General distribution and characteristics of active faults and folds in the Timaru District, South Canterbury

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EXECUTIVE SUMMARY

This report presents a general outline of the locations and character of active geological faults and folds in the Timaru District. 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 14 areas of active faults or folds at the ground surface in the Timaru District. 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. 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.

The main hazards associated with active faults include: (i) strong ground shaking from local 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. Although no large earthquakes have been centred in the Timaru District since European settlement in the mid-1800s, 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 geological record shows clear evidence for prehistoric deformation at several locations within the Timaru District, and highlights that it would be prudent to treat these active fault or fold features as potential hazards.

The active faults and folds of the Timaru District have been mapped at a regional scale. Information in this report and in the accompanying GIS layer is intended to highlight those 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 Timaru District. It is intended to create general awareness of the existence of the 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 Timaru District, 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 (see Figure 1.2). 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, together with fault location, 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).

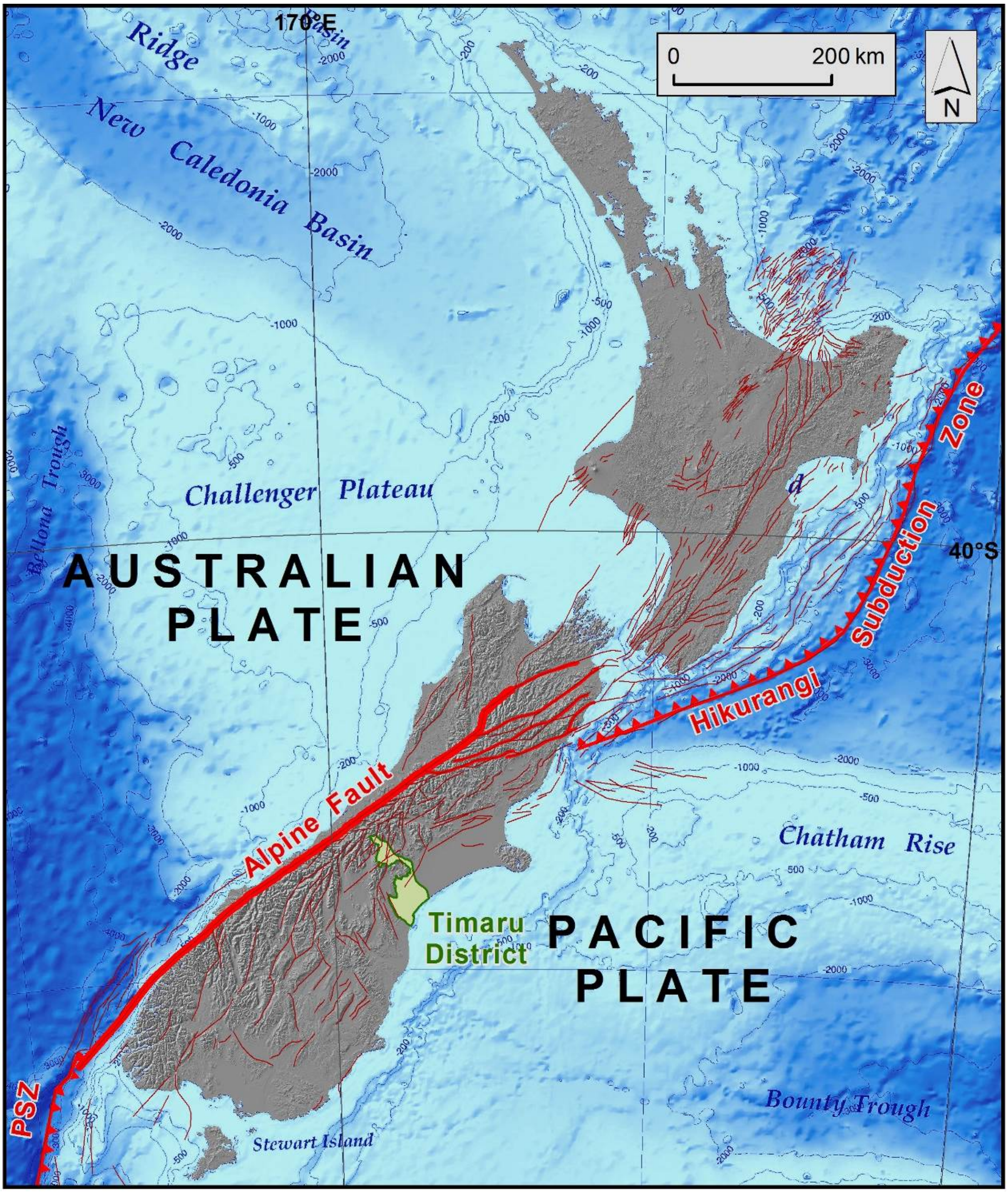

Figure 1.1 The tectonic setting of the Timaru District. The junction between the Australian and Pacific plates of the Earth's crust passes through New Zealand, with the Pacific Plate pushing westward against the Australian Plate. At the Hikurangi Subduction Zone, the rocks of the Pacific Plate slide 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). Although much of the plate movement is concentrated at the subduction zones and the Alpine Fault, there is a wider zone of deformation. Of particular note is the Marlborough Fault System (medium thickness red lines) which transfers motion between the Alpine Fault and the Hikurangi Subduction Zone. The Timaru District lies in the midst of 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 at Glynn Wye 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 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 Timaru District (see Figure 5.1). 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 the Waimate and Waitaki districts (Barrell 2016).

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 Timaru District. 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 Timaru District 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 Timaru District 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 Timaru District by the Aoraki map (Cox & Barrell 2007) and, in the far southwestern part of the district, by the Waitaki map (Forsyth 2001). Some more detailed studies have contributed to the generalised information shown on these maps and their underlying Geographic Information System (GIS) databases. Those 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. (2013, 2014).

This report comprises an office-based review of existing information, with a scope of work that did not include site investigations. 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 data set, 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 Timaru District, the oldest underlying rock (basement rock) consists mainly of hard sandstones and flaky mudstones, commonly called greywacke and argillite respectively. These ancient rocks, of Permian to Jurassic age (between 300 and 145 million years old) were in places (e.g. middle reaches of the Rangitata valley) buried by localised accumulations of volcanic rock (Mt Somers Volcanics) of middle Cretaceous age (~90 million years old). Both sets of rocks were more widely buried by a blanket of younger sedimentary rocks (cover rocks) including coal measures, quartz sands, marine mudstones, limestones and gravelly conglomerates, ranging in age from Late Cretaceous (~85 million years ago) to about 2.5 million years old. At about that time, volcanic eruptions near Geraldine and Timaru produced thin sheets of basalt lava that overlie the older strata. 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, uplift and erosion has stripped away much of the cover rock blanket, exposing the underlying basement rock that forms the main ranges. In a few 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 foothills, and also lie at depth under the Canterbury Plains.

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 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 Timaru District, the most recent glaciation generated sizeable glaciers in the Rangitata catchment, and the glacier flowed down as far as the mouth of the Rangitata Gorge at the head of the Canterbury Plains. Localised glaciers also formed on the highest parts of the Ben McLeod Range, but other parts of the district remained ice-free (Barrell 2011). However, in the ice-free areas, erosion and deposition was nonetheless greatly influenced by episodes of glacial climate. During glaciations, snowlines and treelines were many hundreds of metres lower than they are today. 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 Timaru District 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 around Timaru city. 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 Rangitata catchment, is the preservation of extensive areas of ice-age land surfaces in the Timaru District. 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 3.1 & Figure 3.2).

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 3.2).

Two end-members of fault movement type are shown in Figure 3.2; 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 3.2 are idealised examples. They do not show the full range of variations and complexity that may exist (for example, see Figure 3.1). Indeed, to find such simple examples in nature as displayed in Figure 3.2 would be an exception rather than a rule. The steepness of inclination (dip) of the fault may vary considerably (Figure 3.2). 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 3.2 attempts to convey some impression of the bulldozer effect.

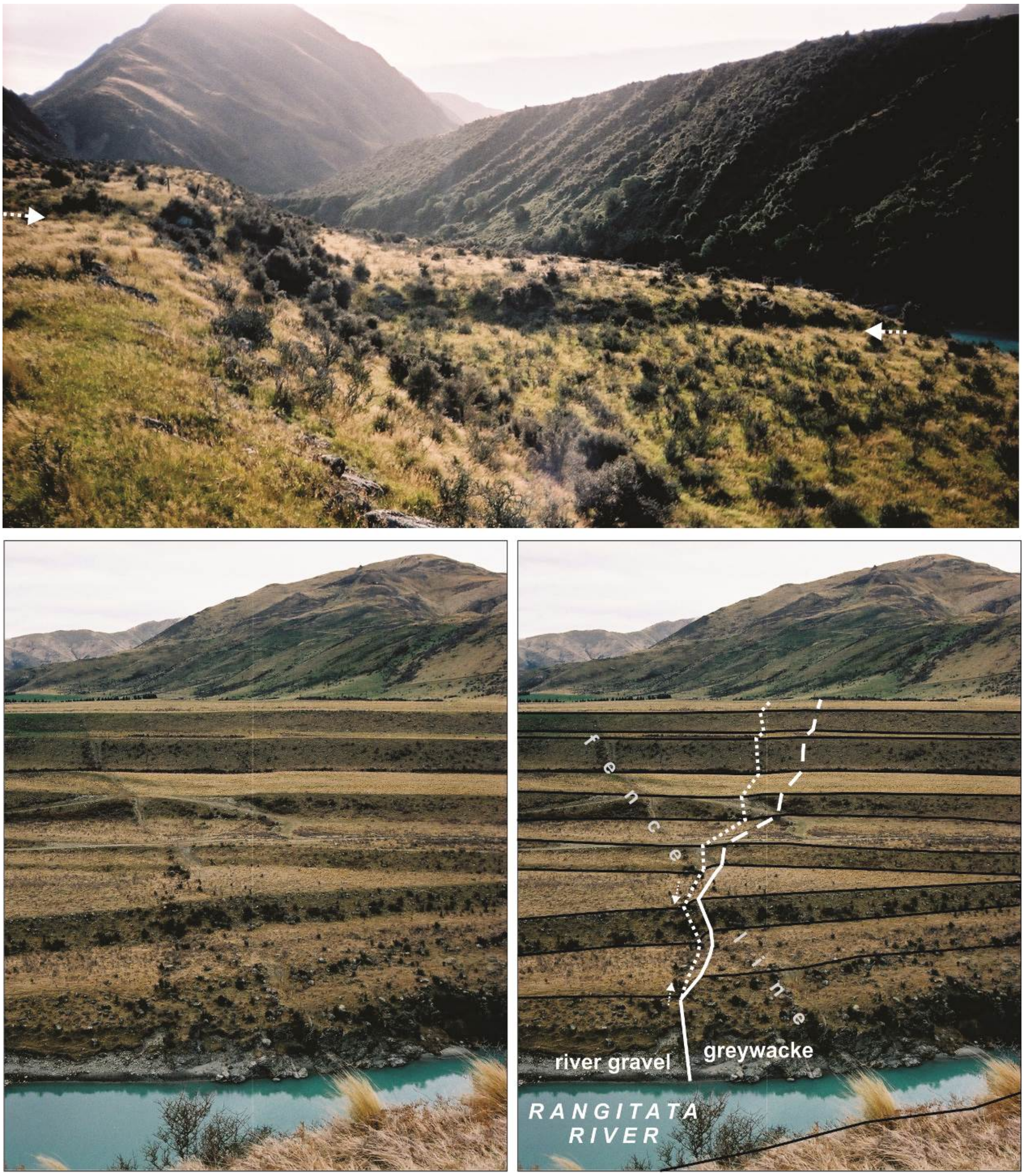

Figure 3.1 The ground surface expression of the Klondyke-Moorhouse fault (feature 9 in Appendix 2; Figure 5.1) across a flight of river terraces on the south bank of the Rangitata River (Timaru District) opposite the Rangitata Diversion Race intake at Klondyke (in Ashburton District). Upper photo: Looking northwest (upstream), the fault scarp is about 2 m high and runs left to right between white arrows, across the two lowest terrace levels. Lower photos: Looking southwest, the fault (solid white line = crest, dotted = base) becomes broader and less well defined on the higher terraces, transforming into a monoclinal fold (dashed line = crest). Black lines mark the river-ward edge of each terrace level. For reference, arrows are placed in the same positions as seen in the upper photo. This fault was first reported by Speight (1941), first depicted on a geological map by Gair (1967). In the GIS dataset (Cox & Barrell 2007; Heron 2014), the feature is classified as a fault, because its extent is too limited, on regional-scale geological maps, to segregate the fault and fold components. The Klondyke-Moorhouse fault is described in more detail by Barrell et al. (1996), and also mentioned by Barrell & Strong (2009). Photos: D.J.A. Barrell, taken 1995.

