apart. The western step comprises a 3.5 m high, 20 m wide, rise across an intermediate-level fan surface, and a 7 m high, 30 to 40 m wide, rise across a higher-level fan surface. The rise on the intermediate-level fan surface was trenched and a fault origin confirmed (Barrell et al. 2002). Although the fault zone was not sharply defined in the trench exposure on account of the poorly consolidated angular alluvial fan gravels through which the deformation has occurred, a 40° dip northwest was indicated, demonstrating a reverse component of movement. This fault scarp is classed as 'definite', 'well expressed'. The eastern step is broader and more diffuse, for which reason no attempt was made to trench it. The step is about 3.5 m high on the intermediate-level fan terrace and it is classed as 'likely', 'moderately expressed'. This step lies between 50 and 100 m west of the mapped line of the Waitangi Fault whose location is pinpointed from bedrock exposures in Wharekuri Creek about 100 m south of the topographic step on the fan surface.

The mapping, trenching and dating at Wharekuri Creek formed the basis for inferring an age of between 14,000 and 30,000 years for the intermediate-level terrace which, taking both topographic steps into account, has undergone definite and likely deformation amounting to a composite vertical offset of between 7 and 9 m. This implies a vertical slip rate in the range of 0.2 to 0.4 mm/yr. Although there is no constraint on the presence or otherwise of lateral movement, there clearly is a significant component of vertical movement. Luminescence dating of sediments in the trench indicates that the most recent surface rupture of the western scarp occurred between 3000 and 10,700 years ago. There is no information on the timing of deformation on the eastern topographic step, if indeed it is a fault scarp. In the absence of any direct constraint on recurrence interval, because only one event has been identified with certainty, the recurrence interval for the Fern Gully Fault is adopted for the Awahokomo Fault, because that range also encompasses the recurrence interval of the Fern Gully Fault. Dating indicates that simultaneous rupture of the Fern Gully Fault and Awahokomo Fault is a possibility, because there is overlap between the age ranges of the most recent rupture event on each fault. The timing of the most recent rupture on the Waitangi Fault is older than the age range of the Awahokomo and Fern Gully faults, which indicates that the Waitangi Fault has a rupture history different from those faults. For that reason, the NSHM defies an extended Fern Gully Fault entity that includes the Awahokomo Fault.

To the southeast of Wharekuri Creek, there is extensive landslide terrain and the location and activity of any faults is unknown. On the southern side of Awahokomo Creek, there is a broad rise at the foot of St Marys Range that, based on its form and setting, is suspected to be of tectonic origin. This marks the southernmost extent of evidence for the Awahokomo Fault. This lies adjacent to where the Kurow Hill Fault (see later section) projects towards the base of the range front. Along the range front farther to the southeast there are a number of locations where well-defined alluvial fan and river terraces emerge from the range front and are considered to cover a range of ages. Thus, if an active fault were present on the range front at those locations, it ought to have deformed at least some of those landform features. This provides some basis for supposing that the deformation associated with the Awahokomo Fault does not extend farther southwest in that direction. As this southeastern limit of deformation coincides closely with the position of the Kurow Hill Fault, it raises some question of whether the Kurow Hill Fault might have experienced some recent primary or secondary activity (see later section).

A2.13.8 Deep Stream Fault (feature 12h, Figure 5.3; see Figure A2.6)

This north-striking fault is only about 5 km long, extending from the Waitangi Fault in the south to the Dryburgh Fault in the north. It is upthrown to the west by as much as several hundred metres. There are no known exposures of the fault plane and so its dip direction is unknown. An eroded remnant of a high-level river terrace, assessed by Read et al. (1998) as being at least 500,000 years old, lies across the projected position of the fault. Van Dissen (1996) noted that the terrace surface is about 20 m higher on the western side of the fault. This may possibly due to offset across the fault. However, because the underlying river gravels and, in particular, the contact between the river gravels and the underlying geological strata, were not exposed, it could not be established whether the height difference in the terrace surface was due to fault movement, or simply due to river or stream erosion having coincidentally lowered the terrace surface elevation on the eastern side of the fault. Given these unknowns, and the likely great age of the river terrace, it does not provide any solid basis for interpreting the fault as being active.

The Deep Stream Fault is notably short compared to the amount of vertical displacement. Because the fault is shorter than the seismogenic zone is deep, it is unlikely that fault's surface expression is the result of independent primary rupture of the fault but rather is more likely to be a splinter of one or more adjacent larger faults, and has experienced interlinked rupture or secondary slip in unison with larger fault(s). Because several nearby larger faults, the Waitangi Fault, Awahokomo Fault and Fern Gully Fault, have definite evidence of activity, the Deep Stream Fault is classified as 'possible', on the grounds that if one of the adjacent faults were to rupture, secondary surface rupture on the Deep Stream Fault would be a conceivable outcome. Because there is no direct evidence for geologically recent activity on this fault, a recurrence interval for surface slip events of >10,000 years is assumed.

The Deep Stream Fault is not included in the NSHM (Stirling et al. 2012) or the NZAFM (Litchfield et al. 2013, 2014). The absence of any confirmed Late Quaternary offset on the fault means that there is no justification for including it in future iterations of those datasets.

A2.13.9 Little Awakino Fault and Kurow Hill Fault (features 12i & 12j, Figure 5.3; see Figure A2.7)

These two approximately east-striking faults are associated with topographically distinctive uplifted blocks of basement rock on the southwestern side of the Waitaki River. The Kurow Hill Fault is marked by the prominent greywacke escarpment of Kurow Hill upthrown to the north, against cover rock strata exposed along the southern side of the hill. Geological exposures west of Kurow indicate that the Kurow Hill Fault comprises two separate, near-parallel faults (Bishop 1976). The Little Awakino Fault is marked by a similar, though smaller, escarpment farther to the north (Marwick 1935). In Google Earth Street View (imagery date: Oct 2012), on State Highway 83 about 850 m southeast of Waitaki Dam (location: 44° 41.862'S, 170° 25.950'E), there is a good view south looking up the peneplain surface of the Kurow Hill block, and to the west is the ~100 m high escarpment of the Little Awakino Fault, with the snow-capped St Marys Range in the background. From north through east is the prominent escarpment of the Dryburgh Fault that forms the steep eastern margin of the Waitaki valley at this location.

Although it has not previously been suggested that either fault is active, an important consideration is that both faults are of notably short length compared to the amounts of displacement across them. The Little Awakino Fault is no more than 4 km long, but has as much as ~100 m throw on the base of the cover strata, while the Kurow Hill Fault is no more than 9 km long, but has as much as 450 m to 600 m throw on the base of the cover strata (Marwick 1935, Macfarlane 1988). As the Little Awakino Fault, in particular, is shorter than the seismogenic zone is deep, it seems unlikely that each fault's surface expression is the result of independent rupture of the fault. Rather, an appealing explanation is that they are splinters of one or more adjacent larger faults, and have accumulated slip is association with ruptures of one or more nearby longer faults. Because several of the nearby longer faults, the Kirkliston Fault, Stonewall Fault, Awahokomo Fault, have definite or likely evidence of activity, the Kurow Hill Fault and Little Awakino Fault are classified as 'possible', on the grounds that if one of the adjacent faults were to experience a large, surface-rupturing earthquake, interlinked or associated surface rupture may be a conceivable outcome on one or both faults. Because there is no direct evidence for geologically recent activity on either fault, a recurrence interval for surface slip events of >10,000 years is assumed.

Where these two faults are marked by a prominent greywacke escarpment on the upthrown side, they are classified as 'moderately expressed', because the fault is likely to lie at the foot of the escarpment, and its location is thus reasonably well defined. Where the faults underlie the alluvial deposits of the Waitaki valley, they are classed as 'not expressed'. It is worth noting that the somewhat unexpected northward curve of the Kurow Hill Fault up the Waitaki valley on the western side of Kurow township is based on geological information, namely the intersection of crushed greywacke in two drillholes (numbered 37 and 41) just north of Kurow township, reported by Mansergh (1973).

Also included in the dataset is what is known as 'Fault 2', an east-striking fault inferred from a gravity survey by Teagle and Moore (1986) beneath Kurow with an estimated throw on basement of about 100 m, up to the north. Although the reliability of this gravity-based interpretation is uncertain, if the gravity anomaly is correctly interpreted as representing a fault, it may be a branch of the Kurow Hill Fault. Although suggested by Barrell & Van Dissen (2003) as terminating against the Dryburgh Fault, it is not inconceivable that Fault 2 could merge with that fault, or perhaps be a continuation of the Stonewall Fault.

At Kurow, an extensive remnant of the Aviemore alluvial terrace lies across all probable projected lines of these faults. There are no visible fault offsets of the terrace surface, indicating that the most recent surface rupture(s) of the Kurow Hill Fault, including Fault 2, occurred prior to the formation of this terrace surface, which at this location is tentatively inferred to be about 10,000 years old (Barrell & Van Dissen 2003). West of Kurow the landscape is deeply dissected by stream and gully erosion, and there are no extensive, well-defined landform surfaces across the lines of the two strands of the Kurow Hill Fault. Several high-level topographic benches lie near the foot of Kurow Hill, stepped parallel to the trend of the faults. The origin of these benches is uncertain; they could relate either to fault offsets of a single formerly continuous bench, or they could be remnants of stream-cut terraces formed as the streams eroded down into the landscape. Thus these benches do not place any useful constraints on the most recent surface rupture(s) of the fault(s).

The Awakino River drains along a narrow, very straight, gorge that bisects a well preserved northward-tilted peneplain remnant on Kurow Hill. The gorge and peneplain landforms are readily visible in Google Earth, for example in the vicinity of 44° 43.955'S, 170° 25.589'E, near the head of the Awakino gorge. This antecedent gorge, on account of its straightness, has been speculated to mark the location of a fault, for example as illustrated in maps in a report by Fellows (1989). Bishop (1976) mapped a fault within bedrock along the upper part of the valley of the Awakino River, of similar trend and projecting towards the gorge in the lower reaches of the Awakino River. The map of Forsyth (2001) interpreted the Awakino Fault as extending northeast from St Marys Range through the Awakino gorge. In order to satisfy geological mapping protocols a nominal offset was shown where one fault intersects other faults. Thus the Awakino Fault is shown as offsetting the Wharekuri Fault as well as the Kurow Hill Fault. The peneplain remnant on Kurow Hill shows no discernible anomaly in height or gradient either side of the Awakino gorge. Thus, there appears to be no necessity for the identification of the Awakino Fault as a Late Cenozoic fault, and it is not included in this dataset. The sector of the Kurow Hill Fault where it is shown in QMAP as being offset across the Awakino Fault has the short cross-cutting segment of the Awakino Fault included within the lines representing the two strands of the Kurow Hill Fault.

These faults are not included in the NSHM (Stirling et al. 2012) or the NZAFM (Litchfield et al. 2013, 2014). Based on current information, there is no reason that they should be included in future iterations of those datasets.

A2.13.10 Dryburgh Fault (feature 12k, Figure 5.3; see Figure A2.6, Figure A2.7, Figure A2.8)

The Dryburgh Fault is a northwest-southeast striking fault with a mapped length of about 50 km. It is upthrown to the northeast and has an offset of the peneplain at the base of the cover rock sequence of as much as 800 m, although throw does vary along its length due to the presence of discrete fault blocks on the southwestern side, such as the block bounded by the Little Awakino Fault and the block bounded by the Kurow Hill Fault (Marwick 1935).

The only reported exposure of the fault zone was from the foundations of Waitaki Dam where Marwick (1935) described the fault zone as “about 10 chains wide (i.e. 200 m), having a pugged zone of at least two chains (i.e. 40 m) in which the argillite and greywacke has been reduced to an unctuous mud”. Retrospective mapping of rock in the foundation gallery of the Waitaki Dam by Read et al. (1995) clarified that the width of the fault zone is 190 m wide, but that the location of the most recent plane(s) of movement of the fault could not be determined, due to incomplete geological exposure in the dam foundation gallery when inspected for the Read et al. (1995) assessment. Geological mapping in a small creek approximately 3 km east-northeast of Aviemore Dam has constrained the fault position to a 50 m wide corridor between a greywacke basement rock outcrop to the northeast and an exposure of vertically-dipping cover rocks (Wharekuri Greensand) to the southwest (location 44° 38.796'S, 170° 23.380'E) (Barrell et al. 2005). The fault is presumed to have a reverse sense of throw (Marwick 1935), although the presence of localised small fault-bounded blocks close to the fault does raise the question as to whether there may have been components of strike slip motion during the evolution of the fault, that created 'lozenge'-like blocks.

Between Waitaki Dam and a point about 1 km upstream of the Kurow bridge, the position of the fault is mapped through gaps in exposure between relatively intact riverbank outcrops of greywacke, assuming that these gaps indicate the presence of crushed rock (Barrell & Van Dissen 2003). On the east bank of the river channel about 2.5 km downstream of the Kurow bridge, three closely spaced drillholes define the fault position to ± 5 m (Barrell & Van Dissen 2003). One hole encountered crushed greywacke at shallow depth and the other two holes terminated at 79 m and 108 m depth still in greyish greywacke gravel. Collectively these drillholes constrain the Dryburgh Fault to having either a northeast dip of at least 63°, or a southwest dip of at least 84°, at that location (Barrell & Van Dissen 2003). The presence of greyish greywacke gravel extending to at least 108 m depth adjacent to fault-crushed greywacke at shallow depth could, at face value, suggest a large amount of Late Quaternary displacement. As this is highly incompatible with other evidence suggesting a very low level of Late Quaternary activity of the fault (see below), Barrell & Van Dissen (2003) interpreted this grey gravel material as being part of the Kowai Formation (the youngest component of the cover rock strata) that has resided in a setting where the groundwater chemistry has encouraged reducing conditions, in contrast to the classic appearance of this deposit as a highly oxidised brown gravel in well-drained outcrops.

Due to its proximity to the Waitaki Valley hydro-electric facilities, paleoseismological investigations were carried out on the Dryburgh Fault during 2004/2005 (Barrell et al. 2005), at a location about 3 km east-northeast of Aviemore Dam, within the catchment of Coal Stream, a tributary of Lake Waitaki. Field reconnaissance identified a transverse topographic step on an old alluvial fan, and this step was suspected to be related to movement of the Dryburgh Fault. A combination of drilling to bedrock to define the fault location at depth beneath the fan gravels, and fault investigation trenching showed that the topographic step is of erosional origin, rather than being due to fault movement. OSL dating was undertaken on unfaulted sediments that span the width of the fault, and therefore are younger than the most recent surface rupture of the fault. The dating showed that there has been no surface-rupture deformation on the Dryburgh Fault at that location since at least 40,100 ± 2400 years ago, and probably not since at least 66,500 ± 4500 years ago. The younger bound of that age (62,000 years) is the preferred estimate of the minimum time elapsed since the most recent surface rupture of the Dryburgh Fault at that location. Collectively, there is no direct evidence that the Dryburgh Fault, at least north of Lake Waitaki, is an active fault. In summary, nowhere on the Dryburgh Fault is there any geological record of a surface rupture event within the recent geological past and it is not possible to place any constraints on the size of individual rupture displacements, or the return period fault rupture events. For the purposes of this report, a minimum recurrence interval of 62,000 years is assumed, equating to the minimum time elapsed since the most recent surface rupture.

Towards the southeast of Kurow, the Dryburgh Fault lies close to the Stonewall Fault and in the area northwest of Little Roderick Road, the several hundred metre wide section of greywacke rock between the two faults has been extensively crushed by tectonic movements over time. There remains a prominent escarpment marking the upthrown side of the

Dryburgh Fault extending a further 15 km to the east-southeast, with the more easterly strike of the Dryburgh Fault resulting in divergence in that direction between the Dryburgh Fault and the Stonewall Fault. The eastward end of the Dryburgh Fault is at a prominent northeast trending greywacke escarpment, identified as the Tussock Hill Fault by Macfarlane (1988). On account of the Dryburgh Fault being identified as a ‘possible’ active fault (with a very low rate of activity), adjacent parts of the Tussock Hill Fault are also identified in this dataset as a ‘possible’ active fault, on the presumption that a rupture of the Dryburgh Fault extending all the way to its eastern end may cause associated slip on the Tussock Hill Fault.

The Dryburgh Fault is represented in the Litchfield (2013, 2014) dataset as the ‘Dryburgh Northwest’ fault zone, in which it is characterised as a northeast-dipping reverse fault with a secondary left-lateral component, a dip range of between 50 and 70° (60° preferred), and a slip rate range of between 0.001 and 0.026 mm/yr, with a preferred estimate of 0.006 mm/yr. The dataset of Stirling et al. (2012) identifies this fault as the ‘Dryburgh‘, assigns a length of 28 km, a slip rate of 0.01 mm per year and calculates a single-event displacement of 2.0 m and a recurrence interval of 325,000 years. It should be noted that because there is no documented evidence for a past surface rupture event on the fault, the slip rate values are derived from inference, and also that the adopted length value is a minimum for the fault’s geologically mapped length of about 50 km.

A2.13.11 Stonewall Fault (feature 12l, Figure 5.3; see Figure A2.7, Figure A2.8, Figure A2.13)

The Stonewall Fault is at least 35 km long, has a northwest-southeast strike and is upthrown to the northeast. Evidence for the most recent surface rupture(s) is preserved only near Little Roderick Road, where Late Quaternary alluvial fan deposits have been displaced across the fault. In the valley of a minor stream that is incised into a large alluvial fan, a stream-side outcrop reveals cover rocks to the southwest in the fault contact with greywacke basement rock to the northeast, both overlain by alluvial fan gravel (approximate location 44° 46.332'S, 170° 33.945'E). There is a fault offset of the bedrock surface and overlying gravel, with a vertical component of movement of between 2.1 and 2.4 m up to the northeast. The fault dips 57° to the northeast indicating a reverse component of offset. Here, at bedrock level, the fault offset is notably sharp with negligible folding. To the southeast on the alluvial fan surface that stands about 30 m above stream level there is a broad fault scarp as much as several metres high. A large trench was excavated across the scarp in 2004 (approximate location 44° 46.407'S, 170° 34.044'E). In contrast to the moderately steep, sharp, fault exposed at bedrock level, the fault deformation is diffuse through the fan gravel deposit, and was expressed as a 14 m wide zone of reverse faulting and warping, that has an overall dip of 37° towards the northeast. This provides a good illustration of the diffusion and dip-reduction of reverse fault movement through poorly consolidated deposits. The overall vertical component of throw across the trench-exposure of the fault zone is between 2.1 m to 2.4 m. The largest component of vertical throw on a discrete individual fault plane is 0.9 m. This individual fault plane offset is considered to represent a minimum estimate for the vertical component of single-event displacement, while the maximum estimate of overall throw of 2.4 m vertical provides a maximum value for single-event displacement for the most recent surface rupture. In the trench exposure, there is definite evidence for at least one surface rupture preserved in these fan deposits. Although the occurrence of more than one rupture cannot be discounted, all of the observed deformation can be accounted for as the product of just one rupture event.

From the deposits exposed in the trench, one OSL date was obtained for a deposit formed before the last rupture, with six OSL dates obtained for deposits formed after the last surface rupture. Collectively, these results show that the most recent surface rupture event occurred prior to 16,800 ± 1100 years, but more recently than 43,000 ± 3000 years. Considering the younger and older bounds of these results, they constrain the most recent surface-rupture to having occurred between 15,700 and 46,000 years ago. The smaller bound of vertical deformation (0.9 m) combined with the older age bound (46,000 years) provides a minimum estimate of vertical slip rate of 0.02 mm/yr, while the larger bound of vertical deformation (2.4 m) combined with the younger age bound (15,700 years) yields a maximum estimate of vertical slip rate of 0.15 mm/yr. Because the investigations provided no data that define any earlier surface rupture events, it is not possible to reliably calculate a recurrence interval. The minimum time elapsed since the most recent surface rupture (15,800 years) provides a minimum working estimate for recurrence interval. For the purposes of this report, a conservative estimate of recurrence interval of at least 16,000 years has been applied.

Southeast of Little Roderick Road, there is a well-defined escarpment along the upthrown side of the Stonewall Fault, and drilling investigations in pursuit of hydro-electric development proposals have shown that the fault lies approximately at the base of the escarpment (Macfarlane 1988, 1989). The fault extends at least as far downstream as the locality of The Stonewall, which presumably takes its name from the sharp escarpment formed in greywacke basement rock on the upthrown side of the fault in that area. Gravity surveys in that area indicate a total throw on basement rock of between 700 and 1200 m (Woodward et al. 2003), and 10 km farther to the southwest, gravity surveys suggest that there is negligible if any displacement across the projected line of the Stonewall Fault. Based on the gravity results of Woodward et al. (2003), Barrell & Van Dissen (2003) repositioned the southeastern sector of the Stonewall Fault onto an east-southeasterly strike aligned with the northern bank of the Waitaki River because the interpretation of Woodward et al. (2003) indicated that if the fault is present in that area that is its most likely position. This puts the fault as much as 3 km or so farther north than was shown by Forsyth (2001), and that revised position was incorporated into the QMAP digital dataset (Heron 2014). Another piece of information is that on the south bank of the Waitaki River, a test excavation for hydro-electric development investigations uncovered an exposure of Rifle Butts Formation (upper part of the cover rock strata) in which the bedding has a 20° northwesterly dip (Macfarlane 1988, Forsyth 2001). Forsyth (2001) positioned the Stonewall Fault to the south of this outcrop, whereas the gravity-based interpretation implies that the fault lies to the north of the outcrop. In producing a structure contour model for selected geological boundaries in South Canterbury, Barrell & Strong (2012) found that a coherent model could be obtained in relation to geological strata on the northern side of the Lower Waitaki Plain without having a fault beneath the northern bank of the Waitaki River. Accordingly, in the present dataset the Stonewall Fault has been returned to its original position as defined by Forsyth (2001), which is also the position that was used for the fault by Barrell & Strong (2012).

For unknown reasons, the Stonewall Fault is not represented in the Litchfield (2013, 2014) dataset. In an earlier assessment (Berryman et al. 2002), the Stonewall Fault was identified as the 'Dryburgh Southeast', and its omission from the Litchfield et al. datasets is probably an oversight (for which the present author, as a co-author of those works, must bear some responsibility). The Stonewall Fault is however identified in the dataset of Stirling et al. (2012) as 'Stonewall' and is characterised as a 20 km long, northeast-dipping, reverse fault with an assigned slip rate of 0.07 mm/yr and calculated values for single-event displacement of 1.4 m and a recurrence interval of 21,430 years. That characterisation draws upon the fault investigation results outlined above and broadly speaking is compatible with the investigation findings, noting that uncertainties are not stated in the Stirling et al. (2012) data table.

A2.13.12 Waitaki Fault (feature 12m, Figure 5.3; see Figure A2.8, Figure A2.13)

This northwest-southeast striking fault, downthrown to the northeast, extends for at least 35 km along the southwestern side of the Lower Waitaki Plain. Towards the northwest the fault extends beneath the valley of the Waitaki River towards a presumed intersection with the Stonewall Fault. Its position in that area as well located, on account of numerous drill holes that were put down as part of investigations for hydro-electric development of the lower Waitaki Valley (Macfarlane 1988, 1989; Barrell & Van Dissen 2003). On the upthrown side, there is a prominent escarpment extending from Black Point southeast to Pukeuri, with basement semischist exposed in the escarpment in the area between Georgetown and Black Point. The upper part of the cover rock sequence occurs on the downthrown side beneath a veneer of alluvial sediments that forms the Lower Waitaki Plain. Gravity surveys across the fault near Black Point and near Peebles suggest a total throw on basement rock of between 700 m in 1200 m at both those locations (Woodward et al. 2003). Geological mapping indicates that the throw on the fault decreases towards the southeast, with cover rock strata preserved on both sides of the fault near Pukeuri. Whether or not the fault extends farther southeast into the offshore area is unknown.

Between Georgetown and Pukeuri, large alluvial fans formed by streams draining northeast from the escarpment have accumulated on top of the Morven Formation alluvial gravel deposited by the Waitaki River. At Pukeuri, the fault projects under the Lower Waitaki Plain, where Morven Formation forms the ground surface. In that area, as much as 1.5 m of loess rests on Morven Formation and dating indicates that the loess is at least 18,000 years old (Barrell & Van Dissen 2003). Because there is no indication of any deformation of the surface of the Waitaki Plain in that area, this implies that the Waitaki Fault has not experienced surface rupture within at least the last 18,000 years. Nowhere along the fault is there any indication of landform offset and thus nothing to indicate that the fault is active. The fault has previously been regarded as inactive, but because there are no landforms unequivocally older than 18,000 years across the line of the fault, it is not possible to definitively state that the fault is inactive. On account of its presumed intersection with the Stonewall Fault towards the northwest, and the Stonewall Fault having demonstrated activity within the last few tens of thousands of years, the Waitaki Fault is classified as ‘possible’, ‘not expressed’. For the purposes of this report, it is assumed to have a recurrence interval of >10,000 years.

This fault is not included in the NSHM (Stirling et al. 2012) or the NZAFM (Litchfield et al. 2013, 2014), and there is presently no evidence available to suggest that it should be included in those datasets.

A2.14 Kirkliston Fault Zone (feature 13, Figure 5.1; see Figure A2.7, Figure A2.9, Figure A2.10)

This northeast-southwest striking system of faults lies along the foot of the Kirkliston Range and has been responsible for the uplift of the range relative to the Hakataramea Valley on the southeast side of the range. It is long been suggested that a ‘master’ fault lies along the foot of the range (Kirkliston Fault Zone (rangefront fault)), but determining its presence has been elusive. What is much clearer is that as much as 3 km southeast of the foot of the range is a series of fault or fold scarps that appear to have been the loci of Middle to Late Quaternary fault-related deformation (e.g. Fellows 1989, Wood et al. 1998, Forsyth 2001, Barrell & Van Dissen 2006a&b, and Barrell et al. 2008).

Due to its proximity to the hydroelectric facilities of the Waitaki valley, the Kirkliston Fault Zone has been examined in some detail by way of mapping, trenching and dating, to determine its level of activity (Fellows 1989, Wood et al. 1998, Barrell & Van Dissen 2006b, Barrell et al. 2008). Information from the earlier work contributed to the depiction of the Kirkliston Fault by Forsyth (2001), but some refinements and improvements have resulted from subsequent work, which warrants some revision of the QMAP linework as shown by Forsyth (2001) and Heron (2014). The dataset accompanying this report incorporates those refinements, which should be incorporated in future refinements of the QMAP dataset. In addition, re-examination of aerial photos, particularly in the northern sector of the Hakataramea valley has provided further information in that area that also may warrant refinement of the fault locations and characteristics in future iterations of the QMAP dataset.

