General distribution and characteristics of active faults and folds in the Waimakariri District, North Canterbury

D. J. A. Barrell J. G. Begg

GNS Science Consultancy Report 2012/326
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EXECUTIVE SUMMARY

This report presents a general outline of the characteristics of active geological faults and folds in the Waimakariri District. The report highlights the approximate ground-surface locations of recognised active faults and folds and provides estimates of their degrees of activity. The report is intended to raise awareness of active faults and folds in the Waimakariri District, to assist land-use planning in regard to fault/fold-related hazards, and to provide a knowledge foundation for future work that addresses fault/fold-related hazard avoidance or mitigation.

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 (e.g. the last 125,000 years or so). In order for us to recognise a fault or fold as being active, it needs to have experienced movement(s) large enough to have emerged at the ground surface, forming offset and breakage of the ground (fault) or buckling or tilting of the ground (fold). Active faults and folds are most readily detected in areas of relatively old landforms, such as river plains formed during the last ice age which ended about 18,000 years ago. Some landforms, such as eroding hill slopes or recently abandoned river floodplains, may be younger than the most recent fault or fold movements, and thus 'conceal' the presence and location of any active faults or folds. In this way, one can recognise active faults or folds in some places (e.g. beneath ice-age river terraces), but elsewhere the existence or location of any active faults or folds may be uncertain (e.g. beneath young river floodplains).

Where an active fault is recognisable at the ground surface, it is testament to the past occurrence of ruptures large enough to have reached the ground surface. When a fault that is capable of surface rupture does rupture, it is likely to produce a large earthquake of magnitude somewhere between the high sixes and mid- to high sevens. 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. around six), although this is not necessarily the case.

Regional geological mapping has detected 15 areas of known or suspected active faults or folds at the ground surface in Waimakariri District. This report is accompanied by Geographic Information System (GIS) datasets, showing the locations of the recognised active faults and folds. The datasets identify the levels of certainty with which active faults and folds are recognised. This is done because in some places it is clear beyond doubt that a feature is an active fault or fold, but in other places, the evidence is less certain. Each fault/fold feature is assigned an estimated average slip rate and an average recurrence interval. These values express the degree of activity of a particular fault. Recurrence interval provides a 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, or near, active faults.

Potential hazards associated with active faults or folds in the Waimakariri District include: (i) strong ground-shaking and associated phenomena (e.g. landslides or liquefaction) resulting from shallow large-magnitude earthquakes centred within the district, and affecting a wide area, as well as (ii) the effects of sudden ground surface offset or buckling which may result,

for example, in the destruction or tilting of buildings or the disruption of electricity/water supply infrastructure or transport routes, in the immediate vicinity of the fault or fold. The nature of hazards posed by active faults was demonstrated recently on the Canterbury Plains during the 2010 Darfield Earthquake that resulted in ground-surface rupture, and sideways land shift, on the Greendale Fault, as well as damage due to ground shaking across the central Canterbury area. Of note is that the Greendale Fault was unknown prior to the earthquake, because it lay concealed beneath the gravels of the Canterbury Plains. Although no large historic earthquakes have been centred in the Waimakariri District, several centred nearby have caused shaking damage and localised liquefaction, such as the 1888 North Canterbury Earthquake, the 1901 Cheviot Earthquake, the 1922 Motunau Earthquake, and the Darfield Earthquake.

The landform geological record shows clear evidence for prehistoric deformation at several locations within Waimakariri District, and highlights that it would be prudent to treat these active fault or fold features as potentially hazardous. Based on available estimates of the amounts of deformation over time, the Lees Valley Fault, the Knowles Top fault zone, the Starvation Hill fault and the Ashley Fault Zone, appear to be the most active features in the district. Other faults in the district appear to be somewhat less active. The Starvation Hill fault, whose presence is suspected from landform evidence but whose existence is yet to be proved by geological data, passes through Oxford township. Further evaluation is recommended to determine whether it is an active fault, and if so whether it is sufficiently active to warrant consideration in land-use planning and the adoption of hazard avoidance measures. The Ashley Fault Zone is close to rural-residential developments in the Ashley and Loburn areas.

The active faults and folds of the Waimakariri District have, for the most part, been mapped at a regional scale, for example at 1:250,000-scale, where 1 cm on a map represents 2.5 km on the ground. Information presented 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 Waimakariri District. The only fault in the district that has been mapped in sufficient detail to allow fault hazard avoidance zonation to be undertaken is the Ashley Fault Zone north of Rangiora, between the Okuku and Makerikeri rivers. An assessment and zonation of this fault zone is scheduled to be done in mid-2013. Elsewhere in the district, where this report highlights the definite or likely presence of active faults or folds, more detailed site-specific investigations of faults should be undertaken before any fault hazard avoidance zoning is attempted.

1.0 INTRODUCTION

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 Waimakariri District (see Figure 6). 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) and Selwyn District (Barrell 2013). The information in this report is intended to assist local authorities in delineating the general areas of the Waimakariri District that are subject to active fault and fold hazards, as well as providing a knowledge platform for planning activities and any further investigation or evaluation of these hazards.

The geologically-active nature of New Zealand reflects our position astride the deforming boundary between two large slabs (plates) of the Earth's crust (Figure 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, 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 northeastern South Island, including the northern part of the Waimakariri District, a substantial part of the plate movement is taken up on a series of large strike-slip faults east of the Alpine Fault, such as the Porters Pass Fault, Hope Fault, Clarence Fault and Awatere Fault. Movement is also accommodated on a variety of folds and faults, whose movement senses range from strike-slip to dip-slip, within the ranges and basins of inland North Canterbury, and to a lesser degree beneath the Canterbury Plains.

Although the movement of crustal plates is continuous 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), or buckling and warping (folding), of the ground surface, and generating a large earthquake. The 2010 Darfield Earthquake has 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. 2011a; Van Dissen et al. 2011; Quigley et al. 2012) (Figure 2 to Figure 4).

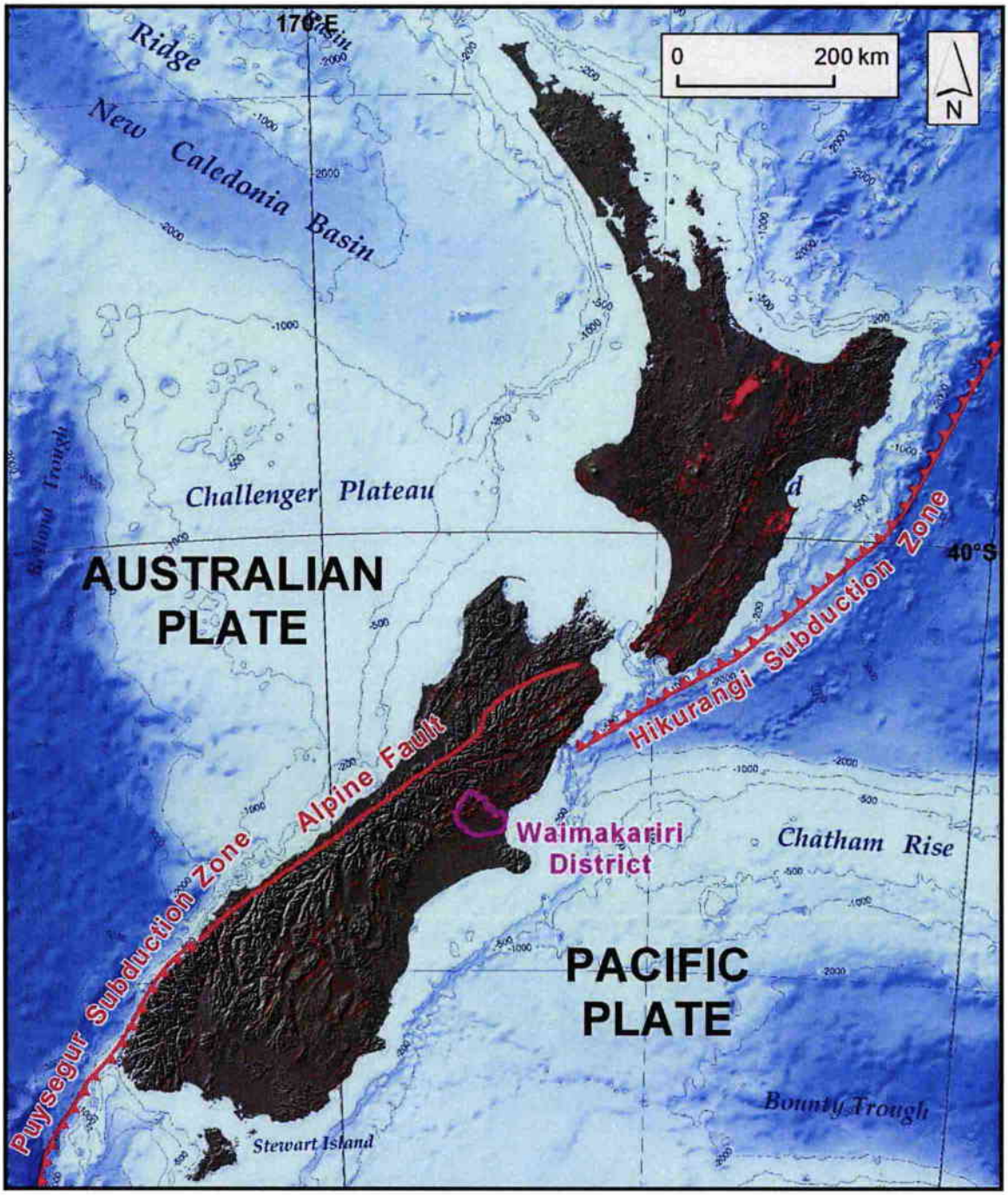

Figure 1 The tectonic setting of the Waimakariri District. The junction between the Australian and Pacific plates of the Earth's crust passes through New Zealand, with the Pacific Plate pushing westward against the Australian Plate. The Hikurangi Subduction Zone marks the place where the rocks of the Pacific Plate slide west under the North Island, while at the Puysegur Subduction Zone, the rocks of the Tasman sea floor slide east under the southwestern South Island. In between is a sideways tear, the Alpine Fault. Although most of the plate movement is concentrated at the subduction zones and the Alpine Fault, there is a wider zone of deformation, marked by numerous active faults, shown by thin red lines (from New Zealand Active Faults Database (NZAFD)). The Waimakariri District lies towards the southeastern edge of this wider zone of tectonic deformation. 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 2 **A**: A fence offset sideways by ~2.4 m of strike-slip rupture on the Hope Fault at Glynn Wye (Hurunui District) 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 (Selwyn District) during the 2010 Darfield Earthquake (Photo: N.J. Litchfield, GNS Science). 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.

In favourable settings, prehistoric fault offsets or fold buckles of the ground may be preserved by way of distinctive landforms, and these landforms are key to identifying 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. For practical purposes, we identify as 'active' any fault or fold that has offset or deformed the ground surface, or any unconsolidated near-surface (i.e. young) geological deposits, even though the exact ages are generally not known. 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. The average recurrence interval for ground-surface rupturing fault movement is a primary consideration in Ministry for the Environment guidelines for planning land-use or development near active faults (Kerr et al. 2003).

Figure 3 A strike-slip fault offset produced by the Greendale Fault rupture (Selwyn District) during the Darfield Earthquake, 4th September 2010. This scene was photographed on 5th September looking south-southwest along Highfield Road, about 8 km west-northwest of Burnham and 0.5 km north of the Highfield Road/Grange Road intersection. The fault rupture here comprised a ~40 m wide zone of fractures, across which the ground was shifted to the right (right-laterally) about 4.5 m, more than half the width of the tarseal, and the far side was bulged up by about 1 m. Prior to the fault rupture, the road was straight and the ground was flat. Photo: D.J.A. Barrell, GNS Science.

2.0 INFORMATION SOURCES

This project 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 Waimakariri District by the Christchurch map (Forsyth et al. 2008), as well as the Greymouth map (Nathan et al. 2002) in the northernmost part of the district. 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 2 of this report. Additional detailed information on active faults is contained in the New Zealand Active Faults Database (NZAFD – see reference list).

This report comprises an office-based review of existing information, with a scope of work that did not include site investigations. However, the authors have previously undertaken geological investigations in the Waimakariri District, including ground-based reconnaissance inspections, and interpretation of aerial photographs (from GNS Science holdings). As part of the present project, this pre-existing information was supplemented with further examination and interpretation of aerial photographs, and examination and interpretation of a high-resolution lidar[1] dataset for Waimakariri District, surveyed in 2005 and supplied by Environment Canterbury. Relevant unpublished observations made during previous work, and during the present project, are provided in Appendix 1, section A.2.

Note that in the captions accompanying the photos of Waimakariri District faults in this report, sufficient information is given so that an interested reader would be able to go to the location where the photo was taken, and examine the feature first-hand.

[1] Lidar = light detection and ranging; same principle as radar, but using light (lasers) rather than radio waves.

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3.0 GEOLOGICAL OVERVIEW

3.1 ROCKS AND LANDFORMS

The geological formations of the Canterbury region, including the Waimakariri District, comprise, from oldest to youngest, three main categories; basement rock, cover rocks and young unconsolidated deposits. The oldest underlying rock (basement rock) consists mainly of hard sandstones and flaky mudstones, commonly called greywacke and argillite respectively, with a few bands of volcanic rock. These ancient rocks, mostly of Triassic age (between 250 and 200 million years old), were buried by a blanket of younger sedimentary rocks (cover rocks) including coal measures, quartz sands, marine mudstones, limestones and gravelly conglomerates. The cover rocks range in age from about 85 million to about 1 million years old. 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. The cover rocks are preserved along the edge of the Southern Alps foothills and beneath 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 Northern Hemisphere ice sheets melted, sea level rose, stabilizing at its present level about 7000 years ago. The last time the sea was as high as it is now was during the last interglacial period, about 125,000 years ago.