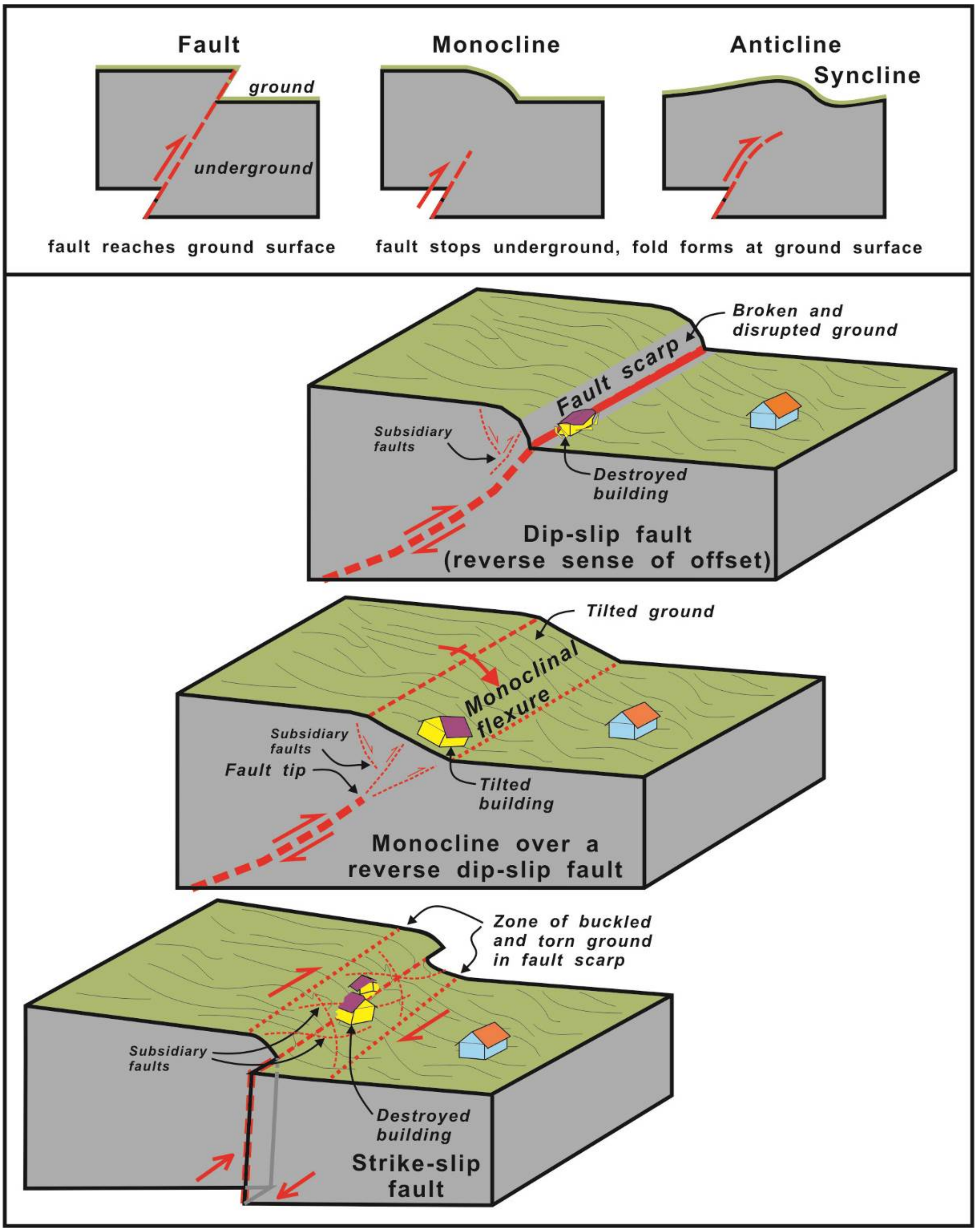

Figure 3.2 Diagrams illustrating styles of active faults and folds. The diagrams illustrate general concepts rather than actual details, and are not drawn to an exact scale. Upper panel: Cross-section (vertical slice) diagrams illustrating an active fault, active monocline and active anticline and syncline. 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 3.2). 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. 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 3.2). 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. 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 may arise 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.

4.0 CLASSIFICATION OF ACTIVE FAULTS AND FOLDS

4.1 DESCRIPTIVE CLASSIFICATION

The original information on the active faults and folds of the Timaru District is extracted from the QMAP dataset (Forsyth 2001; Cox & Barrell 2007), 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 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:

- TDC_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 Timaru District 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. Ben Macleod 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 cannot be sure that it is because, for example, the landforms are unsuitable (e.g. too young) to have preserved any direct evidence of young movement, the feature is designated as '**possible**'. Features identified as 'possible' should not be treated as delineated active faults or folds unless investigated further. 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 Timaru District have been examined 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 OF ACTIVE FAULTS AND FOLDS

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. Timaru District). 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 land surface feature, such as a river plain, divided by the age of the 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 show sideways offsets clearly. 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 faults with predominantly sideways movement 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 6 of the total of 12 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. The Timaru District includes the southernmost sector of the Canterbury Plains, and in that area there may be buried faults. For much of the western part of the district, the older rocks 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. In the area west of Geraldine and Temuka, there are several large faults and folds that have greatly disrupted the basement and cover rock sequence, but they have not caused any discernible disruption or deformation of river deposits and landforms that are estimated to be at least 250,000 years old, as mapped by Cox & Barrell (2007). For that reason, those faults and folds are not included in this dataset.

Those active faults and folds of the Timaru District that have a preserved record of previous ground-surface deformation of young deposits or landforms, and which are included in the dataset described in this report, should be regarded as a minimum representation of the active faults and folds of the district. This is because there could be other active features that are buried under the Canterbury Plains, or lie within hill or mountain country and for which evidence of recent activity has been eroded away. Because we know about the faults and folds documented in this dataset, 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 the ground surface. It is generally thought, for the types of fault 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.

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 Timaru District is presented in Figure 5.1 on two overlapping panels, because the wide extent of the district means that the fault and fold information would be illegible if presented on a single map within this report. 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 Timaru District, 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.

A total of 12 named faults are identified in the Timaru District, of which one, the Forest Creek Fault Zone, includes three separately named entities, making a total of 14 named active fault entities. All of these 14 features are classified as faults, although one of them, the Waihi fault, includes several strands classified as monoclinal folds (Figure 5.1). Seven of the 12 named faults are classified as ‘definite’ or ‘likely’ active features, while the remaining 5 faults are assigned an activity classification of ‘possible’. As far as is known, the faults in the Timaru District are dip-slip faults with a reverse sense of displacement, possibly with a lesser component of strike-slip movement.

The most active faults of the Timaru District delineated in this assessment are the Forest Peak Fault Zone (features 4a, 4b and 4c; Figure 5.1), and the Peel Forest Fault (feature 10; Figure 5.1). There is good reason to think that the RI for surface ruptures on these faults is no more than between 5,000 and 8,000 years or so, and the RI could possibly be as short as ~2,000 years or so. Three faults with definite or likely activity (the Hewson Fault, Klondyke-Moorhouse Fault and Waihi fault) are assessed as having RIs possibly as short as 4,000 to 6,000 years, and possibly as long as between 20,000 and 30,000 years. The remaining seven faults have activity classified as ‘possible’. There is reasonable confidence that none of the ‘possible’ active faults have 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-risk structures (such as a dam).

Apart from the Neutral Creek Fault, for which some constraint exists (Stahl 2014), for all the other faults, it is not known when the most recent rupture(s) occurred. This means that there is no information on where the present-day sits in regard to the rupture cycles of these faults.

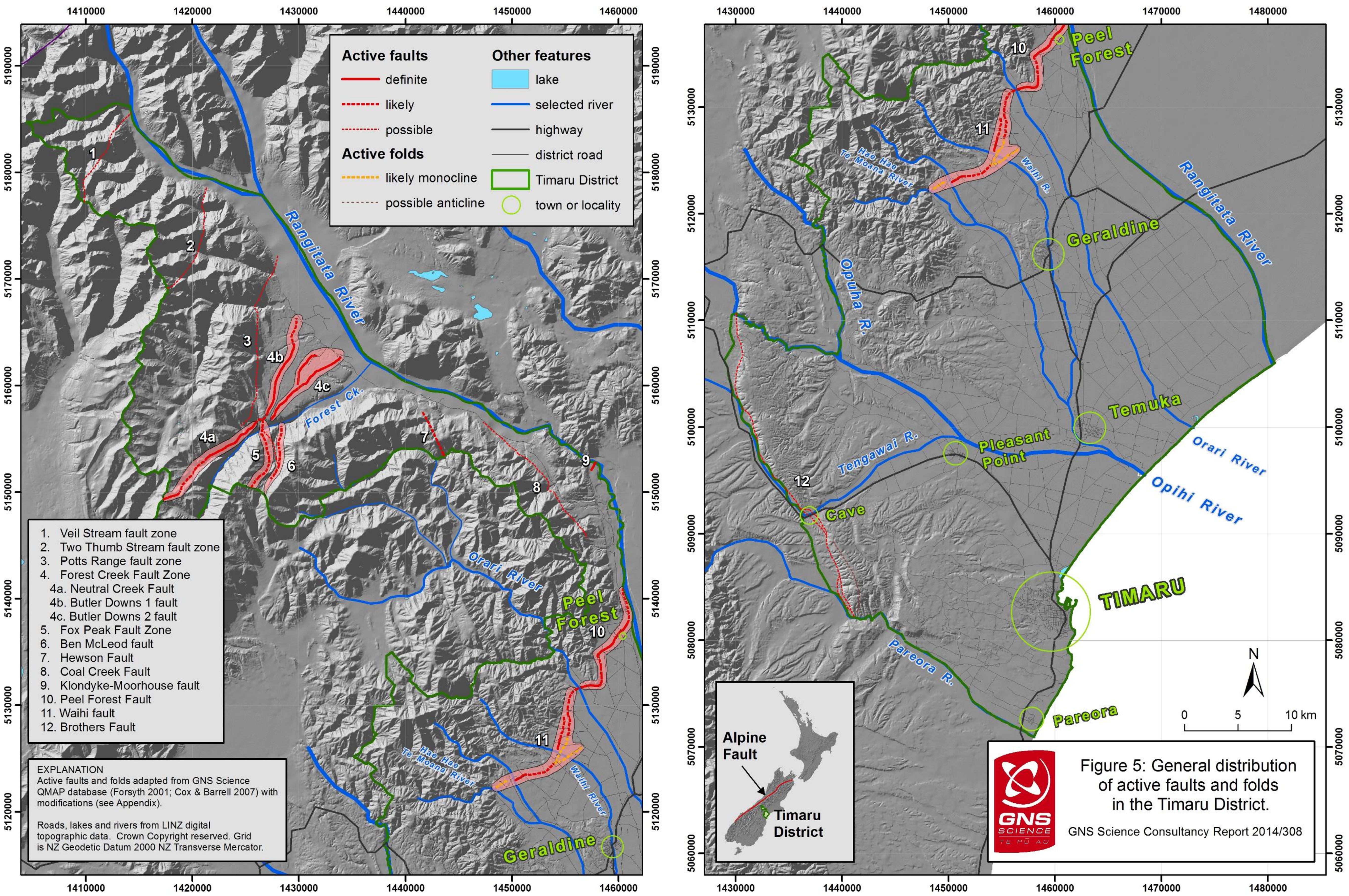

Figure 5.1 General distribution of active faults and folds in the Timaru District. The pink areas simply indicate groupings of faults or folds that collectively form part of a single numbered entity. The pink areas are purely illustrative and do not imply anything about the location or extent of fault-related ground deformation (i.e. they do not represent avoidance zones).