The most comprehensive information on fault activity comes from trenching investigations of what is known as the Cleaves trace of the Kirkliston Fault, which has an overall east-west strike and can be mapped for about 5 km between Farm Stream and Potato Creek, and has been examined in two fault investigation trenches, one on the west bank of Potato Creek at about 44° 37.180'S, 170° 33.400'E, and one on the eastern side of Farm Stream at about 44° 38.118'S, 170° 30.325'E. The more detailed information comes from the Potato Creek trench (see Figure 5 of the main report). As reported by Barrell et al. (2008), the trenching work has shown that the Cleaves trace represents a reverse fault dipping northwest at ~40°. Fault plane striations at Potato Creek indicate pure dip-slip motion. At least two rupture events are preserved in the trench-exposed stratigraphy, with single-event vertical components of between 0.6 and 1.0 m 'at-fault', and 3.25 ± 0.25 m when combining fault offset with monoclinal folding of the hanging wall. Dating of the strata using OSL and radiocarbon indicates that the most recent surface rupture on the Cleaves trace occurred between 5,900 and 22,000 years ago, and most likely between 12,900 and 22,000 years ago. The long-term vertical component of slip rate is between 0.08 and 0.11 mm/yr, and the larger value is considered the more representative. The recurrence interval is constrained to lie in the range of 23,000 to 39,000 years, with approximately 25,000 years considered to be the most likely value.

The Padkins trace of the Kirkliston Fault Zone at the location it was trenched (44° 39.956'S, 170° 30.773'E) is a monoclinal flexure, of 4 m vertical amplitude, affecting brown-weathered gravel overlain by about 7 m of loess (Barrell et al. 2008). About 20 cm above the top of the gravel, the loess returned an OSL age of 89,600 ± 7100 years, the younger bound of which (~82,000 years) provides a robust minimum age for the underlying gravel. Four other stratigraphically concordant OSL ages were obtained from the loess deposit, the shallowest sample about 1.5 m below the ground surface yielding 20,600 ±1600 years. The fold amplitude of 4 m provides a maximum value for vertical single-event deformation, although there are no data on how many events may be represented in the monocline, thus recurrence interval for the Padkins trace cannot be adequately constrained. The dating affords a maximum estimate of vertical slip rate of 0.05 mm/yr. This means that the slip rate is significantly less than on the Cleaves trace at Potato Creek. Potential explanations include a southwestward decrease in slip rate on the Kirkliston Fault Zone, a shallowing of dip of the fault, or accommodation of slip elsewhere towards the southwest. Present data are not sufficient for discriminating between these explanations.

Between the Cleaves and Padkins traces is a set of northwest-striking faults, identified in this dataset as the Kirkliston Fault Zone (Milne Road faults). The two fault scarps at and southwest of Milne Road are classed as 'definite', because they cross natural drainage trends, and they have opposing senses of throw, thus defining a graben between them. The northern one was included in the QMAP dataset. To the northwest, there is a large area (~4 km^2) of multiple topographic steps, centred about 2 km west of the intersection between Milne Road and Corrigals Road. They have a variety of senses of throw, and collectively represent an array of grabens. They were examined in aerial photos and in the field in 2006, and reported on by Barrell & Van Dissen (2006b), who considered that although these features had some characteristics compatible with having been produced by slope instability, the general topographic relief of the area was too small to provide driving forces for slope instability, and there were no nearby low-lying areas towards which movement could have occurred. Consequently, these features were interpreted as most likely the product of tectonic movements, and are classed here as 'likely'. Also of particular note is that they lie in the area between the northeast end of the Padkins trace, and southwest end of the Cleaves trace. The Milne Road faults are inferred to represent some type of 'tear' faulting between the Cleaves and Padkins traces. The Milne Road faults only affect mid- to high level terrace surfaces, and there is no sign of these faults extending onto lower, stony, terraces, of likely late Glaciation age (~18,000 years). Thus, the most recent movements are relatively old, and not incompatible with the ranges of timings and slip rates obtained for the Padkins and Cleaves traces. They are tentatively assigned a recurrence interval range the same as the Cleaves trace.

In order to emphasise the interpretation of interrelationships between these faults, 'possible' connecting faults are drawn between the 'definite' fault scarps east of Milne Road, and the 'likely' fault scarps farther northwest. Similarly, a 'possible' fault is drawn down the Farm Stream valley, from the southwest end of the Cleaves trace to just northwest of the 'likely' Milne Road faults.

The location of the Padkins Fault of QMAP ('Kirkliston Fault Zone (Padkins trace)' of this report) has been adjusted to better reflect the 2006-2008 mapping and trenching results. The eastern sector is attributed as a monocline in accord with the trenching results. The location of the Kirkliston Fault Zone (Cleaves trace) has been similarly adjusted between Farm Stream and Potato Creek. A connecting fault has been added beneath the bed of Potato Creek that joins the Cleaves trace and Caberfeidh trace.

Northeast of Potato Creek, the Caberfeidh trace is evident for about 1.5 km as a several-metre-high topographic step across an older high alluvial fan surface. Just northeast of Station Stream, on a very high, very old fan surface, the broad, quite dissected, scarp is several tens of metres high, but about 1 km from Station Stream towards the Deadmans Stream valley, the scarp becomes progressively broader and appears to lessen in height. The northern 1 km sector is classified as a monoclinal fold. This feature cannot be traced northeast across the relatively young alluvial fan of Deadmans Stream/Poplar Stream, or beyond. It seems likely that this particular strand of the fault/fold peters out in this area.

On the northern side of Poplar Stream, an intermediate-level fan terrace has two topographic steps, both up to the east, about 4 km north of the Hakataramea Station homestead. The farther upstream feature is broad, and at least several metres high, and is classed as a 'likely' monocline. The downstream feature is sharply defined, but only a metre or two high, and is classed as a 'likely', well expressed' fault scarp. Neither can be traced along strike. Field examination would be needed to confirm their origin, and shed light on their context and significance. Noting that they are both upthrown in the opposite sense to the Caberfeidh trace, they may conceivably form part of a step-over zone to the next set of fault/fold features farther north. This next set of fault/fold features comprises a semicontinuous array of 'likely', and in a few places 'definite', fault scarps and monoclines, lying as much as 2 km east from the foot of the range, and extending for approximately 11 km from Poplar Stream to the southern edge of the Grampians Stream catchment. The overall strike is north-northeast and apart from the features mentioned earlier in this paragraph, upthrow is to the west. These fault- and fold scarps are only evident on intermediate- and high-level alluvial fan terraces, with the offset size ranging from a few metres up to several tens of metres, with the greater amounts on higher (older) terraces. There is no discernible deformation of the extensive lower-level terraces, likely to have been formed during the Last Glaciation. At one location between McKays Stream and Rocky Point Stream, there is a short (~1 km long) segment of well-defined fault scarp probably no more than 2 m high that is upthrown to the east, between two strands of westerly upthrown fault/fold. All of the faults and folds described in this paragraph are attributed as Kirkliston Fault Zone (northern traces). Only two short segments of this array of faults and folds were included in the QMAP dataset; the remainder have been mapped using aerial photographs for the purposes of the present report.

Commencing on higher terraces on the northern side of Poplar Stream, at a location about 4 km northeast of Hakataramea Station, is an approximately 10 km long array of monoclinal fold scarps, locally sharpening for 1 km or so to a fault scarp, that can be traced with varying degrees of confidence to Gormans Stream, about 5 km northwest of the Cattle Creek locality. Upthrow is to the east and the deformation for the most part comprises a broad warp prominent on high-standing flat-topped ridges of dissected alluvial fan terrain, with better-preserved scarps on intermediate-level terraces. The best example of the latter is on the southern side of Rocky Point Stream, where a prominent topographic step, classified here as a ‘definite’ fault, is at least several metres high (representative location of this scarp; 44° 32.256'S, 170° 37.853'E). There are hints in aerial photos of drainage anomalies on the lower level terraces along strike from this fault scarp that may represent smaller scarps. These could be fruitful targets for further examination if there is any future need to quantify the activity of this fault/fold (e.g. defining single-event displacement values). To the north of Cattle Creek, topographic anomalies of similar appearance to the fold/fault scarps farther south have a more northwesterly trend and are tentatively included as ‘likely’ fault scarps. All of the features described in this paragraph are identified in the dataset as Kirkliston Fault Zone (McKays trace), named after McKays Stream. The feature described above as a definite fault was depicted on the Forsyth (2001) Waitaki QMAP unpublished data record sheets, but was not compiled onto the published map, probably because its context was unclear. The delineation in this report of a much longer array of fault or fold scarps, has provided a clearer context. Although the sense of throw on the McKays trace is opposite to that of the Kirkliston Fault Zone as a whole, the observation that the McKays trace is parallel to, and almost a mirror image in terms of length, as the array of scarps comprising what are identified here as the ‘northern traces‘, suggests that they may be related in some way. The age of terraces that show deformation on the McKays trace appears likely, on morphological grounds, to be similar to those terraces deformed elsewhere along the Kirkliston Fault Zone.

The faults included in the QMAP dataset that lie along the foot of the Kirkliston Range are identified as the Kirkliston Fault Zone (rangefront fault) and are all classified as ‘possible’, ‘not expressed’. There is no geomorphic indication of any geologically recent activity on these faults, and the overall impression gained is that since at least the Middle Quaternary, tectonic activity has been emergent out in the basin rather than along the foot of the range. The variety and complexity of the surface faulting, including numerous step-overs and the rather enigmatic presumed tear faulting associated with the ‘Milne Road faults‘, highlights that there is yet much more to understand about the character and evolution of the Kirkliston Fault Zone.

The Kirkliston Fault Zone is characterised in the Litchfield (2013, 2014) dataset as a reverse fault zone dipping west at between 45 and 70° (60° preferred). The GIS line representing the fault in the NZAFM digital dataset is 35 km long. Net slip rate is given as ranging between 0.05 and 0.26 mm/yr, with 0.15 mm/yr identified as a best estimate. The Stirling et al. (2012) dataset characterises the Kirkliston Fault Zone as a 56 km long reverse fault dipping to the west at 50°, with slip rate of 0.15 mm/yr, single-event net displacement of 3.9 m and recurrence interval of 26,000 years. The location of the line representing the fault in the NSHM dataset differs from that in the NZAFM, the NSHM line being much longer and curving to the northwest along the eastern flank of the Grampian Mountains. The NZAFM fault length is more compatible with the data presented in this report, and it would be desirable to review and, if necessary, revise the characterisation of the Kirkliston Fault Zone in a future iteration of the NSHM.

A2.15 MT MACGREGOR FAULTS (FEATURE 14, FIGURE 5.1; SEE FIGURE A2.9, FIGURE A2.10)

This name is applied to an array of previously unnamed faults associated with a low range of hills aligned north-south in the centre of the northern part of the Hakataramea valley. There are two named summits on the range, Round Hill to the south and Mt MacGregor to the north and in this report the faults are named after the latter summit. The faults as represented in the QMAP dataset are identified by the presence of greywacke bedrock upthrown to the west against cover rock strata to the east. The fault pattern is quite complicated and although the uplifted fault blocks have topographic prominence, there is no definitive representation of offset landforms. However, because these faults lie along-strike from active strands of the Kirkliston Fault Zone, they are identified in this dataset as ‘possible’ active faults. Southwest of Mt MacGregor, on the western margin of this range of hills, there are two north-trending topographic steps that are classified as ‘possible’, ‘moderately expressed’ faults. The western step is up to the west, and the eastern one is up to the east. Judging from what can be seen in aerial photos, parts of these steps cross landforms that may be old alluvial fans. However, the topography is quite complicated here and these landforms may conceivably be of some other origin, hence the classification of these faults as ’possible’.

The hilly terrain and the absence of the extensive alluvial fans that characterise the central to southern parts of the Hakataramea valley make it difficult to place any constraints on the degree of activity, if any, of these faults. Given that the hilly terrain may be relatively young compared to the high alluvial fans farther south, it is quite conceivable that the activity of the Mt MacGregor faults is not dissimilar to that of the Kirkliston Fault Zone. It is also tempting to speculate as to whether the Mt MacGregor faults are a northern continuation of the Kirkliston Fault Zone, simply with the bedrock standing at a higher elevation and lacking a cover of alluvial fan deposits.

For the purposes of this report, the recurrence interval for the Mt MacGregor faults is inferred to be >10,000 years. The generalised entity representing the Kirkliston Fault in the NZAFM (Litchfield et al. 2013, 2014) is sufficiently long (35 km) to encompass the Kirkliston Fault Zone as well as the Mt McGregor faults, highlighting that the interpretation used in that dataset assumes continuity between the Kirkliston Fault Zone and the Mt MacGregor faults. In the NSHM (Stirling et al. 2012), the Kirkliston Fault Zone is represented by a line that curves northwest along the foot of the Grampian Mountains, and so does not encompass the area of the Mt MacGregor faults, but does more than account for the combined length of these features.

A2.16 LONGDEN FAULT (FEATURE 15, FIGURE 5.1; SEE FIGURE A2.9, FIGURE A2.10)

This feature comprises a relatively young fault scarp crossing low-level terraces of the Hakataramea River northeast of Mt MacGregor. It was first noticed by the writer in 2012, while driving along Hakataramea Valley Road, as an approximately 0.5 to 1 m high topographic step, north-trending and up to the west, running transversely across the channelling of the river terrace, between the road and the Hakataramea River. This step is clearly defined at approximate location 44° 22.823'S, 170° 39.160'E, some 300 m north-northeast of the Round Hill homestead. As this step displaces river-formed features, it is classed as a 'definite' fault scarp, and due to its small height and sharpness, is 'well expressed'. Judging by the stony character and thin soil on this river terrace, which is only a few metres above river level, the terrace age is likely to be no more than a few thousand years. The name is taken from a nearby watercourse, Longden Stream.

The Waimate District boundary runs along the Hakataramea River at this location, and thus the northeastern side of the river lies in Mackenzie District. Despite it being outside the district addressed in this report, it seems desirable to describe all the key information associated with this newly-discovered fault, because that information bears upon the interpretation of the fault within both the Mackenzie and Waimate districts. Along-strike on the northern side of the Hakataramea River, the fault scarp, although subtle, can be readily discerned in aerial photos and on the Google Earth 2012 imagery as a slightly wavy topographic step, up to the west, on a broad river terrace standing about 10 m above river level. Judging by its height, position and form, notably that the channelling is somewhat subdued, this is likely to be a Last Glaciation river terrace of approximate age 18,000 years. Although Forsyth (2001) classified the terraces in this part of the Hakataramea valley as Q2a (terraces a few metres above river level) and Q4a (the ~10 m high terrace), I consider that these are overestimates, because the well preserved channelling on the 10 m high terrace suggests that there is minimal loess cover, whereas around 2 m of loess cover would be expected if the terrace really is Q4a.

Although, in places, the topographic step on the ~10 m high terrace is close to parallel with the river channelling, there is at least one location where the step unambiguously runs transversely across channels, such as at location 44° 22.214'S, 170° 39.118'E, approximately 1.4 km north of the Round Hill homestead. Because the scarp is visually more prominent on this higher terrace, it seems likely that it is somewhat higher, perhaps of the order of 2 m high, than on the lower level terrace beside Hakataramea Valley Road. Whether this indicates that the higher terrace has experienced more deformation events than the lower-level terrace, or simply whether the throw on the fault is diminishing southwards, remains to be established. For the purposes of this report, at least one rupture of vertical offset of no more than ~2 m since ~18,000 years ago is inferred, which given nominal uncertainties (**Table 5.2** of main report) implies a recurrence interval in the range of 4,000 to 20,000 years, and an indicative average vertical slip rate of 0.1 mm/yr.

To the north, the fault scarp approaches the modern bed of Longden Stream and ceases to be visible. Continuing its projection along-strike to the north takes it up the valley of Longden Stream. There are no identifiable fault scarps across the saddle at the head of Longden Stream, or farther north, although it is in relatively steep hill terrain and so the land surfaces there may be relatively young.

To the south, the projection of the fault runs parallel to the Hakataramea River valley, and it is not possible, from present information, to establish whether topographic steps in that direction are of river origin or fault origin.

A fault mapped within basement rock along the upper reaches of Longden Stream is included in the QMAP dataset (Forsyth 2001, Cox & Barrell 2007, Heron 2014). That fault is identified in the Mackenzie District active faults dataset (Barrell & Strong 2010) as the 'West Hunters Fault', based on presumed association with the West Hunters Fault farther south in Waimate District, and is classified as a 'possible' active fault, on account of Late Quaternary fault scarps mapped farther south on the fault by Forsyth (2001). However, the inferred scarps on the West Hunters Fault mapped by Forsyth (2001) are up to the east, whereas the western side of the Longden Stream valley is topographically higher than the eastern side, compatible with a longer history of up-to-the-west movement like that displayed by the fault scarp on the river terraces. The West Hunters Fault is reviewed in the next section.

As matters stand, it is not clear whether the movements that formed the fault scarp on the river terraces relate to movement on the fault structure mapped up Longden Stream, but that remains a possibility. Alternatively, the fault scarp may be a splay from the southern end of the Dalgety Fault, lying on the west side of the upper reaches of the Hakataramea River (Barrell & Strong 2010), and which cannot be traced south of Dalgety Stream into the Waimate District. There are relatively fresh scarps on the Dalgety Fault, and so an association with that fault seems more likely than an association with the Kirkliston Fault Zone, because there are no geologically fresh scarps identified on that system of faults. Because of these uncertainties of association and context, it seems desirable, for the purposes of the present report, to identify the Longden fault as an entity in its own right, until such time as more information is obtained, should the need arise.

A2.17 WEST HUNTERS FAULT (FEATURE 16, FIGURE 5.1; SEE FIGURE A2.10)

This west-northwest striking fault separates basement rock (schistose greywacke) forming the western side of The Hunters Hills range from basement rock locally overlain by cover rock strata to the west. Net downthrow is to the west. It was interpreted as an active fault by Forsyth (2001).

Much of the cover rock terrain, extensively mantled with alluvial fan deposits, has been widely affected by slope instability, and there are numerous dislocations of the landforms, including hill terrain in cover rocks and high-level alluvial fans, with many irregular topographic steps. The position of the fault is moderately prominent in the landscape on account of the generally stable terrain on its eastern side within the basement rock. It is difficult to place any confidence in the origin of some distinctive topographic steps on or close to the line of the fault, mindful of the potential for their having formed as a result of westward-directed landslide movement of cover rock strata on the downthrown side of the fault. Only towards the south-southeast, where basement rock lies on both sides of the fault, is there a reasonably sharp topographic step, down to the west, on the line of the fault that does not appear to be due to be readily attributable to slope instability. It is however difficult to rule out that it is simply be a consequence of differential erosion of weak rock along the fault plane.

As a whole, the West Hunters Fault is classed as a 'possible' active fault, and the southeastern sector described above is attributed as 'moderately expressed', while the remainder is assigned as 'not expressed'. A recurrence interval of >10,000 years is assumed, if indeed it is interpretable as an active fault.

This fault is not included in the NSHM (Stirling et al. 2012) or the NZAFM (Litchfield et al. 2013, 2014). Based on current information, it seems appropriate that it not be included in future iterations of those datasets.

A2.18 NIMROD FAULT (FEATURE 17, FIGURE 5.1; SEE FIGURE A2.10)

This fault is identified on the basis of a sharply-defined north-northwest trending lineament across ridges and slopes in The Hunters Hills, east of Mt Nimrod, from which the name is taken for the purposes of this dataset. The lineament is marked as a line, annotated 'Fault scarp', on the NZ Map Series 260 1:50,000 scale topographic map J39, and was incorporated as an active fault into the map dataset of Forsyth (2001). The active fault as mapped by Forsyth (2001) is ~3 km long (classed here as 'likely', 'moderately expressed') but following a careful examination of aerial photos, I consider there is landform evidence that allows the fault to be mapped a further ~5 km northwestward, and 1 km southeastward. These new extensions are attributed as 'possible', 'moderately expressed'. The 'likely' assignation reflects a small possibility that the offset could be related to gravitational rather than tectonic movement.

The fault was attributed as 'normal' in the Forsyth (2001) dataset, but review of aerial photos for the present report found that the relative sense of upthrow is not uniform across the landforms, with distinct hints of left-lateral offset of slopes. The straightness of the scarp implies that the fault is near-vertical, and the topographic evidence favours interpretation of the most recent surface rupture(s) being predominantly left-lateral strike slip. On ridge crests, the fault trace runs through broad notches that suggest repeated movements over the long term (e.g. hundreds of thousands of years). The sharp preservation of the well-defined surface trace strongly suggests a most recent movement within the past few thousands of years. Recurrence interval in the range of 5,000 to >20,000 years is tentatively assumed.

This fault is not included in the NSHM (Stirling et al. 2012) or the NZAFM (Litchfield et al. 2013, 2014). See the last paragraph of the subsection discussing the Chamberlain fault (feature 18) for recommended revisions of those datasets in relation to the Nimrod fault.

A2.19 CHAMBERLAIN FAULT (FEATURE 18, FIGURE 5.1; SEE FIGURE A2.10)

This name, after Chamberlain Stream which crosses the fault about 20 km southwest of Fairlie, is applied here to a previously un-named north-northwest striking fault. In the Mackenzie District, this fault forms the western margin of a basin containing cover rocks, with basement rock uplifted to the west along this fault. The fault marks the eastern foot of the northern sector of The Hunters Hills range. Southeast of the Pareora River, although all the cover rocks have been eroded off the downthrown side of the fault, the fault remains well evident in the landscape, with higher topography to the west, and there are numerous saddles and low spurs along the line of the fault, probably reflecting the effects of differential erosion close to the fault zone.

Northwest of the Pareora River (which forms the northern boundary of the Waimate District at this location), numerous spurs, alluvial fans and river terraces cross the line of the fault, and there are no indications of landform offsets. Within the Waimate District, the fault lies within mountainous terrain, and there are relatively few uniform landforms (e.g. river terraces) that cross the fault, making it difficult to assess whether or not there has been geologically recent surface rupture of the fault. Gair (1959; p. 281) reported an exposure of the fault plane in the Pareora River, and described the fault plane as very irregular, dipping west at angles ranging from 30° to 70°. This indicates that the fault has a prominent reverse sense of displacement.

Despite a lack of direct evidence for Late Quaternary activity on the Chamberlain fault, its proximity to the Nimrod fault, which does show evidence for recent movement, has led to me classify the Chamberlain fault southeast from the Pareora River to the Otaio River as 'possible', 'not expressed'. As the surface expression of the Nimrod fault is quite short (no more than ~9 km), one should not dismiss the possibility that at least some of the Chamberlain fault may have experienced Late Quaternary surface ruptures, possibly in conjunction with some Nimrod fault ruptures. It is emphasised, however, that there is no positive evidence for activity on the Chamberlain fault, and a recurrence interval of >10,000 years is provisionally assumed.

In the datasets of Litchfield et al. (2013, 2014) and Stirling et al. (2012), the NZAFM and NHSM respectively, there is an entity named the 'Opawa fault zone' (NZAFM) and 'Opawa Fault' (NSHM). The use of this term originated from a regional fault assessment by Berryman et al. (2002), where it was proposed as a northern extension of the Hunters Fault. At that time, there was recently discovered evidence for Late Quaternary offsets, obtained from field and aerial photo work being undertaken by the present writer, for the Aoraki QMAP (Cox & Barrell 2007). However, that evidence related to a nearby, but different fault, upthrown to the east, that forms the southwestern margin of the Albury Range. That fault was identified as the Opawa Fault Zone by Cox & Barrell (2007) and as the Opawa Fault by Barrell & Strong (2010). Thus the evidence for Late Quaternary activity comes from a fault with long-term and recent upthrow to the east. It appears that this evidence for activity was incorrectly attributed to a west-dipping reverse fault at the eastern foot of the northern sector of The Hunters Hills by Berryman et al. (2002), Stirling et al. (2012) and Litchfield et al. (2013, 2014). Their 'Opawa Fault' is the entity identified here as the Chamberlain fault. As the term Opawa Fault is already in use for a nearby, different, fault, the error should be corrected in future iterations of the NSHM and NZAFM datasets. An appropriate course of action would be to reposition and reattribute the Opawa Fault entity as it exists in the NZAFM and NSHM, as per the Cox & Barrell (2007) and Barrell & Strong (2010) datasets, and define a new active fault entity representing the Nimrod fault and nearby parts of the Chamberlain fault, as described in the present report.

A2.20 Hunters Fault (feature 19, Figure 5.1; see Figure A2.10, Figure A2.11, Figure A2.12)

The Hunters Fault lies along the southeastern margin of The Hunters Hills range, and movement of the fault during the Late Cenozoic has been responsible for uplifting the range. The name first appeared on the 1st edition of the 1:250,000 Geological Map of New Zealand (Mutch 1963, Gair 1967), and its use is continued on the QMAP series (Forsyth 2001, Cox & Barrell 2007), and thus has precedence over the term 'Hunters Hills Fault Zone' used by Pettinga et al. (2001), Yetton (2008), and Litchfield et al. (2013, 2014), and the 'Hunter Fault' of Stirling et al. (2012). The term 'Hunters Fault' is used in this dataset.

Along the northern section of the Hunters Fault, Gair (1959; p.278-280) reported several exposures of the fault zone, in which the subsidiary faults within the zone commonly dip west at between 60° to 80°, indicating that at least that strand of the Hunters Fault is a steeply dipping reverse fault.

Where the Otaio River exits from the Hunters Hills rangefront, there is little necessity for a fault at the foot of the range; the lowest part of the cover rock sequence is exposed immediately east of the foot of the range, and its attitude allows the possibility that the basement rock in the range is exposed up-dip, rather than being up-faulted. This is also highlighted by structure contours on basement presented by Barrell & Strong (2012). This was a point also noted by Gair (1959; p. 280), who said the throw on the Hunters Fault decreases southward from the Motukaika River, and that at the Otaio River, the basal coal measures of the cover rock sequence, on the downthrown side of the fault, occur in proximity to basement greywacke on the upthrown side of the fault.

South of the Hook River, Forsyth (2001) drew the fault across the lower flanks of the range, with basement greywacke mapped either side of the fault. There is no particular geological necessity for a fault in this position, with regard to either geology or topography. The Forsyth (2001) Waitaki QMAP unpublished data record sheets do not record any observations indicating a fault at that location (e.g. crushed zones in the rock). However, the fault strand is retained in this dataset. There is, however, a geological need for a fault at the foot of the range, to separate basement greywacke from cover rock strata preserved east of the rangefront (Barrell & Strong 2012). Mutch (1963) also drew a fault at that location. Accordingly a fault has been added to the present dataset, departing from the QMAP-depicted fault at Hook River, and rejoining where Waimate Creek exits the rangefront, which is also the location where the Waimate Fault intersects the Hunters Fault. There are no indications of landform offsets along the line of this fault, so it, and the adjacent one along the lower flanks of the range (from the QMAP dataset), are both attributed as ‘possible’, ‘not expressed’. The geological continuation of the eastern fault is southwest along the Hunters Fault, rather than along the Waimate Fault.