Erosion and deposition has been greatly influenced by episodes of glaciation in the hinterland during 'ice ages', when large ice tongues occupied the upper to middle reaches of Southern Alps river valleys such as the Rakaia and Waimakariri (Barrell et al. 2011b). These glaciers did not reach into the Waimakariri District, although the Puketeraki Range is high enough to have carried a localised ice cap (Barrell 2011). 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, basins and on the Canterbury Plains. During ice ages, environmental conditions in the Waimakariri District would have been harsh, and much of the Canterbury Plains would have been a bleak, dusty windswept river plain 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 high terraces at the inland margin of the Canterbury Plains and on adjacent hill slopes.

The last ice age ended about 18,000 years ago (e.g. Alloway et al. 2007), and was followed by warming climate, retreat of glaciers from the headwaters of major rivers, the spread of woody vegetation and the stabilisation of hill slopes. As a result of improved slope stability, the river systems were no longer choked with sediment, and began to cut down into their valley floors, leaving flights of terraces. Confinement of rivers to narrower courses, across inland basins such as Lees Valley, and the Canterbury Plains, led to large areas of 'fossil' ice-age river beds being preserved. These ice-age landforms, although youthful in a geological sense, are old enough to have been affected by some of the most recent fault and fold movements. Areas of younger landforms or deposits, such as steep, eroding 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. These younger landforms may 'conceal' the locations of active 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. Old landforms, such as river terraces formed during the last ice age, are ideal for revealing the locations of active faults or folds because such landforms may be old enough to have experienced several rupture events and display obvious offsets or buckles. In areas where the landforms are younger than, say, several thousand years, the land surface may post-date the most recent fault/fold movements, and thus these landforms 'conceal' any active faults or folds that may be present. In this way, one can recognise active faults or folds in some places (e.g. where there are ice-age river terraces), but elsewhere it may be uncertain whether or not they are present (e.g. beneath young river floodplains).

Active faults and folds are most easily detected on relatively flat and uniform landform surfaces. A good example is 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 in that location. Topographic steps or rises that cut 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 (Figure 2 to Figure 4).

In this report, and the accompanying GIS dataset, 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 5).

Two end-members of fault type are shown in Figure 5, 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 5 are idealised examples. They do not show the full range of variations and complexities that may exist (for example, see Figure 3 and Figure 9; also see illustrations and explanations in the MfE active fault guidelines (Kerr et al. 2003)). Indeed, to find such simple examples in nature would be an exception rather than a rule. The steepness of inclination (dip) of the fault may vary considerably (Figure 5). 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 Figure 5 attempts to convey some impression of the bulldozer effect.

There is rarely an exact distinction between a fault and a monocline at the ground surface. Fault scarps are commonly associated with some buckling of the ground and near-surface layers, particularly on the upthrown side of the main fault scarp (Figure 5; also see Figure 9). 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.

Figure 4a A definite, well expressed fault scarp (arrowed) on the Lees Valley Fault, east of Lees Valley Road, ~6 km northeast of the upper bridge across Ashley River and ~2.5 km southwest of Okuku Hills homestead. This scarp is several metres high and offsets an alluvial fan built out into the valley by minor streams draining from the range at far right. Geological relationships indicate that this is a dip-slip fault with a reverse sense of displacement. Photo: R. Jongens, GNS Science.

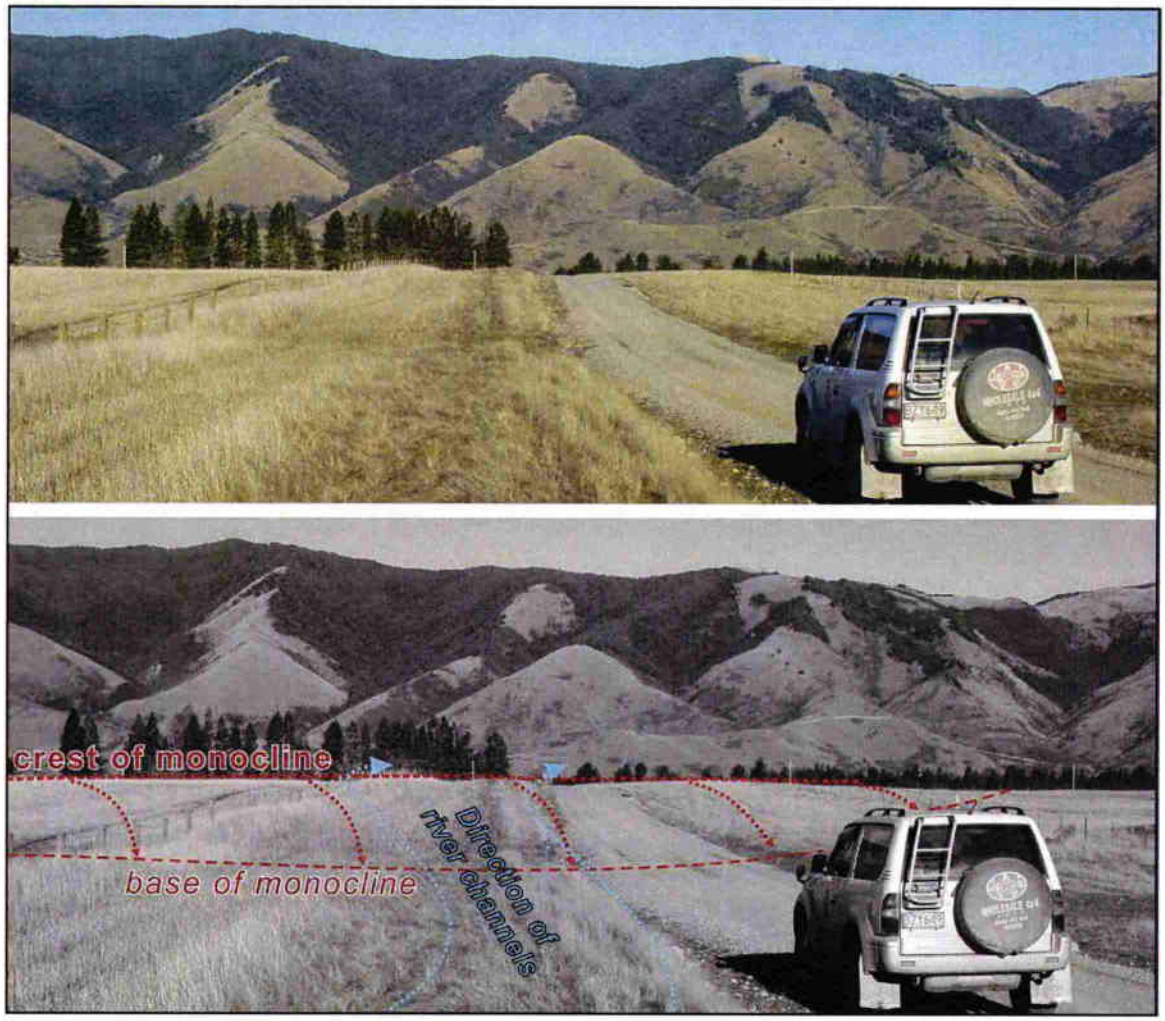

Figure 4b A view southeast along the road to Kingsdown farm, ~0.5 km north of Lees Valley Road, shows a monoclinal flexure, ~5 m high and ~150 m wide, part of the Lees Valley Fault, running across the ~18,000 year old plains of the Whistler River in Lees Valley. It is classed as definite because it warps river-formed channels on the surface of the plains. Photo: D.J.A. Barrell, GNS Science.

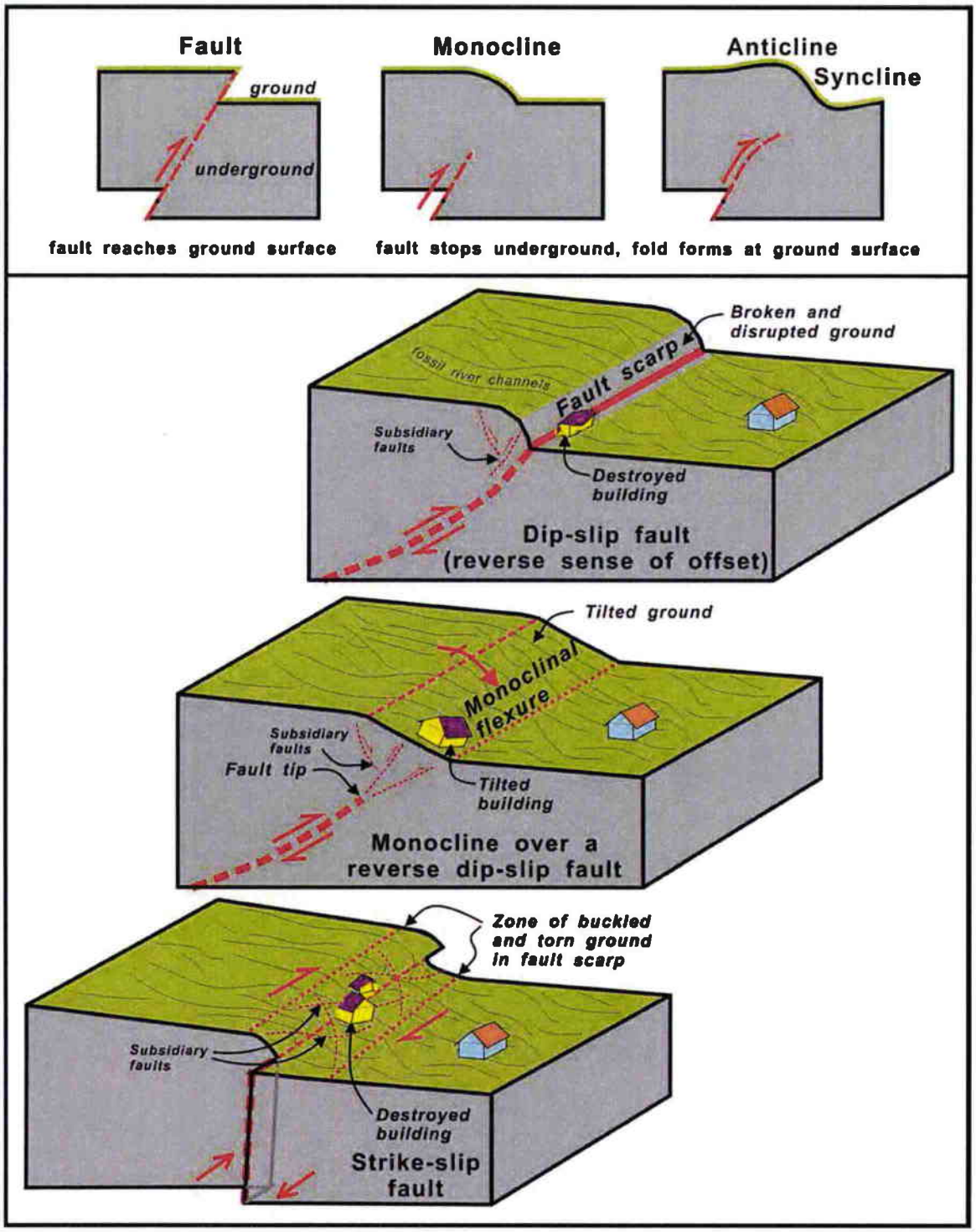

Figure 5 Diagrams illustrating styles of active faults and folds. The diagrams illustrate general concepts rather than actual details, and are not drawn to an exact scale. Upper panel: Cross-section (vertical slice) diagrams illustrating an active fault, active monocline and active anticline and syncline. 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 future fault rupture or monocline growth event. See text for further explanation.

In practice, where a zone of ground deformation is narrow, it is interpreted as a fault, and where it is broad, it is interpreted as a fold (e.g. monocline; Figure 5). The only way to assess 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, one 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 surprises as a result of more detailed geological examinations of active faults or folds. For example, a broad fault scarp, that one may reasonably expect to include a considerable amount of folding may, upon excavation, turn out to have a well-defined fault offset with very little folding. This could occur because after a surface deformation event, natural landscape processes tend to smooth-over the effects. For instance, a steep face of bare broken ground in a fault scarp will settle, subside, and compact due to factors such as rainstorms, frost heave, and soil formation. Over longer periods, wind-blown dust 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.

3.3 AS-YET UNDETECTED ACTIVE FAULTS AND FOLDS

As is explained in more detail in a companion report for Selwyn District (Barrell 2013), the 2010 Darfield Earthquake was very informative scientifically. The earthquake and its effects were able to be measured very precisely, the earthquake itself resulted from a succession of ruptures on several individual faults, all triggered within moments of one another, and all the faults were unknown beforehand, because they lay concealed beneath the gravels of the Canterbury Plains. Of those faults, only the Greendale Fault ruptured the ground surface, but two other faults produced slight 'bulge-like' shifts in the ground, invisible to the human eye but measurable by surveying methods. The 22 February 2011 Christchurch Earthquake was very similar, also resulting from near-simultaneous ruptures of two previously unknown faults, neither of which caused ground-surface rupture, but did produce survey-measurable bulging of the ground (see Barrell 2013 for further information).

The active faults and folds of the Waimakariri District, that have a preserved record of previous ground-surface rupture or bulging in landforms, are a minimum representation of the active faults and folds of the district. Because we know about those faults and folds, they can be taken into account in planning, engineering and hazard mitigation or avoidance. However, the 2010-2011 Canterbury earthquakes highlight that there are as-yet unidentified faults that pose a significant earthquake hazard. 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. On an optimistic note, it is likely that most of the as-yet unknown faults have relatively infrequent activity, otherwise their presence would be more evident in the landscape.

3.4 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 Canterbury, that the amount of slip required for a fault to rupture the ground surface would generate a large earthquake, of magnitude somewhere between the high sixes and mid- to high 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), however it is also possible that a subsurface active fault, whose surface expression is a fold, could produce earthquakes of magnitudes in the sevens. See Barrell (2013) for further information.