Table 5.1 Categories and terms used in this report to describe active faults and folds in the Timaru District.

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 Timaru District (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. Veil Stream fault zone	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. Two Thumb Stream fault zone	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
3. Potts Range fault zone	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
4a. Forest Creek Fault Zone: Neutral Creek Fault	Definite, likely and possible active faults.	Cox & Barrell (2007); Stahl (2014); this report.	airphoto interpretation; paleoseismological investigation; regional geologic mapping.	Stahl (2014) presented evidence for at least two rupture events in the past ~6,000 years. A recurrence interval range of between ~2,000 and ~5,000 years is adopted based on that information.					2,000 to 5,000 years / Classes I to IV
4b. Forest Creek Fault Zone: Butler Downs 1 fault	Definite and likely fault/monoclinal folds.	Cox & Barrell (2007); this report.	airphoto interpretation; field inspection; regional geologic mapping.	18,000	10	0.6	3,600	2,412	1,200 to 6,000 years / Classes I to IV
4c. Forest Creek Fault Zone: Butler Downs 2 fault	Definite and likely fault/monoclinal folds.	Cox & Barrell (2007); this report.	airphoto interpretation; field inspection; regional geologic mapping.	18,000	10	0.6	3,600	2,412	1,200 to 6,000 years / Classes I to IV
5. Fox Peak Fault Zone	Likely active fault.	Upton et al. (2004); Cox & Barrell (2007); Stahl (2014); this report.	airphoto interpretation; field inspection; regional geologic mapping.	In the Timaru District, 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 for that section of the Fox Peak Fault in the Timaru District.					>10,000 years / Class V or greater
6. Ben McLeod fault	Likely active fault.	Upton et al. (2004); Cox & Barrell (2007); this report.	airphoto interpretation; field inspection; regional geologic mapping.	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
7. Hewson Fault	Likely active fault offsetting hill slopes over a mapped fault in bedrock.	Oliver & Keene (1990); Cox & Barrell (2007); this report.	airphoto interpretation; regional geologic mapping.	18,000	3	0.2	12,000	8,040	4,000 to 20,000 years / Classes III to VI
8. Coal Creek Fault	Fault mapped in bedrock, considered to possibly be active.	Oliver & Keene (1990); Cox & Barrell (2007); this report.	airphoto interpretation; regional geologic mapping.	There appear to be no offsets of glacial landforms of assumed age ~18,000 years, and a recurrence interval of more than 10,000 years is adopted in this report.					>10,000 years / Class V or greater
9. Klondyke-Moorhouse fault	Definite active fault/monocline at Rangitata River.	Oliver & Keene (1990); Barrell & Strong (2009); this report.	field inspection and surveying; regional geologic mapping.	18,000	2	0.1	18,000	12,060	6,000 to 30,000 years / Classes IV to VI
10. Peel Forest Fault	Definite and likely active faults.	Barrell et al. (1996); Cox & Barrell (2007); this report.	field inspection and surveying; regional geologic mapping.	18,000	7	0.4	5,143	3,446	1,700 to 8,500 years / Classes I to IV
11. Waihi fault	Definite, likely and possible fault scarps and monoclines.	Cox & Barrell (2007); this report.	field inspection & surveying; regional geologic mapping.	140,000	16	0.1	17,500	11,725	6,000 to 30,000 years / Classes IV to VI
12. Brothers Fault	Fault mapped in bedrock, considered to possibly be active, and anticline on the upthrown side.	Forsyth (2001); Cox & Barrell (2007); Barrell & Strong 2012; Litchfield et al. (2014); this report.	airphoto interpretation; regional geologic mapping.	There appear to be no offsets or deformation of Quaternary landforms across the fault. A recurrence interval of more than 10,000 years is adopted in this report.					>10,000 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 of the Timaru District area (~1840 AD), there have been no known ground-surface fault rupture events in the district. The most strongly felt historic earthquake in the district was probably the 2010 Darfield Earthquake. Despite the absence of large historic earthquakes, the geological record and landforms show clear evidence for several 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 Timaru District as potentially hazardous.

Figure 6.1 illustrates an example of the 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 will occur in a sudden event. The presence of active folds indicates that there may be an underlying active fault at depth that may generate a local, large, shallow earthquake, were it to rupture.

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 Timaru 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 Timaru District:

Most of the active faults are in remote locations, far from any existing 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 near Washdyke, Waimataitai and Saltwater Creek.

The only definitely active fault close to any development is the Peel Forest Fault (feature 10 in Figure 5.1), which lies close to the villages of Peel Forest and Blandswood. The main consequence of a rupture of this fault would be disruption of the Rangitata Gorge Road, which provides the only road access to Blandswood, and to the farms of the middle to upper parts of the Rangitata valley. There would also be disruption to the Orari Gorge Road. In both cases, restoration to serviceability could probably be achieved by large earthmoving equipment within a day or so.

Rupture of the Waihi fault (feature 11 on Figure 5.1) would affect minor roads along the range-front northwest of the Geraldine area.

Although it is judged to be unlikely, on account of the considerable uncertainty as to whether the Brothers Fault is in fact an active fault, a rupture of the Brothers Fault (feature 12 on Figure 5.1) may pass through the village of Cave, and would disrupt State Highway 8 through Cave.

In summary, there are several undoubtedly active faults in the Timaru District 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 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. The mapped delineation of the active faults and folds of the Timaru District presented in this report has been done at a regional scale (1:250,000). The level of mapping precision, as well as most fault data information 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 land use planning and for ‘definite’ features, it would be necessary to increase the mapping resolution for fault location and/or fully characterise the RI. 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.

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7.0 CONCLUSIONS

1. Regional- (1:250,000) scale geological mapping has identified a number of active faults and folds (monoclines, synclines and anticlines) in the Timaru District. In total, 14 areas of known or suspected active faults and/or folds are delineated. All 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 (RI) for deformation events, aided by some assumptions. The RI estimates provide a linkage to Ministry for the Environment guidelines on planning for development on or close to active faults. However, the RIs presented here are only provisional estimates based on many assumptions, and span broad time ranges. If there were any need for improved knowledge regarding the RI of any particular fault (e.g. for land-use planning purposes), site-specific geological investigations would be necessary.

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 our 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. More detailed mapping and other geological investigations would be necessary if there is any future need for defining fault avoidance zones on any particular fault.

8.0 ACKNOWLEDGEMENTS

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APPENDICES

A1.0 APPENDIX 1: GIS LAYERS

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

- TDC_faults.shp
- TDC_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 published as the QMAP Aoraki sheet (Cox & Barrell 2007) and, in the southern part of the Timaru District, the Waitaki sheet (Forsyth 2001). 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:

- TDC_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. 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

A2.1 BACKGROUND INFORMATION

The information in this Appendix is largely of a technical nature. It is written mainly for the benefit of earth scientists, and is intended primarily to aid future geo-scientific enquiry. Nevertheless, some aspects may well be of interest to the general public. In some instances, location co-ordinates are given for topographic features that can be viewed, for example, in 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.

Regional-scale (i.e. 1:250,000) topographic maps, on which the faults and folds are plotted, are provided at the end of the Appendix (Figure A2.1a-e), to assist the reader in locating the geographic features mentioned in this appendix. As not all of the geographic locations (e.g., names of minor streams) are shown on these maps, a reader requiring more information may also wish to refer to 1:50,000 topographic maps from the Topo50 series via http://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 Timaru District is encompassed by two published map sheets, with accompanying descriptive booklets, comprising the Aoraki map (Cox & Barrell 2007) which covers most of the district, and the Waitaki map (Forsyth 2001) which covers the southern corner of the district around Timaru city. Subsequently, 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 Timaru 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 South Island has been taken up, with little modification, into the New Zealand Active Faults Database (NZAFD; Langridge et al. 2016).

A more conceptual interpretation of fault activity in the Southern Alps (i.e. northwestern part of the district in the Rangitata River headwaters) 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.

A2.2 SOUTHERN ALPS FAULTS (FEATURES 1-3)

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 in this discussion as the ‘Southern Alps faults’, which segregates them from other faults that are identified from more direct evidence for their activity.

A2.2.1 Veil Stream fault zone (Feature 1, Figure 5.1; see Figure A2.1)

This entity as depicted in the NZAFM is identified as the Veil Stream fault zone. It approximates the position of an array of bedrock faults mapped on either side of the Havelock River valley by Cox & Barrell (2007) (see Figure A2.1). That mapping was based on scattered exposures of fault-crushed seams within greywacke basement rock. The interpreted faults were classified as inactive, because of a lack of any surface scarps recognisable in aerial photos. Subsequently, Cox et al. (2012) depicted, in a very generalised way, a ‘potentially active’ fault at that location, which formed the basis for its inclusion in the NZAFM. It is characterised in the NZAFM as a right-lateral/reverse fault dipping west at between 45 and 70°.

The feature mapped in the NZAFM extends both north and south of the Timaru District. The mapped, un-named fault in bedrock approximating the location of the Veil Stream fault zone has been taken from the QMAP digital dataset (Heron 2014). This fault in places crosses areas of glacial deposits and ice-sculpted bedrock terrain that became exposed when glaciers retreated at the end of the last ice age (Barrell et al. 2011), and there is no known evidence for landforms having been offset across this fault. This indicates that this fault has not experienced repeated metre-scale surface ruptures in the past ~18,000 years. Accordingly, it is classified in this dataset 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 Two Thumb Stream fault zone (Feature 2, Figure 5.1; see Figure A2.2)

This feature is defined on the same basis as the Veil Stream fault zone, and the considerations presented in the section above also apply to the Two Thumb Stream fault zone. On the northern side of the Havelock valley (Ashburton District) and near the confluence of Two Thumb Stream and North East Gorge Stream (Lake Tekapo catchment, Mackenzie District; see Figure A2.2), Cox & Barrell (2007) depicted the bedrock fault as abutting well-defined glacial moraine deposits and associated landforms. There is no indication in aerial photos of a fault scarp displacing the glacial deposits/landforms, which are presumed to be ~18,000 years old. This indicates that the fault zone has not experienced repeated metre-scale surface ruptures in the past ~18,000 years. Accordingly, it is classified in this dataset 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.

A2.2.3 Potts Range fault zone (Feature 3, Figure 5.1; see Figure A2.2)

This feature is defined on the same basis as features 1 and 2 described above, and the same points and considerations apply. Cox & Barrell (2007) mapped the fault as concealed under glacial deposits of the Butler Downs, along the eastern foot of the Sinclair Range (see Figure A2.1 and Figure A2.2). The associated glacial landforms, of assumed age ~18,000 years, are very well preserved, and no indication of a surface scarp anywhere in the vicinity of the inferred position of the bedrock fault was noted during examination of aerial photos, nor during field inspection by the writer in 2002. This implies that the fault zone has not experienced repeated metre-scale surface ruptures in the past ~18,000 years. Accordingly, it is classified in this dataset 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.

A2.3 FOREST CREEK FAULT ZONE (FEATURES 4A, 4B, 4C; FIGURE 5.1; SEE FIGURE A2.2)

A2.3.1 Background

An east-northeast – west-southwest striking fault or set of faults has long been inferred to underlie the valley of Forest Creek (see Figure A2.2), as depicted for example on the map of Gair (1967) and by Upton et al. (2004). However, Cox & Barrell (2007) did not show a major through-going fault on that trend. Because description and justification for mapping decisions was beyond the scope of the Cox & Barrell (2007) publication, a summary and discussion of evidence for faulting in the Forest Creek area that was evaluated by Cox & Barrell for their 2007 map publication is provided here.

Upton et al. (2004) showed two parallel east-northeast – west-southwest striking faults, which they named the West Forest Creek Fault and the East Forest Creek Fault.