A2.20.1 Comments on the Yetton (2008) report

Pareora River

The features shown in Photos 14 and 15 of Yetton (2008) that are interpreted as fault scarps are erosional features within the cover rock strata. The topographic step shown in Photo 15 is a limestone outcrop, where the limestone band has been buckled upwards beside the fault contact between basement rock at the foot of the range. This same location was illustrated by Gair (1959; his Figure 7) and the geological relationships described. Having closely examined aerial photos of this area, I have found no convincing evidence for fault offset of any landform features. On the contrary, this broad, ancient terrain is developed on cover rocks and extends right up to the foot of the range, without being masked by aprons of debris such as would likely be derived from growth and collapse of uplifted ground along the fault. This implies that there has been little if any uplift along the fault here during the recent geological past. However, had the most recent ruptures involved mainly strike-slip movement, then this may be less readily detectable. As matters stand, there is no direct evidence for Late Quaternary surface rupture on the Hunters Fault at the Pareora River.

Guerins Rd (Mathias Stream)

This area is illustrated in Figure 6 and Photos 9-12 of Yetton (2008). The interpretation is suggested that height-accordant knolls along the lower part of the rangefront are uplifted equivalents of high-level river gravel terraces east of the rangefront. First, the knolls are formed in basement rock, and there are no reports of river gravel being present on their crests. Second, if they were formed by river action, their presence on the upthrown side of the fault is puzzling. Generally a river draining from an uplifting fault block will cut a valley, not form a range-parallel river erosion surface, or deposit a gravel plain. A more likely explanation of these knoll crests is that their crests are eroded remnants of the peneplain formed at the interface between basement rock and cover rock strata. The suggestion that the knoll crests correlate with the high-level terraces east of the fault, classified as being of undifferentiated Middle Quaternary age by Forsyth (2001), seems speculative and appears to be unsupported by geological observations.

The features interpreted as being fault scarps on the north side of Mathias Stream (Photo 11 of Yetton 2008) can, in my opinion, be fully accounted for as the result of landslide movement. The east-trending 'fault scarp', which marks the approximate northern margin of the other faults mapped by Yetton (2008), represents the landslide headscarp. When viewed in Google Earth, the headscarp can be seen to be more arcuate and more continuous than shown in Figure 6 of Yetton (2008). The headscarp extends east from 44° 22.149'S, 170° 52.175'E, with slight curvature, to 44° 22.248'S, 170° 52.516'E, and then curves southward to about 44° 22.374'S, 170° 52.538'E. Movement has been to the southwest.

The feature in the distance of Photo 12 of Yetton (2008) that is interpreted as a graben is a low point on a fairly narrow ridge, and is more likely to be an erosional feature within the cover rock strata, where it has been dragged up steeply against the fault. Although this is not illustrated at the scale of the Forsyth (2001) map, the map of Gair (1959) shows narrow bands of different stratigraphic units at this location, and the map pattern implies that they dip steeply adjacent to the fault. The low area is most likely the result of erosion of one or more weak stratigraphic layer.

Otaio River to Makikihi River

In this area, Yetton (2008) mapped four short northeast-trending anticlines east of the foot of the range. The northern two lie on the axes of topographic ridges, both of which can in my view be fully accounted for as erosional landforms related to the stream dissection of old alluvial fans. The southern two appear to have no discernible topographic expression. No explanation of these features is given in the Yetton (2008) report, and they are not included in the present dataset. There does, however, appear to be adequate topographic evidence for mapping the Otaio monocline (see next section) southwest through this area. Several short strands of the Hunters Fault mapped by Yetton (2008) correspond in location with 'moderately expressed' sectors of the Otaio monocline, with one exception south of Kohika Stream, where the Yetton (2008) fault strand lies several hundred metres east of the topographic feature mapped in the present dataset. This is likely to reflect a plotting error because there are several similarly oriented tributary gullies to the main valley in this area, and the line was probably drawn in relation to an incorrect gully.

Hook River

In the area where the Hook River exits the rangefront, Yetton (2008; his Photo 5, and Figure. 4 & 5) highlighted several gently sloping benches standing more than 70 m higher than the gently sloping dissected terraced terrain east of the range. Forsyth (2001) had mapped Middle Quaternary alluvium on one of those benches. It is not clear whether this mapping was based on the presence of a gently sloping landform, or whether gravel was observed there. There is no observation recorded on the Forsyth (2001) Waitaki QMAP unpublished data record sheets, and therefore it seems likely that the mapping of gravel was just an inference from landforms. Yetton (2008) took the step of suggesting that fault movement has produced the difference in elevation, and calculated slip rates based on the assumed Middle Quaternary age assigned to the deposits. This is a very uncertain approach because it is far from clear whether the features either side of the fault are correlative, and in any case the assigned ages are at best tentative estimates. The features west of the fault may for example be much older than those to the east. Another factor worthy of consideration is that the fault is mapped as comprising several branches, and it is quite possible that the benches on the lower edge of the range are dissected remnants of the peneplain, rather than Quaternary-age deposits. The upshot is that the analysis of Yetton (2008) at Hook River seems to be speculative and in my opinion does not provide useful quantitative information on fault activity at this location.

The rangefront is reasonably abrupt just north of the Hook River, and in this report a short segment of the fault is attributed as possible', 'moderately expressed', and otherwise is attributed as 'possible', 'not expressed'. Photo 6 of Yetton (2008) illustrates an inferred fault-related topographic step; however, at that locality, small, steep alluvial fans have been deposited on the main terrace surface by stream gullies draining from the hills above. That photo is probably taken looking down an alluvial fan towards the grade change where it meets the river terrace, rather than showing a fault deformation feature. My re-interpretation is based on there being no discernible through-going topographic step of fault-related origin on the main terrace surface, which is preserved on both sides of the river on the mapped line of the fault.

A2.21 Hunters Fault (Otaio monocline) (feature 20, Figure 5.1; see Figure A2.10, Figure A2.11)

This feature is represented by a broad topographic step, up to the west, on the high terraces north of the Otaio River. It forms a definite, sharper, tectonic step on the intermediate-level terraces of the north side of the Otaio River valley ('definite', 'moderately expressed'). Although Yetton (2008) has argued that it is a fault, rather than a monoclinal fold as classified by Forsyth (2001), the fold classification is retained here. However, at the topographically low level of the incised terraces of the Otaio valley, where bedrock most likely lies at shallow depth under the terraces, that sector of the feature may well be a fault offset rather than a fold. Nonetheless, on higher ground to the north, the movement is more likely to have diffused into a fold buckle, rather than being a discrete fault. In any event, if there is any future need to determine its true character, further investigation that includes the collection of subsurface data by trenching or drilling, would be needed to resolve this question.

The monocline is readily seen on Colliers Road, which runs along the Otaio valley. There is an unrecognised complexity here, because Colliers Road runs along the river-cut riser between a narrow remnant of a loess-covered terrace, and a stony terrace; the edge of the loess-covered terrace can be seen in Google Earth Street View at 44° 30.857'S, 170° 56.217'E, a location 1.0 km northeast of the Colliers Road/Back Line Road intersection. The loess-covered terrace stands only about 1 m higher than the stony terrace, and this terrace remnant terminates at the monoclinal fold, as can be seen on Colliers Road at 44° 30.811'S, 170° 56.333'E, 1.2 km northeast of the Colliers Road/Back Line Road intersection. East of this location, the gravel forming the stony terrace has overtopped the loess-covered terrace on the downthrown side of the monocline. Yetton (2008) identified elements of this relationship in suggesting that there may be a small offset of this terrace, but the key observation is, in my opinion, that there are two terraces, at similar elevation, but one much older than the other. The ~1 m high step at the downstream limit of the loess-covered terrace may be broadly indicative of single-event displacement/deformation on the Otaio monocline at this location. It is not a robust indicator, because it remains unknown how deeply younger gravel may have buried the loess-covered terrace downstream of the monocline. The next highest terrace has a several metre high buckle of its surface, and the high terrace, standing some 60 m above the main valley floor, has a tectonic buckle of at least 20 m height. Yetton (2008) presents larger estimates, but I suspect that these do not fully account for the fact that these landforms have a substantial natural gradient downstream, which needs correcting before estimating the tectonic deformation.

Because there appears to be no deformation of the stony river terrace, presumed in this report to be ~18,000 years old, this provides an estimate for the minimum time elapsed since the most recent surface deformation event. The indicated deformation of the low loess-covered terrace indicates at least one Late Quaternary deformation event, probably within the past few tens of thousands of years. The progressively larger amounts of deformation on higher terraces indicate repeated deformation events stretching back into the Middle Quaternary. Nevertheless, it seems appropriate to estimate a recurrence interval of >10,000 years for this feature.

The monocline can be traced ('likely, 'moderately expressed') for ~3 km north-northeast of the Otaio River, to the northeastern margin of some low hills, on which 'Trig E1' is located, as shown on the NZMS 260 topographic map J39 (this locality was referred to incorrectly as 'Trig E' by Yetton (2008); confusion may arise because there is a 'Trig E' on a hilltop 9 km northeast of Trig E1). Although Forsyth (2001) mapped the monocline for another 1.5 km to the southern side of the Pareora River South Branch, this appears to be speculative, and this sector is classified here as 'likely', 'not expressed', even though it crosses mid-level terraces that are probably older than the lowest deformed terraces of the Otaio valley.

Yetton (2008) proposed the existence of a feature that he named the 'Trig E anticline' (note; should be 'Trig E1') to account for the high ground associated with this low, elongate, hill in the vicinity of Trig E1. In my opinion, this ridge is no different from many other areas of older higher landforms standing above the general high terraced terrain in this general area, and there are no grounds that I can see for regarding it as an anticline. Erosion of its western margin by the Pareora River South Branch provides more than sufficient explanation for the elongateness of this ridge.

To the south of the Otaio River, the location of the monocline is generally hard to discern but has been tracked by the presence of some topographic steps across ridge lines in the terraced alluvial fan landscape. Interpretation in this area was hindered by the presence of numerous gullies that traverse the landscape and whose floors are relatively young and do not reveal any deformation. The position of the monocline axis as shown by Forsyth (2001) is several hundred metres farther west than the line of vague topographic steps on the ridges and in this dataset I have shifted eastward the position of the line denoting the monocline axis, in order to accord with the topographic features. Towards the south, there are steps on ridges that provide a basis for extending the monocline 2.5 km further south than was shown by Forsyth (2001), and then merging it into the Hunters Fault just north of the Makikihi River. The monocline is classified as 'likely' between the Otaio River and Kohika Stream, and is classified as 'possible' farther south.

Yetton (2008) reported a small fault scarp ~1 m high crossing the low and intermediate terraces of the Otaio River about 500 m downstream of the Otaio monocline. However, no scarp can be discerned either in stereoscopic aerial photos or in Google Earth Street View. A small topographic rise is evident on Colliers Road at that location in Google Earth Street View, with the ground slightly higher (perhaps 0.5 m or a little more) to the upstream side. Close examination of aerial photos reveals a river-cut terrace riser, very low and subtle, but definitely there, that sidles northwest across the valley floor, defining two closely spaced river terrace levels. This is probably the feature that was interpreted as a fault scarp, but there appears to be an entirely satisfactory fluvial explanation for this feature. This does not account for the presence, reported by Yetton (2008), of the scarp on the next higher terrace; a possible explanation is that some other topographic irregularity on that terrace was linked visually with the terrace riser on the lower terrace. Alternatively, there may be some tectonic feature present that is not evident in the imagery. It is not included as a fault in this dataset.

A2.22 WAIMATE FAULT (FEATURE 21, FIGURE 5.1; SEE FIGURE A2.12, FIGURE A2.13)

This north-northwest striking fault, upthrown to the west, is mapped from its intersection with the Hunters Fault south towards the Lower Waitaki Plain. West of Waimate, basement greywacke forms a prominent escarpment several hundred metres high near Mt Ellen. Throw decreases both north and south where in both directions cover rock strata outcrop on the upthrown side of the fault.

It is not clear far south the Waimate Fault extends. Macfarlane (1988) suggested that the Waimate Fault extends south beneath the Lower Waitaki Plain, and that it may have had Late Quaternary displacement, based on the results of drilling along the Waitaki River. Distinctive, moderately to highly weathered gravel and sand, correlated with Kowai Formation which forms the youngest part of the cover rock strata in this region, occurs in all those drillholes. This is overlain by slightly weathered to unweathered sand and gravel that is correlated with Late Quaternary river deposits. West of the projected location of the fault (approximately 2.5 km upstream of the State Highway 1 bridge), the elevation of the top of the Kowai Formation gravel decreases coastward at a gradient commensurate with that of the Waitaki River. This suggests that the top of the Kowai Formation was eroded by the river prior to deposition of the younger, little-weathered, gravel. East of the projected fault location, the little-weathered gravel and sand is much thicker and the contact on Kowai Formation lies at 6 to 8 m below sea level. Geological evidence from Oamaru indicates that the Late Quaternary alluvial deposits that form the Lower Waitaki Plain (Morven Formation) are younger than a prominent ‘interglacial’ sea cliff that was formed about 125 000 years ago (Barrell & Van Dissen 2003). Remnants of this cliff form the prominent, coast-parallel escarpment southwest of Pukeuri and west of Morven village. It is possible that the Waitaki River drillholes have delineated the central part of this former sea cliff, lying buried beneath the alluvial deposits of the Lower Waitaki Plain. If this is the case, the association of the projected line of the Waimate Fault with this apparent 20 m step in little-weathered Quaternary gravel and sand is a coincidence, and there is no necessity to infer Late Quaternary offset on the Waimate Fault, solely on the basis of this step. However, on its own, this drillhole information does not disprove the existence of fault offsets at this location. Another piece of information is that a gravity survey undertaken on the north side of the Waitaki River along Glenavy Tawai Road, across the projected line of the fault, found a slight gravity anomaly, that was interpreted as indicating that if the Waimate Fault does extend that far south, vertical displacement of basement across the fault is no more than about 80 m, up to the west (Woodward et al. 2003). In construction a structural contour model in this area, Barrell & Strong (2012) found there was insufficient information to reliably constrain the structure on the top of basement in this area.

Yetton (2008) described a locality on Green Hills Road (this is the name used on the road sign at the southeast end of the road, but it is shown as Greenhill Road on the Topo 50 map; the latter name is used in this report) where landforms were interpreted to show fault deformation. There certainly is a topographic step, up to the west, and Yetton (2008) presents what appears to be a speculative interpretation that the ground on the high side of the step is an offset correlative of the ground on the low side of the step. I agree that the ground on the high side does appear to be the dissected remnant of an ancient erosion surface of some sort, but it would be worthwhile to consider other explanations for the origin of the ground on the low side of the step. Might the topographic step be the remains of an ancient sea cliff? As noted in the previous paragraph, there is an example of this landform type 3.5 km seaward of this locality where the Waitaki Plains sweep northwards around the front of an ancient sea cliff cut in older terrain. It is not inconceivable that the topographic step at Greenhill Road is an older example of the same sort of thing. A reality check on the inferred activity of the Waimate Fault can be obtained from a locality several kilometres to the south, on the western side of the valley of Dog Kennel Stream, where there is an extensive remnant, highly dissected, of a high-level Waitaki River terrace. That terrace remnant is underlain by the Waimate Fault and the terrace remnant shows no apparent topographic dislocation. Based on elevation considerations, that terrace is likely to be at least as old as the terrain on the lower side of the topographic step at Greenhill Road. If the interpretation that the features at Greenhill Road are the result of offset across the Waimate Fault, then a similar topographic dislocation should be present across the terrace near Dog Kennel Stream. The apparent absence of any deformation of that dissected terrace tends to suggest that the features at Greenhill Road are of non-tectonic origin. This would also lend weight to the interpretation that the step in the elevation of little-weathered sand and gravel beneath the Lower Waitaki Plain, mentioned earlier, is also of non-tectonic origin and instead relates to an ancient buried sea cliff.

Yetton (2008; his Photo 1) showed what he interpreted to be faults offsetting strata exposed beneath a high level terrace on the northern side of the Waihao River. Unfortunately, the photo does not show these interpreted faults with sufficient detail to discern much of their size or character, and of course the age of the strata at that location is not known with any certainty other than a Middle Quaternary age having been inferred by Forsyth (2001). If the strata are of Middle Quaternary age, faults affecting the strata could also conceivably be of that age, and would therefore not necessarily qualify as active faults. Alternatively, they could be the result of fault movement in the Late Quaternary, which cut through older strata.

In order to acknowledge the suggestions made by Yetton (2008), a subsidiary fault has been drawn along the topographic step described above and extended through the area where these faults were illustrated in the Yetton (2008) photo. All things considered, there is no compelling evidence that the Waimate Fault is active, but for the purposes of this dataset and to acknowledge the information and interpretations provided by Yetton (2008), the fault has been classified as ‘possible‘, and where there is topographic expression coinciding with approximate location of the Waimate Fault near Greenhill Road, it is classed as ‘moderately expressed‘, but otherwise as ‘not expressed’. A recurrence interval of more than 10,000 years is assumed for the purposes of this report, but there seems to be a good likelihood that the recurrence interval is considerably more than 10,000 years, if indeed the fault can be interpreted correctly as active.

This fault is not included in the NSHM (Stirling et al. 2012) or the NZAFM (Litchfield et al. 2013, 2014). Present evidence suggests that there is no justification for including it in future iterations of those datasets.

A2.23 SUMMARY OF FAULT PATTERNS ON THE EASTERN FLANK OF THE HUNTERS HILLS

Broadly speaking, there is an array of left-stepping, apparently reverse, faults that lie along the eastern side of The Hunters Hills, comprising, from south to north, the Waimate Fault, the Hunters Fault, the Hunters Fault (Otaio monocline), Chamberlain fault and the Nimrod fault. Late Cenozoic displacements on these have been responsible for uplift of the range. While it is tempting to consider them to be elements of one overall fault zone, the difficulty, with regard to fault hazard, is that only localised components of them (Nimrod fault and Otaio monocline) show any positive evidence for Late Quaternary displacement (i.e. are classifiable as either 'definitely' or 'likely' active). Careful consideration should be given as to how best characterise them in future iterations of datasets such as the NZAFD, NZAFM and NSHM. Present evidence hints at the Late Quaternary activity being confined to two relatively short components, and it is probably only those components that should be taken up into the NZAFD. Those components could be characterised in the NZAFM and NSHM datasets as a ~20 km long active fault entity at the Hunters Fault (Otaio monocline), extending between Hook River and Pareora River South Branch, and another ~20 km active fault entity centred on the Nimrod fault. The other, 'possible', fault entities identified in this report could be incorporated into those datasets, but may warrant being assigned notably lesser levels of slip rate parameter than those two components that display positive evidence for Late Quaternary deformation.

A2.24 NOTES ON THE CANNINGTON SYNCLINE

Yetton (2008; his Photo 3) suggests that the Cannington Syncline, which is a broad fold marking the axis of the Cannington basin, and which extends northwestwards towards Fairlie, is active and has deformed various landform features. However the view shown in that photograph in which it is suggested that landforms are buckled up towards the Maungati Fault (see next section) is an optical illusion. The higher ground is in fact an area of older higher landform that protrudes above the general elevation of the high level terraces that dominate this part of the landscape. This can readily be discerned by stereoscopic examination of aerial photographs, or inspection of topographic maps. The geological analysis undertaken by Barrell & Strong (2012) highlighted that there is more complexity to the Cannington basin structure than was suggested by the drawing of a single synclinal axis by Forsyth (2001) and Cox & Barrell (2007) along the basin. Rather, the geological relationships in detail indicate a need for at least two separate syncline axes separated by a north-plunging anticline underneath the White Rock River. None of these folds have any expression revealed by topographic anomalies in the general context of the high terraced landscape, and they can confidently be regarded as having had negligible activity in the recent geological past (i.e. Late Quaternary). Accordingly, these fold axes are not included in the present dataset.

A2.25 MAUNGATI FAULT (FEATURE 22, FIGURE 5.1; SEE FIGURE A2.10, FIGURE A2.11)

This north-northwest striking fault is well represented by geological relationships and was shown on the 1st edition 1:250,000 geological maps of this area (Mutch 1963, Gair 1967), although was not named on the map faces. The fault was referred to as the 'Cannington Fault' by Yetton (2008), and as a continuation of the Brothers Fault by Barrell & Strong (2012), who presented evidence for structural continuity between the Brothers Fault in the Cave area, a large anticline (Craigmore Anticline of Gair 1959) southwest of the Pareora River lower gorge, and the fault near Maungati. In reviewing literature for the present report, I discovered that on p. 281 of Gair's 1959 paper, he described the fault in the text, and called it the Maungati Fault, even though the name did not appear on the face of the map in that paper. Gair (1959) described geological relationships at the northern bank of the Pareora River South Branch, where a fault is necessary to separate a sequence of Cannington Gravel overlying Southburn Sand (collectively representing the upper part of cover rock strata), both dipping west at 65°, from flat-lying Colliers Coal Measures (basal section of cover rock strata), to the east. He did not state a dip direction for the fault, so presumably the fault plane was not directly exposed. For reasons of precedence, it seems desirable to apply the name for the fault that was used by Gair (1959), and it avoids any possible confusion arising from the fact that ‘Cannington’ is a long-standing name applied to a nearby large syncline (see previous section), and is also applied to a gravel formation in this general area. Geologically, there are strong grounds for inferring a major fault along the northwest flank of the Craigmore Anticline, and Barrell & Strong (2012) drew this fault, referring to it as the Brothers Fault extension. The Brothers Fault (extension) is included in this dataset, and is discussed in the next section. As the Brothers Fault (extension) lies parallel to the anticlinal fold structure, whereas the Maungati Fault cuts southeast across the fold’s axis, it seems desirable to retain a separate name of that fault strand. Whether the Brothers Fault (extension) and the Maungati Fault are contiguous structures, as interpreted by Barrell & Strong (2012) or are separate intersecting structures, remains to be established.

In contrast to the depiction of the Maungati Fault on the maps of Gair (1959), Mutch (1963) and Gair (1959), there is sound basis for curving the fault northeast around the flank of the Craigmore Anticline, as done by Barrell & Strong (2012), rather than extrapolating it northwards.

Towards the southeast, new information has arisen from the aerial photo inspection carried out for the present report, in the form of the detection of a definite fault scarp on older river terraces on the southern bank of the Otaio River, at the locality of Bluecliffs. This location happens to coincide with the mapped contact between Bluecliffs Silt (east) and Cannington Gravel (west), on the Forsyth (2001) Waitaki QMAP unpublished data record sheets. This suggests that the contact is faulted, and marks the location of the Maungati Fault, even though the published map and dataset (Forsyth 2001, Heron 2014) adopted a more direct extrapolation from the bedrock-controlled fault location farther north, and thus showed the fault crossing the southern margin of the Otaio valley about 450 m farther northwest than this exposure (and the newly-discovered fault scarp). In the present report, the fault location has been shifted to accord with the new information.

The key relation for interpretation of the most recent surface rupture(s) of the Maungati Fault is at 44° 30.596'S, 170° 59.085'E, 0.7 km east of Bluecliffs Road /Bluecliffs School Crossing Road intersection, where the fault scarp, up to the northeast, crosses two terrace levels, and offsets both terraces as well as the river-cut riser between them. On Bluecliffs Road at 44° 30.554'S, 170° 59.046'E Google Earth Street View provides some visual information. Looking south-southeast, there is a prominent terrace edge parallel to and about 70 m away from the road. A gully drains off that terrace into the valley floor in the foreground, and that gully coincides with the location of the fault. The terrace edge to the left of the gully is higher, by several metres, than the terrace edge to the right. Loess cover can be seen in the terrace face, at least 2 m thick. On the skyline is the slightly higher terrace that is also offset. Aerial photos indicate clearly that the offset is greater on that terrace, roughly twice as much than on the lower terrace, but this is a tentative interpretation that would need to be evaluated in the field. In the foreground at road level is a stony terrace, lacking loess. Gravel at the ground surface can be seen in the road cutting through the terrace riser, in Street View. Coincidentally, at this location, the road crosses a river-cut terrace edge between this stony terrace, and a lower, much fresher, stony terrace, to the west (upstream). The map of Forsyth (2001) showed both these low-level terraces as Q4 (implied age 59,000 to 71,000 years), but I consider this to be a substantial overestimate. The higher stony terrace, due to absence of loess but otherwise mature form, I estimate to be no older than Late Last Glaciation, nominally 18,000 years old, and the lower stony terrace is probably Holocene (less than 12,000 years), based on its well preserved channel form visible in Google Earth. The higher stony terrace is preserved extensively on the opposite side of the Otaio River, and shows no indication of offset on the line of the fault. The older terraces, across which the fault scarp is preserved, are based on the presence of loess cover, Q4 or older. Forsyth

(2001) did not differentiate these two older terrace levels, instead mapping them as one unit of Q6 age (130,000 to 190,000 years old). This is probably a reasonable estimate for the higher of these terraces, given its position and form. Assuming it is nominally ~140,000 years, and the lower loess-covered terrace is nominally ~65,000 years old, then there have been at least one surface rupture since ~65,000 years ago, and at least two surface ruptures since ~140,000 years ago, and none since about 18,000 years ago. A recurrence interval of >20,000 years is provisionally assumed. For the purposes of estimating slip rate, a vertical component of offset of 10 m is assigned to the higher terrace, and an offset of ~5 m applied to the lower offset terrace. Using the age estimates above, which I consider more likely to be minimum ages (if anything, the terraces are likely to be older than, not younger than, these estimates), it implies an average maximum slip rate of 0.08 mm/yr. As a reality check, assuming an average single-event vertical displacement of 2 m, this average slip rate estimate implies an average recurrence interval of 26,000 years. This is compatible with there having been no deformation of the ~18,000 year old stony terrace.

On the northern bank of the Otaio River, on the line of the fault, is a remnant of a loess-covered terrace, and on this terrace remnant, at 44° 30.325'S, 170° 58.725'E, there is a step, up to the northeast. The step is not as sharply defined as it is on the terrace south of the river valley, and it is classified as ‘likely’, ‘moderately expressed’. Adjacent sectors of the fault are marked as ‘likely’, ‘not expressed’, across the Otaio valley floor.

Farther to the north, because of the evidence near Bluecliffs that the fault has offset landforms, the line representing the fault has been moved slightly to the northwest to accord better to the topography. The new position lies at the base of the topographic escarpment. Where the escarpment is clearly defined, such as between Elder Stream and the Pareora River South Branch, the fault is classified as ‘moderately expressed’. The mapping of the ‘likely’ Maungati Fault ends to the northwest where the fault adjoins the ‘Brothers Fault (extension).