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.

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4.0 DISTRIBUTION AND CHARACTERISTICS OF ACTIVE FAULTS AND FOLDS IDENTIFIED IN WAIMAKARIRI DISTRICT

A regional-scale map of the active faults and folds identified so far in the Waimakariri District is presented in Figure 6. Descriptions of the typical characteristics of active faults and folds and syntheses of the mapping categories in this report are presented in Table 1, while Table 2 summarises the main features of the recognised active faults and folds in Waimakariri District.

The original information on active faults and folds is extracted from the QMAP dataset (Nathan et al. 2002; Forsyth et al. 2008). For this report, the existing mapping has been re-examined and a small number of additions and refinements have been made to the mapping of active faults and folds. These amendments are highlighted in the datasets (see Appendix 1) with the addition of three data fields (also known as 'attributes'):

- WDC_name (local names for the mapped features)
- 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 local names correspond to those used in the New Zealand Active Faults Database (NZAFD), which in the Waimakariri 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 assigned from nearby named topographic features (e.g. Knowles Top fault zone). Where names are informal, fault or fold are in lower case type, while for previously-published names, a capital 'F' is used.

For the purposes of illustration and discussion, in places where several active fault or fold features lie close to one another, they have been grouped together under one name. In total, a total of 17 individual or grouped fault/fold features are identified (Figure 6), of which only 15 are classified as definite or likely active faults (see below).

In the Certainty field, the term '**definite**' is applied to those features that 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 say for 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**'. The purpose of the Certainty field is to indicate the level of confidence in the interpretation of the deformation features. 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.

Many of the active faults and folds have been identified only using aerial photographs, or in reconnaissance walkover, and their geometries and locations 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. 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. For features that are '**well expressed**', we predict that they 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. 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'.

Considering the relatively small size of the Waimakariri District, it has a substantial number of active faults and folds. A total of 17 separate fault/fold features are identified (Figure 6, Table 2). Of these, the High Peak Fault (feature 10) has no reported evidence for late Quaternary deformation (see Barrell 2013), while new evidence from lidar suggests that the Rangiora monocline (feature 16) may be a river-deposited landform rather than a late Quaternary deformation feature. In this report, both are classed only as 'possible', and we elaborate upon this in Appendix 1. In addition, the map and dataset includes some possible faults that are not assigned names or feature numbers. All are taken directly from the QMAP dataset but we consider that these faults are towards the lesser end of likelihood of being currently active faults. They are, however, described briefly in Appendix 1, section A.2, in relation to adjacent named features. The reason for this approach is to avoid placing undue significance on faults that we consider relatively unlikely to be active. Thus in total, there 15 definite or likely active fault/fold features identified so far in the Waimakariri District.

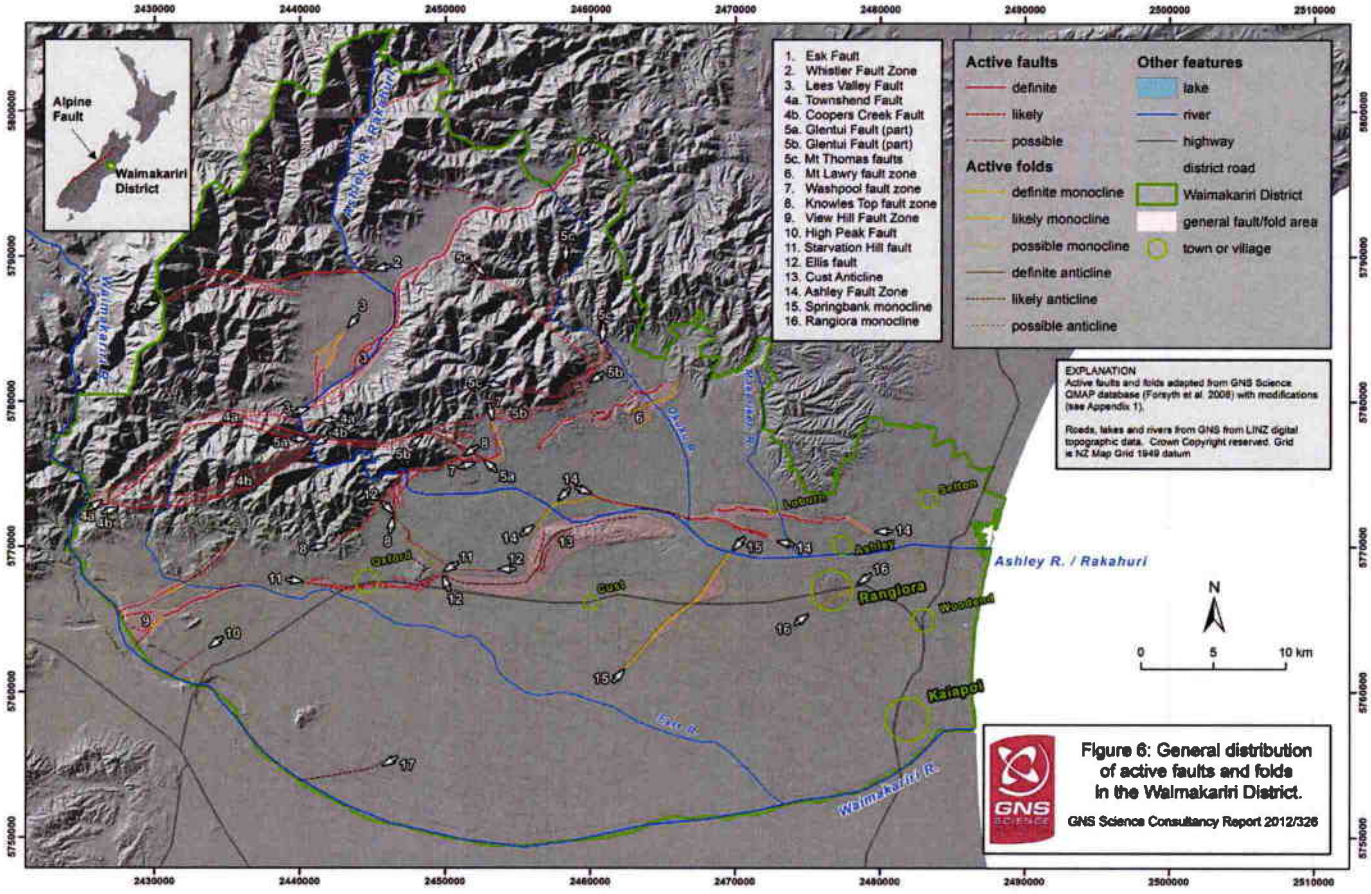

Figure 6: General distribution of active faults and folds in the Waimakariri District.

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Table 1 Categories and terms used in this report to describe active faults and folds in the Waimakariri 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 2 Summary of evidence and estimated deformation characteristics of active faults and folds recognised in the Waimakariri District (see text 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[a] (see notes on last page of table)	Nominal 67% uncertainty in RI (years) [**] (see notes on last page of table)	Implied range of RI Classes (following Kerr *et al.* 2003)
1. Esk Fault	Definite, likely and possible faults.	Noble (2011); Barrell & Townsend (2012); this report.	field inspection; airphoto interpretation; regional geologic mapping.	Noble (2011) identified that the fault consists of several distinct sectors with oblique senses of dextral strike-slip and reverse and normal dip-slip. Noble (2011) reports characteristic single-event displacements of 5 m strike-slip and 2 m dip-slip, horizontal and vertical slip rates of ~0.8 mm/yr and ~0.3 mm/yr respectively, and an average recurrence interval of ~5600 +/- 400 yrs.					IV
2. Whistler Fault Zone	Definite and likely faults.	Cowan (1992); Forsyth et al. (2008); this report.	field inspection; airphoto interpretation; regional geologic mapping.	18,000	5	0.3	7,200	± 4824	II-V
3. Lees Valley Fault	Definite, likely and possible faults. Definite and likely monoclines.	Cowan (1992); Garlick (1992); Forsyth et al. (2008); this report.	field inspection; airphoto interpretation; regional geologic mapping.	18,000	8	0.4	4,500	± 3015	I-IV
4. Townshend Fault - Coopers Creek Fault	Definite, likely and possible faults.	Cowan (1992); Forsyth et al. (2008); this report.	field inspection; airphoto interpretation; regional geologic mapping.	Based on their overall east- to northeasterly strikes, these are suspected to be strike-slip faults. Relatively poor preservation of scarps on these faults suggests relatively low slip rates. Data are insufficient to calculate slip rates or recurrence intervals.					?
5. Glentui Fault - Mt Thomas faults	Possible, likely, and definite faults.	Cowan (1992); Forsyth et al. (2008); this report.	field inspection; airphoto interpretation; regional geologic mapping.	Negligible preservation of scarps on these faults suggests relatively low slip rates and/or long recurrence intervals. Data are insufficient to calculate slip rates or recurrence intervals.					?
6. Mt Lawry fault zone	Definite and likely faults, definite, likely and possible folds.	Cowan (1992); Powell (2000); Forsyth et al. (2008); this report.	field inspection; airphoto & lidar interpretation; regional geologic mapping.	18,000	4	0.2	9,000	± 6,030	II-V
7. Washpool fault zone	Definite and likely faults, likely monoclines.	Forsyth et al. (2008); this report.	field inspection; airphoto & lidar interpretation; regional geologic mapping.	18,000	4	0.2	9,000	± 6,030	II-V
8. Knowles Top fault zone	Definite, likely and possible faults and folds, likely anticline.	Forsyth et al. (2008); this report.	field inspection; airphoto & lidar interpretation; regional geologic mapping.	18,000	10	0.6	3,600	± 2,412	I-IV
9. View Hill Fault Zone	Definite, likely and possible faults and folds.	Forsyth et al. (2008); May (2004); this report.	field inspection; airphoto & lidar interpretation; regional geologic mapping.	18,000	5	0.3	7,200	± 4,824	II-V
10. High Peak Fault	Possible fault.	Refer to Barrell (2013) for further information.	Extrapolation of a feature from the Selwyn district.	No known late Quaternary offsets, this fault may not be active. RI class not less than VI.					≥VI
11. Starvation Hill fault	Definite, likely and possible faults and folds.	Forsyth et al. (2008); May (2004); this report.	field inspection; airphoto & lidar interpretation; regional geologic mapping.	18,000	7	0.4	5,143	± 3,446	I-IV
12. Ellis fault	Likely and possible faults and folds.	Forsyth et al. (2008); May (2004); this report.	Airphoto & lidar interpretation; regional geologic mapping.	18,000	3	0.2	12,000	± 8,040	IV-VI
13. Cust Anticline	Definite anticline and faults.	Cowan (1992); Forsyth et al. (2008); this report.	field inspection; airphoto & lidar interpretation; regional geologic mapping.	18,000	2	0.1	18,000	± 12,060	IV-VI

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 Classes (following Kerr *et al.* 2003)
14. Ashley Fault Zone	Definite and likely faults, definite, likely and possible folds.	Sisson et al. (2001); Forsyth et al. (2008); Jongens et al. (2012); this report.	field inspection; airphoto & lidar interpretation; regional geologic mapping.	18,000	7	0.4	5,143	± 3,448	I-V
15. Springbank monocline	Definite and likely monocline.	Estrada (2003); Forsyth et al. (2008); Jongens et al. (2012); this report.	field inspection; airphoto & lidar interpretation; regional geologic mapping.	250,000	20	0.1	25,000	± 16,750	IV-VI
16. Rangiora monocline	Possible monocline.	Forsyth et al. (2008); this report.	field inspection; airphoto & lidar interpretation.	Evidence for the existence of this feature is equivocal, it may not be an active fold.					?
17. Racecourse Hill Anticline	Likely anticline.	Forsyth et al. (2008); Jongens et al. (2012); Barrell (2013); this report.	field inspection; airphoto & lidar interpretation; regional geologic mapping.	18,000	3	0.2	12,000	± 8,040	III-VI

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 ≤2000 years
II >2000 years to ≤3500 years
III >3500 years to ≤5000 years
IV >5000 years to ≤10,000 years
V >10,000 years to ≤20,000 years
VI >20,000 years to ≤125,000 years

Although the Porters Pass Fault is one of the most active faults of the Selwyn District (Barrell 2013), what are thought to be its eastern continuations into the Waimakariri District, the Townshend, Coopers Creek and Glentui faults, do not display strong evidence for being so active. This may be partly a consequence of the steep, and locally bush-clad, terrain through which these fault pass, which hinders the identification of recent activity. Alternatively, it may be that these faults are currently less active, and the activity evident on the Porters Pass Fault may have become distributed farther east to other faults in the northern parts of the Canterbury Plains. Of the faults on which we have recognised clear evidence for geologically-recent activity, the senses of movement involve a substantial component of vertical (dip-slip) movement, most likely reverse (e.g. Figure 4a). Some of these faults, especially those aligned approximately east-west, may also have a component of sideways (strike-slip) movement, probably right-lateral. This means that to an observer standing on one side of the fault, the other side of the fault has moved to the right (e.g. Figure 2). Overall, the exact senses of movement on active faults in the district are not well established.

Table 1 includes preliminary correlations to the fault complexity classification of Kerr et al. (2003). Table 2 includes preliminary estimates of the deformation characteristics of the active faults and folds, based on estimated amounts of deformation of landform features of specific age. Two common ways of expressing the degree of activity of a fault or fold are average slip rate and average recurrence interval. These parameters also provide a way to compare the levels of activity of faults and folds across a wide area (e.g. within the Waimakariri District).

Fault activity proceeds by 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 slip events are sufficient to produce ground-surface rupture (as applies to all mapped active faults in this report), each slip event typically involves movement on the fault of as much as several metres. The amount of 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. Setting aside complicated details, a large (high) slip rate generally indicates that a fault experiences a ground-surface rupture event more frequently than does a fault with a small (low) slip rate.