The main evidence presented by Upton et al. (2004) for the existence of the West Forest Creek Fault is an exposure of greywacke upfaulted against gravels in Moonlight Stream (see Figure A2.2), between ~650 and 700 m upstream of its confluence with Forest Creek (a representative location of the exposure is latitude 43°43.413'S, longitude 170°50.833'E). They reported the fault attitude (strike/dip) as 035°/54°W, upthrown to the west, although on their map (Figure 3.1 of their paper), they showed a dip value of 60°. They interpreted this fault exposure as an outcrop of the West Forest Creek Fault.

Commencing about 1 km west of the fault exposure in Moonlight Stream, and continuing for at least 5 km southwest (trend of ~050°-230°) is a well-expressed fault scarp, attributed to the Neutral Creek Fault (see feature 4a, next section). Although Upton et al. (2004) suggested this represents the West Forest Creek Fault, a substantial difficulty is that the fault scarp is up to the south-east and is therefore, at face value, incompatible with the up–to–the–west fault exposed in Moonlight Stream.

The only other evidence that Upton et al. (2004; their Figure 5.1) presented for the West Forest Creek Fault was a 10 to 15 m high topographic step, up to the north-northwest, in the middle reaches of Neutral Creek (at representative location 43°45.494' S, 170°46.544' E; Neutral Creek lies on the northern side of Neutral Hill – see Figure A2.2). They interpreted this topographic step as a fault scarp. However, this feature is located in the valley floor, at the edge of the alluvial floodplain of Neutral Creek. When examining aerial photos of this feature, ahead of the 2007 map publication, I formed the opinion, based on the substantial height of this topographic step and its location in a geomorphically-young setting in a valley floor, that it is simply a river-trimmed slope formed against glacial landforms. In 2015, examination of Google Earth imagery at this location further reinforces my opinion that the feature is due to river erosion. It is understandable that its true origin could have been misinterpreted during the ground-based inspection that formed the basis of the Upton et al. (2004) interpretation, especially if they were assuming that correlatives of the west-dipping reverse fault exposed in Moonlight Stream extend up the Forest Creek / Neutral Creek valleys.

The evidence for the East Forest Creek Fault comprises an exposure of fault-crushed rock reported from the lower reaches of Neutral Creek and fault-crushed rock exposed in Forest Creek about 0.9 km downstream of the Neutral Creek – Forest Creek confluence (Upton et al. 2004). However, they reported that neither the dip nor the orientation of the causative fault could be determined. They stated that “The south dip of the fault and south side up sense of movement were interpreted from the shape of the basin in Forest Creek and the uplifted ranges to the south.” This presumably refers to the prominent topographic contrast across the lower reaches of Forest Creek between the Ben McLeod Range to the south (crest at ~1800 to 2000 m above sea level (a.s.l.)) and the Butler Downs, which comprises a flight of lateral moraine benches and glacial meltwater terraces descending eastwards from ~1000 to ~500 m a.s.l. There is also a vague topographic contrast between the highest peaks in the southern part of the Forest Creek catchment headwaters, which reach ~2200 m a.s.l., and the highest peaks farther north in the Sinclair Range and Bush Stream catchment, which reach ~2000 m a.s.l. (see Figure A2.2). Thus the nature and location of the East Forest Creek Fault is based on very little direct evidence.

A2.3.2 The Cox & Barrell (2007) interpretation

Cox & Barrell (2007) recognised substantial uncertainties in regard to the interpretation and correlation of mapped faults in the general area of Forest Creek. In its Butlers Creek tributary, there are exposures of fault zones, and deformed and locally faulted gravelly strata of possible Pliocene and/or Pleistocene age, as detailed for example by Upton et al. (2004) and also in a recently completed PhD thesis (Stahl 2014). However, there is little certainty regarding the age of the deformed or faulted gravelly strata. Furthermore, there are problems resolving, for example, the presence in Moonlight Stream of an up-to-the-west reverse fault offset with the up-to-the-southeast fault scarp nearby to the southwest.

Cox & Barrell (2007) addressed the uncertainties by delineating active faults based mainly on landform offsets. During field examination accompanying compilation of the 2007 map, I identified two fault/fold scarps on Butler Downs east of Moonlight Stream, one trending north-northeast and upthrown by as much as 10 m or so to the west-northwest, and the other tending northeast (previously identified on the Gair (1967) map), downthrown to the northwest by as much as 10 m or so. The former (identified in this Timaru District dataset as Butler Downs 1 Fault) was inferred to extend in location to the up-to-the-west fault offset reported by Upton et al. (2004) from Moonlight Stream. The latter (identified in this Timaru District dataset as Butler Downs 2 Fault) was stopped just east of Moonlight Stream. Cox & Barrell (2007) drew as a separate entity the up-to-the-southeast fault scarp southwest of Moonlight Stream, identifying it as the ‘Neutral Creek Fault’. All three features were identified as components of the ‘Forest Creek Fault Zone’ in the Cox & Barrell (2007) digital dataset (which is incorporated here within the Timaru District digital dataset). Note that the dataset has been recently released, with some data structure revisions, by Heron (2014).

Mapped faults in the Butlers Creek valley, south of the Forest Creek valley, were identified in the Cox & Barrell (2007) digital dataset as components of the ‘Fox Peak Fault Zone’. They were shown as ‘inactive’ by Cox & Barrell (2007), but this was a tentative assignation due to a lack of data on the age of deformed gravelly strata, rather than any definitive evidence of a lack of activity. These are discussed further in relation to the Fox Creek Fault Zone (feature 5) and a newly named entity, formerly part of the Fox Peak Fault Zone, identified in this report as the ‘Ben McLeod fault’ (feature 6).

A2.3.3 Discussion

The features delineated and identified as the ‘Forest Creek Faults’ by Upton et al. (2004) and Upton & Osterberg (2007) are, in my opinion, no longer justified based on available field evidence, as encapsulated in the alternative fault interpretations published by Cox & Barrell (2007). Without doubt, there is scope for further field investigations of fault patterns and degrees of activity across the Two Thumb Range and adjacent mountain blocks. In particular, the middle reaches of Forest Creek, and its tributaries Butlers Creek and Moonlight Stream, would benefit from thorough re-evaluation, if there is a future need for any further information on fault activity in this general area.

The interpretations of faulting presented in this report, and in the report for the adjacent Mackenzie District (Barrell & Strong 2010), have implications for existing regional-scale to national-scale interpretive compilations of active fault locations and characteristics. Stirling et al. (2007, 2008) identified a ‘Lake Heron – Forest Creek Fault’, extending from Neutral Creek northeast for about 50 km to the west of Lake Heron. In the New Zealand National Seismic Hazard Model, Stirling et al. (2012) simplified the name of this feature to ‘Lake Heron’, but retained the same extent. In the New Zealand active fault model, Litchfield et al. (2014)

identified a separate ‘Forest Creek’ fault zone, extending from Lake Tekapo ~50 km northeast across the Two Thumb Range, down Forest Creek and across the Rangitata valley to the northern side of the Harper Range (Ashburton District), where it ends and the ‘Lake Heron’ fault zone commences. In regard to active faulting, at Lake Tekapo, discontinuous fault scarps identified east of Lake Tekapo (‘Coal River faults’) have a north-northeasterly trend (Cox & Barrell 2007; Barrell & Strong 2010), and there is no compelling evidence that they are associated with the northeasterly ‘Forest Creek Faults’ trend proposed by Upton et al. (2004). Therefore, there is at present no convincing evidence for a significant active fault extending northeast from Lake Tekapo on the proposed line of the ‘Forest Creek Faults’ of Upton et al. (2004). Although this line was adopted by Litchfield et al. (2014), the mapping evidence presented by Cox & Barrell (2007), and the considerations presented in this discourse, imply that it is without good foundation, and should be revised. Without doubt, more investigation is needed in the vicinity of Lake Tekapo, to try and define the extents and associations of the active faults and folds as mapped by Cox & Barrell (2007), Upton & Osterberg (2007) and Barrell & Strong (2010), and discussed by Clark et al. (2015).

A2.3.4 Forest Creek Fault Zone: Neutral Creek Fault (Feature 4a, Figure 5.1; see Figure A2.2)

This feature was first reported by Barrell et al. (1996), following its identification in aerial photos. It had not, to the writer’s knowledge, been examined in the field, until the PhD research project by Stahl (2014) (see below). The east-northeast – west-southwest trending fault scarp is prominent in aerial photos, and also clearly discernible in Google Earth. I estimate it to be typically about 5 m high, up to the south-southeast. The trace of the Neutral Creek Fault does not show prominent deflection across the topography, suggesting that it has a steep dip (Barrell et al. 1996). In places, Google Earth imagery shows that the scarp locally breaks into two or more subparallel anastomosing branches (e.g. at 43°44.453'S, 170°48.729'E), in a manner which suggests the possibility of a component of dextral strike-slip displacement. Towards its northeastern end, the expression of the scarp diminishes and it curls to the north at the western margin of the Moonlight Stream valley, beyond which is cannot be seen. Although Cox & Barrell (2007) drew an active fault (inferred) across the lower reaches of the Moonlight Stream valley, there is no indication of it across a well-preserved outwash/moraine bench, and this extension is speculative, and in my opinion should be accorded little weight. Cox & Barrell’s (2007) action in equating the fault exposure in Moonlight Stream with the Fox Peak Fault removed this difficulty, though overall, considerable uncertainty remains about fault relationships in the Moonlight Stream area.

To the west, the up-to-the-south scarp of the Neutral Creek Fault can be followed into the lower reaches of Neutral Creek, and is last evident about 2 km upstream of the Neutral Creek/Forest Creek confluence. It projects into terrain dominated by last ice-age moraines and ice-smoothed valley sides but there is no indication in aerial photographs of any fault scarps. Cox & Barrell (2007) drew a concealed continuation of the active fault farther up the valley, adjoined at its western end by a bedrock fault continuing farther west-northwest up the catchment. However, in an ice-smoothed bedrock basin at the head of Forest Creek, there is a prominent and sharp topographic step, up to the west-southwest, at representative location 43°47.136'S, 170°44.117'E. This step was shown on the Cox & Barrell (2007) unpublished 1:50,000 scale data record sheets (see reference list) as a fault scarp. It was not compiled on the published map, because it was unclear whether it was a true fault scarp, or a ‘ridge rent’ related to rock-mass relaxation. However, given its similarity to the Neutral Creek Fault scarp, both in strike direction, and sense of upthrow, it is included in this data set as a ‘definite’, ‘well expressed’ fault. The bedrock fault mapped between this location and the western end of the Neutral Creek Fault scarp in Neutral Creek are classified as ‘likely’, ‘not expressed’. At the western end of the westernmost mapped fault scarp at the head of the Forest Creek catchment is the Mackenzie/Timaru district boundary, but also at this location is the head of a large rock avalanche that has fallen into the adjacent headwaters of Coal River. No fault scarps are evident on the same trend down the valley of Coal River towards the Lake Tekapo valley. However, scarps identified as the ‘Mt Gerald faults’ by Barrell & Strong (2010) trend southeast towards the western end of the Neutral Creek Fault. Those scarps have morphological similarity to the Neutral Creek Fault. One possibility is that the ‘Mt Gerald faults’ are associated with the Neutral Creek Fault, separated from it by a northwest step-over.

An alternative possibility, and one which was adopted by Stahl (2014), is that, to the west of the Timaru District boundary, the Neutral Creek Fault swings southward along a fault zone mapped in bedrock into the catchment of the South Opuha River and Firewood Creek (Mackenzie District). Stahl (2014) referred to this bedrock fault, and the fault scarp identified here as the Neutral Creek Fault, as the ‘Forest Creek Fault’. He noted that there is no evidence, in the Mackenzie District, of offset landforms along the fault, although there is some topographic expression, in the form of elevated knobs or ridges of bedrock along the eastern, presumed up-thrown, side of the fault mapped in bedrock. The question of the extension (if any) of the Neutral Creek Fault, either south into the Two Thumb Range, as suggested by Stahl (2014) and compatible with the mapping of a fault in bedrock by Cox & Barrell (2007), or stepping northwest to the Mt Gerald faults of Barrell & Strong (2010) remains unresolved for now.

