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

D. J. A. Barrell

GNS Science Consultancy Report 2014/210
Environment Canterbury Report No. R15/23

March 2015

GNS SCIENCE
TE PŪ AO

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

D. J. A. Barrell

GNS Science Consultancy Report 2014/210
Environment Canterbury Report R15/23
March 2015

DISCLAIMER

This report has been prepared by the Institute of Geological and Nuclear Sciences Limited (GNS Science) exclusively for and under contract to Environment Canterbury. Unless otherwise agreed in writing by GNS Science, GNS Science accepts no responsibility for any use of or reliance on any contents of this Report by any person other than Environment Canterbury and shall not be liable to any person other than Environment Canterbury, on any ground, for any loss, damage or expense arising from such use or reliance.

The data presented in this Report are available to GNS Science for other use from March 2015.

BIBLIOGRAPHIC REFERENCE

Barrell, D. J. A. 2014. General distribution and characteristics of active faults and folds in the Kaikoura District, North Canterbury, *GNS Science Consultancy Report* 2014/210. 59 p.

ISBN 978-0-478-15131-2 [HARD COPY]
ISBN 978-0-478-15132-9 [WEB COPY]

CONTENTS

FIGURES

TABLES

APPENDICES

APPENDIX FIGURES

EXECUTIVE SUMMARY

This report presents a general outline of the locations and character of active geological faults and folds in the Kaikoura District. A fault is a fracture within the rock of the Earth's crust, along which movement has occurred. Commonly, strain builds up in the rock of the Earth's crust, and is released suddenly by a slip event (rupture) on a fault, causing an earthquake. Folds represent bending or buckling of rock, and commonly form above an underlying fault.

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

Regional geological mapping has detected 14 areas of active faults or folds at the ground surface in Kaikoura District. This report is accompanied by Geographic Information System (GIS) datasets, showing the locations of the recognised active faults and folds. In some places, it is clear beyond doubt that a feature is an active fault or fold, but in others, the evidence is less certain. Levels of certainty in the recognition of active faults and folds are included in the datasets, as are estimates of average slip rates and recurrence intervals for each fault, in relation to Ministry for the Environment guidelines.

The nature of hazards posed by active faults was demonstrated recently during the 2010 Darfield Earthquake that resulted in ground-surface rupture, and sideways land shift, on the Greendale Fault on the Canterbury Plains. The 1888 North Canterbury Earthquake, centred west of Hanmer Springs, was associated with very similar phenomena on the Hope Fault. No large earthquakes have been centred in the Kaikoura District since European settlement.

The main hazards associated with active faults include: (i) local epicentres for large earthquakes, and (ii) the effects of sudden ground surface offset or buckling which may result, for example, in the destruction or tilting of buildings in the immediate vicinity of the fault. The landform geological record shows clear evidence for prehistoric deformation at a number of locations within Kaikoura District, and highlights that it would be prudent to treat these active fault or fold features as potential hazards.

The active faults and folds of the Kaikoura District have been mapped at a regional scale. Information in this report and in the accompanying GIS layer is intended to highlight those areas potentially affected by active fault or fold hazards, and may help to target locations for any further investigations that may be deemed necessary. This report provides the most up-to-date information available on the locations and nature of active faults and folds in Kaikoura District. It is intended to create general awareness of the existence of the hazards, but is not in itself sufficient for specific zoning to avoid fault hazards.

1.0 INTRODUCTION

The geologically-active nature of New Zealand reflects our position astride the active boundary between two large slabs (plates) of the Earth's crust (Figure 1). The forces involved in plate movement are immense and cause the rock of the Earth's crust to buckle (fold) and fracture (fault) in the general vicinity of the boundary between the plates. The plate boundary in the South Island is marked, at the ground surface, by a series of major faults that extend from Marlborough through North Canterbury, and then merge onto a single major feature, the Alpine Fault, which runs along the western margin of the Southern Alps to the Fiordland region.

In the central South Island from about Arthur's Pass south to Fiordland, most of the plate movement is concentrated on the Alpine Fault. The movement is predominantly sideways, with the western side of the fault moving northeast, and the eastern side moving southwest as well as a little bit upwards, which has produced the Southern Alps. The technical term for a sideways-moving fault is 'strike-slip', while a fault where the movement is mostly up-down is called 'dip-slip'. In the northeastern South Island, especially in the Kaikoura District, a substantial part of the plate movement is distributed on a series of large strike-slip faults east of the Alpine Fault. Lesser amounts of movement are accommodated on a variety of faults and folds within the ranges and basins of northeastern Canterbury, and offshore.

Although the movement along the plate boundary is continuous over geological time, and can be measured by ground and satellite (GPS) surveying, rock of the Earth's crust is remarkably elastic and can accommodate a lot of bending before letting go and breaking suddenly (rupturing) along a fault, causing an earthquake. On large faults, the break may be big, and extend up to the Earth's surface, causing sudden offset and breakage (faulting), and/or buckling and warping (folding), of the ground surface, accompanied by a large earthquake. The 2010 Darfield Earthquake provided a good example of the nature and effects of a large, ground-surface-rupturing earthquake on a geological fault (e.g., Barrell et al., 2011) (Figure 2).

In favourable settings, prehistoric fault offsets and/or fold buckles of the ground may be preserved by way of distinctive landforms, and these landforms allow us to identify the locations of active faults and folds. In New Zealand, an active fault is commonly defined as a fault that has undergone at least one ground-deforming rupture within the last 125,000 years or at least two ground-deforming ruptures within the last 500,000 years. An active fold may be defined as a fold that has deformed ground surfaces or near-surface deposits within the last 500,000 years. Unfortunately, there are few reliable 'clocks' in the natural landscape, and for practical purposes, it is common to identify as active any fault or fold that can be shown to have offset or deformed the ground surface, or any unconsolidated near-surface geological deposits (Figure 2 and Figure 3). This practical approach for identifying active faults or folds is used on most geological maps published in New Zealand, and is followed in this report. It is also common to assess the significance of hazards associated with an active fault or fold by estimating how often, on average, it has undergone a ground-deforming rupture or deformation event. The average recurrence interval is a primary consideration in Ministry for the Environment guidelines for planning land-use or development near active faults (Kerr et al., 2003).