Towards the southeast, the fault can be traced as a topographic step for another kilometre or so across higher, gullied, terrain to Esk Valley. It is not evident across the relatively young terrain of the valley floor, but farther to the southeast topographic steps are evident across higher ground. These steps are mapped as ‘possible’ faults, classed as ‘moderately expressed’ where a step is evident and classed as ‘not expressed‘ across intervening valley floors. The classification as a fault is extended as far southeast as Kohika Stream, but beyond there, the topographic steps are much broader and the structure is classed as a monoclinal fold. A notable feature, long evident even from earlier geological maps, is that the terrain is generally higher to the northeast of the line of these topographic steps. For example, Mutch (1963) showed extensive tracts of the oldest of the Quaternary gravel formations (Smillie Formation) in that area. Even more notable is that Mutch (1963) mapped a concealed extension of what is referred to here as the Maungati Fault in approximately the same position as the topographic steps that are mapped in the present report and classified as fault scarps or fold scarps. It seems likely that this series of topographic steps was noted at the time of the 1963 map compilation but probably deemed insufficiently certain as being of fault origin that a surface fault feature was not identified. The later edition of the 1:250,000 geological map (Forsyth 2001) did not bring forward the fault as mapped by Mutch (1963), but based on the findings of the present report it would be a worthwhile feature to include in future revisions of the 1:250,000 scale geological map of New Zealand.

Mutch (1963) extended the mapping of the concealed fault to the northern side of the Makikihi River, at a location about 2 km northeast of the locality of Hunter. Where it goes from there is not entirely clear in the landforms. The most likely interpretation is that it curves southeast along the northern side of the Makikihi valley, where the terrain is notably higher than to the southwest of the river valley. Corroborating this interpretation is that the Cannington Gravel (equating to Kowai Formation) in the cliffs on the northern side of the river dips gently (2°) to the southwest (Forsyth 2001; Heron 2014 digital dataset), which is compatible with a location on the limb of a southwest-facing monocline. The possibility that the Maungati Fault heads towards Makikihi was presented as an interpretational option by Barrell & Strong (2012). The information obtained in preparation of the present report elevates that possibility to a preferred interpretation.

Other locations along the Maungati Fault where a monoclinal fold scarp is evident include Campbell and Forrests Road about 4.5 km west of the Agnew Road intersection (see Google Earth Street View at 44° 32.544'S, 171° 0.752'E), and Sodwall Road about 2.6 km northwest of the Tavistock Road intersection (no Street View at that location).

Despite ages having been inferred by Forsyth (2001) for the loess-mantled deeply gullied terrain that dominates the higher ground of the Collier Downs, between the Otaio River and Makikihi River, those ages should be regarded as highly uncertain. It is likely that different elements of that terrain are of markedly different ages and based on the existing age inferences which are ill-constrained, it is probably not fruitful to speculate upon whether the amounts of deformation on the fault\fold features to the southeast differ from those inferred near Bluecliffs.

This fault is not included in the NSHM (Stirling et al. 2012) or the NZAFM (Litchfield et al. 2013, 2014). Present information would warrant its inclusion in future iterations of those datasets, as a ~20 km long, steeply northeast dipping, reverse fault entity, extending from about the Makikihi River in the south to Maungati Stream in the north. The 'likely' and 'definite' sectors of the mapped fault should be assessed for their suitability for incorporation into the NZAFD.

A2.26 Brothers Fault and Craigmore Anticline (feature 23, Figure 5.1; see Figure A2.10)

This north-northwest striking fault is associated with the prominent fault-line escarpment that extends from the Pareora River to beyond the Fairlie area. Only a tiny sector at the southern end of the mapped fault lies in the Waimate District – the remainder straddles the boundary between the Timaru and Mackenzie districts. The Brothers Fault was not identified as active in the Mackenzie District report (Barrell & Strong 2010), but is identified as a 'possible' active fault in the Timaru District report (Barrell 2016). The southwestern extension of the fault along the northwestern flank of the Craigmore Anticline inferred by Barrell & Strong (2012) is also mapped as 'possible'. There is no convincing evidence for any landform offsets along the line of the Brothers Fault (extension), so that despite the newly identified evidence for activity on the adjoining Maungati Fault, a classification of 'possible' for the Brothers Fault and its extension seems the most appropriate course of action.

The Brothers Fault north of the Pareora River is included in the NSHM (Stirling et al. 2012) where it is characterised as a 35 km long reverse fault dipping east at 60°, with a net slip rate of 0.07 mm/yr, net single event displacement of 2.4 m and recurrence interval of 37,500 years. In the NZAFM (Litchfield et al. 2013, 2014), further characterisation includes the assigning of a dip angle range of between 50 and 70° (60° best estimate), and a net slip rate in the range of 0.01 to 0.13 mm/yr with a preferred estimate of 0.06 mm/yr. The absence of any observed landform offsets along the fault does raise the question of whether it should be classified as an active fault at all, but nevertheless the very slow slip rates and long recurrence intervals assigned in those two datasets are compatible with a lack of preserved surface deformation features.

In the Timaru District dataset (Barrell 2016), the Craigmore Anticline, which marks the arched crest of the uplifted block on the eastern side of the Brothers Fault is identified as a 'possible' active anticline. Although there is no geomorphic indication of ongoing growth of the Craigmore Anticline, that portion of it in the Waimate District is also classified as 'possible'.

A2.27 BLACK HILL FAULT (FEATURE 24, FIGURE 5.1; SEE FIGURE A2.8)

This northeast-southwest striking fault, upthrown to the southeast, was identified as the Otekaieke Fault in early phases of work relating to Lower Waitaki hydroelectric development (Macfarlane 1988, 1989), but during compilation of the Forsyth (2001) geological map it was found that this name had originally been applied to the Wharekuri Fault by Uttley (1920a). In order to minimise confusion, Forsyth (2001) applied the name Black Hill Fault rather than the Otekaieke Fault of Macfarlane (1988, 1989). The Black Hill Fault forms a prominent escarpment of basement semischist rock along the southeastern margin of the Otekaieke valley. The semischist is locally capped by remnants of the basal part of the cover rock sequence (quartz sandstone and conglomerate of the Papakaio Formation). On the downthrown side (northwest) there is a variety of cover rock strata preserved. There are no known exposures of the fault plane. The Forsyth (2001) geological map was compiled largely from existing information, which indicated that the Black Hill Fault splits northwards into two branches, identified as the Black Hill Fault (west) and Black Hill Fault (east), with an infaulted wedge of semischist and Papakaio Formation lying between the two branches of the fault. Fieldwork undertaken as part of the report by Barrell & Van Dissen (2003) found that this interpretation is probably incorrect and that the geological relationships could be accounted for by the presence of a single fault in conjunction with large-scale landsliding from the fault escarpment that had a displaced some blocks of strata from their original positions. Much of the landslide movement is of considerable antiquity, and streams have cut down into and eroded away much of the debris, removing most of the diagnostic landslide features Barrell & Van Dissen (2003) also found that the Black Hill Fault structure includes a considerable element of folding, and can be considered to be an anticlinal fold with a faulted northwest limb. This dataset adopts the revisions to the position and nature of the Black Hill Fault as defined by Barrell & Van Dissen (2003). Note that the QMAP digital dataset (Heron 2014) has already been modified to reflect the reinterpretations of Barrell & Van Dissen (2003), rather than the interpretation shown on the published map of Forsyth (2001). In that regard, note that for unknown reasons, the current QMAP dataset uses the name Otekaieke Fault for the eastern strand of the fault under the Waitaki valley. In this report, the term 'Black Hill Fault' is applied to both fault strands. Also, any digital data users should note that in the QMAP dataset (Heron 2014), the sectors of the fault that were amended from the version shown on the Forsyth (2001) map were wrongly attributed as having the eastern side downthrown. In the present dataset, this error is corrected, to record northwesterly downthrow.

The location of the Black Hill Fault northeast under the Waitaki valley floor has been investigated by drilling (Macfarlane 1988, 1989) and gravity surveys (Woodward & Mumme 1989). A gravity survey across the Black Hill Fault at State Highway 83 (Woodward & Mumme 1989) showed a well-defined gravity anomaly that was interpreted as a single fault with 520 m of displacement on basement rock, up to the southeast, located about 350 m southeast of the Alpha Downs farm homestead. On the northeast side of the Waitaki River, two parallel gravity lines indicated that the fault splits into two branches, with the throw on basement rock at the northwestern branch interpreted as decreasing northeastward from about 250 m to 160 over about 1 km distance. The southwestern branch was clearly identified on only the northeastern gravity line, with an interpreted throw on basement of 130 m. The other gravity line was interpreted to have been too short to have crossed this fault (Woodward & Mumme 1989). There are some difficulties with these interpretations in regard to some of the drillhole information and this matter is discussed further by Barrell & Van Dissen (2003).

The drilling revealed evidence for northeast plunging anticlinal warping on the upthrown side of the fault, with the semischist/cover rock contact on the upthrown side dropping in elevation northward across the valley floor, and progressively younger cover rock strata preserved on the crest of the fold (Macfarlane 1988).

Macfarlane (1988) inferred the presence of another fault, called the Otekaieke Splinter Fault, thought to branch north-northwest off the Black Hill Fault near State Highway 83. It was recognised on the basis of unexpectedly thick, relatively unweathered brown-grey gravel on the assumed downthrown (west) side of this inferred fault. However a later drillhole found thick greyish gravel at a location between the Otekaieke Splinter Fault and the Black Hill Fault (Macfarlane 1989), raising further questions about the nature and location of the Otekaieke Splinter Fault. A radiocarbon date on charcoal from 14.4 m depth in one drillhole gave an age of 34,900 years before present (Macfarlane 1989). This is very close to the maximum limit of radiocarbon dating, and it is possible that this sample has an infinite age (i.e. >34,900 years BP). According to Barrell & Van Dissen (2003), there are three alternative explanations that can account for the observations:

1. The thick greyish gravels located generally upstream of the Black Hill Fault, compared to thinner gravels downstream of the fault, are the result of up to 30 m or more of, probably Late Quaternary, displacement.

2. The thick greyish gravels are Kowai Formation conglomerate (upper part of the cover rock succession) that at least in places contains zones of greyish coloured non-oxidised material. One drillhole, which encountered brown-grey gravel to at least 40 m depth, had a note on the drillhole log that the greyish greywacke gravel clasts can be broken by hand. Barrell & Van Dissen (2003) took this to indicate that the gravel material is weathered to a relatively weak state, implying a substantial age even though the gravel is not oxidised.

3. The drilling encountered a deep (40 m plus) channel cut by the Waitaki River and backfilled with gravel. Barrell & Van Dissen (2003) considered that the drillholes east of the Black Hill Fault are spaced sufficiently far apart that a deep channel, if present east of the fault, may not have been detected so far.

Because explanation (1) above would define the Black Hill Fault as being an active fault, it is identified in this dataset as a ‘possible’ active fault, and is classified as ‘not expressed’ for its entire length. Barrell & Van Dissen (2003) identified locations where alluvial fan deposits of inferred age up to about 20,000 years lie across the line of the Black Hill Fault, and there are no signs of their having been offset or deformed by fault movement. For the purposes of this report, a recurrence interval of >10,000 years is adopted.

This fault is not included in the NSHM (Stirling et al. 2012) or the NZAFM (Litchfield et al. 2013, 2014). There is presently no information which would justify its inclusion in future iterations of either dataset.

A2.28 AWAMOA FAULT (FEATURE 25, FIGURE 5.2; SEE FIGURE A2.13, FIGURE A2.14)

This north-south striking fault is mapped for a distance of about 7 km from the coast south of Oamaru to the area west of Oamaru. The fault has a relatively small upthrow to the east, identified from relative offset of distinctive units within the cover beds strata and was originally mapped and named by Gage (1957). As depicted on cross-section 'G-H-I' of Gage (1957), the vertical component of displacement of the cover rock strata is between about 100 and 200 feet (i.e. between about 30 and 60 m). Along the coast, the position of the fault coincides with an apparent change in elevation of the Last Interglacial marine terrace, as may be observed in Google Earth Street View (approximate location 45° 8.527'S, 170° 56.182'E). Gage (1957) stated that to the northeast the terrace surface stands about 30 feet (~9 m) above sea level while to the southwest it is only about 2 m above sea level. Also of note is that to the east of the fault, the topography is generally higher than to the west. It is not clear whether the height difference of the terrace surface is simply due to a greater accumulation of deposits on the terrace to the northeast, rather than being a real difference in the elevation of the marine erosion surface that underlies the terrace. Indeed, it is not clear whether or not it is in fact a same-age terrace either side of the fault. Nevertheless, the height change is striking and the possibility that the Awamoa Fault has experienced Late Quaternary surface rupture is worthy of further exploration. For the present report, it is classified as 'possible' although a classification of 'likely' was tentatively considered. Running a scenario that the approximately 7 m difference in terrace height either side of the fault is tectonic and presumably has accumulated since Last Interglacial, approximately 125,000 years ago, implies a vertical slip rate of 0.06 mm/yr. If one assumes 2 m vertical offset per surface rupture event, a recurrence interval of the order of 25,000 years is implied. However, these are very tentative estimates and are dependent upon more definitive information being obtained as to whether or not the difference in terrace height is actually of tectonic origin.

The Awamoa Fault is not included in the NSHM (Stirling et al. 2012) or the NZAFM (Litchfield et al. 2013, 2014). The present evidence is not sufficient to warrant inclusion of the Awamoa Fault in future iterations of either dataset, unless more conclusive information is obtained.

A2.29 WAIHEMO FAULT SYSTEM (FEATURE 26, FIGURE 5.2; SEE FIGURE A2.14, FIGURE A2.15, FIGURE A2.16)

This northwest-southeast striking entity is a long-recognised geological feature that lies along the southwestern foot of the Horse Range and its northern continuations, the Kakanui Range and the Ida Range. A well-documented two-phase history of movement (Forsyth 2001 and references therein) involved an earlier phase of normal faulting, down to the northeast, which led to the accumulation of a thick sequence of sediments during the Late Cretaceous. The later phase saw a reversal of movement, up to the northeast, which resulted in the elevation of the ranges that dominate the present day topography. This fault system and the ranges on its northeastern side form perhaps the most prominent geological feature of North Otago.

The fault system includes several parallel strands identified from the juxtaposition of different types of bedrock, particularly towards its southeastern end. Within the Waitaki District, there are no convincing indications of offset landform features. However, Curran & Norris (2009) documented an exposure of the fault in Pigroot Creek, about 500 m upstream of the State Highway 85 road bridge (approximate exposure location: 45° 11.459'S, 170° 25.560'E). This is the only known exposure of a Waihemo Fault System fault strand, and is described and illustrated in a photo in Curran & Norris (2009), along with dating results that they obtained. The exposure shows semischist basement rock upthrown to the northeast against cover rock strata, with the fault dipping at a moderate angle to the northeast. Above the bedrock, there is interpreted to be a definite offset of stream gravel, by at least 1 m or so, with semischist thrust over the gravel. OSL dating yielded 58,700 ± 12,400 years for the faulted sediments and 14,100 ± 1,300 years for a package of overlying, unfaulted, sediments. These dates bracket the most recent rupture(s) at this location to the interval between 12,800 and 71,100 years. In a conference abstract, Curran et al. (2011) stated that an analysis had been performed and indicated that the actual offset was at least 10 m, but there was minimal explanation of how this estimate was done. I suspect that this estimate is speculative. Furthermore, if the displacement really had been ~10 m, one would expect to see a much stronger expression of a fault scarp in the landscape in this area. For the purpose of this report, I consider that the demonstrated offset of at least 1 m is a more robust working estimate.

In the valley of Pigroot Creek, adjacent to the location of the fault exposure, there is an extensive terrace on both sides of the creek that I estimate, from its form and position, to be of late Last Glaciation age (assumed age ~18,000 years). There is no indication observable in aerial photos, or noted by Curran & Norris (2009), that this terrace is offset. My examination of aerial photos elsewhere along the fault in the Waitaki District revealed that where all terraces of comparable morphology/setting, and therefore age, cross the fault, there are no visible indications of deformation.

From the locality of Morrisons, northwest to the Waitaki District boundary and beyond, there is a notable topographic rise in the general hill terrain at the foot of the range, at about the location of the main strand (basement rock upthrown against cover rocks) of the Waihemo Fault System. Apart from the young stream valley floor terraces, no older terrace landforms extend across the fault, and so provide no direct guide to fault activity. Based on the interpretations presented by Curran & Norris (2009), a short sector of ‘definite’, ‘well expressed’ fault is mapped at Pigroot Creek based on the exposed offset gravels, and the fault mapped at the foot of the range is classed as ‘definite’, ‘not expressed’ northwest to the district boundary, and southeast to Round Hill. Beyond there, the fault along the foot of the range is classed as ‘likely’ as far southeast as Morrisons, on account of the topographic prominence of the terrain northeast of the mapped fault. From Morrisons all the way southeast to the coast, despite a general increase in topographic height on the northeastern side of the mapped fault strands, there are no definitive fault offsets of landforms. Notably, about 6 km north of Palmerston, several mapped strands of the fault cross remnants of high terraces/low hill terrain, without any obvious topographic anomaly. However, it is conceivable that the most recent activity has been farther back at the foot of the range. All things considered, it was judged appropriate to classify all major strands of the fault system (i.e. those that are marked by notable bedrock offsets) between Morrisons and the coast as ‘possible’, ‘not expressed’. An exception is that of fault strands where basement rock occurs either side of the fault, and there is a prominent topographic step on the upthrown side; these are classed as ‘moderately expressed’.

A final consideration is that in a conference abstract, Lindqvist (1997) recorded the heights of the wave-planed bedrock surface underlying Last Interglacial marine terrace deposits (i.e. ~125,000 years old) along Katiki Beach, on the northeast side of the Waihemo Fault System block (i.e. Horse Range) as increasing in height from ~3.5 m above sea level some 3 km north of Shag Point, to 5.5 m above sea level 1.5 km north of Shag Point. Based on personal observation, the terrace may be even slightly higher at Shag Point itself. I also note that no Last Interglacial terrace has been identified in the Shag valley, though its absence may well be due to burial by Last Glaciation alluvium. An important point to consider is that the heights of wave-planed surfaces need to take account of the distance seaward of the paleocliff. The wave-planed surface will be higher close to the cliff than at locations farther seaward. Also, wave energy is much less within a bay than nearer to headlands, thus wave planation may extend to somewhat higher levels in exposed coastal settings. The Lindqvist (1997) observation, which was suggested to attest to post-Last Interglacial uplift on the Waihemo Fault System, is interesting, but further enquiry would be needed to establish a firmer interpretation in regard to Waihemo Fault System activity. The possibility of differential tilt of the Late Interglacial marine terrace deposits due to subsequent uplift on the Waihemo Fault System would, if correct, demonstrate Late Quaternary (and thus 'active') fault movement. This scenario is currently accommodated by the tentative identification of the Waihemo Fault System as a 'possible' active fault all the way to the coast.

In order to add reassurance to the interpretations made here, the fault was examined briefly using aerial photos in the area northwest of the Waitaki district boundary (i.e. within the Central Otago District). About 16 km northwest of the district boundary, a high-level terrace on the eastern side of Old Hut Creek crosses the fault, and shows a prominent topographic step at least 10 m high, up to the northeast (approximate location 45° 3.029'S, 170° 18.666'E). This would be classifiable as a 'likely' fault scarp, with consideration given to marking it as 'definite'. But there is no topographic step on intermediate or low-level terraces in that area. Those terraces include ones with prominently channelled, stony surfaces, as well as more subdued ones, clearly with some loess cover. The general impression gained is that the fault takes a sinuous path along the foot of the hill terrain, suggestive of a generally low to moderate dip to the northeast, and that there has been notably Quaternary deformation, but not in the recent geological past (e.g. the past few tens of thousands of years). The only other strong evidence for activity is about 23 km northwest of where the Waihemo Fault System crosses the Waitaki district boundary, on the west bank of Little Kye Burn, at the mapped location in bedrock of the western continuation of the Waihemo Fault System (Stranraer Fault). There, a transverse step across a mid- to high level terrace, as much as 10 m high and up to the north, is a 'likely' fault scarp (approximate location 45° 1.199'S, 170° 13.449'E). Collectively, these observations provide confidence that at least the northwestern part of the Waihemo Fault System is correctly classified as active, albeit with a low level of activity.

The information outlined above, in particular the absence of any discernible offset of Last Glaciation stream terrace surfaces, implies that the most recent surface rupture(s) of the Waihemo Fault System occurred more than 18,000 years ago. Furthermore, judging from the OSL dating, and also the observation that to the northwest, there are stream terraces across the line of the fault whose form strongly indicates that they have a loess mantle and yet do not show offset, it seems likely that the most recent rupture(s) may have occurred as much as several tens of thousands of years ago. Curran et al. (2011) indicated that for a fault of the 'size' of the Waihemo Fault System, a maximum return period in the range of 10,000 to 20,000 years can be estimated. The basis or robustness of their estimate is unclear, and I consider that it should be treated with caution. For the purposes of this report, the assumption is made that the most recent surface rupture occurred more than ~18,000 years ago, and that the recurrence interval is >10,000 years.

The Waihemo Fault System is not included in the NSHM (Stirling et al. 2012), but a portion of it is included in the NZAFM (Litchfield et al. 2013, 2014). The NZAFM maps classify a 30 km long sector of the Waihemo Fault System as active, extending from the valley of Kye Burn in the northwest to the valley of Coal Creek at the locality of Morrisons in the southeast. The southeastern limit accords well with the interpretations in this report, although the evidence outlined above suggests that its northwestern limit may warrant expansion in future iterations of the NZAFM. The NZAFM characterises the Waihemo Fault System as having a reverse sense of displacement and a component of strike-slip (sense not specified), a dip angle range of between 45 and 65° (55° best estimate), and net slip rate in the range of 0.15 to 0.35 mm/yr with a preferred value of 0.25 mm/yr. Given the considerable time elapsed since the most recent rupture(s), as assessed in this report, a slip rate at the low end of the range, if not lower, seems more likely. Also, a dip value at the low end of the range seems more compatible with the fault exposure illustrated by Curran & Norris (2009) and the somewhat sinuous trace of the fault farther northwest. Present evidence would appear to provide good justification for the Waihemo Fault entity, as depicted in the NZAFM, being incorporated into future iterations of the NSHM.

A2.30 Horse Flat Fault/Taieri Ridge Fault (feature 27, Figure 5.2; see Figure A2.16, Figure A2.17)

This northeast-southwest striking fault forms the southeastern margin of Taieri Ridge. Up-to-the-northwest movement on the fault has displaced the Otago Peneplain with a vertical component of as much as about 300 m. The term Horse Flat Fault is the name by which the fault is most commonly known, for example in geological work associated with the investigation and development of the Macraes gold mine and is identified by that name in the QMAP digital dataset (Forsyth 2001, Heron 2014). The name Horse Flat appears as a geographic term for the locality at the foot of the northeastern end of Taieri Ridge in the topographical overprint on the geological map of Mutch (1963). Although the name Horse Flat does not appear on modern topographic maps, the road through that area is still called Horse Flat Road. It is likely that the fault takes its name either from the former geographic locality, or from the road name.

More recently, in a study assessing seismic hazards in respect of the Macraes gold mine, Litchfield et al. (2005) applied the name Taieri Ridge Fault, and that same name is used in the NZAFM (Litchfield et al. 2013, 2014), and also in the NSHM (Stirling et al. 2012). The only targeted investigation of this fault (Norris & Nicolls 2004) did not apply any name to the fault but rather referred to it as the fault associated with the uplift of Taieri Ridge. Because there is no discussion or justification offered for applying a different name to the fault, in this report I prefer to use the original name of Horse Flat Fault, for reasons of precedence, notably that being how it is identified in the QMAP geological map dataset. Consideration should be given to applying the name Horse Flat Fault in future iterations of the NZAFM (Litchfield et al. 2014) and the NSHM (Stirling et al. 2012).

Basement rock here is Otago Schist, and structural features within the schist (foliation and lineation) suggest that the deformation that has brought about the uplift of Taieri Ridge has been predominantly by faulting without any notable major component of folding (S. Cox personal communication, 2015). In other words, Taieri Ridge can be interpreted to be primarily a fault block rather than a faulted anticline. Norris & Nicolls (2004; e.g. their Figure. 5.2.17 and 5.2.18) inferred the presence of an eroded anticline near the southeastern foot of Taieri Ridge but this is not particularly convincing given the wide variety of schistosity attitudes presented on the maps in their report, and which form the necessary basis for interpreting the presence of folds within the schist.

Norris & Nicolls (2004) reported on field investigations and OSL dating undertaken to try and establish the degree of activity of the fault. These investigations were of a reconnaissance nature, and done as part of a wider investigation of active faults in central and eastern Otago. OSL dating was carried out at two locations, one near Horse Flat Road about 5 km northwest of the Macraes Flat village and the other near Sheehy Road, about 8 km west of the Macraes Flat village. The geological interpretation of these sites in regard to the recognition of deformation is not particularly convincing, in my opinion. Part of the difficulty is that the work is only lightly illustrated and documented for example by a photograph of an exposure accompanied by a schematic interpretive sketch rather than by detailed maps and logs. At Horse Flat Road (approximate location 45° 20.802'S, 170° 23.589'E), OSL sample WLL326 (Norris & Nicolls 2004; their Figure 5.2.12) is from a lens of mud that is interpreted to be faulted against overturned cover rock strata (Hogburn Formation). A difficulty is that the interpreted fault dips to the northwest and is also downthrown to the northwest, but the caption says that it is associated with a 5 m high topographic step that is up to the northwest rather than down. What can be observed in the photo in the report, illustrating this site, is not incompatible with it being lenses of stream sediment that were deposited against irregular topography developed on the cover rock strata. The age of this sample (9,930 ± 1900 years) does not necessarily constrain a deformation event if the arrangement of the sediments is of depositional origin rather than deformational origin. The other sample obtained at Horse Flat Road (WLL 327; 7,140 ± 650 years) is from stream sediments that are interpreted to be folded within a small syncline, a few metres across (Norris & Nicolls 2004; their Figure 5.2.13). However, there is nothing in the photo illustration that would appear to count against the sediments having been deposited as some sort of channel fill and thus their arrangement may be a feature of original deposition rather than subsequent deformation.

At Sheehy Road, (Norris & Nicolls 2004; their Figure 5.2.21), there is an exposure of fluvial gravel overlain by what was described as lacustrine mud which was dated using OSL (approximate location 45° 23.407'S, 170° 19.822'E). The OSL age of 12,900 ± 1100 years is interpreted to provide a maximum age for the tectonic elevation, by 8 m, of those lacustrine deposits relative to correlative deposits out in the valley floor. The context to this is that the valley floor southeast of Taieri Ridge, at the locality called Moonlight Flat, is the site of a natural freshwater lake whose presence is attested to by shoreline deposits and wave-cut cliffs, as well as lacustrine sediments. Although the lake had drained by natural processes prior to European documentation, its geomorphological expression remains strong.

Unfortunately, Norris & Nicolls (2004) did not provide a detailed illustration or documentation of the sediments from which the OSL sample was collected, and it is difficult to assess the strength of the interpretation that the sediments are correlative of the lacustrine deposits out in the valley floor. For example, is it possible that they are muddy sediments deposited within a pond developed within the stream valley at that location?