Stahl (2014) presents findings from a hand-dug trench excavated across the scarp of the Neutral Creek Fault (terminology of this report), at a location approximately 3.5 km west-southwest of Moonlight Stream. Stahl (his Figure 3.16 and Chapter 3.8) found evidence for at least 2 surface rupture events having occurred within the past ~6,000 years, based on radiocarbon dates from the trench. Interested readers should refer to Stahl (2014) for more information. The maximum elapsed time between the two ruptures defined in the trench is ~5,000 years and a working median estimate of recurrence interval is ~3,000 years, which represents the at least two ruptures in the past ~6,000 years. For the purpose of this report, a recurrence interval range of ~2,000 to ~5,000 years is adopted (3,500 ± 1,500 years).

A2.3.5 Forest Creek Fault Zone: Butler Downs 1 fault (Feature 4b, Figure 5.1; see Figure A2.2)

This comprises an up-to-the-northwest fault/fold scarp trending north-northeast across the moraine benches and kame terraces of Butler Downs. Its identification is based on a one-day walkover inspection by the writer in 2002, as part of the compilation of the Cox & Barrell (2007) map. Although shown as a fault on that map, it is largely a monoclinal flexure, as much as ~10 m high, and commonly between 100 and 200 m wide, based on visual inspection. More detail of its mapping is shown on the Cox & Barrell (2007) unpublished 1:50,000 scale data records sheets (see reference list). This fault/fold feature is classified as a component of the Forest Creek Fault Zone in the QMAP digital dataset (Cox & Barrell 2007; Heron 2014). The term ‘Butler Downs 1 fault’ is applied in this report to identify this tectonic entity on its own merits, and to highlight that there is considerable uncertainty in relating it to other mapped fault features, including the fault offset in Moonlight Stream, the Neutral Creek Fault, and the northerly-striking faults identified in the Butlers Creek valley.

This feature would undoubtedly benefit from more thorough examination and mapping in the field. It would be particularly desirable to try and determine its relationship, if any, to the fault offset exposed in Moonlight Stream, as described by Upton et al. (2004). For example, it would not surprise the writer if future more detailed research were to show that the Butler Downs 1 fault is associated with the reverse fault exposed in Moonlight Stream, and that both represent a northerly continuation of the Fox Peak Fault Zone.

For the purposes of estimating recurrence interval, a vertical component of offset of 10 m is estimated on landforms of assumed age of 18,000 years, returning an average slip rate of 0.6 mm/yr. Assuming an average vertical component of single-event displacement of 2 m and applying a 67% uncertainty, a recurrence interval in the range of 1,200 to 6,000 years is indicated (Table 5.2 of the main report).

In the NZAFM (Litchfield et al. 2013, 2014) this feature is identified as the 'Potts River fault zone' and inferred to extend some 35 km to the north-northeast to connect with a fault mapped in bedrock in the Potts River (Cox & Barrell 2007). A limitation of this interpretation is that for some 6 km between the Rangitata River and Potts River, the fault lies beneath exceptionally well-preserved glacial landforms, and these show no sign, in aerial photos, or during walkover inspection of that area by the writer in 2013, of having been affected by tectonic deformation. This erodes confidence in the idea that the Butler Downs fault 1 continues in that direction. No slip rate is assigned by Litchfield et al. (2013, 2014), and the fault is not included in the NSHM (Stirling et al. 2012).

A2.3.6 Forest Creek Fault Zone: Butler Downs 2 fault (Feature 4b, Figure 5.1; see Figure A2.2)

This comprises an up-to-the-southeast fault/fold scarp trending northeast for ~9 km across the moraine benches and kame terraces of Butler Downs. It was first depicted, in very generalised form, on the geological map of Gair (1967). It is relatively easy to discern on vertical aerial photographs, but difficult to discern in Google Earth. It was examined briefly in the field during a one-day walkover inspection by the writer in 2002, as part of the compilation of the Cox & Barrell (2007) map. It is as much as 10 m high. The northeastern ~4 km is relatively sharp in expression and can be regarded as a fault scarp, while farther southwest becomes as much as ~100 m broad, and is better regarded as a monoclinal flexure. Cox & Barrell (2007) showed the entire feature as a fault rather than a monoclinal fold, although details of sectors mapped as a fault versus monoclinal fold are shown on the Cox & Barrell (2007) unpublished 1:50,000 scale data records sheets (see reference list). To the northwest is a subparallel though shorter (~3 km long) tectonic warp of the glacial landforms, also up-to-the-southeast, no more than ~5 m high and as much as 100 m broad. This is also shown by Cox & Barrell (2007) as a fault.

Both are classified as components of the Forest Creek Fault Zone in the QMAP digital dataset (Cox & Barrell 2007; Heron 2014). The term 'Butler Downs 2 fault' is applied in this report to identify these two fault/fold features as an entity on their own merits, and to highlight that there is considerable uncertainty in relating them to other mapped fault features, including the fault offset on Moonlight Stream, the Neutral Creek Fault, and the northerly-striking faults identified in the Butlers Creek valley. The Butler Downs 2 fault/fold features would undoubtedly benefit from more thorough examination and mapping in the field. It would be particularly beneficial to try and determine whether these features bear any relationship to other faults in the general vicinity. Objectives of any further investigation would be to try and ascertain if there is any relation between the Butler Downs 2 fault and faults mapped in the Balmacaan Saddle area (Balmacaan Fault; Barrell & Strong 2009), or with the Neutral Creek Fault (which has a similar sense of throw). Another possibility worth investigating is whether there is any relation to south-east dipping thrust faults identified on the eastern side of the Butlers Creek valley, referred to as the Eastern Fox Peak Fault by

Upton et al. (2004) (but note findings reported by Stahl (2014)), and referred to in this report as the 'Ben McLeod fault'.

For the purposes of estimating recurrence interval for the Bulter Downs 2 fault, a vertical component of offset of 10 m is estimated on landforms of assumed age of 18,000 years, returning an average slip rate of 0.6 mm/yr. Assuming an average vertical component of single-event displacement of 2 m and applying a 67% uncertainty, a recurrence interval in the range of 1,200 to 6,000 years is indicated (Table 5.2 of the main report).

In the NZAFM (Litchfield et al. 2013, 2014) this feature is approximated by an entity called the 'Forest Peak fault zone', for which a steep southeast dip is inferred, along with a predominantly reverse sense of displacement, and slip rate in the range of 0.4 to 2.8 mm/yr, with a preferred value of 0.9 mm/yr. The slip rate is inferred from the Lake Heron fault zone in the Ashburton District (Litchfield et al. 2013), though it should be noted that the Lake Heron Fault is a reverse fault with an opposite direction of dip (i.e. to the northwest), so the application of its slip rate estimate to the Forest Creek fault zone warrants being treated with some caution. In the NSHM (Stirling et al. 2012), the entity identified here as the Butler Downs fault 2 is closely approximated by an entity identified as the Lake Heron Fault, drawn in a slightly different location to the Forest Creek fault zone of the NZAFM. The NSHM entity is assigned a northwesterly dip in the range of 45 to 70°, and preferred slip rate of 1 mm/yr. Thus there is an inherent incompatibility in the information between the NZAFM and NSHM which would be desirable to resolve in future iterations of those datasets. As matters stand, the single-event displacement of 3.5 m and recurrence interval of 3348 years calculated in the NSHM dataset should be treated with caution until these dataset incompatibilities are resolved.

A2.4 FOX PEAK FAULT ZONE (FEATURE 5, FIGURE 5.1; SEE FIGURE A2.2)

The Fox Peak Fault displays prominent offset of landforms along the northern side of the Fairlie basin, in the Mackenzie District (Barrell & Strong 2010; Stahl 2014). Towards the north, the evidence for displacement diminishes, and the fault cannot be readily traced into the headwaters of Butlers Creek (Timaru District), despite the presence of widespread and well-defined glacial landforms, of presumed age ~18,000 years, in the Butlers Creek headwaters (Stahl 2014). Stahl (2014) concluded that although there are fault zones in the Butlers Creek valley, the most recent activity on the Fox Peak Fault has not extended that far. I am cautious about adopting a strong interpretation on this, given that particularly in the lower reaches of Butlers Creek, there is little knowledge of the age of landforms, or of gravelly sediments that have been deformed adjacent to exposed faults. For example, it could be that the high topographic elevation of Butlers Saddle meant that the most recent Fox Peak Fault ruptures may not have 'daylighted' at the ground surface at the elevation of the saddle, but this does not necessarily mean that they did not re-emerge farther north in areas of lower topography in the middle to downstream reaches of Butlers Creek.

For the purposes of this report, the Fox Peak Fault Zone strand on the western side of Butlers Creek (the 'Western Fox Peak Fault' of Upton et al. (2004)), and which is incorporated within the QMAP dataset, is classified as a 'likely' active fault in the Timaru District dataset. It is tentatively assigned a recurrence interval of at least 10,000 years, due to the lack of positive evidence for recent offsets, as discussed by Stahl (2014), but noting that further work, as discussed in relation to the Forest Creek Fault Zone in the preceding section, would be beneficial.

For the purposes of this report, the lack of evidence for offset of landforms estimated to be ~18,000 years old by the Fox Peak Fault Zone within the Timaru District has led to a recurrence interval of more than 10,000 years being assigned to this fault zone in the Timaru District. The lack of identified offsets means that in this report no estimate of slip rate is made for this fault in the Timaru District (Table 5.2 of the main report).

In the NZAFM (Litchfield et al. 2013, 2014), a generalised depiction of this fault ('Fox Creek fault zone') is assigned a northwesterly dip in the range of 45 to 55°, a predominantly reverse, with minor right-lateral, sense of movement, and net slip rate in the range of 0.4 to 4.4 mm/yr, with a preferred value of 2.2 mm/yr. The NSHM version of the Fox Peak Fault is identical in location to that of the NZAFM, and is assigned the same parameters, except that the preferred slip rate value is 1.8 mm/yr. The NSHM calculates a single-event displacement of 3.5 m and recurrence interval of 1979 years. The values in these datasets would benefit from re-evaluation in light of the data presented by Stahl (2014).

The feature identified as the 'Eastern Fox Peak Fault' by Upton et al. (2004), and discussed by Stahl (2014), is identified in this dataset as the 'Ben McLeod fault' and is described below.

A2.5 BEN MCLEOD FAULT (FEATURE 6, FIGURE 5.1; SEE FIGURE A2.2)

There is a conceptual difficulty in regard to the eastern component of the Fox Peak Fault Zone in the lower reaches of Butlers Creek ('Eastern Fox Peak Fault' of Upton et al. 2004), and discussed further by Stahl (2014). Because it is a reverse fault dipping east at a low to moderate angle, it must be a separate and essentially unrelated fault to the western component of the Fox Peak Fault Zone ('Western Fox Peak Fault' of Upton et al. 2004), which is a reverse fault dipping at a low to moderate angle northwest. I take the view that the eastern fault in Butlers Creek is most likely the fault upon which the Ben McLeod Range has, over perhaps millions of years, been uplifted to topographic prominence overlooking the lower reaches of Forest Creek and the adjacent Butler Downs to the north. In the Timaru District dataset, it is given the name 'Ben McLeod fault', classified as a 'likely' active fault, and tentatively assigned a recurrence interval of at least 10,000 years, due to the lack of positive evidence for recent offsets. Further field investigation of this feature, in relation to this proposed new interpretation, would be advantageous, should there be a future need for any further information on this fault.

As this fault is newly defined as active, it is not included in current versions of the NSHM (Stirling et al. 2012) or the NZAFM (Litchfield et al. 2013, 2014).