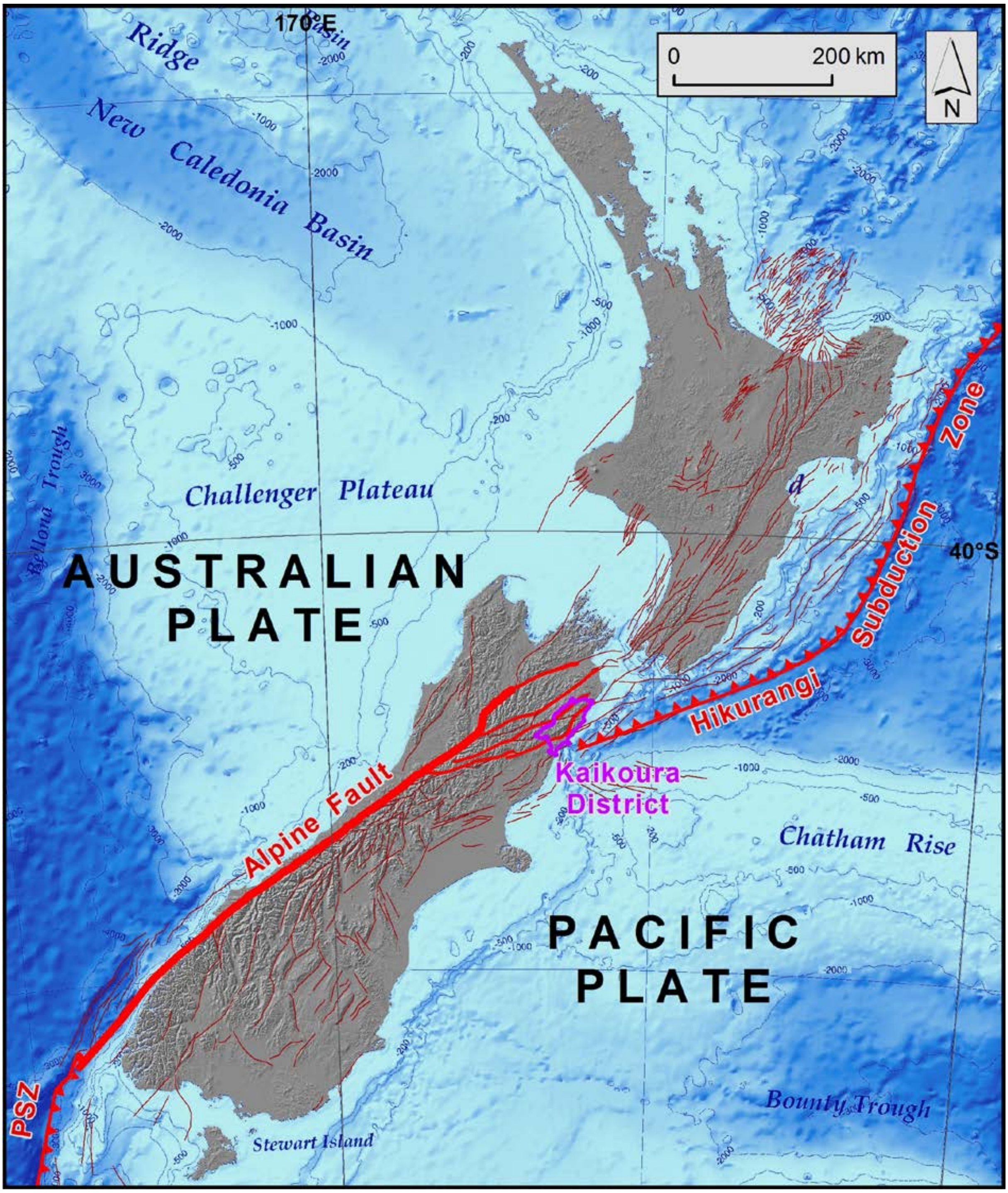

Figure 1 The tectonic setting of the Kaikoura District. The junction between the Australian and Pacific plates of the Earth's crust passes through New Zealand, with the Pacific Plate pushing westward against the Australian Plate. At the Hikurangi Subduction Zone, the rocks of the Pacific Plate slide west under the North Island, while at the Puysegur Subduction Zone (PSZ), the rocks of the Tasman sea floor slide east under the southwestern South Island. In between is a sideways tear, the Alpine Fault (thick red line). Although much of the plate movement is concentrated at the subduction zones and the Alpine Fault, there is a wider zone of deformation. Of particular note is the Marlborough Fault System (medium red lines) which transfers motion between the Alpine Fault and the Hikurangi Subduction Zone. The Kaikoura District lies in the midst of this wider zone of tectonic deformation. Other active faults, taken from Litchfield et al. (2014), are shown by thin red lines. The offshore image is the New Zealand Continent map (GNS Science) showing shallower water in light blue and deeper water in darker blue. Bathymetric contours are in metres below sea level.

Figure 2 Illustrations of fault surface rupture offset. A: A fence offset sideways by ~2.4 m of strike-slip rupture on the Hope Fault at Glynn Wye during the 1888 North Canterbury Earthquake (Photo: A. McKay, GNS Science CN4852). B: A fence offset sideways by ~4.5 m of strike-slip rupture on the Greendale Fault during the 2010 Darfield Earthquake (Photo: N. J. Litchfield). Half-arrows either side of the fault indicate the direction of movement. In both cases, the movement is 'right-lateral', sometimes called 'dextral'. This means that to an observer, the ground on the far side of the fault has shifted sideways to the right. The effect is the same regardless of which side of the fault the observer is standing. The other type of strike-slip movement is 'left-lateral', sometimes called 'sinistral', but is not common in New Zealand.

There are many active geological faults and folds recognised in the Canterbury region. As part of ongoing improvements in the recognition and mitigation of natural hazards, Environment Canterbury engaged the Institute of Geological and Nuclear Sciences Limited (GNS Science) to summarise the state of knowledge regarding active geological faults and folds in the Kaikoura District (see Figure 8). This report presents that summary, and forms a companion to similar reports commissioned for the Ashburton District (Barrell & Strong, 2009), Mackenzie District (Barrell & Strong, 2010), Hurunui District (Barrell & Townsend 2012), Selwyn District (Barrell, 2013) and Waimakariri District (Barrell & Begg, 2013).

The information in this report is intended to assist local authorities in delineating the general areas of the Kaikoura District that are subject to active fault and fold hazards, particularly those hazards related to ground-surface fault rupture and ground deformation.

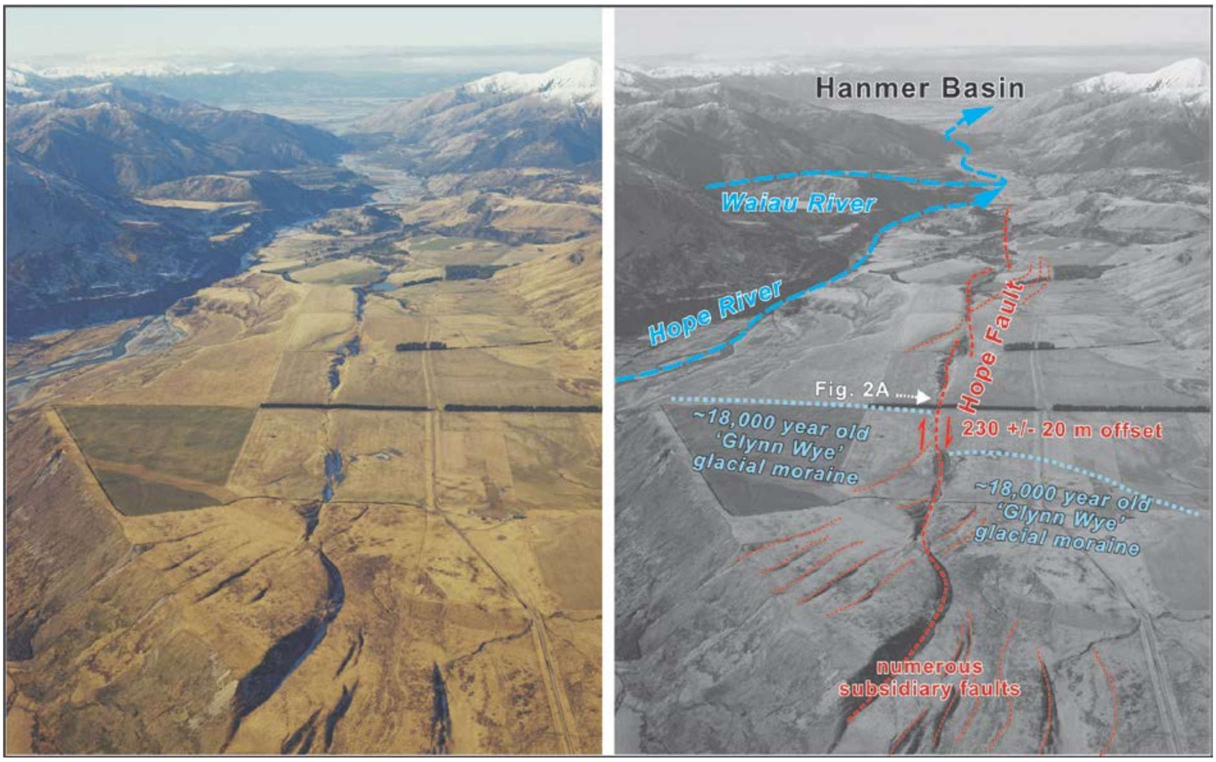

Figure 3 Aerial view looking east along the Hope Fault Zone at Glynn Wye, Hope River valley, Hurunui District. The fault trace is accentuated by a dusting of snow persisting on shaded areas along the fault. After stepping across the Hanmer Basin, the Hope Fault Zone continues northeast into the Kaikoura District (Photo: D.L. Homer, GNS Science CN3602/26).

2.0 INFORMATION SOURCES

This summary 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 Kaikoura District by the Kaikoura map (Rattenbury et al., 2006). 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 information on active faults is contained in the New Zealand Active Faults Database (NZAFD – see reference list), and in publications by Stirling et al. (2012) and Litchfield et al. (2014).