Another point emphasised by Norris & Nicolls (2004) is the widespread occurrence of what they regarded as tilted fluvial terraces on the lower flanks of the Taieri Ridge escarpment. It is not clear from their documentation as to whether the fluvial sediments are associated with valley-parallel water flow and deposition, or whether they are alluvial fan sediments. If they are the former, then tilt of the terrace surfaces would be more convincingly argued. In my opinion, the idea is an interesting one but would really require additional data and more thorough documentation in order to be more convincing.

While the work documented by Norris & Nicolls (2004) is an important contribution, further evaluation would seem to be necessary in order to confirm or otherwise of the rates of tectonic deformation that they interpreted for Taieri Ridge. They stated an uplift rate of 0.62 mm/yr, but if considering the younger and older bounds of their OSL date (11,800 to 14,000 years), the uplift rate lies in the range of 0.57 to 0.68 mm/yr. For example, their interpretation of 8 m of vertical deformation within no more than the past 14,000 years is difficult to reconcile with the fact that there are no convincingly expressed fault scarps. The surrounding landscape is relatively mature and rates of geomorphological processes (uplift or erosion) would seem to be relatively slow. For example, if the rates of erosion were high then much more voluminous alluvial fan deposits ought to be present, especially as there is only limited capability for transporting sedimentary detritus from the valley on the southeast side of Taieri Ridge, because the drainage is by way of relatively minor streams rather than a major river. In landscape contexts such as this, recent tectonic deformation either by faulting or folding, of the order of 8 m in 14,000 years, ought to be noticeable in the landforms. The lack of compelling evidence for anticlinal folding associated with Taieri Ridge observed within the schist structure does call into question whether the substantial tilts suggested for some of the geomorphic surfaces ('terraces') are simply alluvial fan or slope colluvial landforms still disposed at the slope on which they were originally formed. If these landforms really are tilted, of the order of several degrees over distances of hundreds of metres over time frames as short as 10,000 years or so, then folding of that nature ought to be abundantly evident within the rock strata and its associated structure. Considering another aspect, at Horse Flat Road, Norris & Nicolls (2004) illustrate overturned cover rock strata at the foot of the range and it would be hard to account for this if the dominant tectonic process is near-surface folding rather than fault rupture. Taking the scenario, as the evidence overall would tend to favour, that Taieri Ridge has attained its elevation primarily as a result of fault rupture and displacement with only subordinate folding, it is hard to imagine that it has reverted in recent geological times to a regime where faulting has ceased to daylight at the ground surface and instead given way to near-surface folding.

In my opinion, the estimate of deformation associated with the Horse Flat Fault (uplift rate of 0.62 mm/yr) may well be an overestimate. If it were deemed important in the future to establish the level of activity of this structure, great benefit would arise from it being subjected to a more comprehensive investigation than was possible within the scope of reconnaissance studies documented by Norris & Nicolls (2004).

In the NZAFM, Litchfield et al. (2013, 2014) characterised the fault as being 35 km long with a reverse sense of displacement, a dip angle range of between 30 and 60° (45° best estimate), and net slip rate within a large range of 0.12 to 1.26 mm/yr with a preferred value of 0.71 mm/yr. Litchfield et al. (2013) state that the slip rate range is based on consideration of the inferred offset lake deposits (Norris & Nicolls 2004) as well as estimates based on the offset of the Otago Peneplain, although they do not explain what age value was used for the latter estimate, or what the preferred estimate is based upon. In the NSHM, Stirling et al. (2012) employed a dip angle of 45° and assigned a net slip rate of 0.25 mm/yr, a net single-event displacement of 2.4 m and a recurrence interval of 9,750 years. The origin of this slip rate is documented in the report by Litchfield et al. (2005), wherein they state that they regard the 0.62 mm/yr uplift rate defined by Norris & Nicolls (2004) as a maximum value, and they chose to divide that value in two, and apply that halved amount in equal parts to their Taieri Ridge Fault, and to the newly-named Billys Ridge Fault (see next section). Their presumption was that because the two faults are parallel and typically about 3 km apart, they probably merge at depth. Although it is not clear why the Norris & Nicolls (2004) rate was regarded as a maximum value, the justification for dividing an estimate obtained for one fault in half, and applying that halved estimate to two faults is not clear to me. In any case, the Litchfield et al. (2005) report assigned a maximum slip rate of 0.31 mm/yr to both the Taieri Ridge Fault and the Billys Ridge Fault, and for each fault gave a preferred vertical slip rate of 0.25 mm/yr. This explains the values used by Stirling et al. (2012) in the NSHM, but it does not explain why much larger maximum and preferred values were used in the NZAFM by Litchfield et al. (2013, 2014).

Based on the discussion above relating to concerns about the robustness of the geological interpretations, it is far from convincing that the slip rates assigned to the Horse Flat Fault/Taieri Ridge Fault are well founded. On the contrary, if the slip rate is more than ~0.5 mm/yr, as inferred by Norris & Nicolls (2004) and Litchfield et al. (2013, 2014), and the recurrence interval for surface-deforming earthquakes more frequent than 10,000 years, then I consider that there should be more obvious sign of landforms related to fault rupture evident on this landscape. It is noteworthy that the vertical slip rate of 0.25 mm/yr applied by Litchfield et al. (2005) and Stirling et al. (2012) implies a recurrence interval that is relatively long, and more commensurate with geomorphological evidence. Because Litchfield et al. (2005) and Stirling et al. (2012) did not directly use slip rate derived by Norris & Nicolls (2004), it implies at least partial non-acceptance of the Norris & Nicolls (2004) interpretation of 8 m uplift in no more than the past 14,000 years on the Horse Flat Fault. The reason for the apparent discrepancy between the landform evidence (no well-defined fault scarp) and the Norris & Nicolls (2004) interpretation of 8 m uplift in the geologically recent past remains elusive. It may be that the dating in this case is an unreliable indicator of the age of deposition of the sediments, or perhaps the sedimentary interpretation (correlation to lake sediments in the valley) is incorrect. Alternatively, perhaps the rates of landscape change (scarp modification) in that area are unexpectedly large. For the purposes of this report, a recurrence interval of greater than 10,000 years is tentatively inferred, based primarily on geomorphological considerations.

Given all of these considerations, the Horse Range Fault is provisionally identified in this dataset as a ‘possible’, ‘not expressed’ active fault, pending the future collection, should it be deemed desirable, of more data pertaining to the activity of the fault.

An evaluation should be undertaken as to whether adequate justification exists for continuing to include the Horse Flat Fault (aka Taieri Ridge Fault) in future iterations of the NZAFM and NSHM.

A2.31 BILLYS RIDGE FAULT (FEATURE 28, FIGURE 5.2; SEE FIGURE A2.17)

This fault is mapped along the southeastern foot of Billys Ridge, which lies approximately parallel to and about 3 km east of Taieri Ridge. Billys Ridge is very similar to Taieri Ridge, but has a slightly smaller vertical offset of the Otago Peneplain, up to the northwest, of no more than about 200 m. The fault was shown on the geological maps of Mutch (1963) and Forsyth (2001), though was not named. Forsyth (2001) showed continuity between the Billys Ridge Fault and the Macraes Fault to the northeast. Litchfield et al. (2005) erected the name Billys Ridge Fault, and suggested three scenarios for the length of the fault, one being the topographic length of the Billys Ridge landform (22 km), and other options being 31 and 38 km if the fault is extended to include part or all of the Macraes Fault. There has been no specific investigation of the Billys Ridge Fault and there is no direct evidence for any Late Quaternary offset of any landform features or deposits. As discussed above in relation to the Horse Flat Fault, the inference that the Billys Ridge Fault is active is based on the interpretation of activity on the Horse Flat Fault. Litchfield et al. (2005) applied the same characterisation to the Horse Flat Fault and the Billys Ridge Fault, with a dip range of between 30 and 60° and a preferred value of 45°, and vertical slip rate in the range of 0.05 to 0.31 mm/yr with a preferred value of 0.25 mm/yr. The preferred value was employed by Stirling et al. (2012), along with an assigned length of 34 km, to calculate a single-event displacement of 2.4 m and recurrence interval of 9,470 years. In contrast, Litchfield et al. (2013, 2014) assigned a net slip rate in the range of 0 to 1 mm/yr with a preferred value of

0.5 mm/yr. No explanation was given for these values, though it is worth noting that the minimum value equates to the fault being inactive.

As noted in the following section in relation to the Macraes Fault, there is some reasonably persuasive geological evidence against the Macraes Fault being active, and certainly there is good reason to limit the length of the Billys Ridge Fault to just be the approximately 22 km that defines its topographic expression. In the absence of any positive indications of landform offsets or other deformational evidence, there is no direct basis for identifying the Billys Ridge Fault as active. However, because it is included within the NZAFM and the NSHM, it is retained in this dataset as a 'possible', 'not expressed' active fault. For the purposes of this report a recurrence interval of >10,000 years is adopted, to highlight that if it is in fact an active fault, its level of activity is very low, based on geomorphological considerations.

An evaluation should be undertaken as to whether adequate justification exists for continuing to include the Billys Ridge Fault in future iterations of the NZAFM and NSHM. Present information suggests that it probably would be better removed from those datasets.

A2.32 Macraes Fault (feature 29, Figure 5.2; see Figure A2.15, Figure A2.16)

This northeast-southwest striking fault is very well delineated in the subsurface close the Macraes gold mine, because it has offset the zone of gold-bearing mineralisation and the offset has been intensively characterised by closely-spaced drilling. The fault has a moderate to steep dip towards the northwest and is upthrown to the northwest. The data can be rationalised as supporting pure reverse movement without any necessity for a strike slip component. The fault itself comprises a zone of fractures and, whether by step-displacement or simply by buckling, there is what amounts to an element of drag in both the hanging wall and the foot wall. Total offset of the mineralised zone (known as the Hyde-Macraes Shear Zone; HMSZ), which dips gently towards the northeast, is approximately 150 m (S. Cox, personal communication, 2015).

There is a topographic step, up to the northwest, at about the location of the Macraes Fault, that is at most about 70 m high. In other words, the topographic expression of the fault is no more than about half of the total offset on the Mesozoic-age HMSZ. Immediately to the west of Macraes Flat village, cover rock strata (Hogburn Formation, of Eocene age) lie across the projected line of the Macraes Fault, with no indication of relative displacement. Because these strata rest on the Otago Peneplain, it raises the question of whether the reverse fault deformation associated with the Macraes Fault pre-dates the peneplain, and the apparent topographic expression of the fault may simply be the product of differential erosion on the downthrown side of a pre-existing fault within bedrock. This would account for the geological offset being larger than the topographic expression, which is evident for only about 4 km of the length of the fault.

Craw & Chappell (1999) investigated a deposit of alluvial/loessial sediment southeast of the Macraes Fault, and obtained an uncorrected radiocarbon age of 28,000 ± 600 years BP from near the base of an ~5 m thick deposit of sediments. They attributed the source of the sediment to erosion from a nearby 'active' fault, meaning the Macraes Fault, but did not provide any evidence for it being active.

In order to place limits on the activity of the Macraes Fault in relation to a then-proposed tailings dam at Tipperary Creek (now constructed), a paleoseismological investigation was carried out by Golder Associates (Ltd) in 2010, at locations about 4 km northeast of Macraes Flat village (Golder Associates 2011), with peer review by GNS Science, which involved site inspection of trenches as well as report review (Barrell & Van Dissen 2011). Full exposure down to schist bedrock was obtained across the entire Macraes Fault zone, and there was no indication of any deformation of the overlying colluvial sediments and loess. As the loess in eastern Otago is regarded as having accumulated during glacial periods, with the most recent glacial episode having ended about 11,500 years ago, it was interpreted to a high degree of confidence that there has been no surface deformation associated with rupture of the Macraes Fault for at least the past 11,500 years.

Overall, there is a considerable question-mark as to whether the Macraes Fault has had any Late Cenozoic activity, as evidenced by Eocene-age cover strata overlying the fault without any indications of deformation. This was underscored by Forsyth (2001) mapping the Macraes Fault west of Macraes Flat as 'concealed' under the Eocene strata. While for engineering purposes, it was desirable to investigate the fault close to the tailings dam, with very conservative assumptions, the most direct geological evidence (no displacement of Eocene strata) suggests that the fault is most likely inactive. A special case could be made that perhaps there was earlier phase of normal movement, which has more recently been corrected by reverse movement that has fortuitously returned the Eocene strata either side of the fault into contact with one another. Perhaps other explanations could also be advanced. But for this report, it is judged likely that there is no continuity between the Billys Ridge Fault and the Macraes Fault, and accordingly a 3.5 m long sector of the Macraes Fault connecting with the Billys Ridge Fault, as shown in the QMAP dataset, has been removed from the present dataset. The Macraes Fault is classed as 'possible', 'not expressed', and a recurrence interval of >11,500 years is applied. In future iterations of the NZAFM and NSHM, consideration should be given to restricting the Billys Ridge Fault to the length of its topographic expression (~22 km), and removing the Macraes Fault component of the modelled Billys Ridge Fault. Also note the comments in the previous subsection regarding the Billys Ridge Fault, as to whether there is sufficient justification for retaining the Billys Ridge Fault in those datasets.

A2.33 APPENDIX 2 REFERENCES

Amos, C.B.; Burbank, D.W.; Nobes, D.C.; Read, S.A.L. 2007. Geomorphic constraints on listric thrust faulting: Implications for active deformation in the Mackenzie Basin, South Island, New Zealand. Journal of Geophysical Research 112: B03S11.

Amos, C.B.; Burbank, D.W.; Read, S.A.L. 2010. Along-strike growth of the Ostler fault, New Zealand, and consequences for drainage deflection above a non-propagating thrust. Tectonics 29(4): TC4021.

Amos, C.B.; Lapwood, J.J.; Nobes, D.C.; Burbank, D.W.; Rieser, U.; Wade, A. 2011. Palaeoseismic constraints on Holocene surface ruptures along the Ostler Fault, southern New Zealand. New Zealand Journal of Geology and Geophysics 54: 367-378.

Barrell, D.J.A. 2010. Assessment of active fault and fold hazards in the Twizel area, Mackenzie District, South Canterbury. GNS Science Consultancy Report 2010/040; Environment Canterbury Report No R10/25. 22 p.

Barrell, D.J.A. 2016. General distribution and characteristics of active faults and folds in the Timaru District, South Canterbury. GNS Science Consultancy Report 2014/308, Environment Canterbury Report No. R15/112. 49 p.

Barrell, D.J.A.; Cox, S.C. 2003. Southern Alps tectonics and Quaternary geology. Field Trip 6 ¬In Geological Society of NZ Annual Conference 2003: Field Trip Guides. Geological Society of New Zealand Miscellaneous Publication 116B. May be downloaded from www.gsnz.org.nz

Barrell, D.J.A.; Van Dissen, R.J. 2003. Project Aqua Geotechnical Investigations: Activity of geological faults in the lower Waitaki Valley. Institute of Geological & Nuclear Sciences Client Report 2003/107. Prepared for URS (NZ) Limited. 43 p.

Barrell, D.J.A.; Van Dissen, R.J. 2006a. Seismic loads on dams - Waitaki system: Kirkliston Fault mapping. GNS Science Consultancy Report 2006/75. Prepared for URS (NZ) Limited. 21 p. + Figure, maps, photos.

Barrell, D.J.A.; Van Dissen, R.J. 2006b. Seismic loads on dams - Waitaki system: Mapping of Padkins Fault, Kirkliston Fault Zone. GNS Science Letter Report 2006/242LR. Prepared for URS (NZ) Limited. 6 p. + 1 fig and 6 photos. Presented as Appendix A of Barrell et al. (2008).

Barrell, D.J.A.; Van Dissen, R.J. 2011. Review of Golder Associates (NZ) Ltd Report 1078301051: “Top Tipperary TSF: Active fault hazard assessment”. Electronic file: 1078301051-R100E.pdf, supplied by Golder Associates, 21 February 2011. GNS Science Consultancy Report 2011/04LR. Prepared for Oceana Gold (New Zealand) Limited. 2 p.

Barrell, D.J.A.; Van Dissen, R.J.; Berryman, K.R.; Read, S.A.L.; Wood, P.R.; Zachariasen, J.; Lukovic, B.; Nicol, A.; Litchfield, N.J. 2002. Seismic loads on dams - Waitaki system: Aviemore Power Station - Geological investigations for fault displacement characterisation. Institute of Geological & Nuclear Sciences Client Report 2001/125. Prepared for URS (NZ) Limited. 2 volumes. v.1: 99 p. + Figure and photos; v.2: appendices A-E.

Barrell, D.J.A.; Langridge, R.M.; Berryman, K.R.; Lukovic, B. 2004. Seismic loads on dams - Waitaki system: Dryburgh - Stonewall fault displacement characterisation. Institute of Geological & Nuclear Sciences Client Report 2004/56. Prepared for URS (NZ) Limited. 47 p. + maps and figures.

Barrell, D.J.A.; Langridge, R.M.; Litchfield, N.J.; Fraser, H.L.; Lukovic, B. 2005. Seismic loads on dams - Waitaki system: Dryburgh Fault displacement characterisation. Institute of Geological & Nuclear Sciences Client Report 2005/70. Prepared for URS (NZ) Limited. 64 p.

Barrell, D.J.A.; Berryman, K.R.; Mejia, L.; Macfarlane, D.F.; Read, S.A.L.; Van Dissen, R.J.; Walker, J. 2006. Fault displacement evaluation at Aviemore Dam, South Island, New Zealand. In: Proceedings New Zealand Geotechnical Society Symposium “Earthquakes and Urban Development”: 37-50.

Barrell, D.J.A.; Van Dissen, R.J.; Langridge, R.M.; Cox, S.C.; Wilson, K.J.; Rieser, U.; Lukovic, B. 2008. Seismic loads on dams - Waitaki system: Kirkliston Fault displacement characterisation. GNS Science Consultancy Report 2007/146. Prepared for URS (NZ) Limited. 26 p. + photos, Figure, and appendices.

Barrell, D.J.A.; Read, S.A.L.; Van Dissen, R.J.; Macfarlane, D.F.; Walker, J.; Rieser, U. 2009. Aviemore – a dam of two halves. Field Trip 6 In Geological Society of New Zealand and Geophysical Society of New Zealand Joint Annual Conference 2009: Field Trip Guides. Geological Society of New Zealand Miscellaneous Publication 128B. 30 p. Can be downloaded from www.gsnz.org.nz

Beanland, S. (compiler) 1987. Field guide to sites of active earth deformation: South Island, New Zealand. New Zealand Geological Survey Record 19.

Berryman, K.R.; Webb, T.H.; Hill, N.; Stirling, M.W.; Rhoades, D.A.; Beavan, R.J.; Darby, D.J. 2002. Seismic loads on dams - Waitaki System: Earthquake source characterisation. Institute of Geological & Nuclear Sciences Client Report 2001/129. 80 p., + appendices.

Bishop, D.G. 1976. Sheet S126 - Mt Ida. Geological Map of New Zealand 1:63,360. Wellington, Department of Scientific and Industrial Research. 1 folded map and booklet (22 p.).

Blick, G.H.; Read, S.A.L.; Hall, P.T. 1989. Deformation monitoring of the Ostler Fault Zone. Tectonophysics 167: 329-339.

Campbell F.M.; Kaiser, A.; Horstmeyer H.; Green, A.G.; Ghisetti, F.; Gorman, A.R.; Finnemore, M.; Nobes, D.C. 2010a. Processing and preliminary interpretation of noisy high-resolution seismic reflection/refraction data across the active Ostler Fault zone, South Island, New Zealand. Journal of Applied Geophysics 70: 332–342.

Campbell, F.M.; Ghisetti, F.; Kaiser, A.E.; Green, A.G.; Horstmeyer, H.; Gorman, A.R. 2010b. Structure and evolution of the seismically active Ostler Fault Zone (New Zealand) based on interpretations of multiple high resolution seismic reflection profiles. Tectonophysics 495(3-4): 195-212.

Cox, S.C.; Barrell, D.J.A. (compilers) 2007. Geology of the Aoraki area. Institute of Geological and Nuclear Sciences 1:250,000 Geological Map 15. 71 p. + 1 folded map.

Cox, S.C.; Stirling, M.W.; Herman, F.; Gerstenberger, M.; Ristau, J. 2012. Potentially active faults in the rapidly eroding landscape adjacent to the Alpine Fault, central Southern Alps, New Zealand. Tectonics, 31: TC2011. 24 p.

Craw, D.; Chappell, D.A. 1999. Evolution and sulphide mineral occurrences of an incipient nonmarine sedimentary basin, New Zealand. Sedimentary Geology 129: 37-50.

Curran, C.; Norris, R.J. 2009. The Waihemo Fault System, North Otago. In: Turnbull, I.M. (ed.). Field Trip Guides, Geosciences 09 Conference, Oamaru, New Zealand. Geological Society of New Zealand Miscellaneous Publication 128B. 27 p. Can be downloaded from www.gsnz.org.nz

Curran, C.; Norris, R.; Rieser, U. 2011. The Waihemo Fault of north Otago: constraints on late Quaternary activity. In: Litchfield, N.J.; Clark, K. (eds). Abstract volume, Geosciences 2011 Conference, Nelson, New Zealand. Geoscience Society of New Zealand Miscellaneous Publication 130A, p. 29.

Davis, K.; Burbank, D.W.; Fisher, D.; Wallace, S.; Nobes, D. 2005. Thrust-fault growth and segment linkage in the active Ostler fault zone, New Zealand. Journal of Structural Geology 27: 1528-1546.

Forsyth, P.J. (compiler) 2001. Geology of the Waitaki area. Institute of Geological and Nuclear Sciences 1:250 000 Geological Map 19. 64 p. + 1 folded map.

Forsyth 2001. QMAP Waitaki – unpublished 1:50,000-scale data record sheets. Available to inspection or download from the GNS Science Database Catalogue. www.gns.cri.nz, search term < Database catalogue >. Enter QMAP 19 Waitaki into the Catalogue search bar.

Gage, M. 1957: The Geology of the Waitaki Subdivision. New Zealand Geological Survey Bulletin 55. Wellington, Department of Scientific and Industrial Research.

Gair, H.S. 1967. Sheet 20 - Mt Cook. Geological Map of New Zealand 1:250 000. Wellington, Department of Scientific and Industrial Research. Map and notes (1 sheet).

Gair, H.S.; Gregg, D.R. 1960. Relation of Kakanui schist to Kaihikuan sedimentary rocks at Mt St Mary, North Otago. New Zealand Journal of Geology and Geophysics 3: 618-625.

Ghisetti, F.C.; Gorman, A.R.; Sibson, R.H. 2007. Surface breakthrough of a basement fault by repeated seismic slip episodes: The Ostler Fault, South Island, New Zealand. Tectonics 26: TC6004.

Golder Associates 2011. Top Tipperary TSF: Active fault hazard assessment. Golder Associates (NZ) Ltd Report 1078301051-R100E, dated 21 February 2011. Prepared for Oceana Gold (New Zealand) Limited. 21 p. plus appendices.

Heron, D.W. (custodian) 2014. Geological map of New Zealand 1:250,000. GNS Science Geological Map 1. 1 CD

Landis, C.A.; Campbell, H.J.; Begg, J.G.; Mildenhall, D.C.; Paterson, A.M.; Trewick, S.A. 2008. The Waipounamu erosion surface: questioning the antiquity of the New Zealand land surface and terrestrial fauna and flora. Geological Magazine 145: 173-197.

Langridge, R.M.; Reis, W.; Litchfield, N.J.; Villamor, P.; Van Dissen, R.J.; Barrell, D.J.A.; Rattenbury, M.S.; Heron, D.W.; Haubrock, S.; Townsend, D.B.; Lee, J.M.; Berryman, K.R.; Nicol, A.; Cox, S.C.; Stirling, M.W. 2016. The New Zealand Active Faults Database. New Zealand Journal of Geology and Geophysics 59: 86-96.

Lindqvist, J. 1997. Quaternary sequence stratigraphy, Katiki Beach, Otago. In: Skinner, D.N.B. (ed). Programme and Abstracts, 1997 Annual Conference of the Geological Society of New Zealand, Wellington, New Zealand. Geological Society of New Zealand Miscellaneous Publication 95A, p. 102.

Litchfield, N.J.; McVerry, G.H.; Smith, W.D.; Berryman, K.R.; Stirling, M.W. 2005. Seismic hazard study for tailings embankments at Macraes gold project. Institute of Geological & Nuclear Sciences Client Report 2005/135. Prepared for Oceana Gold Limited. 75 p.

Litchfield, N.J.; Van Dissen, R.J.; Sutherland, R.; Barnes, P.M.; Cox, S.C.; Norris, R.J.; Beavan, R.J.; Langridge, R.M.; Villamor, P.; Berryman, K.R.; Stirling, M.W.; Nicol, A.; Nodder, S.D.; Lamarche, G.; Barrell, D.J.A.; Pettinga, J.R.; Little, T.A.; Pondard, N.; Clark, K.J. 2013. A model of active faulting in New Zealand: fault zone parameter descriptions. GNS Science Report 2012/19. 120 p.

Litchfield, N.J.; Van Dissen, R.J.; Sutherland, R.; Barnes, P.M.; Cox, S.C.; Norris, R.; Beavan, R.J.; Langridge, R.M.; Villamor, P.; Berryman, K.R.; Stirling, M.W.; Nicol, A.; Nodder, S.; Lamarche, G.; Barrell, D.J.A.; Pettinga, J.R.; Little, T.; Pondard, N.; Mountjoy, J.J.; Clark, K.J. 2014. A model of active faulting in New Zealand. New Zealand Journal of Geology and Geophysics 57: 32–56.

Macfarlane, D.F. 1980. Lower Waitaki Power Investigations: Geological conditions, Black Point to the Pacific coast. New Zealand Geological Survey Engineering Geology Report EG 344.

Macfarlane, D.F. 1988. Lower Waitaki power investigations: Summary and assessment of engineering geological investigations up to December 1987. New Zealand Geological Survey Engineering Geology Report EG 406.

Macfarlane, D.F. 1989. Lower Waitaki Power Investigations: Summary and assessment of additional engineering geological investigations: December 1987 – April 1989. New Zealand Geological Survey Engineering Geology Immediate Report EGI 89/035.

Mansergh, G.D. 1973. Summary of geological investigations in the Lower Waitaki River. New Zealand Geological Survey Engineering Geology Report EG 161.

Marshall, P. 1915. Cainozoic fossils from Oamaru. Transactions and Proceedings of the New Zealand Institute 47: 377-387.

Marwick, J. 1935. The geology of the Wharekuri Basin, Waitaki Valley. New Zealand Journal of Science and Technology 16: 321-338.

Mutch, A.R. 1963. Sheet 23 - Oamaru. Geological map of New Zealand, 1:250 000. Wellington, Department of Scientific and Industrial Research.

McClymont, A.F.; Green, A.G.; Villamor, P.; Horstmeyer, H.; Grass, C.; Nobes, D.C. 2008. Characterization of the shallow structures of active fault zones using 3-D ground-penetrating radar data. Journal of Geophysical Research 113: B10315.