A2.6 HEWSON FAULT (Feature 7, Figure 5.1; see Figure A2.3)

This northwest-southeast striking fault is identified from bedrock relationships, notably towards its northern end where Mt Somers Volcanics are downfaulted to the east against greywacke basement. Oliver & Keene (1990) reported a displacement of landforms at the fault, but did not specify the amount of offset. The scarp is vaguely discernible in aerial photos, from which I infer that the offset is not very large. For the purpose of estimating slip rate and recurrence interval, I assume a vertical component of offset of 3 m, and an age for the offset land surface of 18,000 years. Both are tentative assumptions. On account of the poor representation of the fault in aerial photos, and not knowing what nature or quality of physical evidence Oliver & Keene (1990) drew upon in interpreting the fault to be active, the Hewson Fault is classified in this dataset as a 'likely' active fault. The estimates of the amount of offset and the age of the offset landforms given above imply a vertical component of slip rate of 0.2 mm/yr. Assuming an average vertical component of single-event displacement of 2 m and applying a 67% uncertainty, a recurrence interval in the range of 4,000 to 20,000 years is indicated (Table 5.2 of the main report).

This fault is identified in the NSHM (Stirling et al. 2012) and the NZAFM (Litchfield et al. 2013, 2014) as the 'Quartz Creek' fault or fault zone. This appears to be an interpretation error from the map of Oliver & Keene (1990), who identified the northeast-southeast striking Hewson Fault, which is the feature delineated in the NSHM and NZAFM, as well as a much shorter west-northwest-east-southeast striking feature, named the Quartz Creek Fault, on which they reported a short recent trace at its western end. It appears that the NSHM and NZAFM have erroneously applied the name Quartz Creek to the entity defined by Oliver & Keene (1990) as the Hewson Fault. In this report, the name Hewson Fault is applied, following the mapping of Oliver & Keene (1990) and adopted in the QMAP dataset. It would be desirable for future iterations of the NSHM and NZAFM to correct this error of nomenclature. In the NZAFM, the Hewson Fault (as used in this report) is classified as a steeply southwest-dipping reverse fault, with a net slip rate in the range of 0.1 to 0.2 mm/yr and a preferred value of 0.15 mm/yr. The NSHM assigns a preferred slip rate of 0.2 mm/yr and a recurrence interval of 5,000 years.

A2.7 COAL CREEK FAULT (FEATURE 8, FIGURE 5.1; SEE FIGURE A2.3)

The existence of the Coal Creek Fault is established from offset of different types of bedrock. It is a northwest-striking, southwest-dipping thrust fault (Oliver & Keene 1990). Because it is a significant range-bounding fault, having uplifted the Tara Haoa Range relative to Tertiary-age strata preserved in a trough to the east, it is included in this dataset as a 'possible' active fault, even though there is no indication along it of any fault scarps. It is tentatively assigned a recurrence interval of >10,000 years, due to the lack of positive evidence for recent offsets. For that reason, no slip rate estimate is made.

As this fault is newly defined as a possible active fault, it is not included in current versions of the NSHM (Stirling et al. 2012) or the NZAFM (Litchfield et al. 2013, 2014).

A2.8 KLONDYKE-MOORHOUSE FAULT (FEATURE 9, FIGURE 5.1; SEE FIGURE A2.3)

On the south bank of the Rangitata River (i.e. within the Timaru District), this is represented by a definite fault scarp, which transitions southward into a monoclinal fold across a rising flight of river terraces (Figure 3 of main report). The name was assigned by Barrell & Strong (2009), who inferred a correlation between the fault/fold scarp at the Rangitata River and a fault mapped in bedrock aligned roughly north-south along the eastern foot of the Moorhouse Range (Ashburton District). At river level on the south side of the Rangitata, the fault is exposed, comprising a near-vertical fault plane across which greywacke bedrock has been displaced up to the northwest against river gravel (Barrell et al. 1996).

Towards the southwest (Timaru District), the monoclinal fold can be traced to the highest terrace level, by which location it is about 100 m wide, while being only 2 m high. It is really only visible at the terrace edge, and cannot be discerned farther southwest, where its location is a matter of guesswork. Probably it trends southward along the western edge of the river valley, but due to a lack of evidence for its location, or indeed whether it continues rather than just dying out, no attempt has been made to map the fault in that direction. The problem is exacerbated by there being no exposure of the bedrock in that area, to determine for example whether a fault exists in bedrock (e.g. a continuation of the fault bounding the eastern foot of the Moorhouse Range). Insofar as the topographic relief represents by the Moorhouse Range dies out southwards of the Rangitata River, it is possible that the Klondyke-Moorhouse fault similarly dies out as a surface-rupturing entity.

The ~2 m high scarp crosses the lowest terrace surface of the Rangitata River, the age of which is unknown but presumed to be Holocene, and is no higher on the adjacent higher terraces, the highest of which is estimated to be ~18,000 years old. This implies an average vertical component of slip rate of 0.1 mm/yr. Assuming an average vertical component of single-event vertical component of displacement of 2 m and applying a 67% uncertainty, a recurrence interval in the range of 6,000 to 30,000 years is indicated (Table 5.2 of the main report).

This fault has not been included in either the NSHM (Stirling et al. 2012) or the NZAFM (Litchfield et al. 2013, 2014).

A2.9 PEEL FOREST FAULT (FEATURE 10, FIGURE 5.1; SEE FIGURE A2.4)

This feature, named by Barrell et al. (1996), forms a prominent scarp aligned broadly northeast-southwest and up to the northwest, near the foot of the hills forming the inland edge of the Canterbury Plains between the Orari and Rangitata rivers. For the most part the scarp is several tens of metres wide, and as much as ~7 m high. Although it is depicted by Cox & Barrell (2007) as a fault, it includes a considerable component of monoclinal folding at the ground surface, as illustrated in Barrell et al. (1996).

At the edge of the Rangitata River channel, the fault is depicted in the Timaru District dataset as bending northwards, in order to meet the southwest end of a similar scarp on the northeastern side of the river (Ashburton District). Collectively, all these features are grouped as the 'Geraldine-Mt Hutt Fault System', a term adopted in the Ashburton District report (Barrell & Strong 2009) and conceptually includes the features identified here as the Peel Forest Fault and the Waihi fault. It was intended to formalise the fault system name in a journal paper, referred to in the Ashburton District report as 'Barrell et al. 2009 in prep', but this has not yet eventuated. In the QMAP digital dataset (Cox & Barrell 2007; Heron 2014), it is identified as the 'Cant Range Front Fault Zone'. The same general entity is rendered at a very generalised way in the 'national'-scale fault datasets within the New Zealand National Seismic Hazard Model (Stirling et al. 2012) and in the New Zealand Active Fault Model (Litchfield et al. 2014), both of which identify the entity by the name 'Hutt Peel'. This is a generalisation of the name 'Mt Hutt - Mt Peel Fault Zone' used by Pettinga et al. (2001). The reason that Barrell & Strong (2009) applied the name 'Geraldine-Mt Hutt Fault System' is to allow inclusion of the Cox & Barrell (2007) identification of active fault features continuing southwest of Mt Peel towards the Geraldine area (as the Waihi fault).

In the interests of clarity, the names of the recognisable and mappable entities (Peel Forest Fault and Waihi fault) are emphasised in the present report, rather than the overarching conceptual fault system terms.

The Peel Forest Fault can be traced to the northeastern edge of the Orari River channel, but no definitive continuation has been identified on the southwestern side of the river. Cox & Barrell (2007) inferred a southward continuation along the eastern edge of low hills at the margin of the Orari River valley (see Waihi fault section). This uncertainty of inter-relationships is why a boundary is marked at the Orari River between the Peel Forest Fault and the Waihi fault.

Useful views of the Peel Forest Fault scarp can be obtained on Rangitata Gorge Road, which rises, and curves, across the fault scarp about 100 m northwest of the Peel Forest Outdoor Pursuits Centre. The scarp is notably much broader than a typical river-cut terrace edge. The fault scarp is also crossed by the Orari Gorge Road, about 1.2 km northwest of its intersection with Sowerby Road, where the scarp is a little sharper and about 4 m high.

Assuming an overall vertical component of offset of ~7 m, on landforms assumed to be ~18,000 years old implies an average vertical component of slip rate of 0.4 mm/yr. Assuming an average vertical component of single-event vertical component of displacement of 2 m and applying a 67% uncertainty, a recurrence interval in the range of 1,700 to 8,500 years is indicated (Table 5.2 of the main report).

The NHSM identifies this fault feature as the 'Hutt-Peel South' fault source, assigns a length of 45 km, northwesterly dip of 60° and slip rate of 0.5 mm/yr, and calculates a single-event displacement of 3.1 m and recurrence interval of 6,268 years. In contrast, the NZAFM depicts a length of 65 km, a northwesterly dip in the range of 45 to 65° (55° preferred value), and slip rate in the range of 0.2 to 2.0 mm/yr, with a preferred value of 0.8 mm/yr. The 'Hutt-Peel South' entity represented in these datasets includes the Waihi fault that is discussed in the next section.

A2.10 Waihi Fault (Feature 11, Figure 5.1; see Figure A2.4)

The Waihi fault is most clearly expressed on the northeastern side of the Waihi River, across a relatively high, loess-covered terrace mapped as 'Q6a' by Cox & Barrell (2007), indicating that it is inferred to have formed during the penultimate glaciation (nominally between ~190,000 and ~130,000 years ago). There, the Waihi fault comprises a definite fault scarp, trending north-northeast and up to the south-southeast, about 4 m high and two 'likely' near-parallel monoclines, both up to the west-southwest, the largest ~8 m high, and the other, more eastward one about 4 m high. The monoclines are interpreted to represent two primary near-breakouts of a reverse fault or thrust, while the fault scarp is presumed to be a secondary back-fault that has splintered off the main fault at depth. Collectively, the estimated vertical separations of these features were summed, yielding a value of 16 m, which was then divided by an assigned age for the deformed river terrace of 140,000 years, in order to obtain estimates of slip rate of 0.1 mm/yr and recurrence interval in the range of 6,000 to 30,000 years (Table 5.2 of main report). As noted below, the evidence points towards there having been no identifiable surface rupture within the past 18,000 years on the Waihi fault, suggesting that the recurrence interval is likely to be towards the older end of this range.

On the southwestern side of the Waihi River, there is a prominent and extensive terrace with minimal loess cover but a well-developed soil profile, that is inferred to date from the end of the last glaciation ('Q2a'; Cox & Barrell 2007), across which there no discernible fault scarp. The indication is that there has not been a surface rupture of the Waihi fault since at least 18,000 years ago. Farther to the southwest, Cox & Barrell (2007) drew an inferred continuation of the fault across low rolling hill terrain, where the location and character of the fault is speculative at best. Closer to the Hae Hae Te Moana River, the fault becomes clearly expressed as a broad scarp, as much as 10 m high on an old terrace of presumed middle Quaternary age, and a lesser scarp, as much as 5 m high, on an undulating terrace mapped as 'Q4a' by Cox & Barrell (2007), presumed to be about 60,000 years old.

Farther to the southwest, a broad monocline is inferred across low rolling hills before a north-south trending range-front is encountered, inferred to be a bedrock fault uplifted to the west, against which the Waihi fault is inferred to end.

A useful view of the Waihi fault scarp can be obtained at the intersection of Wooding Road and Mees Road, approximately 9 km west-northwest of Geraldine towards Hae Hae Te Moana Gorge. About 200 m west-northwest of the intersection, Mees Road ascends a ~10 m high broad fault scarp. To the southwest, Wooding Road sidles across a smaller fault scarp that runs across a river terrace.

The contrast in degree of activity between the Waihi fault, which gives compelling indications of not having experienced surface rupture in the past ~18,000 years, and the Peel Forest Fault which is prominent across river plains of assumed age 18,000 years, provides good reason for treating them as separate entities for the purposes of this report. Whether they have entirely separate rupture histories (i.e. are two unrelated faults), or whether ruptures involving the Peel Forest Fault have only rarely extended southwest along the Waihi fault, remains to be established.