This report comprises an office-based review of existing information, with a scope of work that did not include site investigations. High-resolution laser radar (lidar) for the coastal sector of the Kaikoura District, acquired in July 2012 according to information at http://canterburymaps.govt.nz, provides detailed information on the land surface. As part of the information review, close examination was made of the lidar datasets, looking for topographic anomalies that may indicate the presence of active faults.

Appendix 1 presents a brief description of the GIS datasets that form a companion to this report. Appendix 2 provides commentary on aspects of the existing information, as well as explanations of the interpretations adopted in this report. The fault and fold map accompanying this report was derived from the QMAP digital data set, with additions and refinements, as outlined in Section 4.0 of this report.

3.0 GEOLOGICAL OVERVIEW

3.1 ROCKS AND LANDFORMS

In North Canterbury, including Kaikoura District, 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, of Triassic to Early Cretaceous age (between 250 and 100 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 many of the ranges of the Kaikoura District, uplift and erosion has stripped away much of the cover rock blanket, exposing the underlying basement rock. The cover rocks are preserved around the flanks of many of the ranges in the Kaikoura District, and on Kaikoura Peninsula.

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.

In the Kaikoura District, the most recent glaciation generated sizeable glaciers in the mountain valleys of the Inland Kaikoura Range (Bacon et al., 2001) but they did not extend onto adjacent lowlands. Although no detailed glaciological investigation has been undertaken in the Seaward Kaikoura Range, it is likely that ice-age glaciers also existed in the upper parts of the catchments draining the highest mountains (Barrell, 2011).

Erosion and deposition has been greatly influenced by episodes of glacial climate. During glaciations, snowlines and treelines were many hundreds of metres lower than they are today. The lack of trees aided erosion in the hills and mountains, and promoted build-up of river and stream sediments within valleys and on plains. Ice-age environmental conditions in the Kaikoura District would have been harsh, with the lowlands dominated by exposed, dusty windswept river plains with few trees and patches of grassland. River silt picked up from floodplains by the wind formed accumulations of yellow-brown silt deposits, known as loess, that are common on stable terraces, notably the marine terraces of the Kaikoura Peninsula.

The last ice age ended about 18,000 years ago (e.g., Barrell et al., 2013), and was followed by warming climate, retreat of glaciers from the mountain catchments, the spread of woody vegetation and the stabilisation of hill slopes.

A particular impact of glacial cycles on the Kaikoura District arises from the presence of a deep submarine canyon (Kaikoura Canyon) extending close in to shore immediately south of Kaikoura Peninsula. The head of the canyon, and therefore the position of the glacial coastline, is only 2.5 km offshore from the present mouths of the Kahutara and Kowhai rivers. Under lowered sea level during glaciations, the gradients of those rivers would have been steepened greatly in order to intersect the coastline at the canyon head, and the lower to middle reaches of these rivers would have flowed within incised valleys. At those same times, rivers north of Kaikoura, such as the Waimangarara and the Hapuku, drained onto a broad area of the continental shelf whose gradient is flatter than the gradients of the rivers, and so during lower sea level, these rivers would have constructed fan-shaped plains. The consequence of post-glacial sea level rise is that the Kahutara and Kowhai rivers would have had their gradients reduced, causing sediment to accumulate in their incised valleys, and subsequently the rivers constructed extensive fans of young sediments. In contrast, north of Kaikoura, wave erosion of the toes of the glacial fans of river sediments have caused rivers such as the Hapuku to incise into its plains, creating an incised valley. This very complex geomorphological setting poses challenges for the interpretation of the age and origin of landforms in the Kaikoura District.

Close to the coast, wave-cut shore platforms were formed during past episodes of interglacial climate (with sea level about the same as it is today). In places where the land is being uplifted, these former sea-bed areas have been raised, and preserved as distinctive coastal terraces. There are good examples on Kaikoura Peninsula, and northeast of about the Clarence River (Ota et al., 1996). These coastal terraces are relatively old landforms, ranging from between about 60,000 to about 105,000 years old on Kaikoura Peninsula (Figure 4), with older terraces, dating back to perhaps as much as 330,000 years, farther north. These coastal terraces, because of their considerable age, are therefore well suited for showing the long-term cumulative effects of fault movements or fold growth.

3.2 RECOGNITION OF ACTIVE FAULTS AND FOLDS

The key evidence for recognising active faults or folds is the offset or buckling of landforms or young geological deposits. This is seen most clearly on old river terraces or river plains, where the original channel and bar patterns of the former riverbed are 'fossil' landforms dating from when the river last flowed at that location. Topographic steps or rises that run across such river-formed features could not have been created by the river, and therefore result from subsequent deformation of the ground. As long as factors such as landsliding can be ruled out, these topographic features may confidently be attributed to fault or fold movements (e.g., Figure 2 and Figure 3).

Figure 4 A view northwest looking along Kaikoura Peninsula towards the Seaward Kaikoura Range. Prominent in the foreground is an abandoned shoreline (marked as ~3,000 years) backed by a now inactive sea cliff. These features relate to uplift of the land, suggested to have occurred in at least three uplift events, of at least 1 m each, with an average of about 1,000 years intervening between each event (see Appendix 2). In most places the sea no longer reaches the old cliff line, but as coastal erosion continues, the old cliff is starting to become reoccupied (e.g., far left). Much of Kaikoura township lies on this young raised coastal platform. The surface of the peninsula comprises an array of broad terraces at differing elevations. These features are marine terraces that were formed by wave erosion during the last interglacial period, between about 60,000 and 105,000 years ago. Since then these terraces have been raised well above sea level by ongoing tectonic uplift. The uplift is thought to be resulting from movement on an active fault that underlies the peninsula, and projects up towards the sea floor about 2 km offshore from the southeast margin of the peninsula (Kaikoura Peninsula fault; Figure 8). Each uplift event is likely to be accompanied by a large earthquake centred as shallow depth under the peninsula. Photo: D.L. Homer, GNS Science CN23908/19.

In this report, and the accompanying GIS dataset, we distinguish 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 complexity that may exist (for example, see Figure 3). 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 the upper panel of 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 6 and Figure 7). In some cases, part of the fault movement may have broken out on a series of smaller subsidiary faults in the vicinity of the main fault. In the case of monoclines or anticlines, subsidiary faults may also occur over buried faults that underlie these folds, resulting in small ground surface offsets (e.g., Kelson et al., 2001). The important message is that on any active fault or fold, there commonly are elements of both faulting and folding close to the ground surface. The amount of deformation due to faulting, relative to the amount expressed as folding, may vary over short distances.

In practice, where the zone of ground deformation is quite narrow, we interpret it as a fault, and where it is broad, we interpret it as a fold (e.g., monocline) (see Figure 5). The only way to determine the accuracy of this interpretation is to excavate a trench across the deformed zone to see whether, or to what extents, the near-surface deposits have been offset, or merely folded. Sometimes, natural exposures in stream banks provide the necessary information. This highlights a key issue; without detailed work involving examination of what lies within the first few metres beneath the ground surface, we can at best only make informed guesses about the exact locations, form and likely future consequences of fault or fold activity.