Average recurrence interval is the average length of time that elapses between slip events, and is a more explicit measure of how frequently slip events occur. However, it is more difficult to estimate because it depends on having an estimate of the amount of offset that occurs in a single rupture event, 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. Despite the challenges involved in its estimation, recurrence interval 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.

Determining accurate values for slip rates and recurrence intervals usually requires detailed and expensive geological investigations. Commonly, we do not know the exact ages of landforms, and we 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 much harder to measure, simply because there are virtually no 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 would have been difficult to recognise and virtually impossible to measure accurately (Quigley et al. 2012).

Figure 6 A ~15 m high fault scarp ('Cust Fault west') on the western flank of the Cust Anticline, looking east from Elliotts Road, 0.5 km southeast of its intersection with Ashley Road near Summerhill, ~5 km northwest of Cust village. This fault, upthrown to the southeast, offsets an ancient river terrace, which forms the foreground as well as the skyline. This river terrace has been profoundly warped by growth of the Cust Anticline, the axis of which is parallel to the fault and lies just over the skyline. Although this terrace would originally have had a very gentle seaward slope of less than 1°, as characterises the Canterbury Plains today, the terrace as seen here now slopes inland at about 3°, a consequence of it having been bowed upward at the anticline axis by about 50 m. This fault scarp appears to be relatively short (less than 3 km) and, a few hundred metres beyond the skyline seen here and east of the anticline axis, is a parallel fault, the Cust Fault, which is similarly short and has a similarly high scarp, but is upthrown the other way, to the northwest. It is likely that these two faults are shallow-seated features related to tension near the anticline crest, rather than being deep-seated, earthquake-generating faults. If this interpretation is correct, they are probably dip-slip faults with a normal sense of movement. The age of this river terrace is uncertain, but it is tentatively correlated with the third-to-most-recent ice-age, which ended about 250,000 years ago. Even though the deformation is visually substantial, the rate of activity may be relatively slow, because of the great antiquity of the river terrace. Photo: D.J.A. Barrell, GNS Science.

Only the Ashley Fault Zone has been the subject of a targeted geological investigation (Sisson et al. 2001). For other faults in the district, we have estimated the heights of fault scarps or fold arches. These heights represent an approximation of the amounts of vertical deformation. If the faults are dip-slip, this is a good measure of overall deformation, but if the faults have a component of strike-slip movement, the scarp height will represent a minimum value for the overall deformation. The ages estimated for landforms are based on generalised inference and assumed correlations to climatic (glacial/interglacial) events (from Barrell et al. 2011b). For river or glacier landforms attributed to the most recent ice age, we adopt an age of 18,000 years (see Figure 2 to Figure 4, and Figure 7). In the case of the Springbank monocline, we assume an age of 250,000 years (the third to most recent ice-age) for the ancient river terrace that underlies the downlands near Cust (see Figure 6).

Figure 7 Looking east along Rockford Road, ~1.5 km west of the Waimakariri Gorge Road intersection, the road rises over a ~4 m high monoclinal flexure of the ~18,000 year old surface of the Canterbury Plains. This monocline, ~120 m wide and warped up to the east, is the surface expression of the View Hill Fault at this location, and is one of several fault/fold features that together comprise the View Hill Fault Zone. This monocline is classed as definite because it is aligned transverse to the direction of the natural river channel patterns on the plain. Photo: D.J.A. Barrell, GNS Science.

All of these ages are no more than very generalised 'ballpark' estimates. The amounts of vertical deformation were estimated according to the methods listed in Table 2. Features examined only in aerial photos, or on the ground but from some distance away, are assigned a nominal height of either 2 m or 5 m. In cases where lidar interpretation is listed as a method, we used lidar data to estimate the height of tectonic features. Using these estimated values, we have calculated a long-term average vertical slip rate for each fault or fold, as

detailed in Table 2, and described in Appendix 1, section A.2. In the Waimakariri District, some of the mapped faults comprise a single active strand, and a single representative value was derived from the best-preserved landform offset, or the oldest offset landform. In several other places, there are multiple strands (e.g., Knowles Top fault zone, feature 8 (see Figure 8), and Ashley Fault Zone, feature 14; Figure 6) and a collective value was estimated across two or more parallel strands of the fault zone, as detailed in Appendix 1. In general, it is likely that detailed mapping would reveal additional subtle deformation associated with each feature, and so the calculated slip rate should be regarded as a minimum value for the overall fault/fold feature.

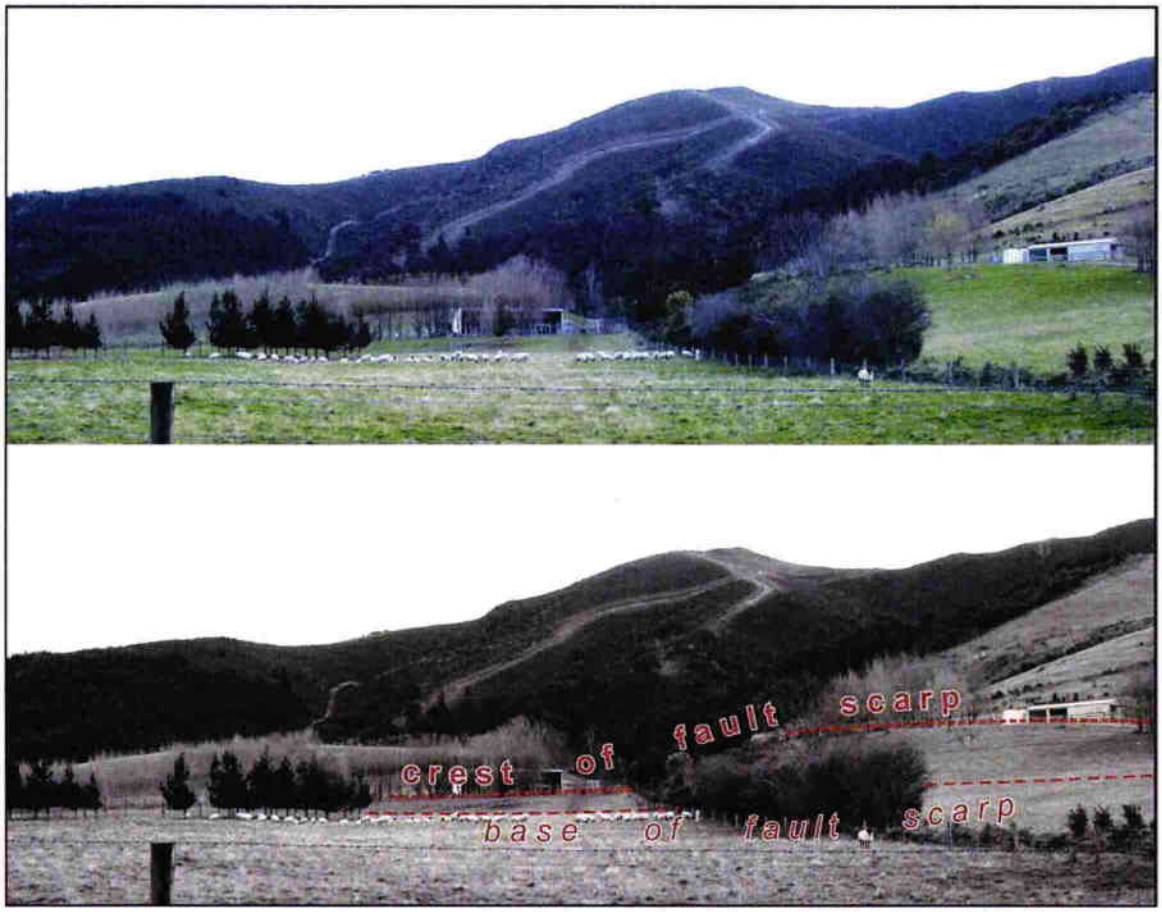

Figure 8 This view west from Ashley Gorge Road, about 4 km north of Oxford township, and 0.5 km south of the German Road intersection, shows a fault scarp within the Knowles Top fault zone. This topographic step runs across the slope of alluvial fans formed by streams draining from the hills behind. This step cannot have been formed by stream action, and therefore is classed as a definite fault. There is no scarp on the youngest fan surface (left) but the scarp first appears as a ~2 to ~3 m high step (centre), and is ~8 to ~10 m high on the oldest alluvial fan terrace (right). The ~2 to ~3 m high scarp represents at least one ground surface-rupturing earthquake, while the ~8 to ~10 m high scarp, being at least 3 times higher, most likely is the cumulative expression of at least three surface-rupturing earthquakes on the fault at this location. If the ages of these landforms could be determined, a more precise history of earthquake ground ruptures could be established for this strand of the Knowles Top fault zone. Photo: D.J.A. Barrell, GNS Science.

Examination of lidar data in the preparation of this report has greatly enhanced our understanding of the locations and significance of the fault/fold features on and at the margins of the Canterbury Plains in Waimakariri District. The Knowles Top fault zone and Starvation Hill fault are newly named active faults, whose existence has long been suspected, but it is only in recent years that field examination, and now lidar, has provided more persuasive evidence for their likely presence and significance. The recognition of the Starvation Hill fault depends largely on indicative evidence from landforms and, because this

suspected fault passes through Oxford township, it would be desirable to prove one way or the other whether it is in fact an active fault.

The Ministry for the Environment guidelines (Kerr et al. 2003) provide a framework and methodology to assist in avoiding or mitigating the risks associated with development of land (especially building) on or close to active faults. The relative significance of active fault hazards is quantified by means of the Recurrence Interval (RI) of ground-surface deforming rupture of an active fault. The RI represents an estimate of how much time, on average, has elapsed between successive surface ruptures of any particular fault. Because RIs may be as short as a few hundred years for the most-active faults, and commonly several thousands of years for other faults, the geological record of deformation of young deposits and landforms is the main source of evidence for defining a RI for a particular fault. However, detailed information is needed in order to define a reliable RI value.

An important quantity for estimating the RI is the amount of movement that occurs on a fault during a ground-surface rupturing earthquake event (single-event displacement, or SED). To use the example of the View Hill Fault at Rockford Road on the Canterbury Plains (Figure 6 and Figure 7, Table 2), the fault, expressed at this locality as a monocline, has buckled a last glaciation river plain, of estimated age ~18,000 years, by as much as 4 m vertically. Lidar reveals that the fault has offset an adjacent incised (i.e. slightly younger) terrace of the Waimakariri River by about 1.5 m vertically (see Appendix 1, Section A.2). This means that the most recent ground-surface rupturing earthquake on this strand of the fault produced a vertical offset of no more than ~1.5 m, and that within the last ~18,000 years, there has been at least one other surface rupturing earthquake on this fault, with vertical offset of no more than ~2.5 m. Of course, these offsets may have been produced by more than two ground-rupturing earthquakes, if the SED of each surface rupture was less than 1.5 m.

We use the following example to illustrate why it is difficult to estimate an exact value for RI. In order to keep this example simple, we assume that the height of the View Hill Fault's offset of the incised river terrace is 2.0 m rather than 1.5 m. If we run a hypothetical scenario that the ~2.0 m deformation of the incised Waimakariri terrace was achieved in one earthquake, and that 2.0 m is a typical offset on this strand of the fault at this location, it implies that two earthquakes produced the ~4 m buckle on the ~18,000 year old landform at Rockford Road. This indicates a RI of no more than 9,000 years (18,000 years ÷ two events). If, however, this strand of the fault were to be investigated in detail and if ages could be determined for offset events, by applying geological dating methods such as radiocarbon, it might be shown that the first ~2-m offset occurred several thousand years after 18,000 years ago, and that the most recent ~2-m offset occurred several thousand years ago. By this scenario, a RI of ~6,000 years is quite plausible for this strand of the fault. Both these values lie within RI class IV, but this scenario nevertheless illustrates why it is difficult to define an exact value for RI, especially without detailed geological investigation of the particular fault. It also highlights that detailed investigation may be worthwhile for a fault where it is important to determine the RI, for example for the purposes of land-use planning or engineering design.

Of the various methods for estimating the SED on a particular fault, the best is to excavate a trench across the scarp of the fault in question, and make measurements of the deformed deposits (i.e. site-specific investigation), as was done for the Ashley Fault Zone by Sisson et al. (2001). However, there are other, less direct, methods, such as those described by Wells & Coppersmith (1994) who used a catalogue of observed earthquake events worldwide to define formulae for estimating SED values, based on, for example, the mapped length of a fault. A disadvantage of the catalogue-estimation approach is that the length of a fault may

be uncertain. Furthermore, the Greendale Fault rupture of 2010 had a much larger single-event displacement (as much as ~5 m) than would be expected for a fault whose surface rupture length as only ~30 km (Quigley et al. 2012). For most faults in the Waimakariri District, no estimates of fault SED have been made to a good level of confidence. For the purposes of this report, we follow the approach described in similar reports for Ashburton District (Barrell & Strong 2009), Mackenzie District (Barrell & Strong 2010), Hurunui District (Barrell & Townsend 2012) and Selwyn District (Barrell 2013), and use 2 m as a working first approximation for SED on active faults and folds in Waimakariri District (see Table 2). It is unlikely that this approximation will be a good representation for all faults in the district, but we consider that it enables comparative assessments of active fault and fold hazards, pending better-constrained site-specific data on faults and folds.

Assuming that each surface rupture or deformation event involves 2 m of vertical deformation, we have estimated an indicative average recurrence interval for deformation events on each active fault/fold feature listed in Table 2. For this calculation we divide the landform age by the landform offset, and multiply by 2 m. These generalised estimates are intended only as a general indication of deformation characteristics. For this reason a nominal +/- 67% error is assigned to the recurrence interval estimates (see Table 2). Except for the Ashley Fault Zone, none of the age or deformation estimates presented here is based on detailed site-specific investigations, which are a prerequisite 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 and allow these faults/folds to be placed in general context with the Kerr et al. (2003) guidelines. It is clear from the wide ranges of RI estimates that, in most cases, further technical information specific to a particular fault would be needed to properly apply the Kerr et al. (2003) guidelines for planning and hazard mitigation/avoidance purposes, or in order to characterise a fault's hazard to a precision necessary for other purposes, such as detailed engineering design.