A point to note is that in a digital dataset on active faults developed by Environment Canterbury in the 1990s-2000s, discontinuous active fault strands, identified as part of the Mt Hutt – Mt Peel Fault Zone in the dataset, extend south-southeast from the western end of the entity that is mapped here as the Waihi fault, along the western side of the Hae Hae Te Moana River towards the Rangitira Valley, southwest of Geraldine. Although the Pettinga et al. (1998) report is given as a source, there appears to be no depiction of these fault strands in the maps in that report, and there is no description or discussion of them. Based on my field examination of these areas during compilation of the Cox & Barrell (2007) map, including examination of aerial photos, I have not found any convincing indications of topographic anomalies or landform offsets at the location of these features, and so they are not included in the present dataset.

As noted in Section A2.9, the Waihi fault is currently included in the 'Hutt-Peel' fault entity of the NSHM and NZAFM.

A2.11 BROTHERS FAULT (FEATURE 12, FIGURE 5.1; SEE FIGURE A2.5)

The Brothers Fault forms a very striking linear escarpment aligned north-northwest – south-southeast along the western margin of the Brothers Range, and associated areas of high ground from near Fairlie (Mackenzie District) to ~10 km south-southeast of Cave. It is without doubt a substantial fault in bedrock, with greywacke bedrock on its eastern side upthrown against Tertiary cover rocks on the western side. Its topographic prominence led to it being proposed as an active fault at the time of regional earthquake hazard assessments undertaken during the late 1990's for the Waitaki valley hydroelectric facilities, to which the writer was a contributor. There was however no direct evidence for activity on the Brothers Fault. Nonetheless, it was first listed as an active fault by Stirling et al. (2007, 2008), and is also included in the National Seismic Hazard Model (Stirling et al. 2012) and in the New Zealand Active Fault Model (Litchfield et al. 2014).

There is a range of terrace and alluvial fan landforms across the Brothers Fault, which show no indication of fault offsets, and nowhere along the fault has a Quaternary-age offset yet been convincingly demonstrated. There is good stratigraphic evidence that the Brothers Fault was initiated prior to the Quaternary; uplift, tilting and erosion of the upthrown side of the Brothers Fault between Cave and Timaru occurred prior to the eruption of the Timaru Basalt sheet ~2.5 million years ago (Barrell 2008; Barrell & Strong 2012). It is possible that the topographic prominence of the Brothers Fault escarpment relates to the presence of hard greywacke rock on its upthrown side, rather than necessarily requiring any recency of movement. For the purposes of this report, the Brothers Fault is identified as a 'possible' active fault, and a recurrence interval of no less than 10,000 years is nominally assumed. This acknowledges that evidence may yet emerge for relatively recent activity of the fault, but also underscores that the average slip rate is undoubtedly very slow, otherwise there should be more geomorphic indications of offset landforms. Further discussion is provided in the active fault report for the Waimate and Waitaki districts (Barrell 2016), in relation to the

Brothers Fault, the associated anticline on the upthrown side of the southern sector of the fault, and possible southeast-ward extensions of this fault.

The Brothers Fault 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 Waimate and Waitaki districts active fault 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 Timaru District is also classified as 'possible'.

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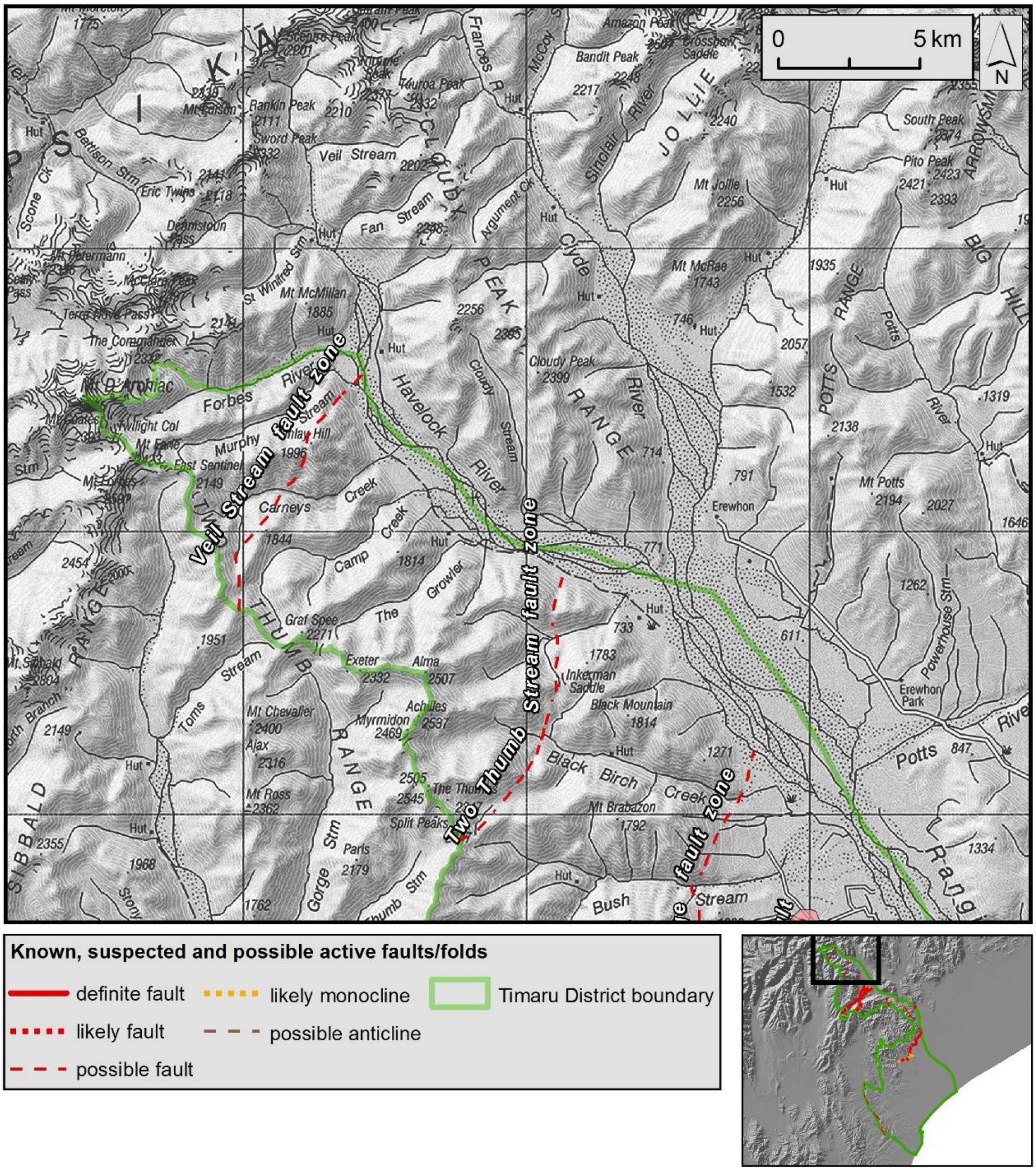

Figure A2.1 The possible active faults/folds of the northwestern sector of the Timaru District plotted on a greyscale version of topographic map Topo250 (Land Information NZ, Crown Copyright reserved). The map area is shown in the context of the Timaru District in the index map at lower right. Fault or fold entities that consist only of 'possible' features are labelled in smaller font than fault or fold entities that include 'definite' or 'likely' features.

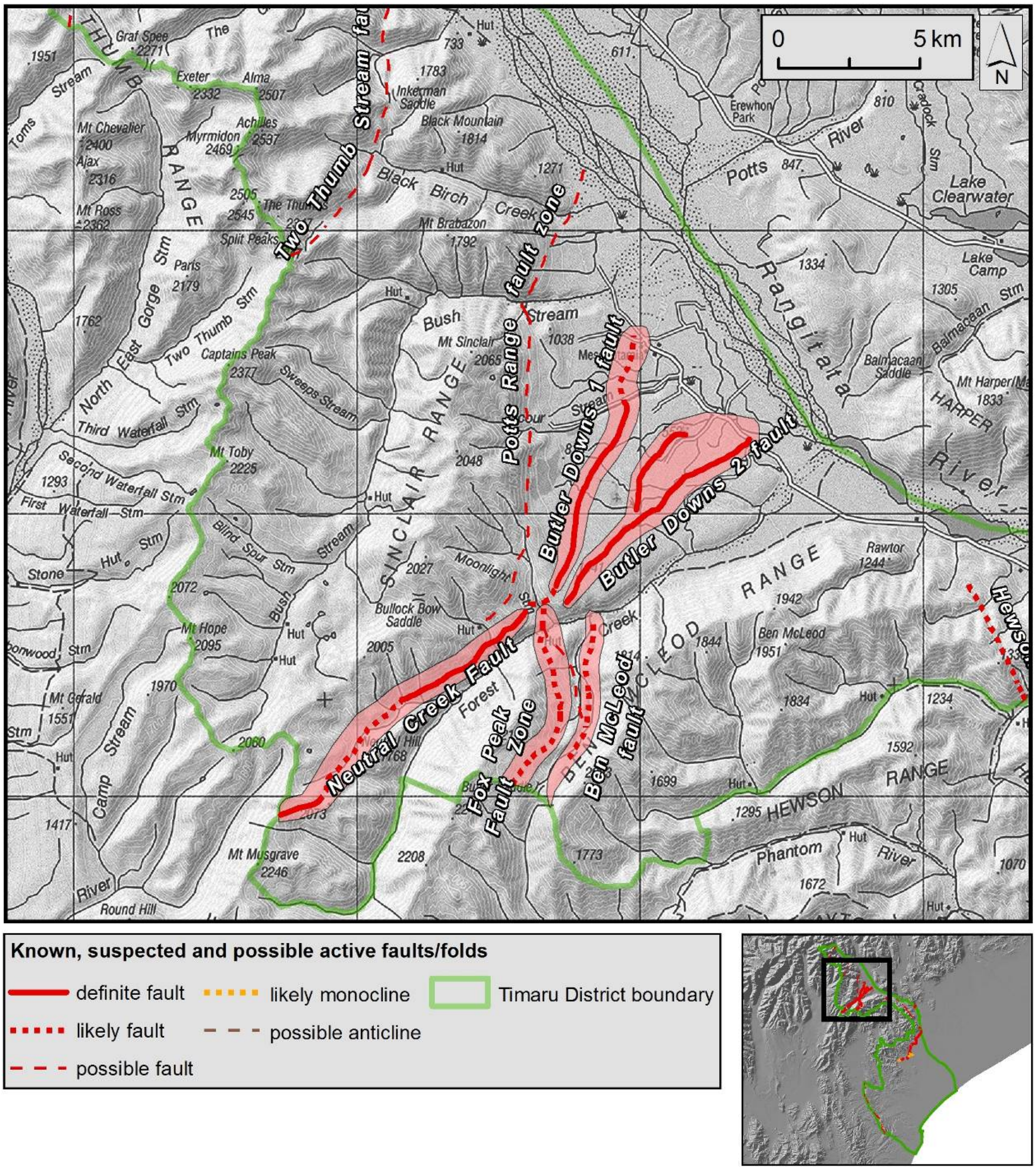

Figure A2.2 The known, suspected and possible active faults/folds of the inland western sector of the Timaru District plotted on a greyscale version of topographic map Topo250 (Land Information NZ, Crown Copyright reserved). The pink areas simply indicate groupings of faults or folds that collectively 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 (i.e. they do not represent avoidance zones). The map area is shown in the context of the Timaru District in the index map at lower right. Fault or fold entities that consist only of 'possible' features are labelled in smaller font than fault or fold entities that include 'definite' or 'likely' features.