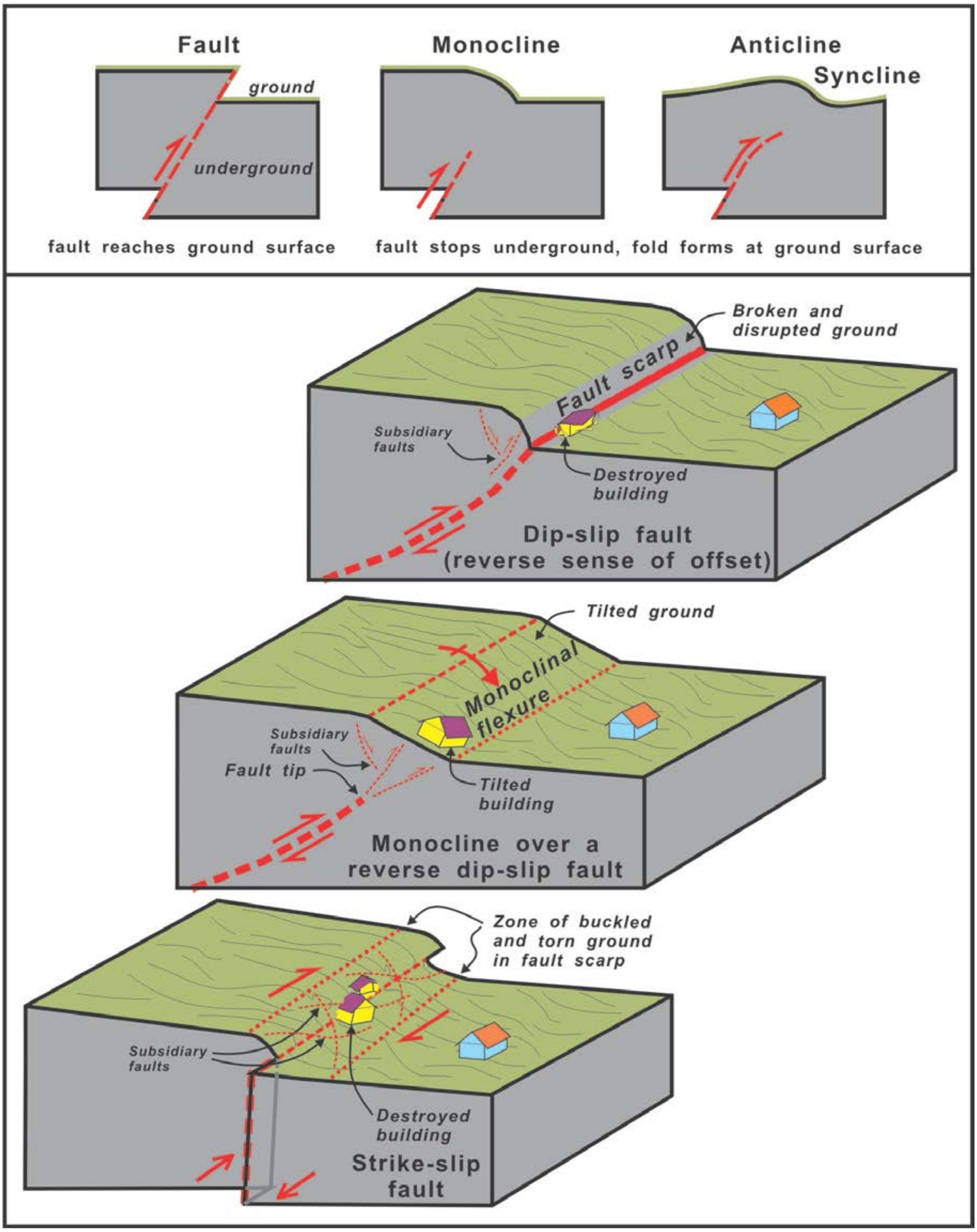

Figure 5 Diagrams illustrating styles of active faults and folds. The diagrams illustrate general concepts rather than actual details, and are not drawn to an exact scale. Upper panel: Cross-section (vertical slice) diagrams illustrating an active fault, active monocline and active anticline and syncline.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

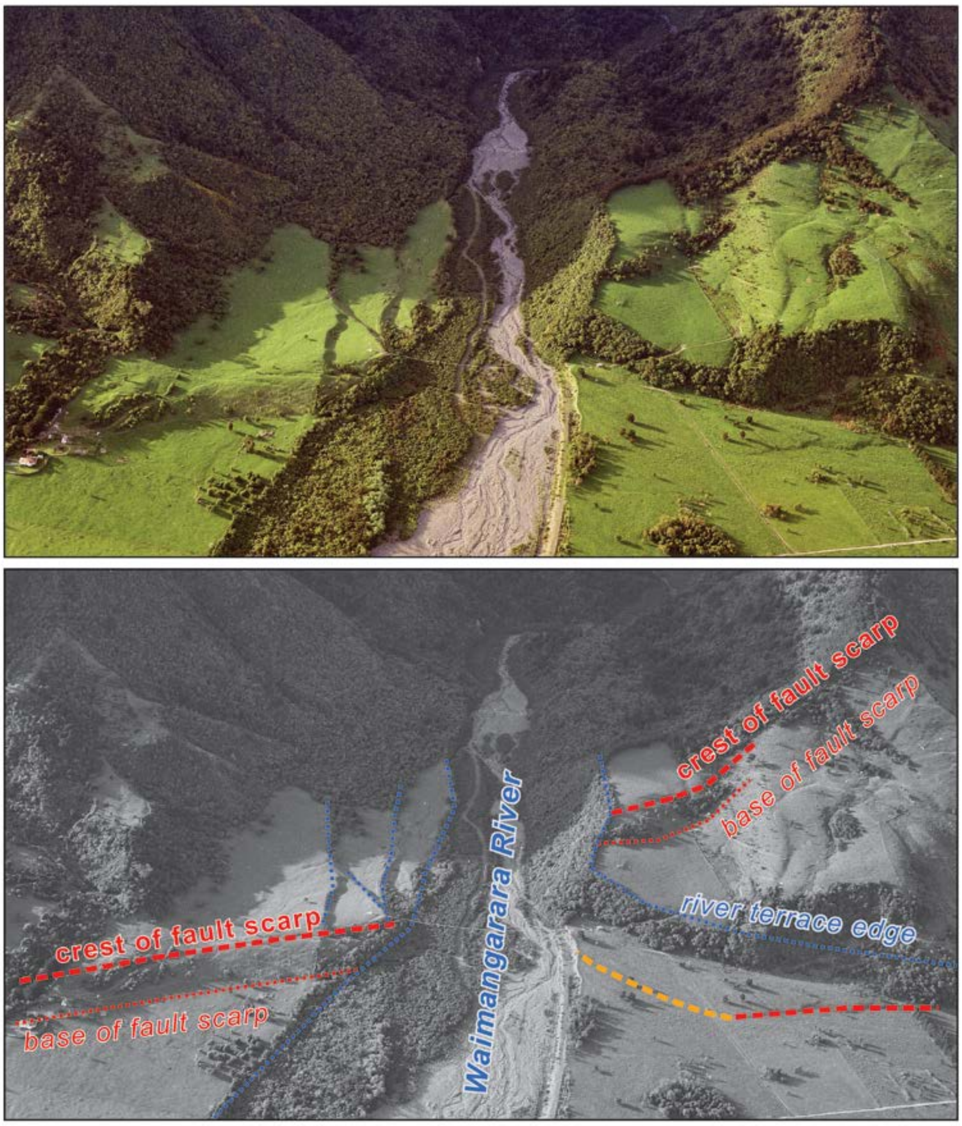

Figure 6 A view north-northwest up the valley of the Waimangarara River where it crosses the Hope Fault Zone at the foot of the Seaward Kaikoura Range. On the lower duplicate image, the edges of river-cut terraces are marked in blue, while fault scarps are shown in red and a monoclines is shown in orange. The fault and fold scarps are 'definite' and are classified as 'well expressed'. A lidar map, and topographic profiles, of this area are presented in Figure 7. West of the river channel (left in photo), the prominent fault scarp is 18 m high (Van Dissen, 1989). The fault scarp on the high terrace on the east side of the river is 26 m high. The fault scarp on the river plain in the right foreground is as much as ~4 m high (Van Dissen, 1989), west of which is a monocline, newly identified using lidar survey data. Due to their relatively small sizes, both are shown just using the 'crest' symbol. Collectively, these features illustrate the considerable degree of complexity that occurs in some places along the Hope Fault Zone. Photo: D.L. Homer, GNS Science CN11015/28.

It is common to find some surprises as a result of more detailed geological examination of active faults or folds. For example, a broad fault scarp, that we would 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 (loess) emanating from river beds tends to accumulate most thickly in hollows and depressions, further smoothing any irregularities produced by fault offset of the ground.