The GIS layers of active folds (WDC_folds) and active faults (WDC_faults) accompanying this report are derived from the QMAP dataset, with modifications. These modifications include the addition of some previously unmapped features and the reclassification of some features. New features in the dataset may 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 presented here differs notably from previous mapping, is provided in Appendix 1, Section A.2.

The information in this report is more comprehensive than that currently (January 2013) in the NZAFD. This report also builds on and, in places, refines information presented by Pettinga et al. (2001), Van Dissen et al. (2003) and Stirling et al. (2008, 2012), and references therein.

5.0 IMPLICATIONS FOR HAZARDS

The main potential hazards associated with active faults or folds in the Waimakariri District include: (i) strong ground-shaking and associated phenomena (e.g. landslides or liquefaction) resulting from shallow large-magnitude earthquakes centred within the district, and (ii) the effects of sudden ground surface offset or buckling which may result, for example, in the destruction or tilting of buildings or the disruption of electricity/water supply infrastructure or transport routes, in the immediate vicinity of the fault or fold. In this section, the particular focus is ground surface offset or buckling associated with fault rupture or fold growth events. Ground shaking hazards are assessed regionally by Stirling et al. (2008), while liquefaction hazard in regard to Waimakariri District is addressed by Brackley (2012).

Since European settlement of the Waimakariri District area, there have been no recorded instances of ground-surface fault rupture. Only two sizable historic earthquakes have originated beneath the district, a magnitude (M) 5.1 earthquake centred north of Loburn in September 1974 and an M 5.2 earthquake near Ashley Gorge in July 1986 (Seismological Observatory 1974, 1986). Both were felt widely but no significant damage was reported. Several other earthquakes centred outside the district have caused shaking damage in the district, including the 2010 M 7.1 Darfield Earthquake, the 1922 M 6.4 Motunau Earthquake, the 1901 M 6.8 Cheviot Earthquake and the 1888 M 7.1 North Canterbury Earthquake (Cowan 1991; Downes 1995; Pettinga et al. 2001).

Nevertheless, the geological record and landforms show clear evidence for many zones of geologically-recent (though pre-dating European settlement) fault and fold deformation of the ground surface. This highlights that it would be prudent to treat the active fault or fold features of the Waimakariri District as potentially hazardous.

Figure 2, Figure 3 and Figure 9 illustrate examples of the types of ground-surface deformation hazards that may arise from active faults or active monoclines, noting that at any location, elements of both faulting and folding may be present within a deformation zone. In general, faults and monoclines present the most focused forms of ground deformation, in regard to direct rupture or significant tilting of the ground surface. Such effects may occur in a sudden event. Active anticlines are likely to present a much lesser level of ground surface deformation hazard with regard to buildings, but may pose relevant hazards to developments such as canals or power stations (e.g. by tilting the ground). Furthermore, the presence of active folds points to the likely existence of an underlying active fault at depth, that may potentially generate a local, large, shallow earthquake, were it to rupture.

Geological evidence from landforms indicates that the Lees Valley Fault, the Knowles Top fault zone, the Starvation Hill fault and the Ashley Fault Zone, are the most active features in the district. However, in the absence of more detailed geological information, in particular the dating of offset landforms, the recurrence intervals of these faults can only be placed within a broad range of between about ~1,500 years and ~8,000 years (Table 2). The geological estimates presented in this report for other mapped active faults and folds in the district indicate that they have comparatively lower rates of deformation, with an average recurrence interval on each fault/fold system of the order of many thousands of years. This does not mean, however, that they are not potentially hazardous. For example, the Greendale Fault (Selwyn District) is estimated to have a surface-rupture recurrence interval of more than 5,000 years (Villamor et al. 2011, 2012), and so the Darfield Earthquake on the Greendale Fault is an example of a rare event. There are about 15 identified fault/fold systems in the

Waimakariri district. Speaking hypothetically, if each of these fault/fold systems has its own pattern of behaviour, and on average each fault/fold system has a recurrence interval for ground-deforming earthquake rupture of, say, 5,000 years, then on average (5,000 years divided by 15 fault/fold systems) we should expect one of them to rupture in any ~300-year period. This illustrates the point that even though each fault may move infrequently, collectively a major fault movement somewhere in the district should be expected to be a relatively frequent occurrence. It is also important not to overlook the point that there may be other, as-yet unrecognised, active faults in the district, noting the example of the Selwyn District's Greendale Fault, whose presence was unknown prior to the Darfield Earthquake. In summary, there are many active faults in the Waimakariri 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, within the district, over future decades to centuries (Stirling et al. 2008, 2012).

It is important to appreciate that the mapped delineation of the active faults and folds of the Waimakariri District presented in this report has been done at a regional scale (1:250,000). The level of precision is not adequate for any site-specific assessment of hazards (e.g. planning for building or other infrastructure developments), except for the Ashley Fault Zone between Okuku and Makerikeri rivers, for which Sisson et al. (2001) presented a detailed map of the fault scarps, and for which a fault avoidance zonation map is scheduled to be done in mid-2013 (Barrell & Van Dissen 2013). In addition, many of the fault/fold features that have been mapped have not yet been proven to be active faults or folds. For features classed as 'likely', or 'possible', it would be highly 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.

Figure 9 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. 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 on active reverse faults of the Waimakariri District the next time any particular fault experiences a surface rupture earthquake. Photo and information from Kelson et al. (2001).

We reiterate 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.

Following are some general comments in relation to active fault ground-deformation hazards in the Waimakariri District:

a. Most of the towns, villages and settlements of Waimakariri District do not lie over known or suspected active faults or folds. Exceptions are Oxford township, which straddles a suspected active fault (see d) below), and the rural-residential developments of the Ashley and Loburn areas, parts of which lie on or close to the Ashley Fault Zone.

b. Based on lidar data examined for the present report, a landform that was interpreted by Forsyth et al. (2008) to be a monocline passing through Rangiora is now thought more likely to be a river-formed feature.

c. As far as the authors are aware, the only major infrastructural elements that lie close to the recognised active faults/folds of the Waimakariri District are the 350 kV High Voltage Direct Current (HVDC) transmission line which crosses the suspected Starvation Hill fault (see d) below) as well as the western end of the Ashley Fault Zone. A pair of 220 kV transmission lines cross the eastern end of the Ashley Fault Zone north of Ashley village. Of the major roads, the Scenic Highway (formerly SH72) crosses the Starvation Hill fault near Oxford and Springbank monocline east of Cust. Lees Valley Road crosses at least three active faults, and Ashley Gorge Road in places runs close to, and locally crosses, the Knowles Top fault zone. Several roads in the Loburn area cross the Ashley Fault Zone.

d. There is increased suspicion that a series of topographic steps extending from near Starvation Hill through Oxford township is the product of surface ruptures on an active fault, identified here as the Starvation Hill fault. If this is, in fact, an active fault, it is possible that its recurrence interval is sufficiently short to come under the auspices of Ministry for the Environment constraints on existing and new residential developments in proximity to active faults. It would be advantageous for a specialist geological investigation to be undertaken to establish whether or not the Starvation Hill fault is an active fault. If it proves to be an active fault, more detailed mapping and fault avoidance zonation may be warranted.

The general recommendation of this report is that the locations and characteristics of active faults and folds be taken into account in regard to existing and new developments, especially in regard to structures or facilities of high importance (e.g. flood protection works, emergency response buildings, water supplies). A specific recommendation is that a specialist geological investigation be undertaken to establish whether or not the Starvation Hill fault is an active fault.

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6.0 CONCLUSIONS

1. Regional geological mapping has identified a significant number of active faults and folds (monoclines and anticlines) in the Waimakariri District. In total, 15 areas of known or suspected active faults and/or folds are delineated.

2. A GIS dataset of information on the active faults and folds accompanies this report. For each mapped fault and fold, an attribute 'certainty' indicates the level of confidence in the mapping of the feature, whether 'definite', 'likely' or 'possible'. Also included is classification of 'surface form', whether 'well expressed', 'moderately expressed', 'not expressed' or 'unknown'. The surface form classification indicates how easy it is to pinpoint the location of the fault or fold feature on the ground.

3. Table 2 summarises what exists in the way of geological evidence for the degree of activity of each feature. Average slip rate is a common way to compare the level of activity of a fault or fold. This can also be expressed as an average recurrence interval for deformation events, aided by some assumptions. The recurrence interval estimates provide a linkage to Ministry for the Environment active fault planning guidelines.

4. The recurrence interval estimates indicate that the Lees Valley Fault, the Knowles Top fault zone, the Starvation Hill fault and the Ashley Fault Zone are the most active faults in the Waimakariri District. Of the other faults or folds in the district each appears to have a relatively long recurrence interval, but collectively there are many of them.

5. The Starvation Hill fault and Ashley Fault Zone are the only active fault/fold features lying beneath, or close to, towns or settlements. In particular, it would be desirable to confirm whether or not the Starvation Hill fault, which passes through Oxford township but whose existence is suspected rather than proven, is in fact an active fault, and if so whether it is sufficiently active to warrant hazard avoidance measures.

6. The information presented here is not sufficiently precise for site-specific hazard assessment. Instead, the information is intended to highlight those areas potentially affected by active fault or fold hazards, and may help to target site-specific investigations required prior to development, allow identification of lifeline vulnerabilities and assist in the formulation of emergency management response and recovery plans.

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APPENDICES

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APPENDIX 1: SUPPLEMENTARY INFORMATION

A1.1 GIS LAYERS

The GIS layers referred to in this report and contained on the accompanying CD consist of the following shapefiles:

- WaimakDC_faults.shp
- WaimakDC_folds.shp

The original attribute fields for active faults and folds are extracted from the QMAP 'seamless' dataset, sourced from map data published as QMAP Greymouth (Nathan et al. 2002) and QMAP Christchurch (Forsyth et al. 2008). 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:

- WDC_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 are +/- 100 m at best. An exception is the Ashley Fault Zone, where the results of detailed mapping by Sisson et al. (2001) and Barrell & Van Dissen (2013) are incorporated, in slightly generalised form, into these datasets.

The geographic coordinate system for the data is New Zealand Map Grid 1949. The shapefiles were generated using ArcGIS 10. Layer (.lyr) files are included that allow each GIS layer to be coloured in the same way as is shown in Figure 6.

In addition, the shapefile 'WaimakDC_generalised_fault_fold_areas.shp' contains the general areas of faults and folds shown in Figure 6 of the report.

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. The purpose of retaining them is to highlight the location of major geological structures, and in cognisance that future work may demonstrate that their status should be revised to 'active'.

A1.2 COMMENTARY ON SOME FAULT/FOLD AREAS IN WAIMAKARIRI DISTRICT

A topographic map (Figure A.1a and Figure A.1b) is provided at the end of the Appendix, to assist the reader in locating the major geographic features mentioned in this section.

Esk Fault (feature 1, Figure 6): The name Esk Fault was applied by Gregg (1964) to a north-east striking fault, upthrown to the northwest, on the northwestern side of the upper valley of the Waitohi River and extending north across the Hurunui River (Hurunui District). Gregg (1964) applied the same name to a fault zone, upthrown to the southeast, along the western

margin of the Puketeraki Range (Selwyn District). At that time, prior to the theory of plate tectonics, the concept of 'scissors faulting' was popular, in which two faults, broadly along-strike from one another and with opposing directions of throw, were suggested to be interconnected as a single structure. Today, such structures, where predominantly dip-slip, are generally regarded as separate, independent, structures. For this reason, in the fault data sets for the Canterbury region, the fault zone on the western side of the Puketeraki Range, in Selwyn District, is referred to as Esk Fault Zone (southwest) (Barrell 2013), while the fault zone east of the Puketeraki Range, is simply called the Esk Fault (Barrell & Townsend 2012; this report).

Noble (2011) undertook a geological investigation of the Esk Fault (which he referred to as Northern Esk Fault) including measurements of offsets and dating of offset deposits. Noble's data and calculations are adopted in this report. Note that Noble's (2011) study was not accessible at the time the Barrell & Townsend (2012) Hurunui District report was compiled, and the Hurunui District datasets may need re-evaluation in regard to Noble's work.

That section of the Esk Fault lying in Waimakariri District is termed Mt Gordon Fault by Noble (2011), who described a topographic step on the northern side of Mt Gordon that we classify as 'likely', because it may conceivably be due to slope movement rather than fault rupture. The line denoting the fault is this report is generalised and is only broadly indicative of the fault location; more detail is provided by Noble (2011).

Whistler Fault Zone (feature 2, Figure 6): Named by Cowan (1992) based on mapping of fault crushed zones in bedrock, field inspection by D. Barrell in 2007 detected a monoclinal flexure of river terraces on the west side of the Ashley River / Rakahuri (note: these two terms are the official name of this river) where it enters Lees Valley (Forsyth et al. 2008). Subsequent re-examination of airphotos and Google Earth (this report) revealed topographic steps farther west along the range-front that are classed here as definite and likely fault traces. The monocline is estimated to be ~5 m high on a river terrace estimated to be about 18,000 years old.

Lees Valley Fault (feature 3, Figure 6): This prominent fault zone with numerous definite fault scarps, locally well expressed, bounds the southeastern margin of Lees Valley. A fault crushed zone mapped in bedrock towards the southwestern end of Lees Valley, abutting the Townsend Fault, is classed as 'possible'. Dip-slip movement, assumed to be reverse, is visually prominent, but it is not known whether or not there is any strike-slip component.

Further information is contained in a BSc Honours dissertation (Garlick 1992) but as it is not accessible electronically via the internet, it was not examined as part of the present desktop review report.