Norris, R.J.; Nicolls, R. 2004. Strain accumulation and episodicity of fault movement in Otago. EQC Research Report 01/445, also identified as EQC Research Paper 3710 (downloadable from www.eqc.govt.nz). 146 p.

Putnam, A.E.; Schaefer, J.M.; Denton, G.H.; Barrell, D.J.A.; Birkel, S.D.; Andersen, B.G.; Kaplan, M.R.; Finkel, R.C.; Schwartz, R.; Doughty, A.M. 2013. The Last Glacial Maximum at 44°S documented by a 10Be moraine chronology at Lake Ohau, Southern Alps of New Zealand. Quaternary Science Reviews 62: 114-141.

Rattenbury, M.S.; Jongens, R.; Cox, S.C. (compilers) 2010. Geology of the Haast area. Institute of Geological and Nuclear Sciences 1:250,000 Geological Map 14. 58 p. + 1 folded map.

Retallack, G.J.; Reyburn, R.J. 1982. Middle Triassic deltaic deposits in Long Gully, near Otematata, north Otago, New Zealand. Journal of the Royal Society of New Zealand 12: 207-220.

Read, S.A.L. 1984. The Ostler Fault Zone. In P.R. Wood (compiler): Guidebook to the South Island Scientific Excursions (Part 2: Greymouth to Christchurch). International Symposium on Recent Crustal Movements of the Pacific Region (Wellington, NZ, February 1984). Royal Society of New Zealand Miscellaneous Series 9: 121-134.

Read, S.A.L.; Blick, G.H. 1991. Late Quaternary deformation and geodetic monitoring in the area of `The Knot' on the Ostler Fault Zone, South Island, New Zealand. p. 85-91 IN: Officers of DSIR Geology and Geophysics 1991. Research Notes 1990. New Zealand Geological Survey 43.

Read, S.A.L.; Dellow, G.D.; Barrell, D.J.A. 1995. Waitaki Power Station: Review of geological and foundation data. Institute of Geological and Nuclear Sciences client report 353911.01. Prepared for Electricity Corporation of New Zealand. 52 p. + figures and appendices.

Read, S.A.L.; Barrell, D.J.A.; McIntosh, P.D. 1998. Mid-Waitaki power stations: Correlation of Quaternary alluvial terraces in the Waitaki Valley. Institute of Geological & Nuclear Sciences Client Report 43626B.11. Prepared for Electricity Corporation of New Zealand. 58 p. + figures.

Stirling, M.; McVerry, G.; Gerstenberger, M.; Litchfield, N.; Van Dissen, R.; Berryman, K.; Barnes, P.; Wallace, L.; Bradley, B.; Villamor, P.; Langridge, R.; Lamarche, G.; Nodder, S.; Reyners, M.; Rhoades, D.; Smith, W.; Nicol, A.; Pettinga, J.; Clark, K.; Jacobs, K. 2012. National seismic hazard model for New Zealand: 2010 update. Bulletin of the Seismological Society of America 102: 1514–1542.

Turnbull, I.M. (compiler) 2000. Geology of the Wakatipu area. Institute of Geological and Nuclear Sciences 1:250,000 Geological Map 18. 72 p. + 1 folded map.

Teagle, D.A.H.; Moore, J.G. 1986. Preliminary gravity survey of the Kurow area, Lower Waitaki valley. New Zealand Geological Survey Engineering Geology Immediate Report EGI 86/013.

Uttley, G.H., 1920a. Tertiary geology of the area between the Otiake River and Duntroon, North Otago. Transactions and Proceedings of the New Zealand Institute 52: 137-153.

Uttley, G.H. 1920b. Tertiary geology of the area between Wharekuri and the Otiake River, North Otago. Transactions and Proceedings of the New Zealand Institute 52: 154-168.

Van Dissen, R.J. 1996. Aviemore Power Station: seismotectonic hazard analysis. Institute of Geological & Nuclear Sciences Client Report 35505-B.10. Prepared for Works Consultancy Services Ltd. 23 p. + 11 figures.

Van Dissen, R.J.; Hull, A.G.; Read, S.A.L. 1993. Timing of some large Holocene earthquakes on the Ostler Fault, New Zealand. p. 381-386 In: Proceedings of the Eighth International Symposium on Recent Crustal Movements (CRCM '93), Kobe, December 6-11, 1993.

Wallace, S. C.; Nobes, D.C.; Davis, K.J.; Burbank, D.W.; White, A. 2010. Three-dimensional GPR imaging of the Benmore anticline and step-over of the Ostler Fault, South Island, New Zealand. Geophysical Journal International 180: 465-474.

Wood, P.R.; Barrell, D.J.A.; Read, S.A.L. 1998. Mid-Waitaki power stations: characteristics of active faults for refining earthquake hazards. Institute of Geological & Nuclear Sciences client report 44780B.10. Prepared for Electricity Corporation of New Zealand. 121 p. + 5 appendices.

Woodward, D.J.; Mumme, T.C. 1989. Gravity survey to locate faulting in the Lower Waitaki valley near Duntroon. DSIR Geophysics Division Contract Report No.92.

Woodward, D.J.; Stagpoole, V.; Graham, D. 2003. Project Aqua geotechnical investigations: Gravity survey of the Lower Waitaki valley to locate geological faults. Institute of Geological and Nuclear Sciences client report 2003/106. Prepared for URS (NZ) Limited. 24 p.

Yetton, M.D. 2008. Hunters Hills Fault Zone Study - Earthquake Hazard Assessment. Environment Canterbury Report: UO8/27.

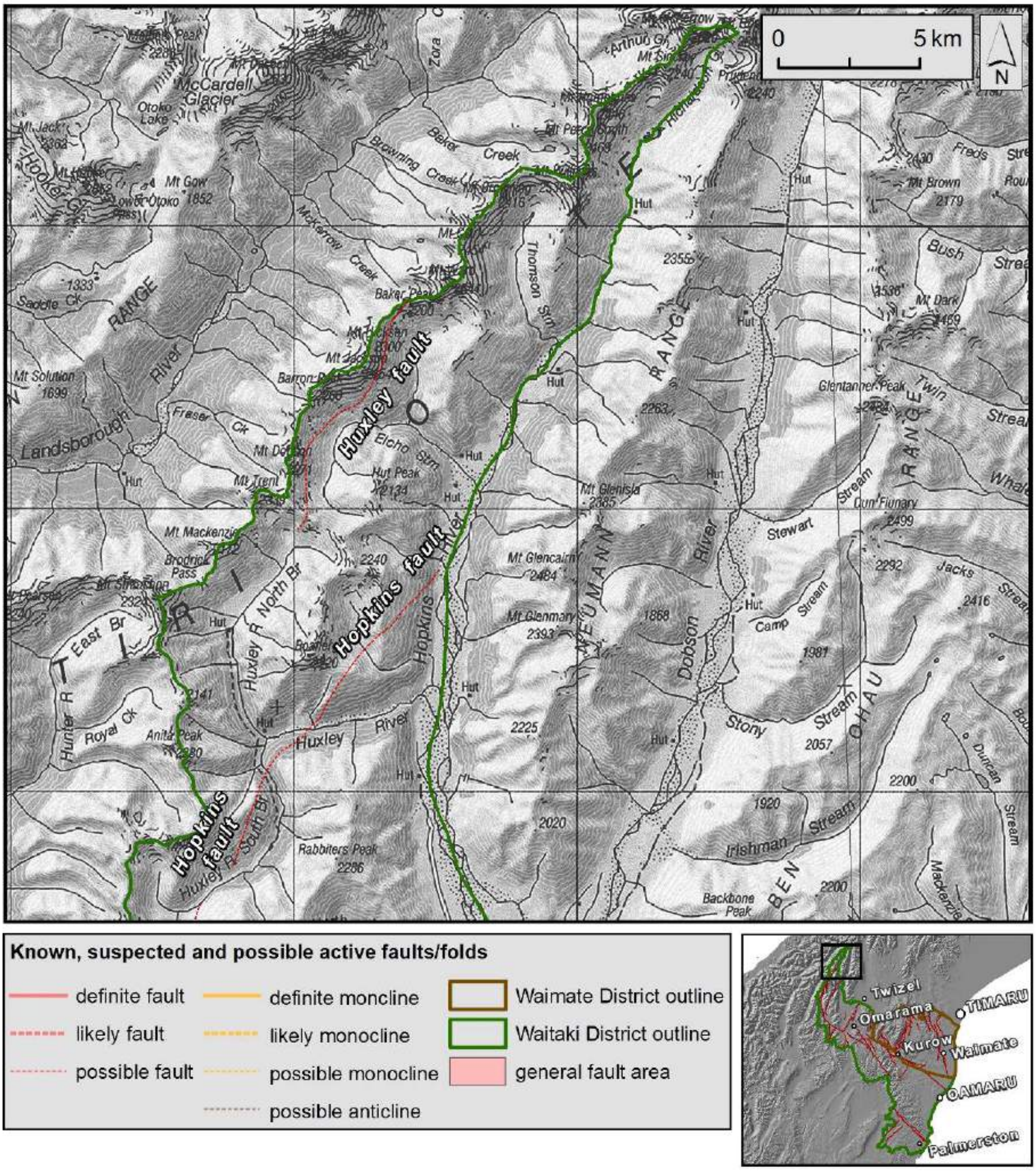

Figure A2.1 The active faults of the northern sector of the Waitaki District, in the headwaters of the Lake Ohau catchment. The background image is a greyscale version of topographic map Topo250 (Land Information NZ, Crown Copyright reserved). The map area is shown in the context of the Waimate and Waitaki districts in the index map at lower right. In Figure 5.1, Figure **5.2** and Appendix 2 text, Huxley fault is feature 1a, Hopkins fault is feature 1b.

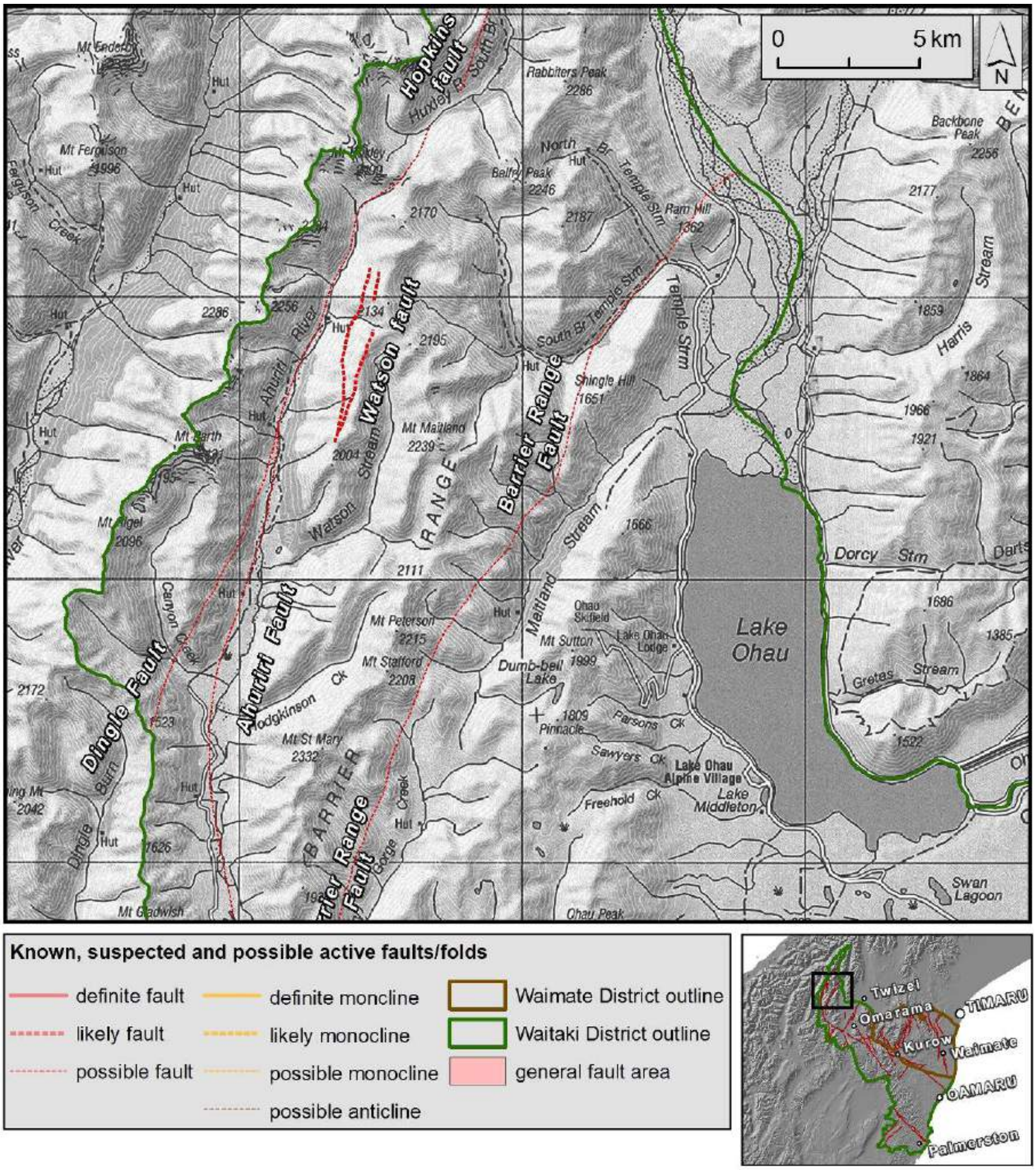

Figure A2.2 The active faults of the northern sector of the Waitaki District, in the headwaters of the Ahuriri River and Lake Ohau catchments. The background image is a greyscale version of topographic map Topo250 (Land Information NZ, Crown Copyright reserved). The map area is shown in the context of the Waimate and Waitaki districts in the index map at lower right. In Figure 5.1, Figure **5.2** and Appendix 2 text, Hopkins fault is feature 1b, Dingle Fault is feature1c, Ahuriri Fault is feature 1d, Barrier Range Fault is feature 1e, and Watson fault is feature 2.

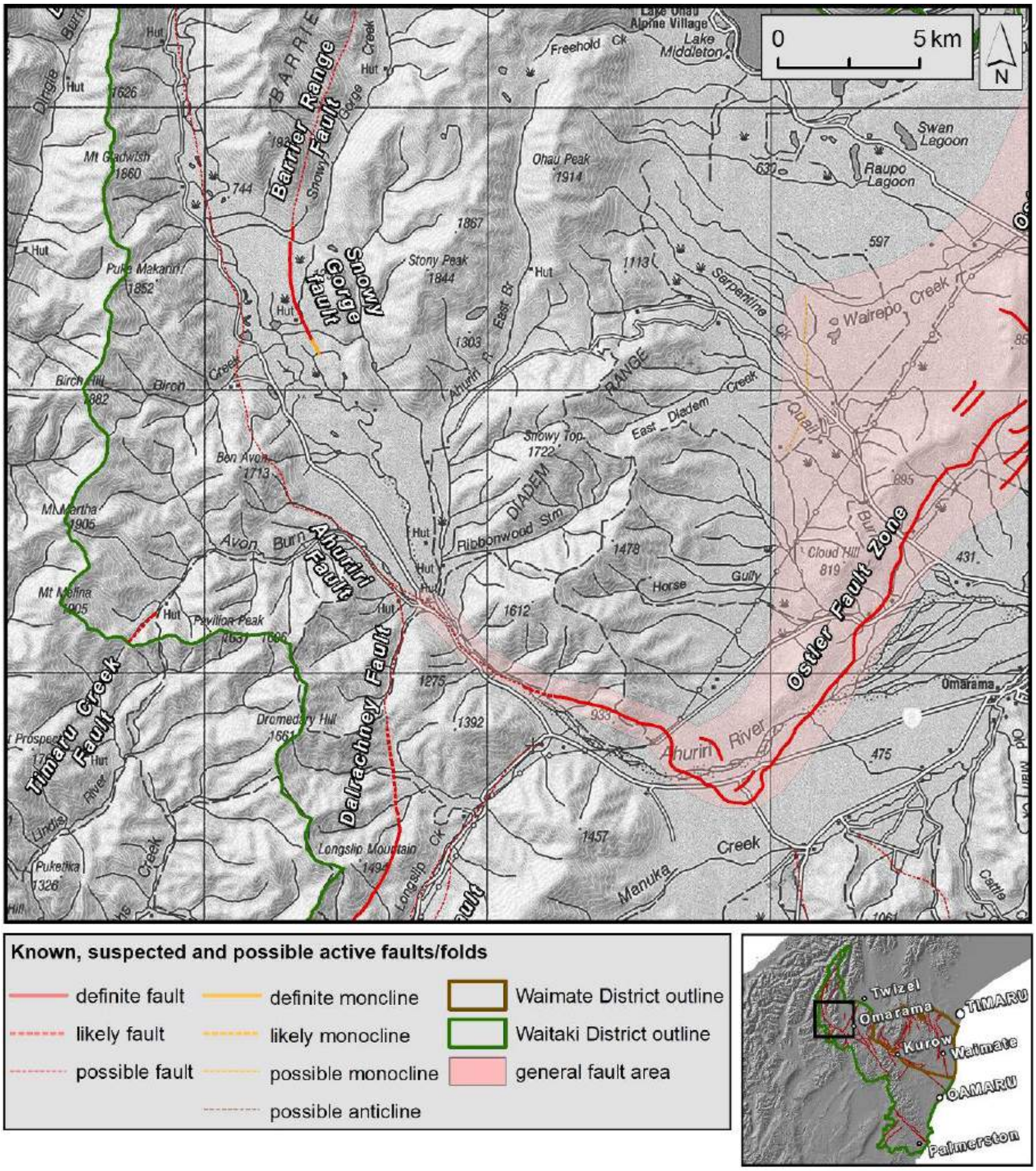

Figure A2.3 The active faults of the western sector of the Waitaki District, in the Ahuriri River catchment. The background image is a greyscale version of topographic map Topo250 (Land Information NZ, Crown Copyright reserved). The map area is shown in the context of the Waimate and Waitaki districts in the index map at lower right. In Figure 5.1, Figure **5.2** and Appendix 2 text, Ahuriri Fault is feature 1d, Barrier Range Fault is feature 1e, Snowy Gorge fault is feature 3 Timaru Creek Fault is feature 4, Dalrachney Fault is feature 5a and the Ostler Fault Zone is feature 6. The 'general fault area' is used purely for illustrative purposes to denote the spatial extent of components of a particular feature, and implies nothing about the location or extent of ground deformation hazards.

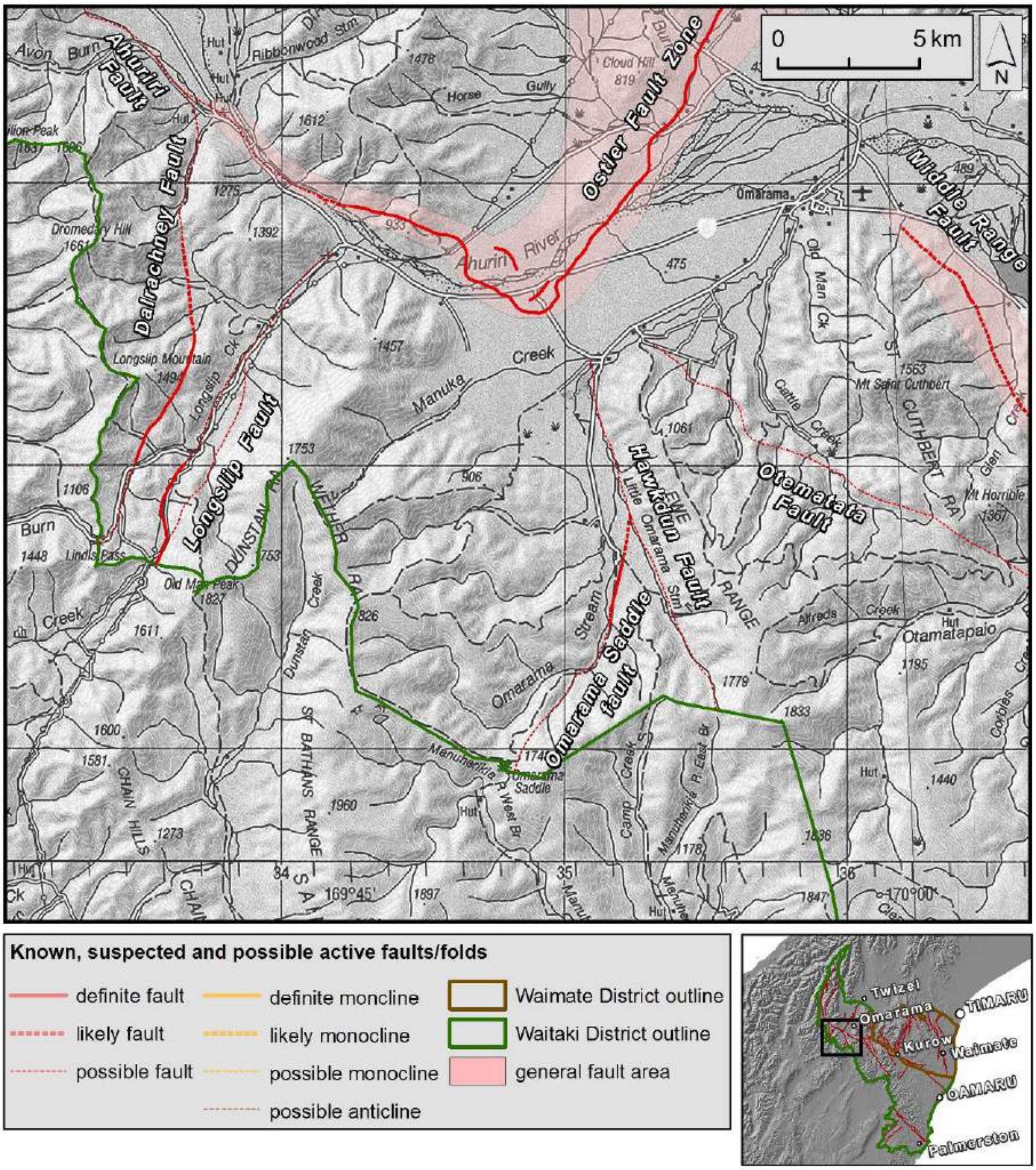

Figure A2.4 The active faults of the southwestern sector of the Waitaki District, in the Ahuriri River catchment and Lindis Pass area. The background image is a greyscale version of topographic map Topo250 (Land Information NZ, Crown Copyright reserved). The map area is shown in the context of the Waimate and Waitaki districts in the index map at lower right. In Figure 5.1, Figure **5.2** and/or Figure 5.3, and in Appendix 2 text, Ahuriri Fault is feature 1d, Dalrachney Fault is feature 5a, Longslip Fault is feature 5b, Ostler Fault Zone is feature 6, Omarama Saddle fault is feature 7, Hawkdun Fault is feature 8, Otematata Fault is feature 9, and Middle Range Fault is feature 12a. The 'general fault area' symbol is used purely for illustrative purposes to denote the spatial extent of components of a particular feature, and implies nothing about the location or extent of ground deformation hazards.

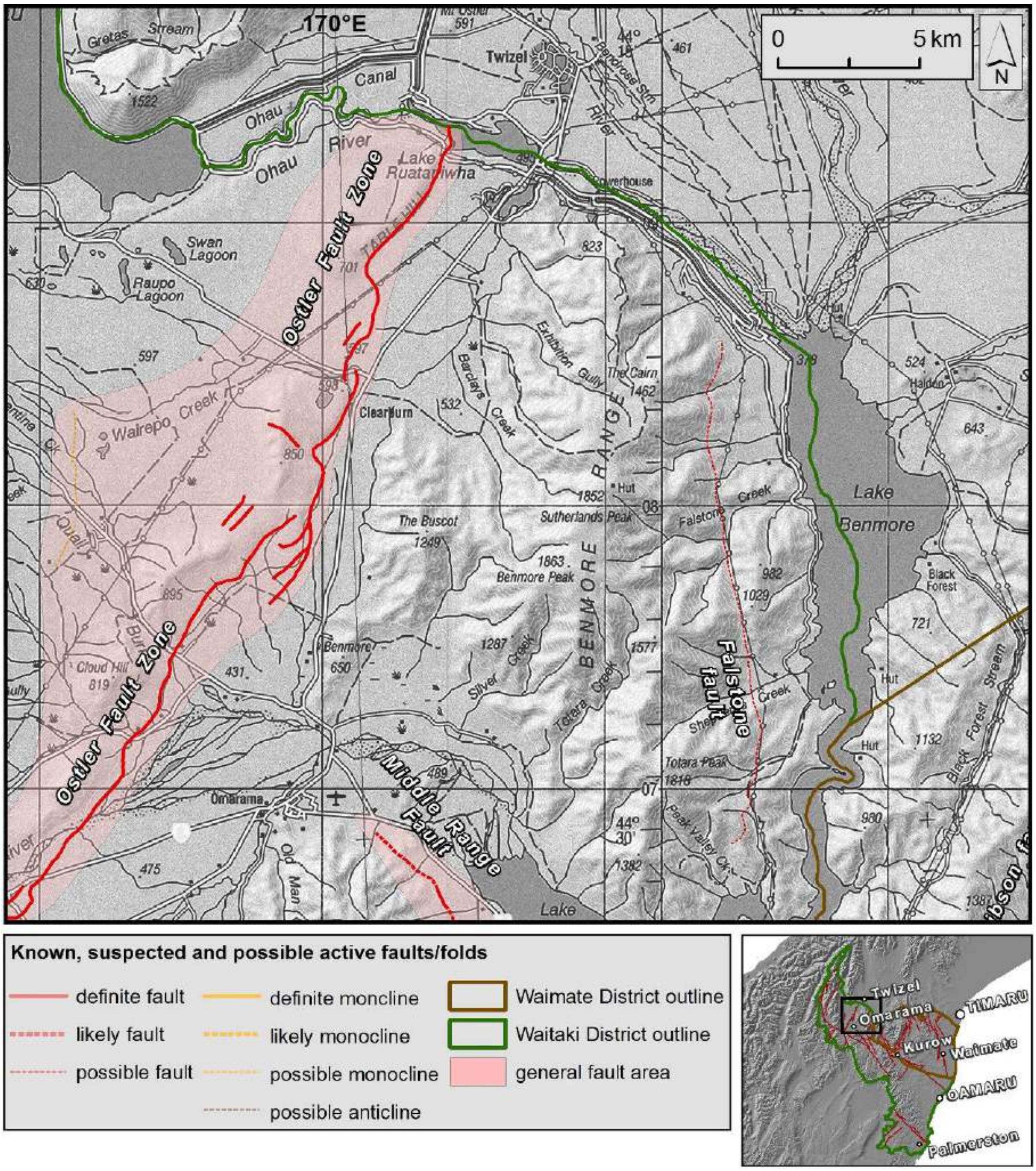

Figure A2.5 The active faults of the northern sector of the Waitaki District, in the Lake Ohau to Laker Benmore areas. The background image is a greyscale version of topographic map Topo250 (Land Information NZ, Crown Copyright reserved). The map area is shown in the context of the Waimate and Waitaki districts in the index map at lower right. In Figure 5.1, Figure **5.2** and/or Figure 5.3, and in Appendix 2 text, Ostler Fault Zone is feature 6, Falstone fault is feature 10, and Middle Range Fault is feature 12a. The 'general fault area' symbol is used purely for illustrative purposes to denote the spatial extent of components of a particular feature, and implies nothing about the location or extent of ground deformation hazards.