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

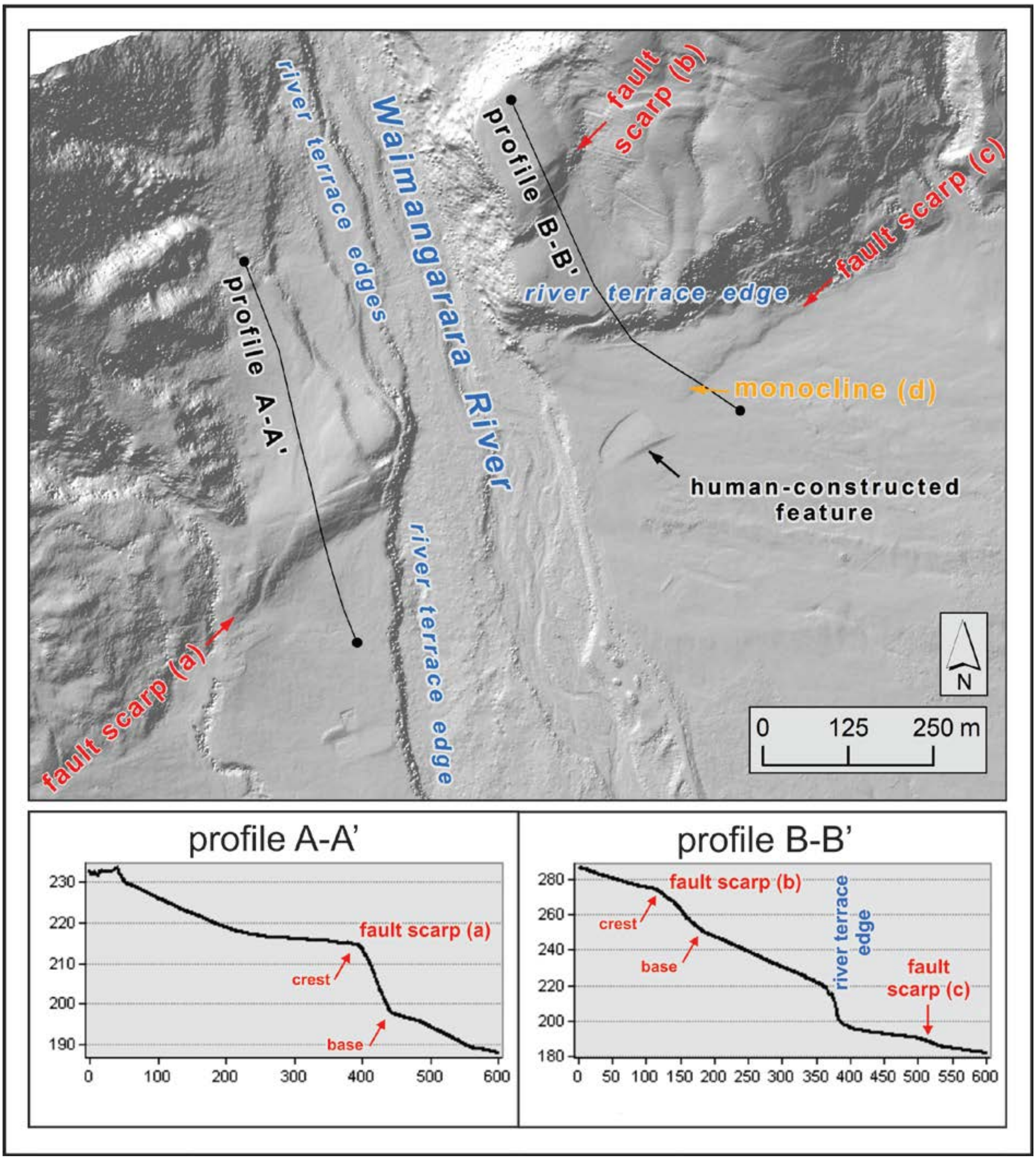

Figure 7 A lidar digital elevation model of the area shown in Figure 6, illustrating the precise topographic information revealed by the aerial laser scanning method. Areas of rough or lumpy terrain are clothed in trees. The topographic profiles are generated from the lidar data. Note the prominent backtilt on the upthrown side of the fault scarp in profile A-A'. Also note that on the lidar map, to the right of the A-A' profile, several light coloured linear troughs along the crest of the fault scarp; these mark subsidiary faults that have disrupted the overall fault scarp (see Figure 5).

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

A regional-scale map of the active faults and folds identified so far in the Kaikoura District is presented in Figure 8. Descriptions of the representative characteristics of active faults and folds and syntheses of the mapping categories used in this report are presented in Table 1, while Table 2 summarises the main features of the identified active faults or folds in Kaikoura District. Extended discussion of the mapping and interpretations is provided in Appendix 2.

The original information on the active faults and folds is extracted from the QMAP dataset (Rattenbury et al., 2006). For this report, the existing mapping has been re-examined and a number of additions and refinements have been made to the mapping of active faults and folds. Amendments were also made to the GIS datasets (see Appendix 1) with the addition of three data fields (also known as ‘attribute’ fields):

- KDC_name (local names for the mapped features)
- Certainty (see below)
- Surf_form (see below)

By and large the names correspond to those in the New Zealand Active Faults Database (NZAFD), which in the Kaikoura District is closely related to the QMAP dataset. The main departure in the datasets accompanying this report is that local names have been applied to some of the fault or fold features, in places where no name has previously been given to active fault/folds. A representative name was taken from nearby named topographic features (e.g., Hapuku fault zone). Where names are informal, fault or fold are in lower case type, while for formally-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, 14 individual or grouped active fault/fold features have been delineated (Figure 8).

In the Certainty field, those features designated as ‘**definite**’ can only be explained by active faulting or folding. Designated as ‘**likely**’ are those features that are most probably due to active faulting or folding, but where 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 either way because, for example, the landforms are unsuitable (e.g., too young) to have preserved any direct evidence of young movement, such features are 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.