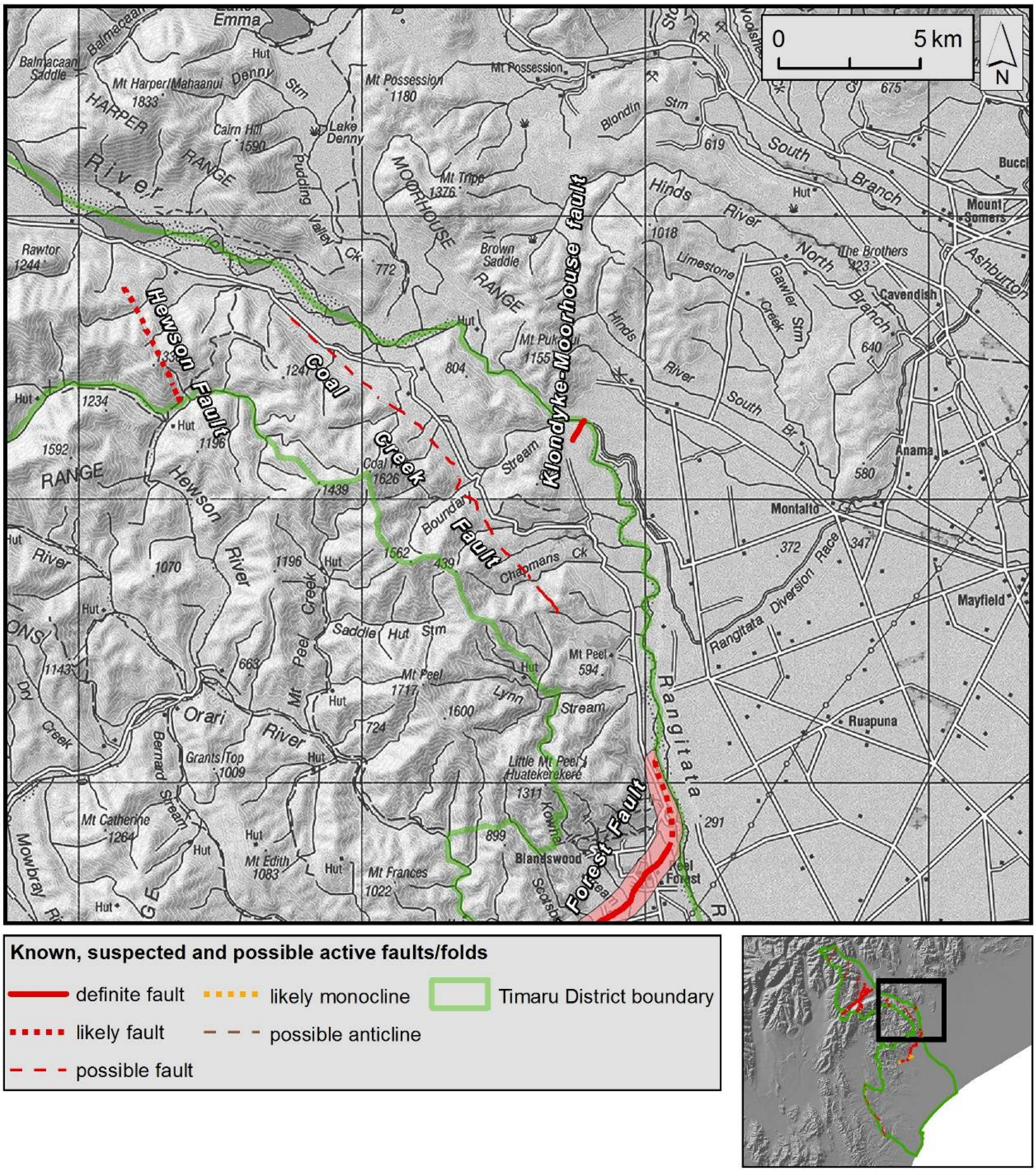

Figure A2.3 The known, suspected and possible active faults/folds of the inland eastern sector of the Timaru District plotted on a greyscale version of topographic map Topo250 (Land Information NZ, Crown Copyright reserved). The pink areas simply indicate groupings of faults or folds that collectively 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 (i.e. they do not represent avoidance zones). The map area is shown in the context of the Timaru District in the index map at lower right. Fault or fold entities that consist only of 'possible' features are labelled in smaller font than fault or fold entities that include 'definite' or 'likely' features.

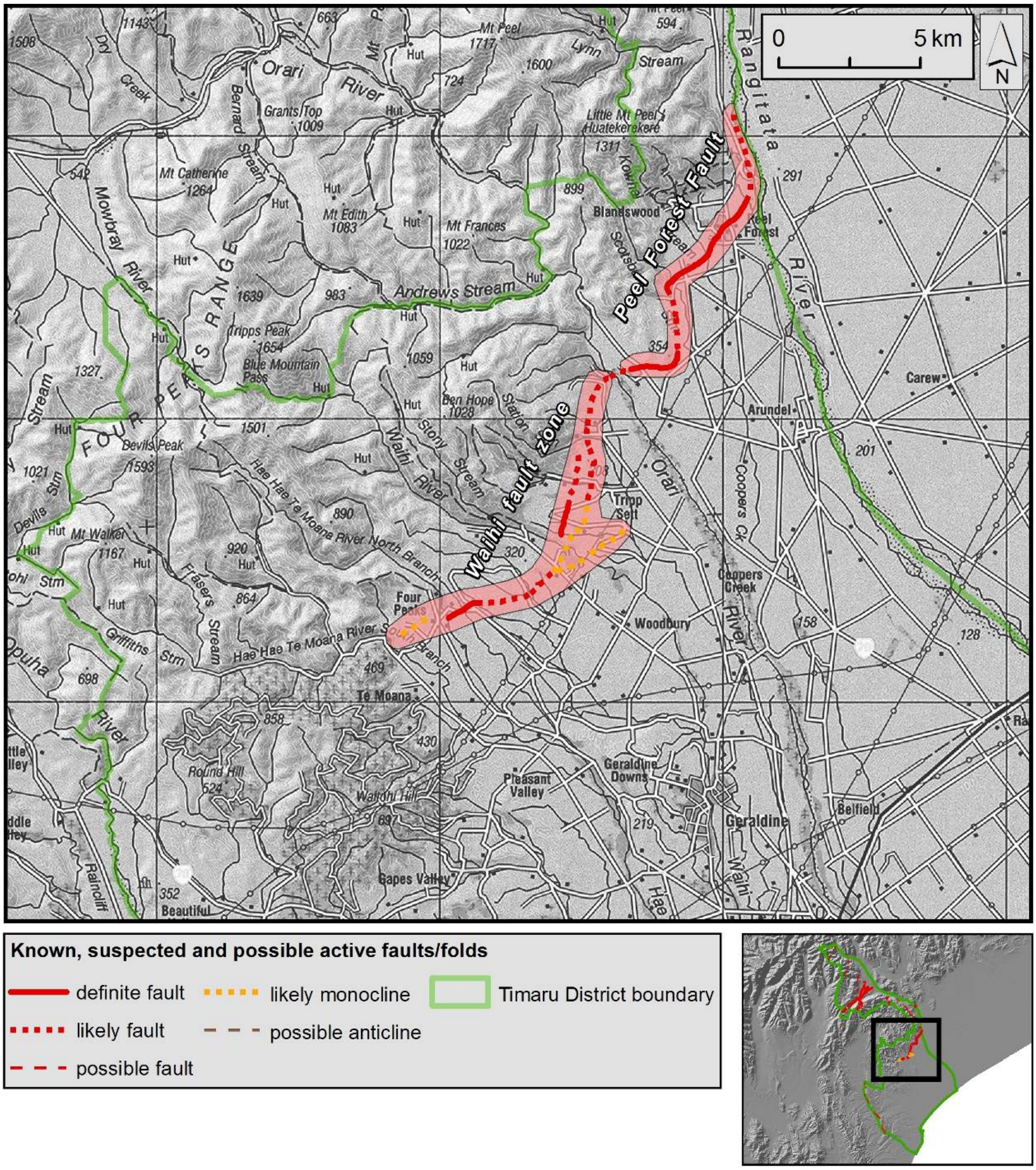

Figure A2.4 The known and suspected active faults/folds of the northwestern plains sector of the Timaru District plotted on a greyscale version of topographic map Topo250 (Land Information NZ, Crown Copyright reserved). The pink areas simply indicate groupings of faults or folds that collectively form 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 (i.e. they do not represent avoidance zones). The map area is shown in the context of the Timaru District in the index map at lower right. Fault or fold entities that consist only of 'possible' features are labelled in smaller font than fault or fold entities that include 'definite' or 'likely' features.

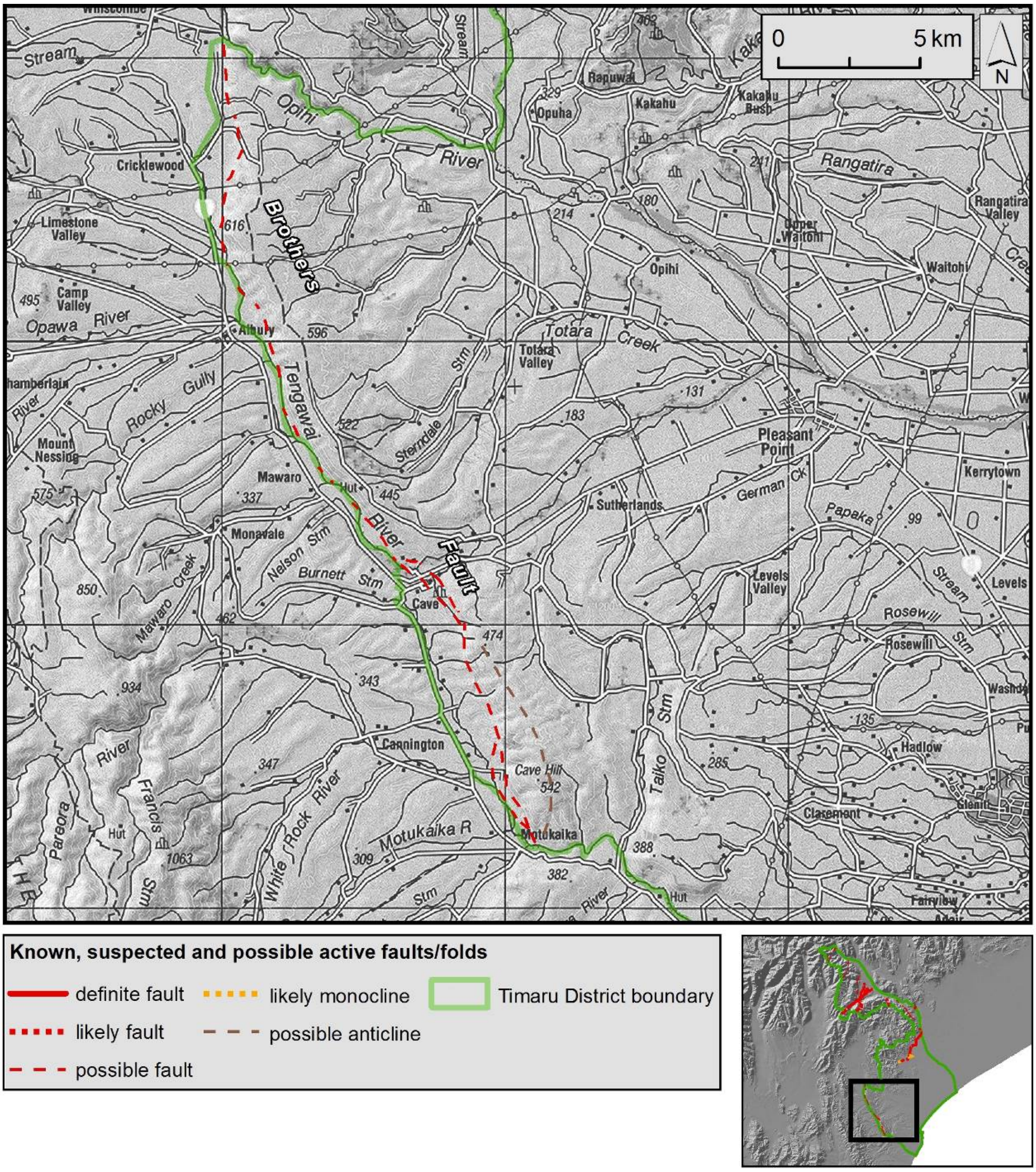

Figure A2.5 The possible active faults/folds of the southwestern sector of the Timaru District plotted on a greyscale version of topographic map Topo250 (Land Information NZ, Crown Copyright reserved). The map area is shown in the context of the Timaru District in the index map at lower right. Fault or fold entities that consist only of ‘possible’ features are labelled in smaller font than fault or fold entities that include ‘definite’ or ‘likely’ features.

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