In central to eastern parts of Lees Valley, the fault scarp is as much as ~6 m high on alluvial fans built out into the valley by streams draining the range to the east. Most of these fans are actively aggrading out into Lees Valley, and it is likely that their surfaces are younger than the ~18,000 year old plains of the Whistler River and Ashley River / Rakahuri that form much of the floor of Lees Valley. Thus, even the older parts of these fans, where the fault scarp height approaches ~6 m, are probably younger than about 18,000 years. Towards the southwest, splinter fault scarps and monoclines extending north-northeast out in the Lees Valley basin are included as part of the Lees Valley Fault. This is particularly useful for fault characterisation because these splinters extend across areas of ~18,000 year old river plains. Collectively, the offsets across these splinter faults/monoclines sum to as much as

~10 m vertically on surfaces judged to be about 18,000 years old (Barrell, field inspection 2007). This collective value is used to estimate slip rate and recurrence intervals (Table 2).

Extending west-northwest from the northeastern sector of the Lees Valley Fault is a 'possible' fault, identified in the dataset as 'Pancake fault' after the nearby range of hills. This fault marks a boundary between different types of basement rock, and part of it is identified as active in the NZAFD. There is a topographic lineament on or close to the basement fault, as mapped in the QMAP dataset, but despite careful examination in airphotos and Google Earth, it is far from clear whether the lineament is a rupture scarp, an erosional feature, an expression of slope instability or simply a different in vegetation either side of the lineament. It is included here as 'possible' to acknowledge its inclusion in the NZAFD, while noting that it is not clear whether or not it is an active fault.

Townshend Fault – Coopers Creek Fault (feature 4, Figure 6): These faults are mapped on the basis of fault crushed zones in bedrock, as well as from topographic considerations (Cowan 1992). In Coal Creek, near the Horseshoe Bends in the Waimakariri River, on the line of what is mapped as the Townshend Fault, Cowan (1992) described an exposure of a fault offset between Quaternary gravel and basement rock, and this is classified as 'definite'. The continuation of this strand of the Townshend Fault is classed as 'likely' while other nearby fault crushed zones are marked as 'possible'.

Cowan (1992) reported a fault offset of river gravel in the west branch of Coopers Creek, on the line of crushed zones that comprise the Coopers Creek Fault This is classed as 'definite', while sectors of the mapped fault along strike to the southwest and northeast as identified as 'likely'. Another parallel strand a short distance to the northwest, which has little topographic expression, is marked as 'possible'.

Together, Cowan (1992) regarded the Townshend Fault and Coopers Creek Fault as a 'fault duplex', with an uplifted 'pop-up' in between, whose crest is Mt Oxford. These two fault systems lie along strike from the Porters Pass Fault, and may represent the eastward continuations of that fault. However, the limited preservation of scarps on the Townshend and Coopers Creek faults suggests that their rates of slip may be significantly less than that of the Porters Pass Fault. As the offset gravels in Coopers Creek and in Coal Creek are of uncertain age, though photos in Cowan (1992) show the gravel deposits to be highly oxidised and likely at least 18,000 years old, and especially at Coal Creek, more likely much older, it is not feasible from present knowledge to attempt to estimate slip rates for these faults, or recurrence intervals.

Glentui – Mt Thomas faults (feature 5, Figure 6): These features are mapped largely on the basis of fault crushed zones in basement rock, and in places by juxtaposition of basement rock and cover rocks. In this report, we divide the Glentui Fault into two sectors (5a and 5b), while the 'Mt Thomas faults' comprise the named Mt Thomas Fault (Cowan 1992) along with an array of nearby unnamed faults (5c).

Extending eastwards from the intersection of the Townsend and Coopers Creek faults at Ashley Gorge, the western sector of the Glentui Fault (5a) is mapped along crushed zones in basement rock through a saddle between Ladbrooks Hill and Knowles Top, and then curves southeast down the Glentui River. Near Glentui settlement, the fault has juxtaposed basement rock against cover rocks on its southwest side (Cowan 1992; Forsyth et al. 2008). A topographic step on the slopes on the east bank of the Ashley River / Rakahuri, identified as a fault trace by Cowan (1992), is interpreted in this report as a 'likely' fault scarp, because it is difficult to rule out the possibility that this step is a product of slope movement. The

crushed zone in basement rock farther east is also classified as 'likely', primarily because at Glentui, a prominent, definite, scarp of the Knowles Top fault zone trends into, but does not cross, the Glentui Fault. This makes it highly probable that at the northern end of the Knowles Top fault zone, at least some slip from ruptures on that fault zone is taken up on the Glentui Fault.

The eastern sector of the Glentui Fault comprises fault crushed zones in basement that extend northeast along the prominent range-front of Mt Thomas (Cowan 1992). In places these faults are also defined by juxtaposition of basement rock against cover rocks southeast of Mt Thomas (Forsyth et al. 2008). However, despite the geologic and topographic prominence of these faults, there are no other identified surface scarps. Review of airphotos as part of the present report identified numerous places where fault scarps would likely be evident, had there been surface rupture(s) during the Holocene. It seems that the most probable explanation is that, at least during the Late Quaternary, the faults comprising the eastern sector of the Glentui Fault have had relatively low rates of slip and/or long recurrence intervals, and are classed as 'possible'. The same comments pertain to the Mt Thomas faults (feature 5c). Overall, there is little convincing evidence to indicate that these faults (5b and 5c, and to some extent 5a), are significantly active. Perhaps the strain that was formerly accommodated on these faults has more recently become expressed on several of the more definitively active faults farther southeast, including the Knowles Top fault zone, the Mt Lawry fault zone, and the Ashley Fault Zone.

Mt Lawry fault zone (feature 6, Figure 6): A belt of unnamed hills extending northeast from Garry River to the Okuku River are the product of uplift along a complex array of faults and folds, referred to here as the Mt Lawry fault zone. At Okuku River, there is an anticline in bedrock (Hillside Anticline; Cowan 1992; Forsyth et al. 2008) close to, but not directly coinciding with the late Quaternary surface folds and fault traces of the Mt Lawry fault zone. A prominent, although complex, fault scarp runs semi-continuously along the northwestern base of the unnamed hills. This fault, upthrown to the southeast and, judging by the sinuosity of its trace, is a reverse fault with a moderate dip to the southeast.

There are notable uplifted and abandoned stream channels across the fault zone, especially between Mt Thomas Stream and Bullock Creek, in places with a prominent hanging wall anticline with an axis as much as 150 m southeast of the fault trace. Northeast of Bullock Creek, there is a prominent monocline, down to the southeast, forming the southeast flank of the unnamed hills. This monocline is evident in the river-cut cliff on the west bank of Okuku River, if viewed from Loburn Whiterock Road. The monocline also affects the main river terrace on the east side of the Okuku valley, north of the Loburn Whiterock Rd and Fords Road intersection. The monocline is relatively subtle, being about 200 m broad, but lidar elevation data indicate that across the monocline, there is about 2 m of vertical deformation on this river terrace, for which we assume an age of about 18,000 years.

Long recognised is the Mt Lawry Fault scarp, also crossing this terrace about 200 m south of Mt Lawry homestead. The scarp is upthrown to the southeast and well expressed and, based on lidar, is about 2 m high near Okuku River, diminishing in height over ~0.8 km northeastward to about 1 m near Karetu River. However, lidar data also reveal a significant flattening of terrace gradient in the general vicinity of the scarp, suggesting an anticlinal dome. It seems likely that the Mt Lawry Fault scarp is a partial breakout from a larger blind fault, whose surface expression here is primarily anticlinal bulging. It seems likely that close to the Okuku River, throw on the southeast dipping fault, prominent in the landforms farther

west, has diminished, and the fault is largely blind, with surface deformation predominantly expressed on a southeast-facing monocline.

Overall vertical deformation across the main, assumed 18,000-year-old, terrace of the Okuku River, including the Mt Lawry Fault and the monocline, is ~4 m, estimated from lidar data, and forms the basis of slip rate and recurrence interval estimates in this report (Table 2). This is a minimum as it does not account for anticlinal bulging near the Mt Lawry Fault.

The mapping in this report is aided by lidar imagery, and is more detailed than that of Forsyth et al. (2008). One notable amendment from Forsyth et al. (2008) is that the monocline on the east bank of the Okuku River is now extrapolated westward to the large monocline forming the southeastern flank of the unnamed hill west of the Okuku River (note that this monocline was not recognised by Forsyth et al. (2008)). The Forsyth et al. (2008) monocline extending southwest of Okuku River along the edge of the downlands is downgraded to a 'possible' status. Also, the lidar data now provides a basis for mapping a likely fault at the northwest edge of the hill country between Mt Thomas Stream and Garry River, where Forsyth et al. (2008) just showed an inactive anticline along the axis of the hills. We have not retained this anticline in the dataset as an active feature, as the likely fault farther northwest appears to be main active tectonic feature.

Further information on this area is contained in a BSc Honours dissertation (Powell 2000) but as it is not accessible electronically via the internet, it was not examined as part of the present desktop review report.

Washpool fault zone (feature 7, Figure 6): We apply this name, from a nearby stream, to a previously unnamed array of definite and likely faults, and likely monoclines, extending east from Glentui settlement around the southern foot of hills and rolling downlands east of Glentui River, then swinging almost 90° to a northerly trend on river terraces west of Garry River. These features were identified during field inspection by Barrell in 2007 and subsequent airphoto examination, as part of compilation of the Forsyth et al. (2008) map. As part of the present report, we have also examined these features using lidar imagery.

The most distinctive fault scarp is a ~1.5 m high north-facing (downthrown to the north) step traversing the western part of the Garry River plains. This scarp is definite because it impedes the course of a minor stream draining down the Garry River plains. Immediately to the west this scarp forms a larger (~15 m high) step across a downland terrace surface. Because its sense of throw is opposite to the south-facing sense of the downlands, we interpret this feature as a secondary 'backthrust' of a primary fault that has uplifted the downlands.

To the east the backthrust cannot be traced east of a diffuse series of north-trending steps on the Garry River plain, traversed by Maori Reserve Rd. These steps are interpreted as likely fault scarps and monoclines, because their approximate parallelism with fluvial channelling on the Garry River plain means that we cannot discount the possibility that they are of fluvial, rather than tectonic, origin. Further detailed investigation of these features would be needed to establish whether these are in fact tectonic steps. Overall, based on visual estimates in the field and supported by lidar information, we estimate vertical deformation of ~4 m across these suspected tectonic features on the Garry River plain, of estimated age ~18,000 years.

In regard to wider tectonic interpretation, the Washpool fault zone is relatively short (~4 km) and so is likely to be a continuation of either the southernmost branch of the Glentui Fault

(feature 5a) or the Knowles Top fault zone (feature 8). If the Washpool fault zone is a continuation of the Knowles Top fault zone, the lesser amounts of post-18,000 years ago deformation on the Washpool structure may be due to some Knowles Top fault zone slip having been accommodated on the Glentui Fault. Alternatively, if the Knowles Top fault zone terminates against the southernmost branch of the Glentui Fault, the Washpool fault zone deformation may represent a continuation of Glentui Fault deformation.

Knowles Top fault zone (feature 8, Figure 6): Referred to as the 'Oxford Glentui Range Front' by Cowan (1992), who noted that there were 'warped fans' and also recorded a prominent fault scarp at Glentui settlement, mapping for the Forsyth et al. (2008) compilation was the first attempt to identify and quantify active tectonic features along the range front between Oxford and Glentui. The name Knowles Top fault zone, taken from the only named summit ('Knowles Top') on the crest of the range front, is applied in this report to tectonic features along the range front, which comprise definite, likely and possible faults and folds.

In this report, access to lidar for this area has enabled considerable refinement and addition of details that supersede the Forsyth et al. (2008) map. Of particular note are:

- A definite fault scarp with ~2 m of upthrow to the northwest, on a ~18,000 year old terrace on the west bank of the Ashley River where it emerges from its gorge;
- Identification of a previously unmapped fault scarp crossing terraces on the east bank of the river ~0.5 km downstream of the Ashley Gorge bridge, with a ~8 m vertical offset of the ~18,000 year old terrace, and ~5 m and ~3 m offsets of progressively younger degradation terraces. This implies at least 3 surface ruptures, of as much as 2 to 3 m per rupture, since ~18,000 years.
- Identification of a belt of likely faults and folds striking south from the west side of the Ashley Gorge mouth;
- At Glentui settlement, there is a pair of fault scarps, downthrown to the southeast, with collective vertical offset of ~12 m; these affect terraces of the Glentui River that are assumed to be ~18,000 years old. Tectonic relationships here at the northeastern end of the Knowles Top fault zone are discussed in the previous section on the Washpool fault zone (feature 7).

The south-trending belt of faults and folds can be traced as far south as a major north-northwest striking fault, identified at depth in bedrock using seismic reflection surveys (Jongens et al. 1999). Forsyth et al. (2008) showed this bedrock fault as a single structure, striking northwest from near Starvation Hill, and then curving to a northerly strike towards the mouth of Ashley Gorge. In this report, we take the step of referring to the north-striking sector of this fault, with numerous likely surface scarps, as part of the Knowles Top fault zone, and that to the south, it abuts or adjoins the northwest-striking sector of the bedrock fault, which we refer to the Ellis fault (feature 12).

The south-striking sector of what we now call the Knowles Top fault zone was shown on the Forsyth et al. (2008) map as an inactive fault in bedrock concealed by the river deposits of the Canterbury Plains, and it was depicted on the cross-section on the Forsyth et al. (2008) map sheet as a west to northwest-dipping reverse fault. Farther west at the range-front, the northeast-southwest striking sector of the Knowles Top fault zone, which was identified as active by Forsyth et al. (2008), was shown an active splay of the main bedrock fault. Based on the new evidence from lidar examined as part of this report, both this splay and the main fault are identified as active.