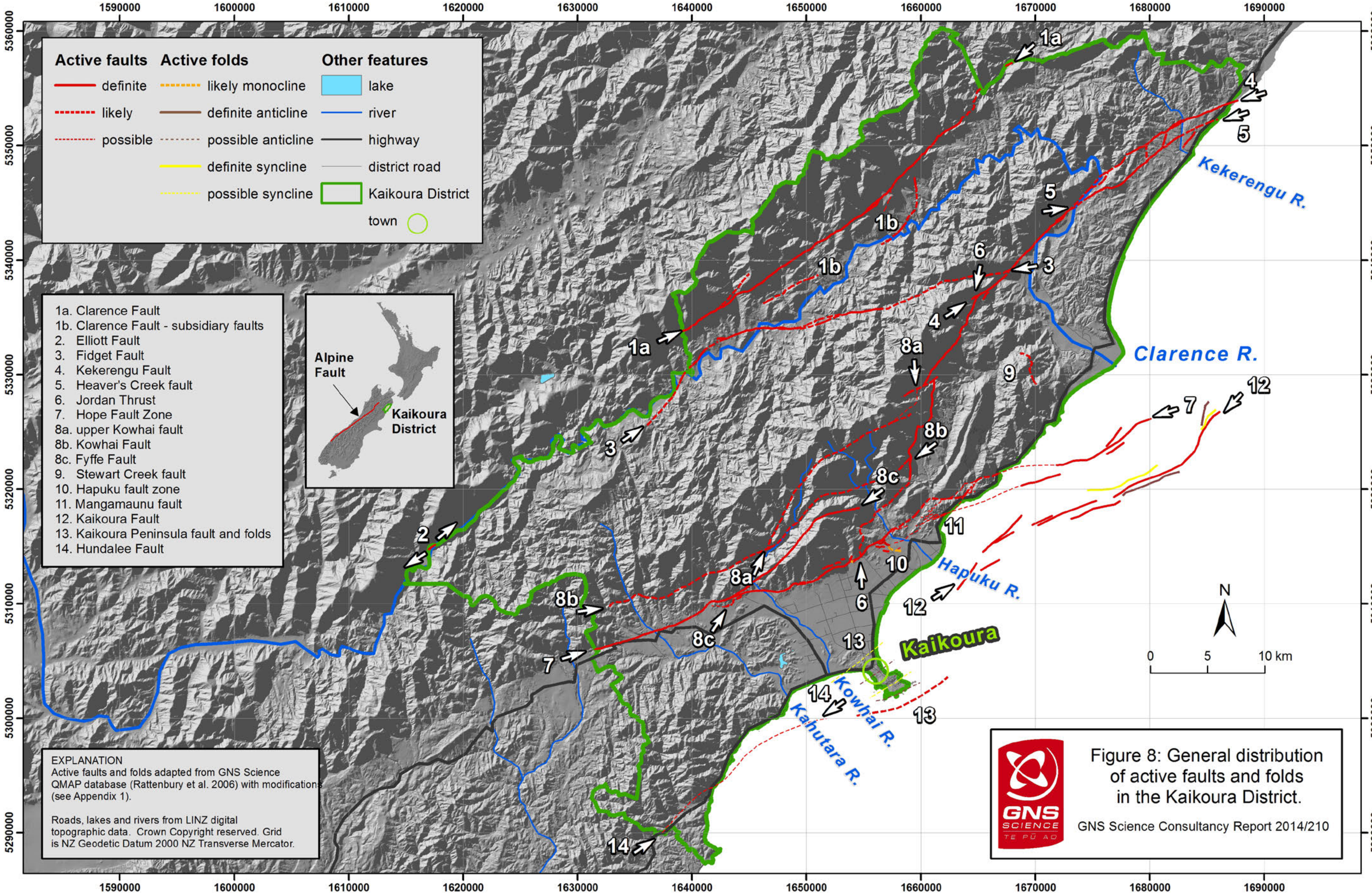

Figure 8 General distribution of active faults and folds in the Kaikoura District.

Table 1 Categories and terms used in this report to describe active faults and folds in the Kaikoura 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 Kaikoura 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** (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. Clarence Fault 1a - Clarence Fault 1b - subsidiary faults	1a: Definite and likely active faults. 1b: Definite, likely and possible active faults.	Rattenbury et al. (2006); Van Dissen & Nicol (2009).	field inspection; geological mapping; radiocarbon dating.	Predominantly horizontal movement; detailed studies of the fault in the Kaikoura District indicate an average slip rate of ~4 mm/yr and average recurrence interval of ~1700 years, an average horizontal offset of ~7 m per earthquake, and the most recent ground-surface rupture earthquake was between ~1700 and ~1900 years ago (Van Dissen & Nicol 2009). Sense of movement and degree of activity of subsidiary faults unknown.					I
2. Elliott Fault	Definite active fault.	Kieckhefer (1979); Reay (1993); Rattenbury et al. (2006).	airphoto interpretation; field inspection.	Predominantly horizontal movement; Van Dissen et al. (2003) assigned a recurrence interval in the range 2,000 to 3.500 years; that range is adopted in this report.					II
3. Fidget Fault	Definite and likely active faults.	Van Dissen (1989); Reay (1993); Rattenbury et al. (2006).	airphoto interpretation; field inspection.	Predominantly horizontal movement; Van Dissen et al. (2003) assigned a recurrence interval in the range 2,000 to 3.500 years. Litchfield et al. (2014) assigned a slip rate 2 ± 1 mm/yr which, if combined with single-event strike-slip displacement scenarios of 2 m and 5 m, implies a recurrence interval in the range of 700 to 5000 years.					I-III
4. Kekerengu Fault	Definite and likely active faults.	Van Dissen (1989); Van Dissen et al. (2005); Rattenbury et al. (2006); this report.	airphoto interpretation; lidar interpretation; field inspection.	Predominantly horizontal movement; Van Dissen et al. (2005) assigned a maximum slip rate for the Kekerengu Fault of between 18 and 23 mm per year. As explained in Appendix 1 of this report, a slip rate of between 10 and 20 mm per year is adopted as a working estimate. These slip rates imply a recurrence interval of between 500 and 100 years, assuming between 2 and 5 m of strike-slip surface offset per rupture event.					I
5. Heaver's Creek fault	Definite and likely active faults.	Van Dissen et al. (2005); Rattenbury et al. (2006).	airphoto and lidar interpretation; field inspection.	Predominantly horizontal movement; approximate ~25 m horizontal offset of a stream terrace landform at least ~30,000 years old, implies a slip rate of ~0.8 mm/yr. This implies a recurrence interval of between 2,400 and 6,000 years, assuming between 2 and 5 m of strike-slip surface offset per rupture event. A 67% uncertainty is applied to these values in order to assign a range of RI classes.					I-IV
6. Jordan Thrust	Definite and likely active faults.	Van Dissen (1989); Van Dissen & Yeats (1991).	field inspection; airphoto interpretation.	Oblique reverse/dextral strike-slip movement. A slip rate of as much as ~20 mm/yr based on modelling (Robinson et al. 2011; Litchfield et al. 2014) applies to the fault structure as a whole, but much of this is thought to be accommodates as folding and diffuse shearing (Van Dissen and Yeats 1991). At the ground-surface trace of the fault, Van Dissen (1989) reported evidence for single-event displacements of between 1.2 and 2 m, and evidence for at least three rupture events in the past ~3,500 years, implying a recurrence interval of no more than ~1200 years.					I
7. Hope Fault Zone 7a - eastern section 7b - Seaward segment 7c - Hope Fault (offshore)	Within Kaikoura District, the eastern section comprises the Conway (aka Kahutara) and Mt Fyffe segments. Boundary between the two is at Kowhai River. The Hapuku River marks the boundary betwen Mt Fyffe segment and the Seaward segment to the north east. Definite, likely and posible active faults.	7a: Langridge et al. (2003); Van Dissen (1989). 7b: Van Dissen (1989); this report. 7c: Barnes & Audru (1999).	airphoto interpretation; field inspection; regional geological mapping; offshore seismic reflection profile interpretation.	7a: Predominantly horizontal movement; trench investigations and radiocarbon dating near Green Burn indicate a slip rate of as much as ~25 mm/yr, average offset per event of as much as 6 m, and recurrence interval of ~200 to ~300 years (Langridge et al. 2003). 7b: There are many uncertainties regarding locations and rates of activity of the Seaward segment of the Hope Fault Zone. Van Dissen & Yeats (1991) suggested a slip rate of 5 mm/yr, and Robinson et al. (2011) modelled a recurrence interval of 1700 years. This recurrence interval value is adopted here for all components of the Seaward segment, including the Patutu Fault. 7c: A vertical component of slip of as much as ~2 mm/yr was identified by Barnes & Audru (1999), while a horizontal component of slip of 5 mm/yr was inferrerd by Robinson et al. (2011). A recurrence interval that is the same as that for the Seaward segment was adopted by Robinson et al. (2011).					7a: I 7b: I 7c: I
8. Seaward Kaikoura Range faults 8a - upper Kowhai fault 8b - Kowhai Fault 8c - Fyffe Fault	8a-b: Likely and possible active faults. 8c: Definite active fault.	Van Dissen (1989); Van Dissen & Yeats (1991); Rattenbury et al. (2006); this report.	Geological mapping; field inspection; airphoto interpretation.	Predominantly horizontal movement assumed. There are no clear landform offsets preserved across any of these faults, so no direct estimates of slip rate or recurrence interval can be made. In this report, slip rates of 0.5 mm/yr, 1 mm/yr and 2 mm/yr are inferred for the upper Kowhai fault, Kowhai Fault and Fyffe Fault respectively. Assuming single event strike-slip displacements of between 2 and 5 m this implies recurrence intervals of between 4,000 and 10,000 years (8a), 2,000 and 5,000 years (8b) and 1,000 and 2,500 years (8c). A 67% uncertainty is applied to these ranges in order to assign a range of RI classes.					8a: II-V 8b: I-IV 8c: I-III
9. Stewart Creek fault	Likely active fault.	Rattenbury et al. (2006); this report.	Airphoto interpretation.	Offset of hillslope terrain; predominantly vertical movement. It is not clear if this feature is due to true fault movement, or gravitational settlement within the rocks forming the hill terrain. Inferred to have a recurrence interval of between 10,000 and 20,000 years.					V
10. Hapuku fault zone	Definite, likely and possible active faults. Likely monocline. Assumed to have predominatly vertical movement.	This report.	Lidar, airphoto, and GoogleEarth Street View interpretation.	7,000	5	0.7	2,800	1,876	I-III