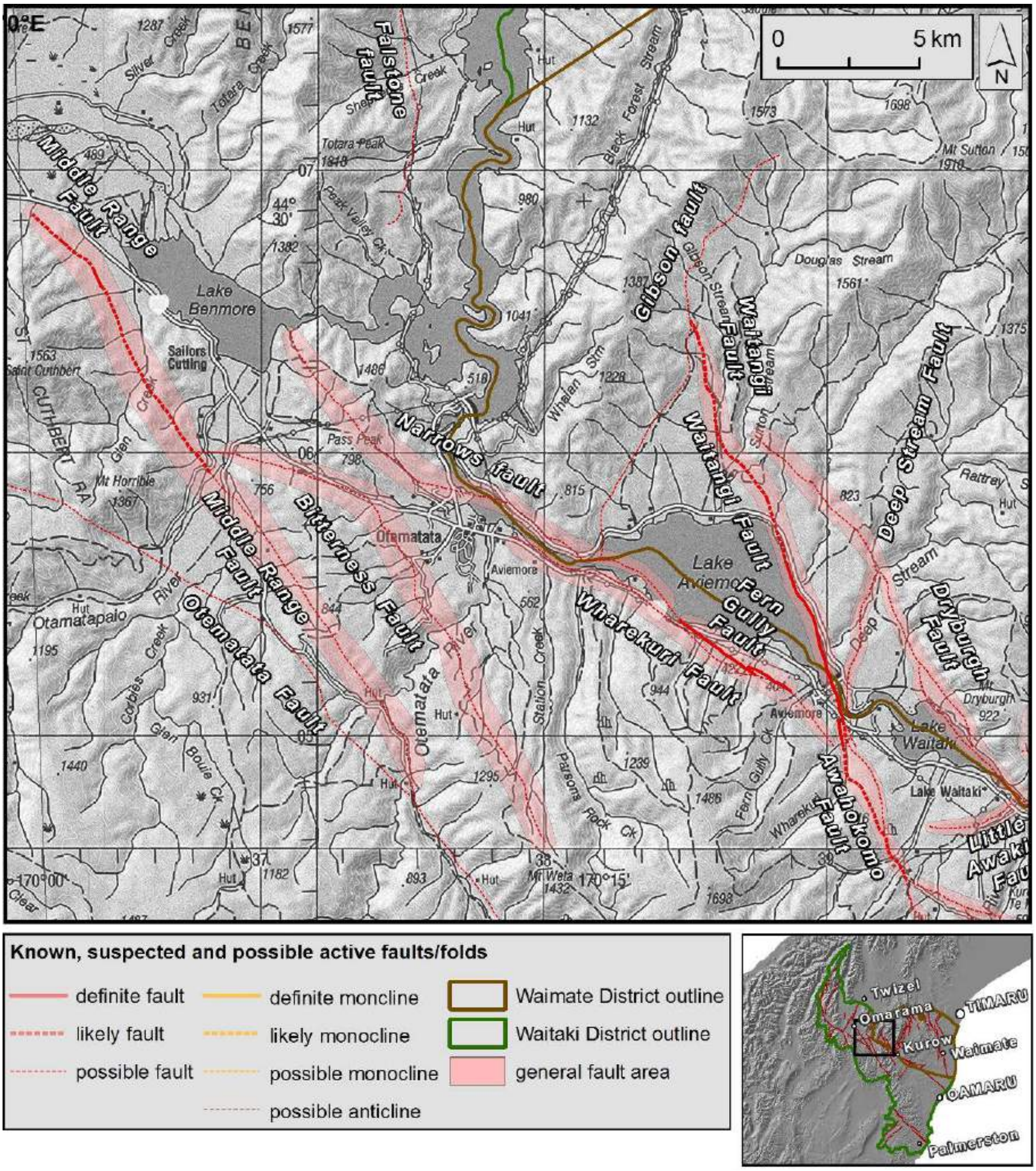

Figure A2.6 The active faults of the Waimate and Waitaki districts in the Lake Benmore to Lake Waitaki areas. The background image is a greyscale version of topographic map Topo250 (Land Information NZ, Crown Copyright reserved). The map area is shown in the context of the Waimate and Waitaki districts in the index map at lower right. In Figure 5.1, Figure **5.2** and/or Figure 5.3, and in Appendix 2 text, Otematata Fault is feature 9, Falstone fault is feature 10, Gibson fault is feature 11, Middle Range Fault is feature 12a, Bitterness Fault is feature 12b, Narrows fault is feature 12c, Wharekuri Fault is feature 12d, Fern Gully Fault is feature 12e, Waitangi Fault is feature 12f, Awahokomo Fault is feature 12g, Deep Stream Fault is feature 12h, Little Awakino Fault is feature 12i, and Dryburgh Fault is feature 12k. The 'general fault area' symbol is used purely for illustrative purposes to denote the spatial extent of components of a particular feature, and implies nothing about the location or extent of ground deformation hazards.

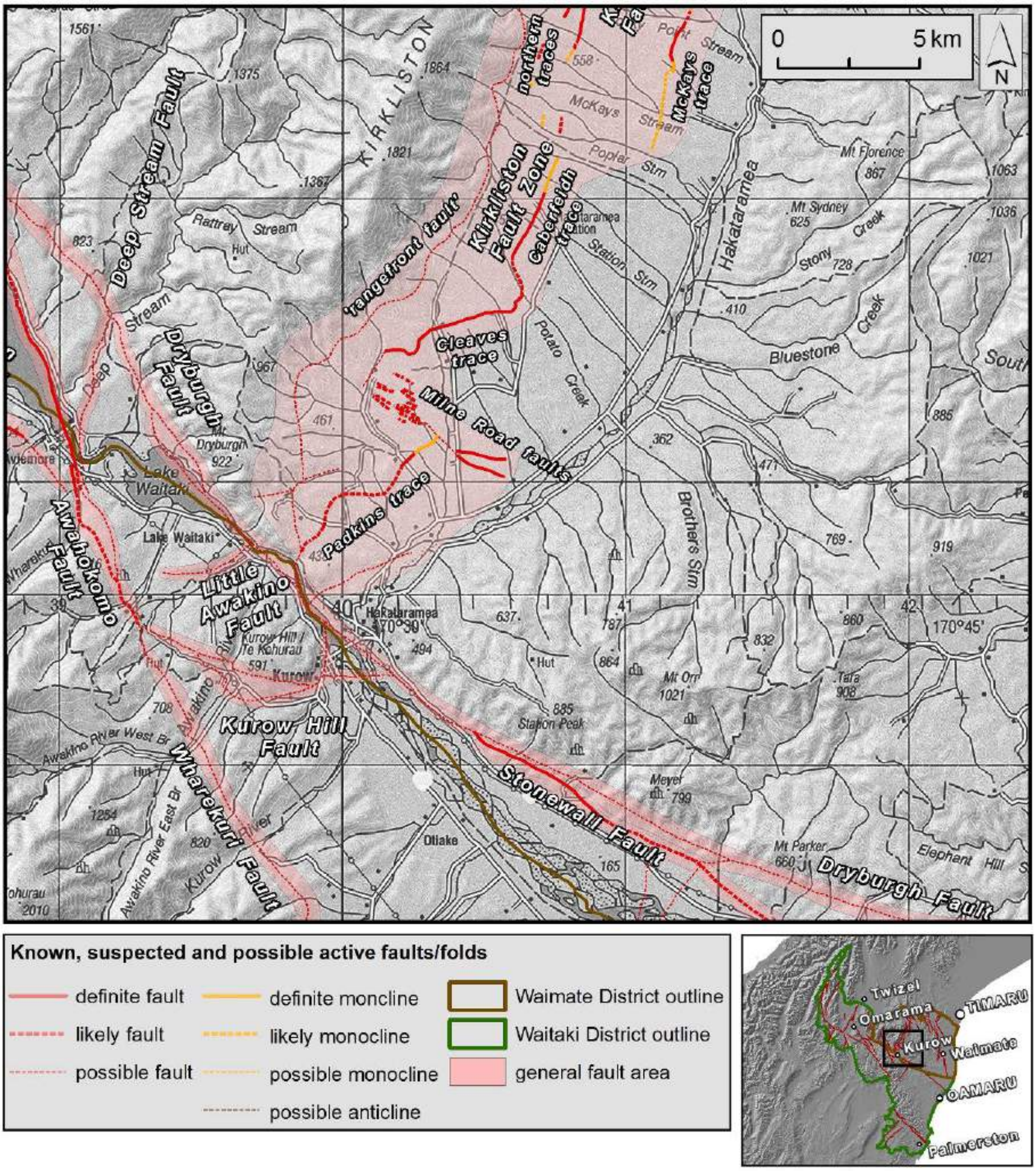

Figure A2.7 The active faults of the Waimate and Waitaki districts in the Kurow and lower Hakataramea valley areas. The background image is a greyscale version of topographic map Topo250 (Land Information NZ, Crown Copyright reserved). The map area is shown in the context of the Waimate and Waitaki districts in the index map at lower right. In Figure 5.1, Figure **5.2** and/or Figure 5.3, and in Appendix 2 text, Wharekuri Fault is feature 12d, Awahokomo Fault is feature 12g, Deep Stream Fault is feature 12h, Little Awakino Fault is feature 12i, Kurow Hill Fault is feature 12j, Dryburgh Fault is feature 12k, Stonewall Fault is feature 12l, and Kirkliston Fault Zone is feature 13. The 'general fault area' symbol is used purely for illustrative purposes to denote the spatial extent of components of a particular feature, and implies nothing about the location or extent of ground deformation hazards.

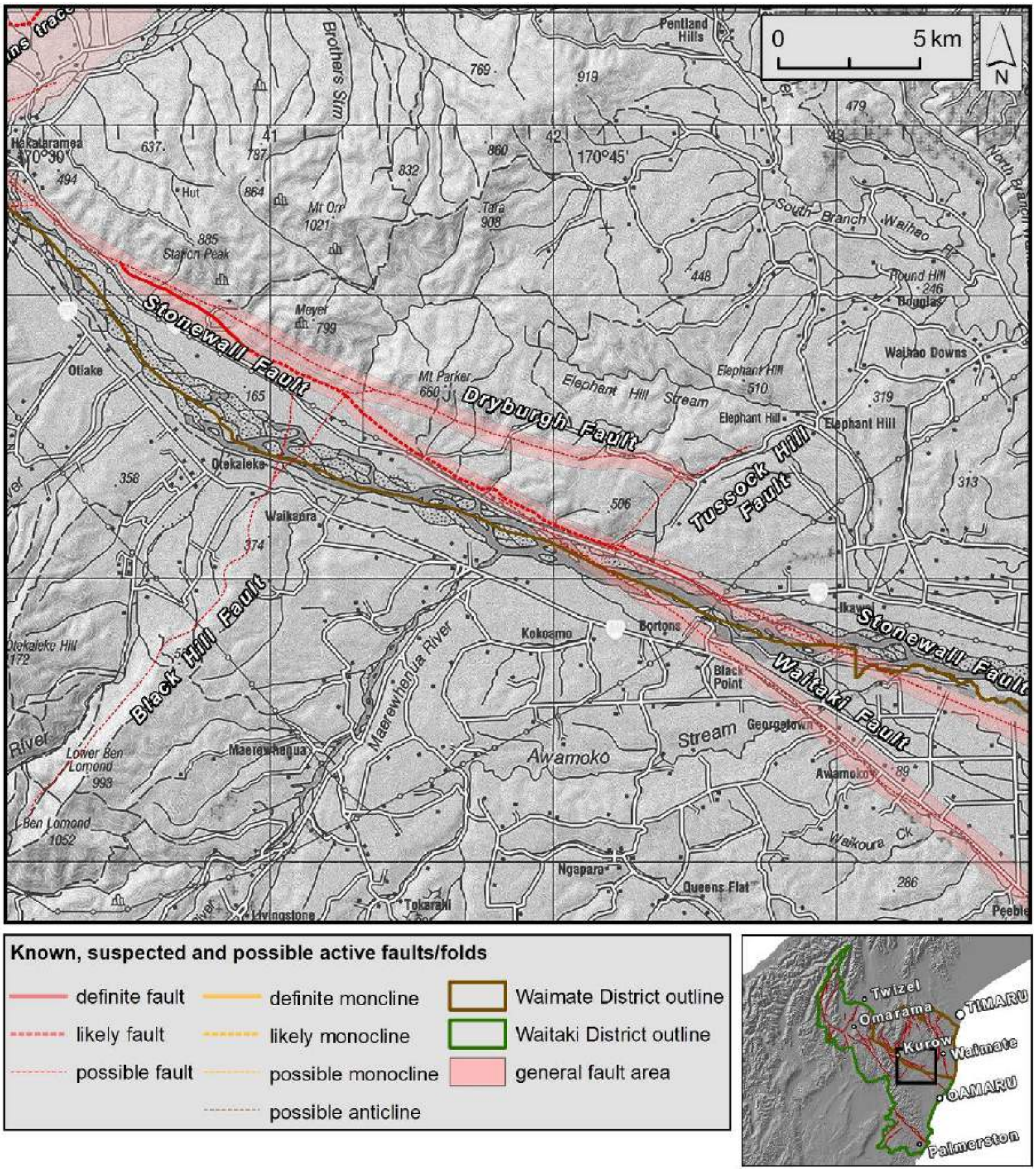

Figure A2.8 The active faults of the Waimate and Waitaki districts in the lower Waitaki valley area. The background image is a greyscale version of topographic map Topo250 (Land Information NZ, Crown Copyright reserved). The map area is shown in the context of the Waimate and Waitaki districts in the index map at lower right. In Figure 5.1, Figure **5.2** and/or Figure 5.3, and in Appendix 2 text, Dryburgh Fault is feature 12k, Stonewall Fault is feature 12l, Waitaki Fault is feature 12m, and the Black Hill Fault is feature 24. The Tussock Hill Fault is described in the section pertaining to the Dryburgh Fault. The 'general fault area' symbol is used purely for illustrative purposes to denote the spatial extent of components of a particular feature, and implies nothing about the location or extent of ground deformation hazards.

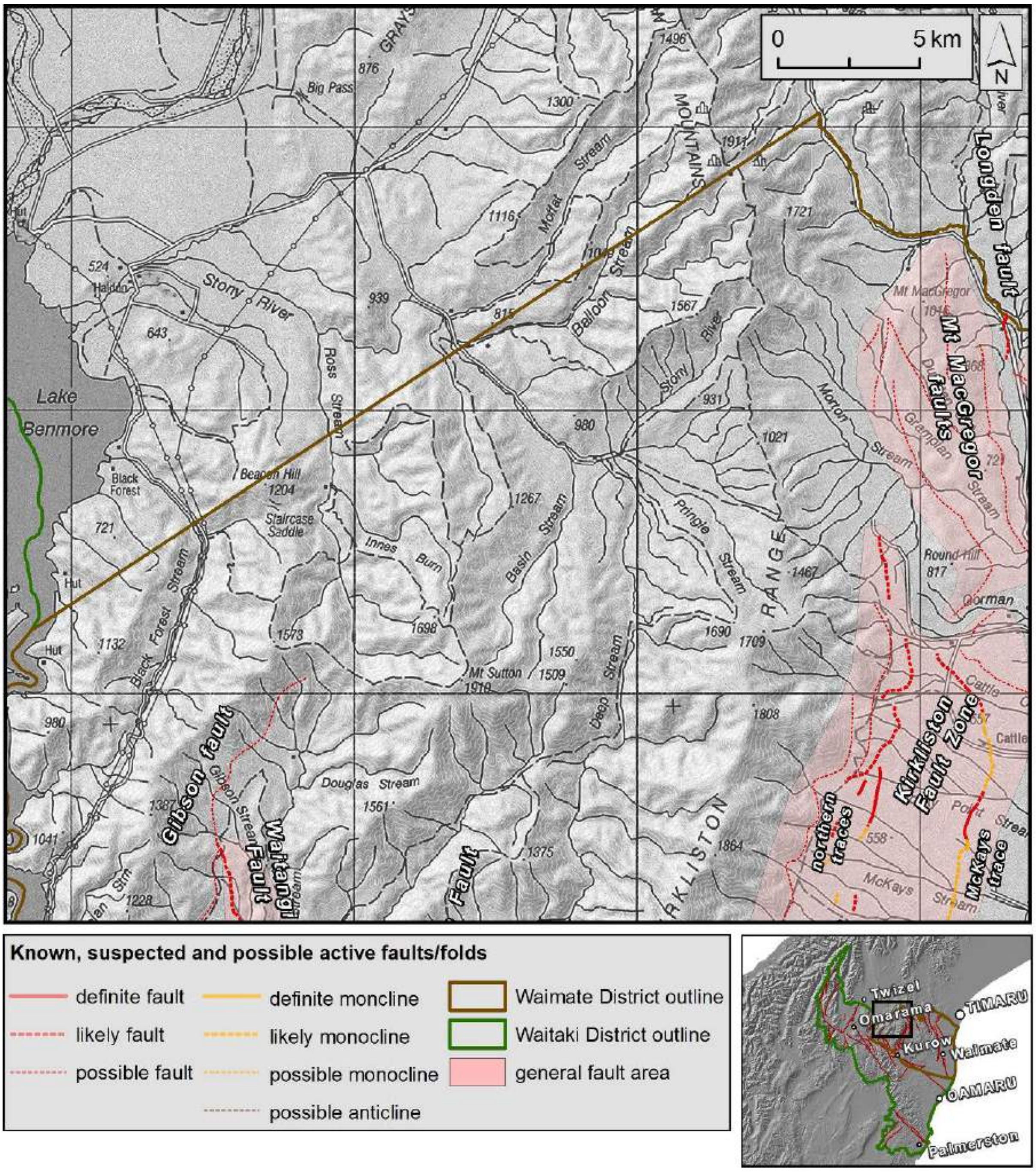

Figure A2.9 The active faults of the northern part of the Waimate District, including the upper part of the Hakataramea valley. The background image is a greyscale version of topographic map Topo250 (Land Information NZ, Crown Copyright reserved). The map area is shown in the context of the Waimate and Waitaki districts in the index map at lower right. In Figure 5.1, Figure **5.2** and/or Figure 5.3, and in Appendix 2 text, Gibson fault is feature 11, Waitangi Fault is feature 12f, Kirkliston Fault Zone is feature 13, Mt MacGregor faults are feature 14 ,and Longden fault is feature 15. The 'general fault area' symbol is used purely for illustrative purposes to denote the spatial extent of components of a particular feature, and implies nothing about the location or extent of ground deformation hazards.

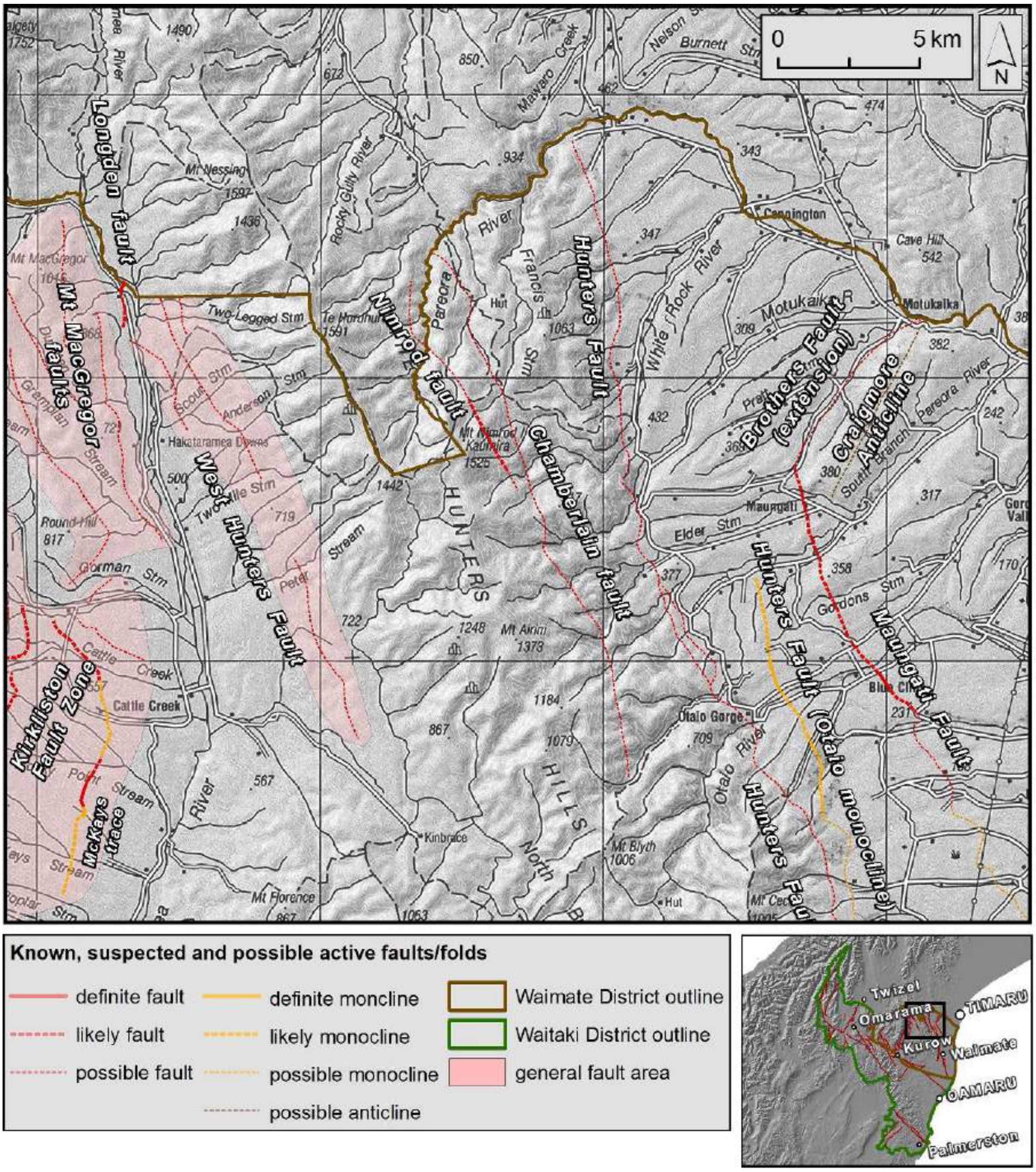

Figure A2.10 The active faults of the Waimate District in the northern part of the Hunters Hills and parts of the Hakataramea, Pareora and Otaio catchments. The background image is a greyscale version of topographic map Topo250 (Land Information NZ, Crown Copyright reserved). The map area is shown in the context of the Waimate and Waitaki districts in the index map at lower right. In Figure 5.1, Figure 5.2 and in Appendix 2 text, Kirkliston Fault Zone is feature 13, Mt MacGregor faults are feature 14, Longden fault is feature 15, West Hunters Fault is feature 16, Nimrod fault is feature 17, Chamberlain fault is feature 18, Hunters Fault is feature 19, Hunters Fault (Otaio monocline) is feature 20, Maungati Fault is feature 22, and the Brothers Fault (extension) and Craigmore Anticline are feature 23. The ‘general fault area’ symbol is used purely for illustrative purposes to denote the spatial extent of components of a particular feature, and implies nothing about the location or extent of ground deformation hazards.

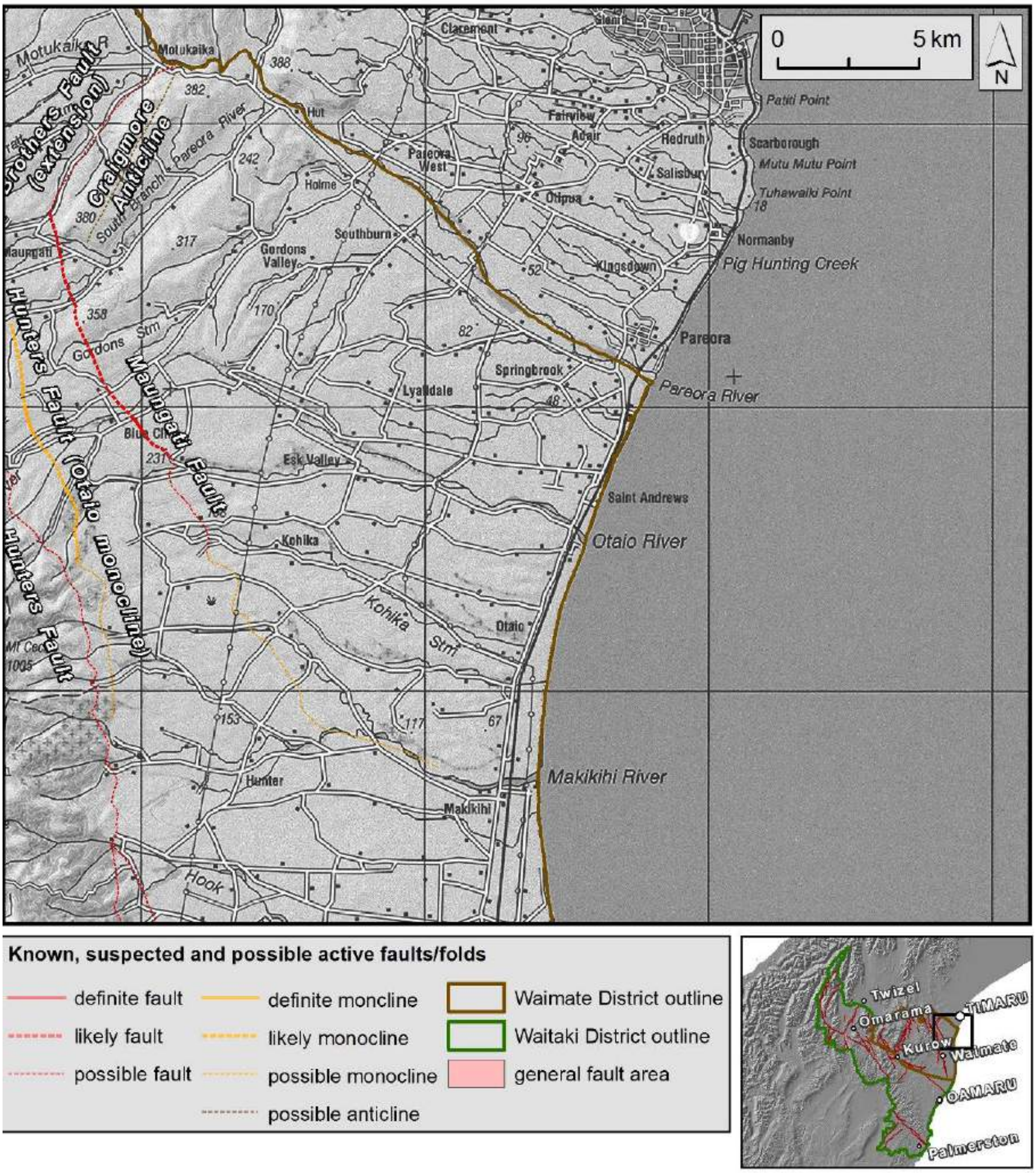

Figure A2.11 The active faults of the northeastern part of the Waimate District, including parts of the Pareora, Otaio and Makikihi catchments. The background image is a greyscale version of topographic map Topo250 (Land Information NZ, Crown Copyright reserved). The map area is shown in the context of the Waimate and Waitaki districts in the index map at lower right. In Figure 5.1, Figure 5.2 and in Appendix 2 text, Hunters Fault is feature 19, Hunters Fault (Otaio monocline) is feature 20, Maungati Fault is feature 22, and the Brothers Fault (extension) and Craigmore Anticline are feature 23.