For estimation of slip rate and recurrence interval, we add the ~2 m scarp and ~8 m scarp on either bank of the Ashley River near the Ashley Gorge mouth, as a minimum for vertical offset since 18,000 years ago on the Knowles Top fault zone. We do not know whether or not there is a component of strike-slip on this fault zone, and for the present report, we assume that there is none.

View Hill Fault Zone (feature 9, Figure 6): The View Hill Fault lies northwest of the bedrock promontory of View Hill and extends northeast from the Waimakariri River to the Eyre River. It comprises definite and likely faults and monoclines and is upthrown to the southeast (May 2004). The scarp is typically 3 to 4 m high on the ~18,000 year old Waimakariri plains (photo in main report), based on field estimation and confirmed by lidar data. In addition, the scarp is present, but only ~1.5 m high, again based on lidar, on the highest incised terrace at the margin of the Waimakariri River valley. This terrace is incised ~10 m below the main surface of the plains, and this terrace stands ~60 m above the modern riverbed. The differing amounts of offset on the plains, versus the incised terrace, implies a minimum of two surface ruptures, of no more than about 1.5 to 2 m per event (vertical), since ~18,000 years ago. It is not clear from the nature or form of the scarp whether or not there is a strike slip component of movement.

Northwest of the main scarp, and west of Waimakariri Gorge Road, in an area where GNS Science does not hold any detailed air photo coverage, lidar data reveal two west-southwest-trending steps, up to the south, that appear, and progressively increase in height, before their expression is lost where the edge of the plains is truncated by the incised valley of the Waimakariri. Lidar indicates that each is between ~1 and ~2 m high at the edge of the Waimakariri valley. They are classified as 'likely' faults because, although improbable, it is conceivable that these steps are simply the edges of northeast-trending relict channels on the Waimakariri plains.

The more northerly of these two steps lies over the location of a substantial subsurface fault identified in a seismic reflection profile run along Waimakariri Gorge Road (Fault FA1 of Dorn et al. 2010). About 3 km to the northeast this fault, upthrown to the southeast, is exposed in bedrock in the foothills and is known as the Chalk Hill Fault. Because of the likely fault scarp in proximity to this fault, 'fault FA1/Chalk Hill Fault' is marked as 'possible'.

On Woodstock Road, just south of Eyre River and on the line of 'fault FA1/Chalk Hill Fault', the lidar reveals a ~1 m high broad step, running transverse to the gradient of the plain, and down to the southeast. Although this was not noticed during fieldwork in 2007 by Barrell for the Forsyth et al. (2008) compilation, careful examination of Google Street View confirms the presence of this broad step. It is marked as a likely monocline. This raises the question of whether it would be better to classify 'fault FA1/Chalk Hill Fault' as 'likely' rather than 'possible'. We prefer 'possible' because the only two identified landform features indicating fault/fold activity, the monocline described earlier in this paragraph, and the fault scarp in the previous paragraph, are classed as 'likely'. If we were to identify the remainder of 'fault FA1/Chalk Hill Fault' as 'likely', it would obscure the only two items of physical evidence that point tentatively towards this being a currently active fault. Thus, we judge it best to retain the classification 'possible', while noting that 'fault FA1/Chalk Hill Fault' may well lie towards the more 'likely' end of 'possible'.

Lidar also shows that southwest of Rockford Road, a small step, down to the southeast, diverges from the View Hill Fault scarp. This step increases in height southwest to ~1.5 m, and also crosses the incised Waimakariri terrace on which the main View Hill Fault scarp is ~1.5 m. It's classification as a 'likely' fault scarp acknowledges a faint possibility that it marks

the north side of an incipient wedge-block failure of the side of the Waimakariri valley wall. Most likely it is a fault scarp demarcating the northern edge of a graben between that fault and the main View Hill Fault.

We use the term View Hill Fault Zone to encompass all of these features. As noted in Barrell (2012), seismic reflection lines documented by Dorn et al. (2010) indicate that these faults (more precisely, their subsurface counterparts down in the bedrock) extend southwest to underlie part of the southern sector of the Waimakariri plains (Selwyn District).

On the plains north of the Waimakariri River (this project area), the co-existence of both northwest- and southeast-facing fault or fold scarps suggests that in addition to the obvious dip-slip component of movement in the View Hill Fault Zone, there may be a component of strike-slip, probably dextral. In the few places where a fluvial riser crosses the View Hill Fault main scarp, there is no discernible strike-slip deflection. However, despite their prominence in the landscape, these fluvial risers, as well as the fault/fold scarps, are not sharply defined and it is conceivable that on the several-metre-high View Hill Fault scarp, as much as several metres of strike-slip deformation could elude visual detection (i.e. oblique slip of the order of 1:1 dip-slip/strike-slip cannot be ruled out).

For the purposes of estimating slip rate and recurrence interval of the View Hill Fault Zone, we assume that the deformation is vertical, without a horizontal component, and we estimate a collective amount of vertical deformation of ~5 m on the 18,000 year old river plain.

High Peak Fault (feature 10, Figure 6): This fault is well known from bedrock juxtapositions in the Malvern Hills (Speight 1924) in the Selwyn District, and what is believed to be the northeastern continuation of this fault has been detected beneath the Canterbury Plains on both sides of the Waimakariri River (Fault FA3a of Dorn et al. 2010). The fault is upthrown to the southeast, and there is a prominent anticline on its upthrown side, named Sheffield Anticline (Dorn et al. 2010). Bedrock promontories such as Abners Head on the northeastern edge of the Malvern Hills, and Gorge Hill projecting from the Canterbury Plains at Waimakariri Gorge (the lower gorge, spanned by Gorge Bridge spans) are on the crest of this anticline. As noted by Barrell (2013), there is no discernible deformation of the main surface of the Canterbury Plains (assumed to be ~18,000 years old) by either the High Peak Fault or the Sheffield Anticline. The extension of the High Peak Fault beneath Waimakariri District is classified as 'possible', in keeping with its classification within Selwyn District.

Starvation Hill fault (feature 11, Figure 6): A substantial east-west striking fault in the subsurface, detected in seismic reflection surveys (Jongens et al. 1999), has brought bedrock close to the ground surface on the upthrown northern side of the fault. Starvation Hill is a bedrock promontory on the upthrown side, near the eastern end of the fault. There is an ill-defined east-west trending topographic step, also up to the north, at about the location of the subsurface fault, and Jongens et al. (1999) suggested that it is a fault scarp. A complicating factor is that this step is approximately parallel to fluvial channelling on this sector (Eyre River) of the Canterbury Plains, making it entirely plausible that this topographic step is a river-cut terrace edge. May (2004) examined these features and undertook comprehensive investigation of soils and deposits on terrace surfaces either side of the topographic step. May (2004) did not draw any definitive conclusions about its origin; but favoured the view that it was a river-cut feature. In 2007, as part of the compilation of the Forsyth et al. (2008) map, Barrell inspected these features using airphotos, and also in the field from roads crossing the step. He noted a number of characteristics that were suggestive of a fault origin, including the step varying in height, character and width over short distances along its length, and in places becoming two or more approximately parallel steps. However,

based on these observations, Barrell could not exclude a fluvial origin. After discussion with Jongens, who favoured the step being a fault scarp because of its close co-location with the subsurface fault, it was agreed that it would not be shown as an active fault on the Forsyth et al. (2008) map, but instead would be shown as an inactive subsurface fault.

Upon gaining access to the lidar data as part of geological work in the wider Canterbury region following the 2010-2011 earthquakes, Begg examined this topographic step in the lidar imagery, and drew attention to several features of the topographic step that are particularly suggestive of a fault origin. Close examination of the lidar data has revealed two particularly 'tell-tale' aspects:

- The presence of localised topographic steps that are up the opposite way to the main step, in positions suggestive that they are 'backfaults'; one lies near the southeast foot of Starvation Hill, approximately 0.4 km northwest of the Oxford Road/Quigleys Road intersection, in a position that is very difficult to account for as a river-cut feature. The other step runs close to Woodside Rd west of Oxford, near Gammans Creek. The larger part of this step, several metres high, was previously noted by Barrell in 2007 during field surveys and examination of aerial photos, but examination of lidar reveals that at its western end, the step swings southwest, and there is a smaller step on a lower river terrace, apparently offsetting this river-formed feature, with a depression on the upstream side. We consider that this evidence is sufficient to classify it as a definite fault.
- Just east of Oxford township, the lidar indicates a low-lying trough between two approximately parallel steps, at a location about 0.5 km east-southeast of the Oxford Road/High Street intersection. The geometry of the river-plain channels and bars in this area makes it somewhat unlikely, in our opinion, that this trough is a river-formed feature. So, unless it is a human-made feature, which seems improbable from its size and form, there is a reasonable chance that it may be tectonic.

Thus we now have some fairly persuasive indications that this east-west topographic step is at least in part tectonic, and we apply the name 'Starvation Hill fault'. However, we do not yet have hard evidence, from geological investigation trenching, for example, that these features are faults. Also, because it is possible that some of the minor steps in the vicinity of the main topographic step are formed by fluvial action, we have preferred to classify all the steps as 'likely', pending further investigation to confirm whether or not they are actually fault scarps.

Assuming for the moment that this topographic step is correctly interpreted as the scarp of the Starvation Hill fault, the somewhat irregular form of the topographic scarp suggests an oblique sense of fault slip, probably reverse-dextral. The maximum height of the suspected fault scarp is about 7 m, and we assume this to have deformed an approximately 18,000 year old river plain. May (2004) reports stony soils on both sides of the topographic step, and the lack of thick loess soils is compatible with this age estimate. These height and age estimates are very much first approximations that could doubtless be improved upon with further, more detailed, field investigations.

Finally, May (2004) undertook in-depth geomorphic analysis of landforms, particularly flat or gently sloping benches, on Starvation Hill, and arrived at a detailed interpretation of active folding. A problematic aspect is that the nature and origin of these benches remains unclear, which diminishes the certainty of any assessment of deformation based on these benches. We agree that Starvation Hill is probably an active fold or dome of some sort, and that some of the benches near the foot of the hill are tilted river terraces. We have drawn a generalised likely anticline axis curved from northeast to northwest around the crest of the hill.

For the purposes of estimating slip rate and recurrence interval of the Starvation Hill fault, we assume that the deformation is vertical, without a horizontal component, and we estimate ~7 m of vertical deformation on the river plain of assumed 18,000 year age.

Ellis fault (feature 12, Figure 6): Seismic reflection surveys (Jongens et al. (1999) reveal the presence of a major northwest-striking fault in bedrock northeast of Starvation Hill, upthrown to the southwest. It was shown on the Forsyth et al. (2008) map as an inactive fault concealed by the river deposits of the Canterbury Plains. This fault from Forsyth et al. (2008), with minor modification at its northern end where it approaches what we now identify as the Knowles Top fault zone, is retained in the dataset as a possible fault, and we have applied the name 'Ellis fault', after a nearby artificial watercourse, Ellis Drain, shown on the NZTopo50 map series.

The lidar reveals a gentle, but noteworthy change in gradient of the Canterbury Plains surfaces along the northeastern side of Starvation Hill, extending northwest from the eastern end of the Starvation Hill fault (feature 11). We mark this gradient change as a 'possible' monocline. Although we were tempted to classify it as likely, we consider that careful field examination would be needed in order to justify its status being raised to 'likely'. This possible monocline does not lie exactly on the mapped location of the bedrock fault, but we consider that they are sufficiently close to warrant the classification of both as part of Ellis fault. At the northern end of this mapped 'possible' monocline, is a sharper topographic step that curves around the eastern and northern sides of Kilbride farm buildings on Stubbs Road (the buildings are on the higher, western, side of the step). As this step's form and position are difficult to explain as a result of river and stream processes, it is classed as a 'likely' fault scarp. It is only a short distance northwest of the northern end of where this step can be traced, to the southern end of identifiable likely scarps of the Knowles Top fault zone, and a possible fault is drawn between the northern end of the 'likely' scarp of the Ellis fault and the Knowles Top fault zone 'likely' scarps.

We estimate that the step at Kilbride is about 3 m high, and assume that the river and stream landforms are ~18,000 years old, in order to estimate a slip rate and recurrence interval.

Cust Anticline (feature 13, Figure 6): This long-recognised anticline has, on part of its crest, the conspicuously high ground of Mairaki Downs. The fold axis is well preserved on the north side of the Cust River, where an ancient river terrace, mapped by Forsyth et al. (2008) as 'middle Quaternary alluvium' (mQa), is prominently arched upwards, by 50 m or more, across the fold axis. Cowan (1992) identified a fault scarp, which he called the Cust Fault, on the eastern side of the fold axis on this warped high terrace. Barrell in 2007 identified a similar fault scarp on the western side of the fold axis, and both are shown as active faults by Forsyth et al. (2008). The western fault is downthrown to the west by ~10 m on the mQa terrace (photo in main report), while the eastern 'Cust Fault' is down a similar amount to the east. Given their closeness together and opposing senses of throw, we think it likely that they are subsidiary, shallow-seated, faults developed as a consequence of the anticlinal warp, and are thus probably tensional normal faults. Both, along with the anticline axis, are classed as definite.

To the northeast, the Ashley River has eroded the western limb of the Cust Anticline, and thus the fold axis location, and the presence or otherwise of any associated surface faults, is uncertain. To the west, the anticline axis is traced somewhat uncertainly across the ~18,000 year old plains of the Eyre River towards Starvation Hill. Although field inspection by Barrell in 2007 identified evidence of slightly disrupted gradients of the plains in this area, the lidar

implies that warping is at best very subtle. We assume ~2 m of arching of these ~18,000 year old plains.