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)
11. Mangamaunu fault	Likely and possible active faults. Assumed to have predominantly horizontal movement.	This report.	Lidar and airphoto interpretation.	Indications of between 10 and 30 m horizontal offset of landforms with an inferred age of 7,000 years. This equates to a slip rate in the range of 1.4 to 4.3 mm/yr. Assuming single-event strike-slip displacements of between 2 and 5 m, this implies a recurrence interval in the range of 470 to 3,500 years. To these values, a 67% uncertainty is applied in order to assign a range of RI classes.					I-IV
12. Kaikoura Fault	Definite faults and folds.	Barnes & Audru (1999).	Offshore seismic reflection profile interpretation.	Barnes & Audru (1999) found evidence for as much as 0.9 ± 2 mm/yr vertical displacement across the fault. Litchfield et al. (2014) inferred predominantly horizontal motion on the fault, and assigned a 'best' estimate of slip rate of 0.13 mm/yr. The reason for the discrepancy with the Barnes & Audru (1999) estimate is uncertain. As the fault is offshore, no RI Class estimate is provided.					n/a
13. Kaikoura Peninsula folds and fault. From NW to SE, comprise Golf Course Syncline, Race Course Anticline, Fyffe Syncline, Atia Anticline, Kaikoura Peninsula fault	Likely active fault and possible active folds.	McFadgen (1987); Ota et al. (1996); Campbell et al. (2005); Rattenbury et al. (2006).	Geological mapping; field inspection; radiocarbon dating.	The interpretation used to assign a slip rate to the Kaikoura Peninsula fault is that the main uplift of the Kaikoura Peninsula is due to movement on the Kaikoura Peninsula fault. The uplift rate of 1.1 mm/yr on the southeeast sector of the peninsula is taken as an approximation of vertical slip rate on the Kaikoura Peninsula fault. McFadgen (1987) reported evidence for approximately 1 m of uplift per event, and this value is taken as an approximation of single-event vertical displacment on the Kaikoura Peninsula fault. This implies a recurrence interval of ~900 years.					I
14. Hundalee Fault	Possible active fault.	Rattenbury et al. (2006); this report.	Lidar, airphoto, and GoogleEarth Street View interpretation; geological mapping.	No indications of Holocene activity. No known offset of landforms in the Kaikoura District. Recurrence interval of between 5,000 and 10,000 years assigned as a minimum estimate.					IV or more

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

Several of the active faults of the Kaikoura District have been subject to detailed walkover examination, whereas other faults or folds have been identified primarily using aerial photographs or other imaging such as lidar, or in reconnaissance walkover. In all cases, the geometries and locations of active faults and folds as depicted in the QMAP-based datasets are very generalised. At the scale of QMAP, none is located more accurately than plus or minus (+/-) 100 m, at best, and +/- 200 m as a general rule. The Surf_form field provides a preliminary estimate of how well defined the surface expression of these features is likely to be, were they to be subjected to a detailed, site-specific, examination. Features that are '**well expressed**' should be able to be located to better than +/- 50 m. Those that are identified as '**moderately expressed**' should be able to be located to better than +/-100 m. Those labelled as '**not expressed**' are not expected to have any physical expression on the ground, because they lie in areas of landforms that are probably younger than the most recent deformation. Features that are '**unknown**' may be found to have evidence for activity if subjected to investigation. 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'.

The Kaikoura District, due to its proximity to the plate boundary, has a large number of active faults and folds. Most of the active faults, including the Clarence (Figure 9), Elliott, Fidget, Hope and Kekerengu faults (Figure 8), have predominantly strike-slip movement. These sideways-moving faults have a right-lateral sense of movement. 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). The Jordan Thrust has a notable component of reverse movement. There are several faults about which not much is known, including the newly recognised Hapuku fault zone, and the Kaikoura Peninsula fault, which is inferred to be responsible for the uplift of Kaikoura Peninsula.

In the companion reports undertaken for other districts in the Canterbury region, no attempt has been made to include information, where any exists, on offshore faults, because an important intended use of the active fault information is for land-use planning. However, in the case of the Kaikoura District, there were several uncertainties relating to the locations and significance of some of the onland faults, or fault-related uplift or deformation. Therefore it was considered useful to incorporate information on notable nearshore submarine faults or folds, in order to try and place mutual context on the onland and offshore active faults. It is important to appreciate that the nearshore mapped limit of the offshore faults is influenced by the inability to undertake seismic reflection surveys in very shallow water. In the offshore Kaikoura area, nearly all the seismic surveys have been done in areas where the water is deeper than 20 m or so (Barnes & Audru, 1999). Accordingly, the nearshore limit of the mapped faults does not necessarily indicate that the fault terminates there, but rather that was as close to the shore as the fault could be mapped from seismic survey data.

The two main active fault/fold systems identified close offshore in the Kaikoura District are identified by Barnes & Audru (1999) as the offshore continuation of the Hope Fault and the Kaikoura Fault (Figure 8). There are many more faults and folds identified offshore than are shown in the dataset accompanying this report, wherein just the major structures with reasonable evidence for along-strike continuity, are included. Note that in the northeast corner of the district, the Kekerengu Fault also projects offshore, but its offshore projection is not included in this dataset because it lies in the offshore sector of the Marlborough District.

Table 1 includes preliminary correlations to the fault complexity classification of Kerr et al. (2003). Table 2 provides estimates of the deformation characteristics of the active faults and folds, based on estimated amounts of deformation of landform features of specific age. For the major strike-slip faults, where the deformation is mainly horizontal, deformation rates have been adopted from published studies, with some refinements, or assessed from available unpublished information, as discussed in Appendix 2. The reasoning for the values used in Table 2 is set out in Appendix 2.

Figure 9 A view northeast along the Clarence Fault, which lies at the southeastern foot of the Inland Kaikoura Range (at left). Red arrows highlight light-coloured linear features running along the foot of the range. These features are the surface offset scarps of the Clarence Fault. Cover rocks underlie the basin floor southeast (lower right) from the fault, whereas basement rock has been uplifted to form the Inland Kaikoura Range, and its former blanket of cover rocks has been stripped off by erosion. In the foreground from centre left to bottom right is Red Hut Stream, which forms the southwestern boundary of Kaikoura District at this location (i.e., the bottom left of the photo is outside the Kaikoura District). Mt Alarm and Tapuae–o-Uenuku, both a little over 2800 m above sea level, are the highest peaks. Photo: D.L. Homer, GNS Science CN4938/5.

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 are typically a few hundred years for the ‘most active’ faults, and as much as 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, for example, from well-dated and precisely measured offset features, 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). In the case of strike-slip faults, which are the most common fault type in the Kaikoura District, single-event displacements are commonly several metres. Two observational examples are shown in Figure 2, a ~2.4 m displacement on the Hope Fault in 1888, and a ~4.5 m displacement on the Greendale Fault in 2010. For the purposes of RI estimation, a range of SED of between 2 m and 5 m has been used, as is discussed in Appendix 2 for strike-slip faults. Following the methodology used in companion fault evaluations for Canterbury (for example, see Barrell & Townsend, 2012), a SED value of 2 m for the vertical component of displacement is used for faults with a prominent dip-slip component. As an example of the local worth of this, Van Dissen (1989) found that the three most recent offsets on the Jordan Thrust each involved between 1.2 and 2 m of vertical displacement.

It is unlikely that these approximations for SED of between 2 and 5 m for strike-slip faults, and 2 m for dip-slip faults will be good representations for all faults in the district, but they do at least enable comparative assessments of active fault and fold hazards, pending better-constrained site-specific data on faults and folds.

Except in cases where there are existing data from detailed studies, these approaches have been used to estimate an indicative average recurrence interval for deformation events on each active fault/fold feature listed in Table 2. The generalised estimates are intended only as a general indication of deformation characteristics. For this reason, the faults that have not been previously investigated in detail, or have substantial question-marks about their degree of activity, have had a nominal +/- 67% uncertainty applied to their recurrence interval estimates (see Table 2), unless indicated otherwise. It is emphasised that these estimates are provisional, pending further information from 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/folds and allow them to be placed in context with the Kerr et al. (2003) guidelines.