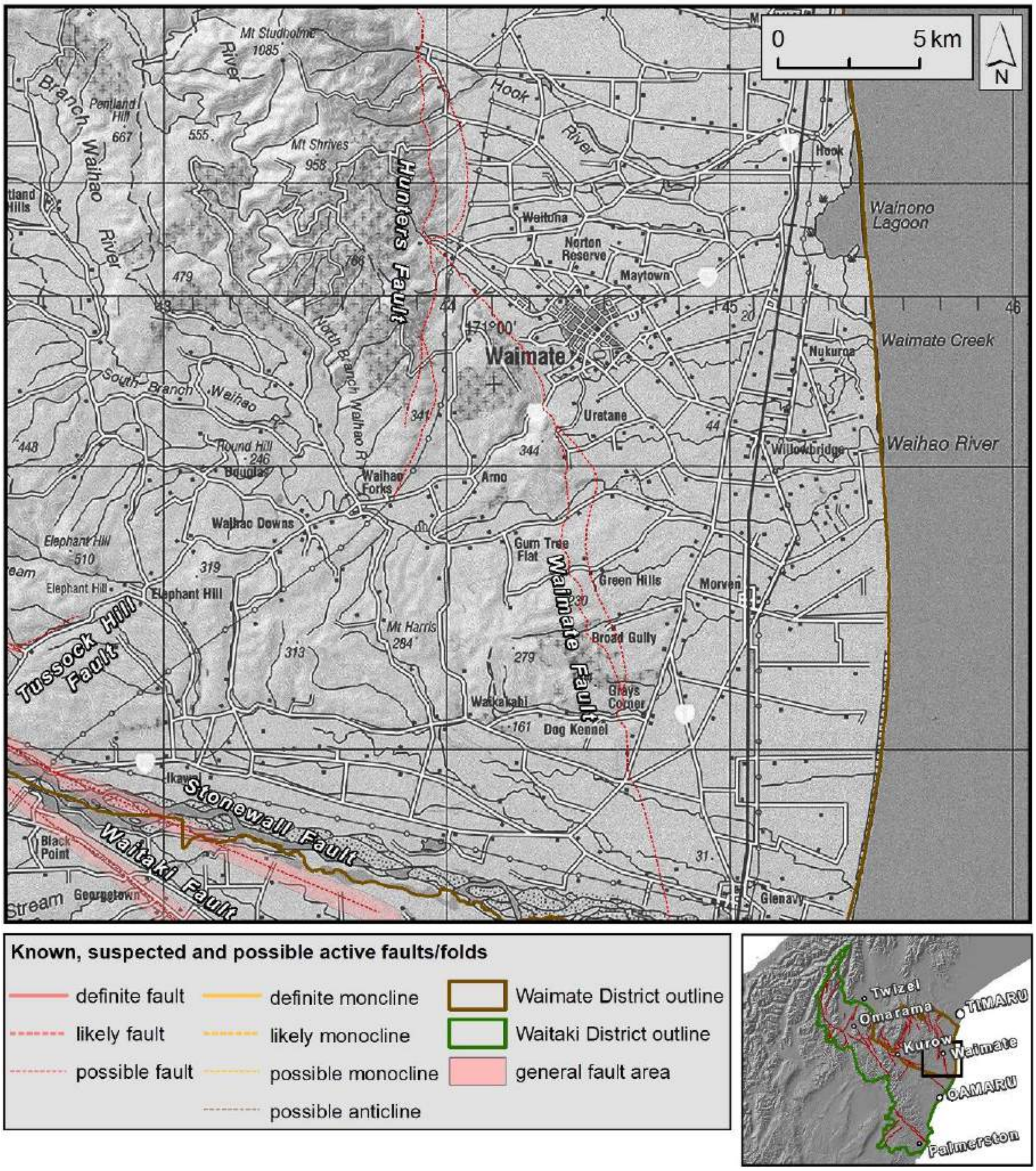

Figure A2.12 The active faults of the Waimate District in the Waimate to lower Waitaki areas. The background image is a greyscale version of topographic map Topo250 (Land Information NZ, Crown Copyright reserved). The map area is shown in the context of the Waimate and Waitaki districts in the index map at lower right. In Figure 5.1, Figure 5.2 and/or Figure 5.3, and in Appendix 2 text, Stonewall Fault is feature 12l, Waitaki Fault is feature 12m, Hunters Fault is feature 19, and Waimate Fault is feature 21. The Tussock Hill Fault is described in the section pertaining to the Dryburgh Fault (feature 12k). The 'general fault area' symbol is used purely for illustrative purposes to denote the spatial extent of components of a particular feature, and implies nothing about the location or extent of ground deformation hazards.

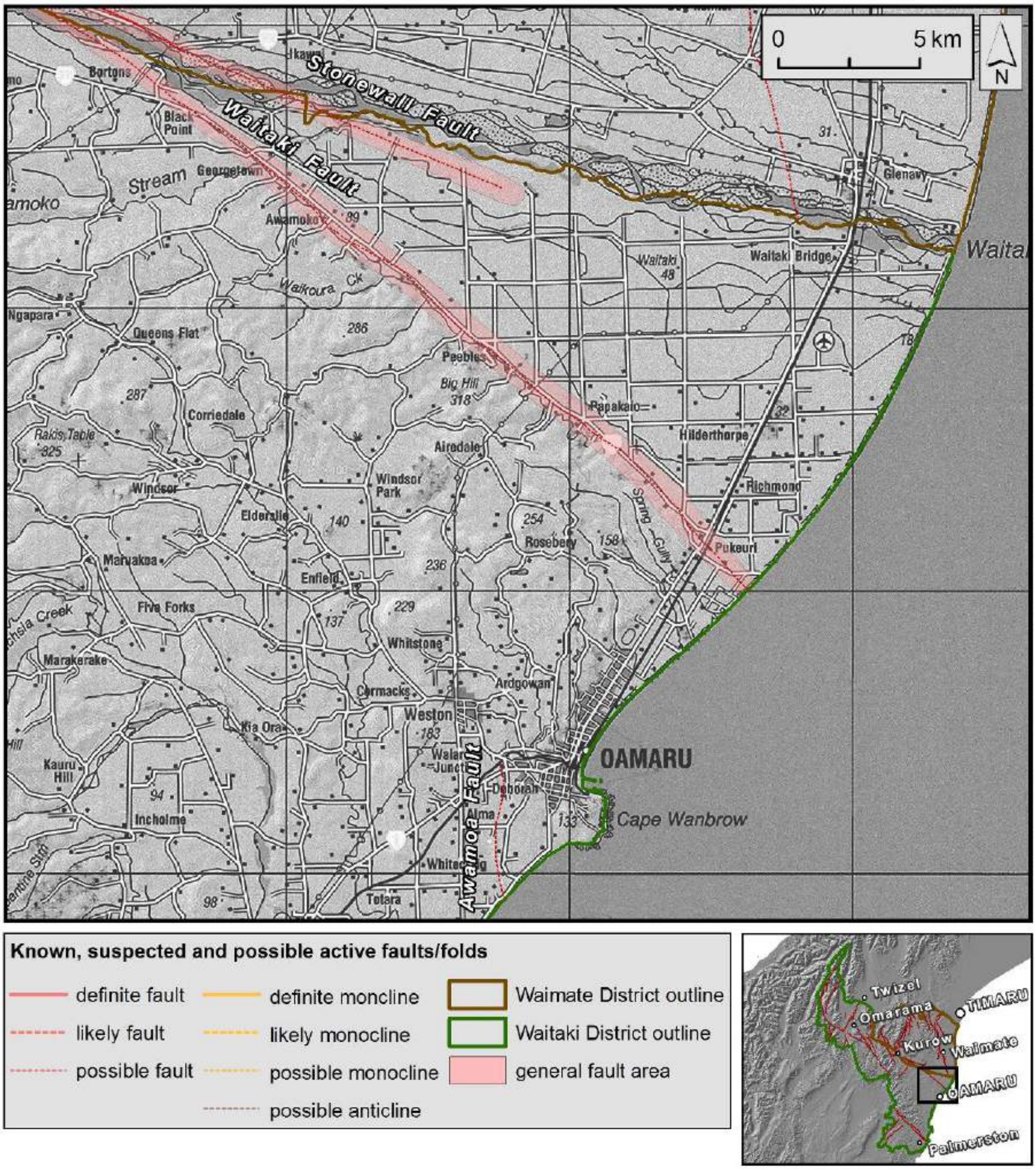

Figure A2.13 The active faults of the Waimate and Waitaki districts in the lower Waitaki to Oamaru areas. The background image is a greyscale version of topographic map Topo250 (Land Information NZ, Crown Copyright reserved). The map area is shown in the context of the Waimate and Waitaki districts in the index map at lower right. In Figure 5.1, Figure 5.2 and/or Figure 5.3, and in Appendix 2 text, Stonewall Fault is feature 12l, Waitaki Fault is feature 12m, and Awamoa Fault is feature 25. The ‘general fault area’ symbol is used purely for illustrative purposes to denote the spatial extent of components of a particular feature, and implies nothing about the location or extent of ground deformation hazards.

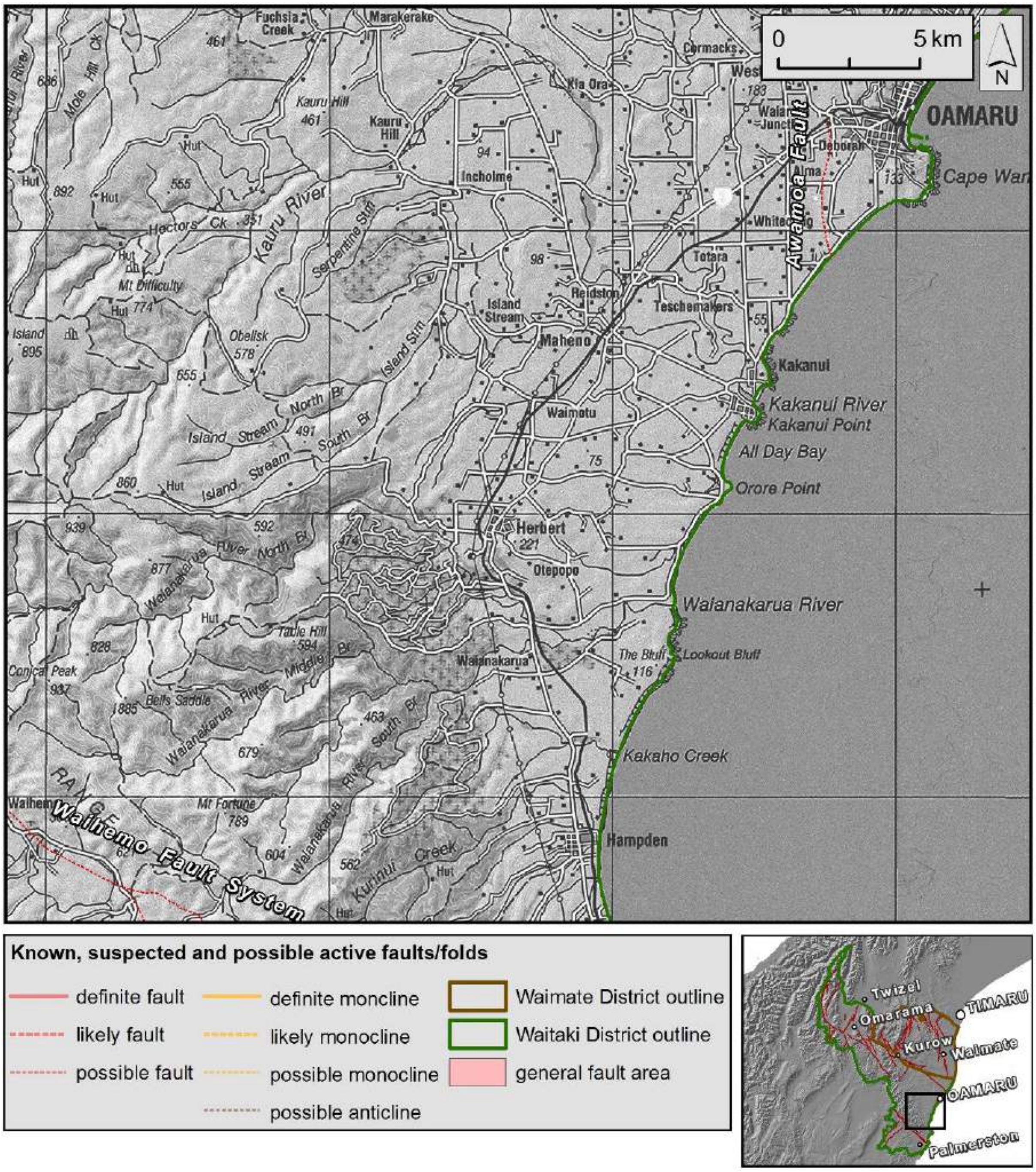

Figure A2.14 The active faults of the Waitaki District in the area southwest of Oamaru. The background image is a greyscale version of topographic map Topo250 (Land Information NZ, Crown Copyright reserved). The map area is shown in the context of the Waimate and Waitaki districts in the index map at lower right. In Figure 5.1, Figure 5.2 and in Appendix 2 text, Awamoa Fault is feature 25 and Waihemo Fault System is feature 26.

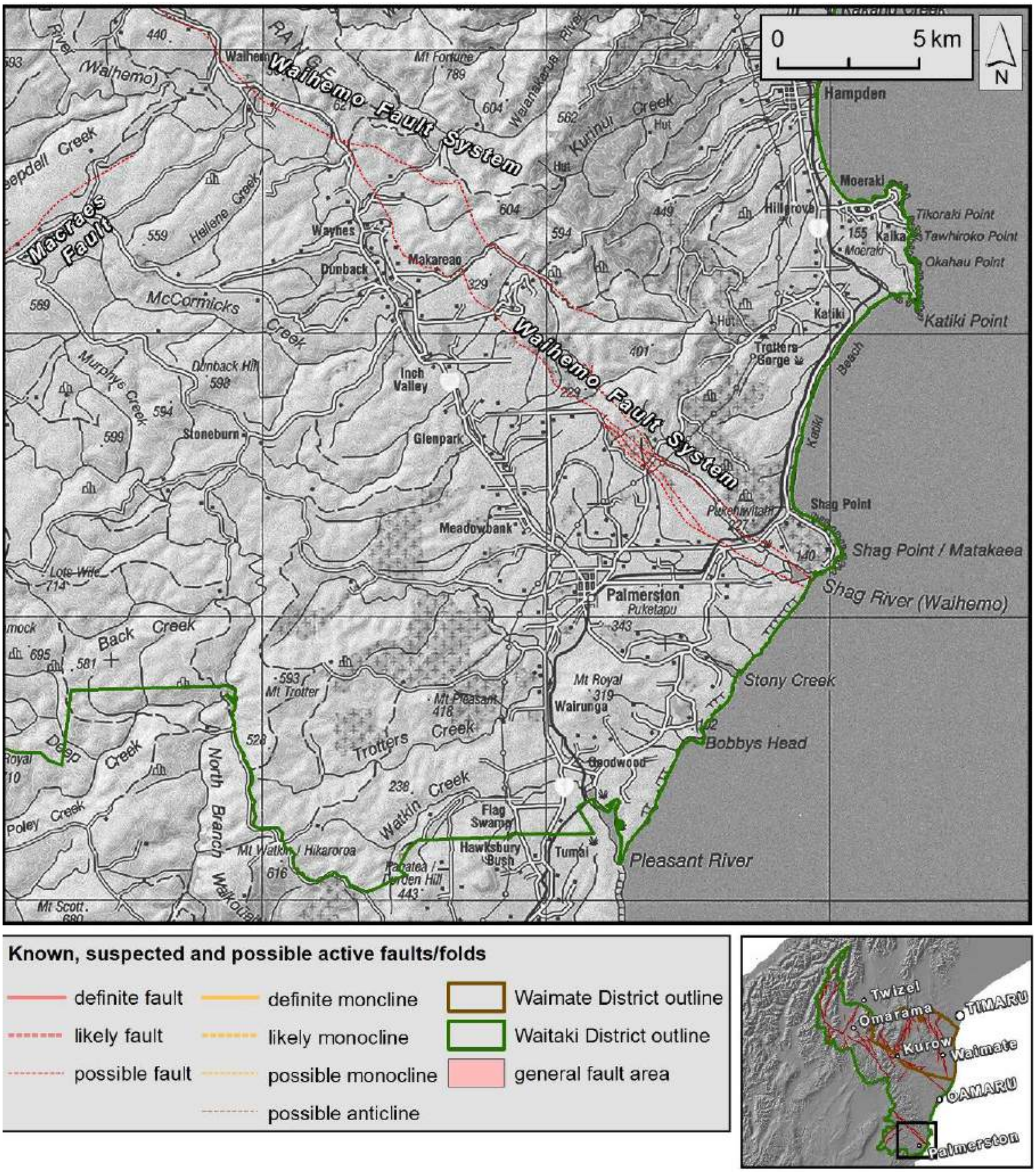

Figure A2.15 The active faults of the Waitaki District in the Palmerston area. The background image is a greyscale version of topographic map Topo250 (Land Information NZ, Crown Copyright reserved). The map area is shown in the context of the Waimate and Waitaki districts in the index map at lower right. In Figure 5.1, Figure 5.2 and in Appendix 2 text, Waihemo Fault System is feature 26 and Macraes Fault is feature 29.

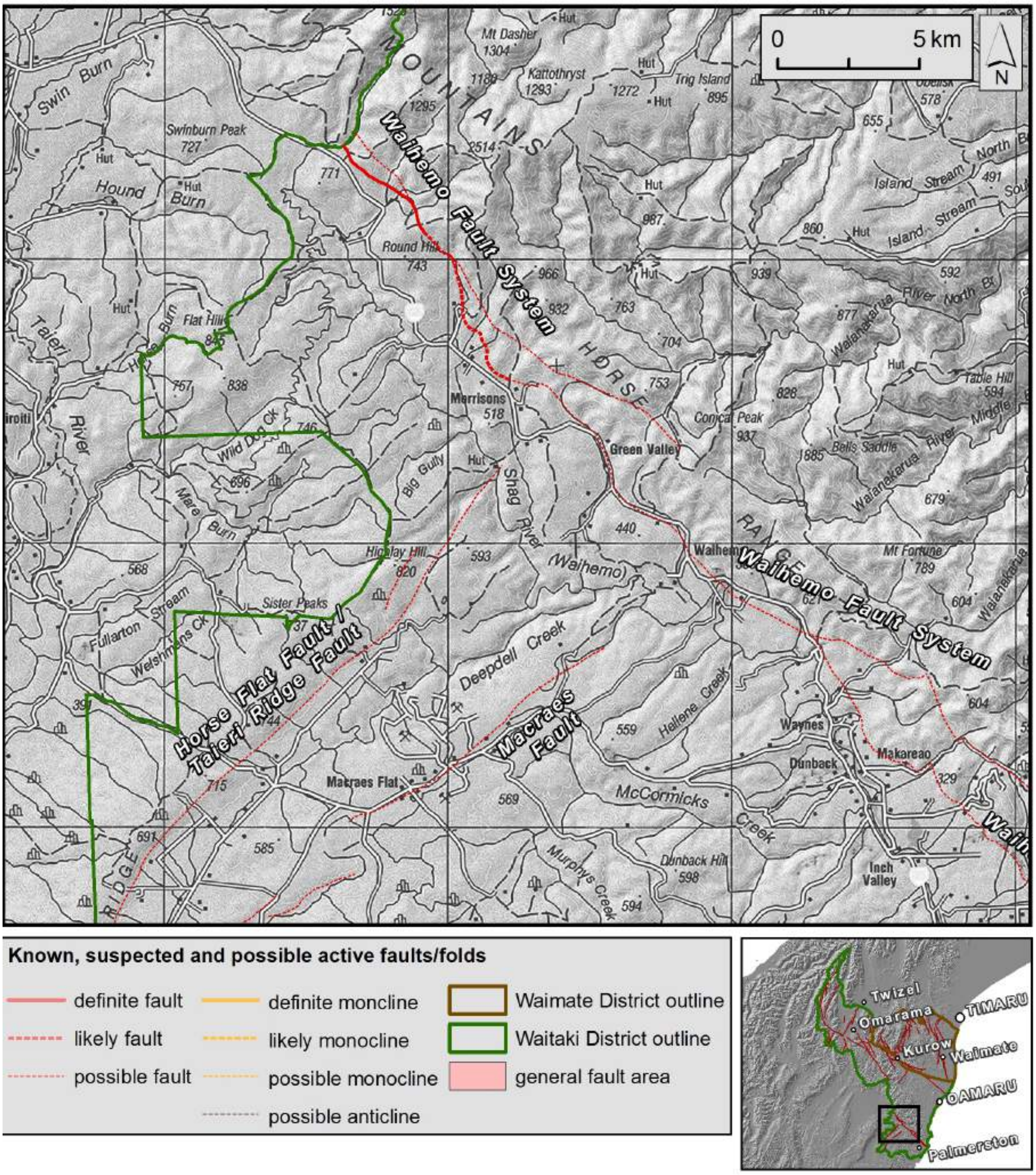

Figure A2.16 The active faults of the Waitaki District in the western sector of the Horse Range and in the Macraes Flat area. The background image is a greyscale version of topographic map Topo250 (Land Information NZ, Crown Copyright reserved). The map area is shown in the context of the Waimate and Waitaki districts in the index map at lower right. In Figure 5.1, Figure 5.2 and in Appendix 2 text, Waihemo Fault System is feature 26, Horse Flat Fault/Taieri Ridge Fault is feature 27, Billys Ridge Fault is feature 28, and Macraes Fault is feature 29.

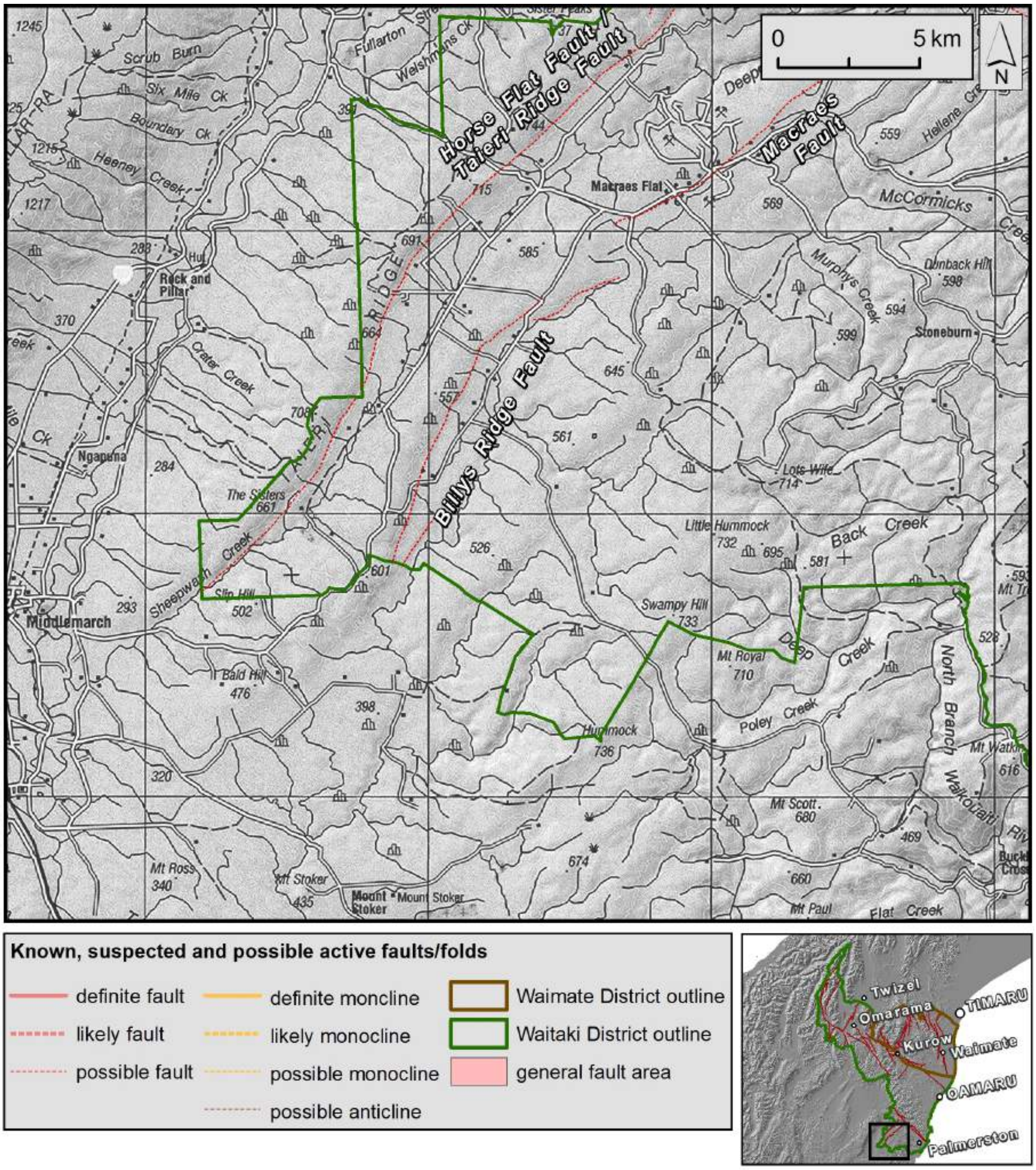

Figure A2.17 The active faults of the Waitaki District in the area northeast of Middlemarch. The background image is a greyscale version of topographic map Topo250 (Land Information NZ, Crown Copyright reserved). The map area is shown in the context of the Waimate and Waitaki districts in the index map at lower right. In Figure 5.1, Figure 5.2 and in Appendix 2 text, Horse Flat Fault/Taieri Ridge Fault is feature 27, Billys Ridge Fault is feature 28, and Macraes Fault is feature 29.