Ashley Fault Zone (feature 14, Figure 6): This fault was first recognised several decades ago and forms a series of prominent scarps on the northern and southern margins of an east-trending belt of low hills and downs between Makerikeri River and Okuku River southwest of Loburn settlement. The fault scarp on the northern margin of the hills/downs has been named the Loburn Fault, while those scarps on the southern side are the Ashley Fault (Sisson et al. 2001). During 2006-2007, Barrell detected additional fault and fold scarps along strike to the west and east of the previously mapped Ashley Fault and Loburn Fault. In this report, we refer to all these features collectively as the Ashley Fault Zone, representing a refinement of the term Ashley Fault System, proposed by Sisson et al. (2001) for a larger group of features including the Cust Anticline.

With lidar now available for the entire area of this fault zone, at least to the extent to which it is expressed by surface scarps, we have re-examined and refined the fault as mapped by Forsyth et al. (2008). This will be described in more detail in an upcoming report on fault avoidance zonation of the Ashley Fault Zone (Barrell & Van Dissen 2013). The only major amendments are: (i) recognition of a monocline extending southwest of the Ashely River towards Summerhill, and; (ii) that the active monocline mapped northeast of Ashley village by Forsyth et al. (2008) is not prominently apparent in the lidar, although it is difficult to be sure because the terrain there is topographically irregular, comprising remnants of old loess-covered alluvial fans, greatly dissected by streams and valleys. That monocline is retained in the datasets but is classified as 'possible'.

The deformation on the Ashley Fault and Loburn Fault components of the Ashley Fault Zone are the most prominent and it is this area that displays the largest overall amounts of late Quaternary deformation. However, the scarp expression is quite variable along strike and, notably on the Ashley Fault, there are localised grabens between fault strands, whose presence hints that the fault zone may be oblique-slip. However, as this is not well quantified, and because Sisson et al. (2001; p. 8-9) could not demonstrate any unequivocal evidence for a horizontal component of offset, we assume the motion is entirely vertical, and estimate an overall offset (Ashley Fault plus Loburn Fault) of about 7 m on the ~18,000 year old river plains and terraces.

Springbank monocline (feature 15, Figure 6): although when first identified as a tectonic feature, it was named the Springbank Fault (Pettinga et al. 2001; Estrada 2003), it is clear from the surface expression, being a broad flexure of the ground, that it is better described as a monocline. Seismic reflection surveys across this structure also show that it is primarily a monocline to perhaps as much as 0.5 km depth, below which it is discernible as a fault within bedrock (Forsyth et al. 2008; Jongens et al. 2012). Although the surface of a 'middle Quaternary alluvium' (mQa) river terrace that forms the Cust Downs is warped by at least ~20 m at the monocline, the age of this terrace is not known with any confidence. An isolated inset terrace of the Cust River valley is also warped, by a few metres, but its age also is unknown. Most important is that the monocline has caused no discernible deformation of the ~18,000 year old surface of the Canterbury Plains, as determined by field reconnaissance inspection by Barrell in 2007, and examination of lidar data. Although Estrada (2003) identified some minor topographic anomalies on the plains near the monocline, that she interpreted to be tectonic, we consider these to be river-formed features. We have assigned the ~20 m warped mQa terrace surface a nominal age of 250,000 years (corresponding to

the end of the third most recent glaciation), for the purposes of estimating slip rate and recurrence interval. For an assumed monocline vertical growth rate of 2 m per event, this implies an average recurrence interval of ~25,000 years. We regard this as no more than a hypothetical indicative value. We note that this is compatible with there being no discernible deformation of the ~18,000 year old plains at the monocline, but nevertheless, we acknowledge that there are numerous unknowns in regard to the interpretation of activity of this fold, not least that we simply do not know the age of the deformed mQa terrace.

We also wish to note here that south of the Springbank monocline, Estrada (2003) proposed another northeast-trending tectonic feature, named the Eyrewell Fault, based on seismic surveying and analysis of minor variations in gradient on the plains (Campbell et al. 2012). We find neither of these datasets persuasive that this fault actually exists, and no surface expression could be identified during field examination by Barrell in 2007. Nor do the lidar data reveal any surface features on this part of the plains that could be attributable to tectonic deformation. We consider that more convincing evidence is needed in order for this feature to be regarded as 'possible', and therefore have not included the so-called Eyrewell Fault in the dataset accompanying this report.

Rangiora monocline (feature 16, Figure 6): an east-west trending anomaly in the gradient of the ~18,000 year old surface of the Canterbury Plains through Rangiora township was identified by Barrell during field work in 2007. Because this rise in the ground, up towards the north, appeared to be transverse to the general gradient of the plains, it was considered to be tectonic, and was shown as an active monocline on the Forsyth et al. (2008) map. However, examination of the lidar data reveals that in the area where the feature was mapped, the river channel patterns have more of an easterly trend than was implied by the 20-m interval contour patterns on the published 1:50,000 topographic maps. This rise now seems reasonably plausible as a river-formed sediment depositional feature, and while the monocline is retained in the dataset, it is downgraded to 'possible'.

Racecourse Hill Anticline (feature 17, Figure 6): This is a likely continuation of an anticlinal fold mapped in the Selwyn District. The reader should consult Barrell (2013) for description and discussion of this anticline. In Waimakariri District, lidar is available for the location of the anticline, and confirms the rise in the ground identified during fieldwork by Barrell in 2006. Although the scope of the present report allowed for only a brief visual examination of the lidar data at this location, there is a distinct impression of an ~20° azimuthal discordance between the trend of fluvial channels and what is currently the downslope direction on the plains on the flank of this rise. At face value, this supports the interpretation of this feature as tectonic. The lidar data imply that on the plains alongside the incised valley of the Waimakariri River, the anticline crest has been elevated ~3 m relative to adjacent ground, and that the fold dies out eastward over a distance of about 1.5 km. For the purposes of estimating slip rate and recurrence interval, we use 3 m of vertical deformation on the Waimakariri Plains of assumed age of ~18,000 years.

Additional references not listed in the body of the report

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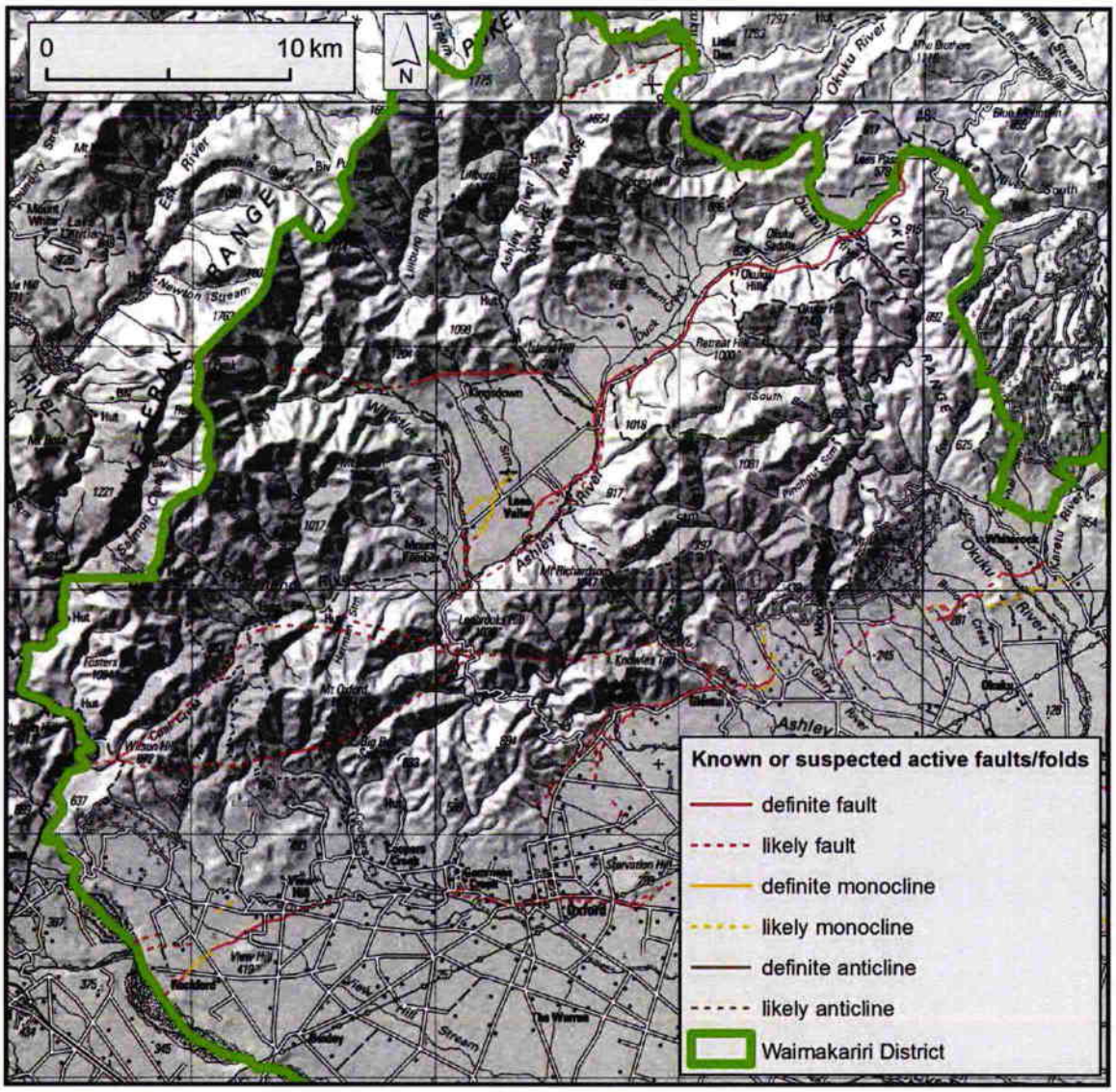

Figure A.1a The known and suspected faults/folds of the northwestern part of the Waimakariri District plotted on a greyscale version of topographic map NZMS 262 (Land Information NZ, Crown Copyright reserved).

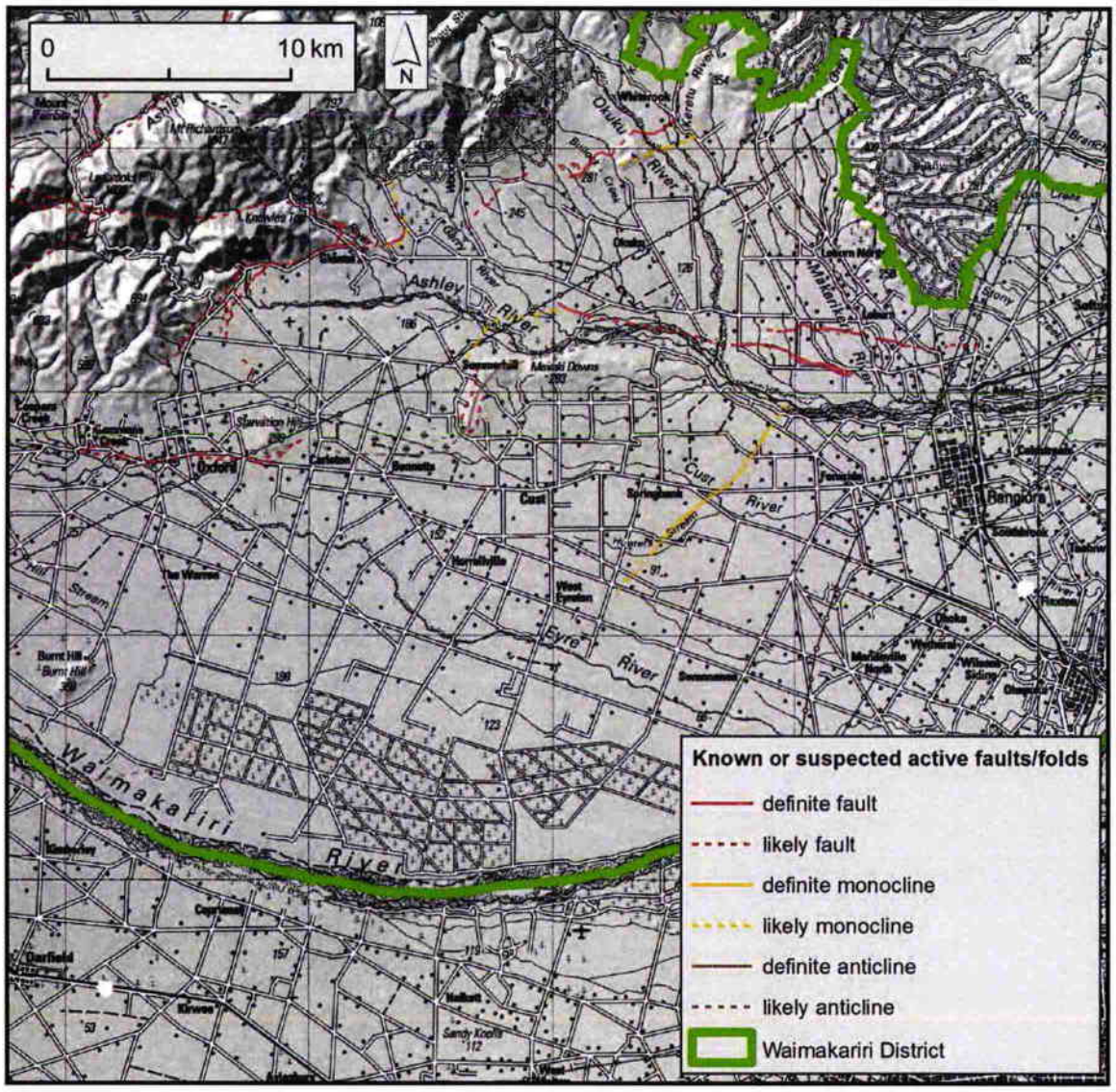

Figure A.1b The known and suspected faults/folds of the southeastern part of the Waimakariri District plotted on a greyscale version of topographic map NZMS 262 (Land Information NZ, Crown Copyright reserved).

www.gns.cri.nz

Principal Location

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

Other Locations

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

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

National Isotope Centre
30 Gracefield Road
PO Box 31312
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4657