The GIS layers of active folds (KDC_folds) and active faults (KDC_faults) accompanying this report are derived from the QMAP dataset, with modifications. These modifications include 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 2.

The information in this report is more comprehensive than that contained in the NZAFD, as it stood in August 2014. The information in this report also builds on and refines information presented by Pettinga et al. (2001), Van Dissen et al. (2003) and Stirling et al. (2008, 2012), Litchfield et al. (2014) and references therein.

5.0 IMPLICATIONS FOR HAZARDS

Since European settlement of the Kaikoura District area, there have been no known ground-surface fault rupture events in the district. Several large historic earthquakes have been felt strongly in the district, the 1848 Marlborough Earthquake, the 1855 Wairarapa Earthquake, and the 1888 North Canterbury Earthquake, for example. Recent research suggests that the 1855 earthquake sequence may possibly have extended onto the northern end of the Kekerengu Fault (Grapes & Holdgate, 2014). 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 Kaikoura District as potentially hazardous.

Figure 2, Figure 5 and Figure 10 illustrate examples of the types of ground-surface deformation hazards associated with active faults or active monoclines, noting that at any location, elements of both faulting and folding may be present within a deformation zone. In general, faults and monoclines present the most focused forms of ground deformation, in regard to direct rupture or significant tilting of the ground surface. Such effects may occur in a sudden event. Active anticlines or synclines are likely to present a much lesser level of ground surface deformation hazard with regard to buildings, but may pose relevant hazards to developments such as canals or power stations (e.g., by tilting the ground). Furthermore, the presence of active folds suggests that there may be an underlying active fault at depth that may potentially generate a local, large, shallow earthquake, were it to rupture.

The geological estimates presented in this report indicate that many of the faults in the Kaikoura District may have recurrence intervals of less than 2,000 years (Table 2). There are also at least two newly identified suspected active faults, the Hapuku fault zone and Mangamaunu fault (see Figure 11 and Figure 12)**.** If their interpretation as active faults is borne out by further assessment, these features will need to be placed into tectonic context with other nearby faults, including those offshore.

In summary, there are many active faults in the Kaikoura District and every reason for authorities and residents to be prepared for the occurrence of ground-surface rupturing fault movements, and resulting large, locally damaging earthquakes, over future decades to centuries (Stirling et al., 2008). It is important to appreciate that the mapped delineation of the active faults and folds of the Kaikoura 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 at locations where more detailed assessments have been undertaken (e.g., Wairimu; URS 2008). In addition, several of the fault/fold features that have been mapped have not yet been proven to be active faults or folds. For features classed as ‘likely’, or ‘possible’, it would be 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.

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

Figure 10 Fault scarp formed on the Chelungpu Fault during the magnitude 7.6 Chi-Chi Earthquake, Taiwan, 1999. The disrupted running track shows damage typical of a reverse fault ground-surface rupture, which is well expressed on the brittle surface (note the smoother rupture across grass behind). This location lies on a stream terrace that is younger than the previous rupture event on the fault, so that there was no scarp here before the earthquake. This example illustrates the sorts of effects that can be expected across fault scarps in the Kaikoura District the next time any particular fault experiences a surface rupture earthquake. Photo from Kelson et al. (2001).

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

Many of the active faults on land are in remote locations, far from any existing or likely future developments. Accordingly, in regard to ground-surface fault rupture hazard, they are of minimal consequence. However, they do represent potential sources of major earthquakes that would be accompanied by widespread strong ground shaking, possibly along with earthquake-triggered landslides and liquefaction.

The Hope Fault Zone, and associated features such as the suspected active faults or folds delineated as the Hapuku fault zone and Mangamaunu fault, lie close to current low-intensity development east of the Seaward Kaikoura Range, and are in proximity to major highways and, near the coast, the railway line.

A future uplift event at Kaikoura Peninsula, on the suspected Kaikoura Peninsula fault, would impact on berthing facilities and may possibly generate a local tsunami. The offshore Kaikoura Fault is also another potential source of local tsunami.

It would be prudent to identify specific vulnerabilities, and develop contingency plans for streamlining first-response emergency management and disaster recovery in the event of a major ground-surface rupturing earthquake in the Kaikoura District. Such plans should also take account of other potential earthquake hazards, such as liquefaction and landsliding.

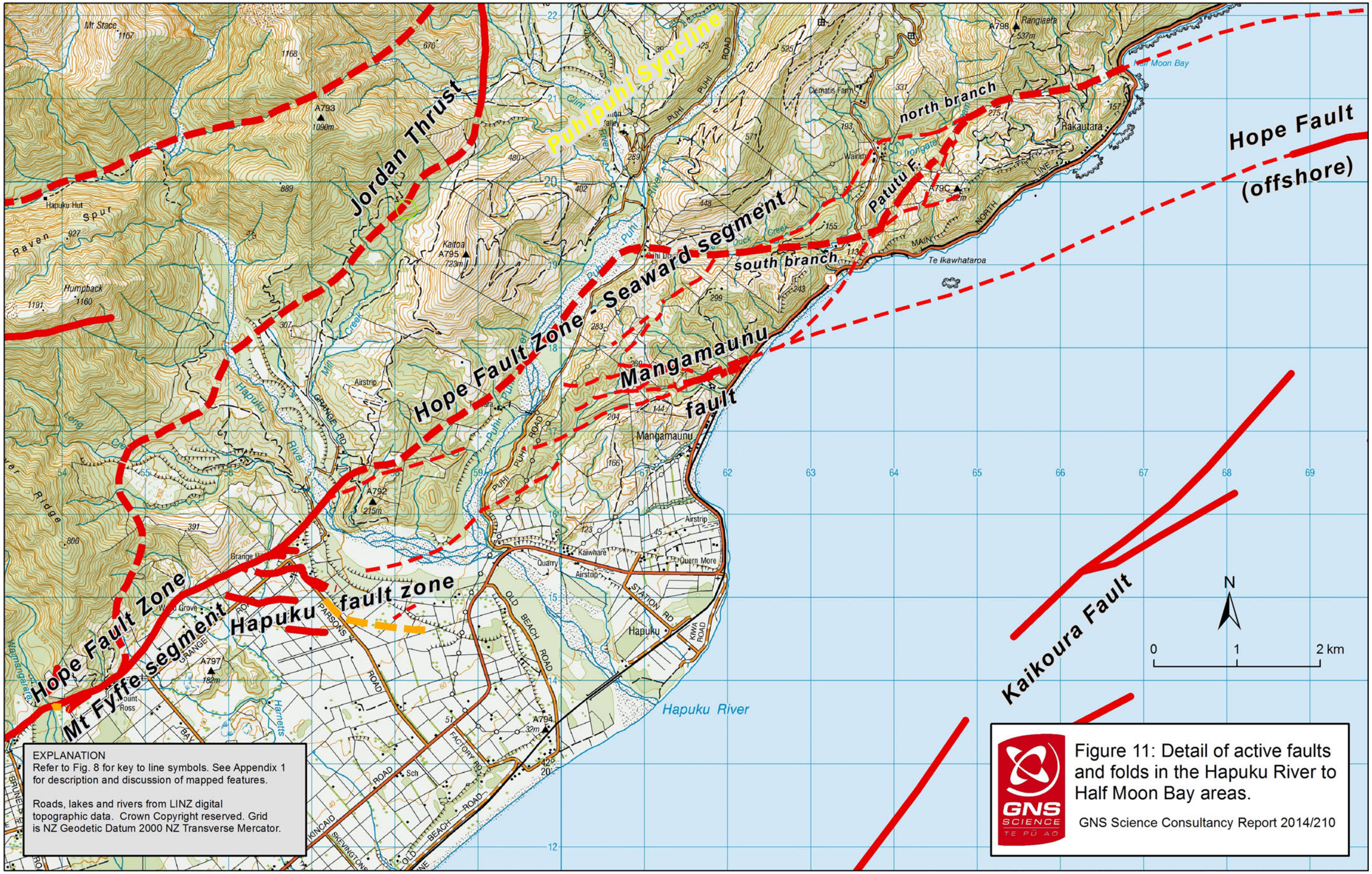

Figure 11 Detail of active faults and folds in the Hapuku River to Half Moon Bay areas.

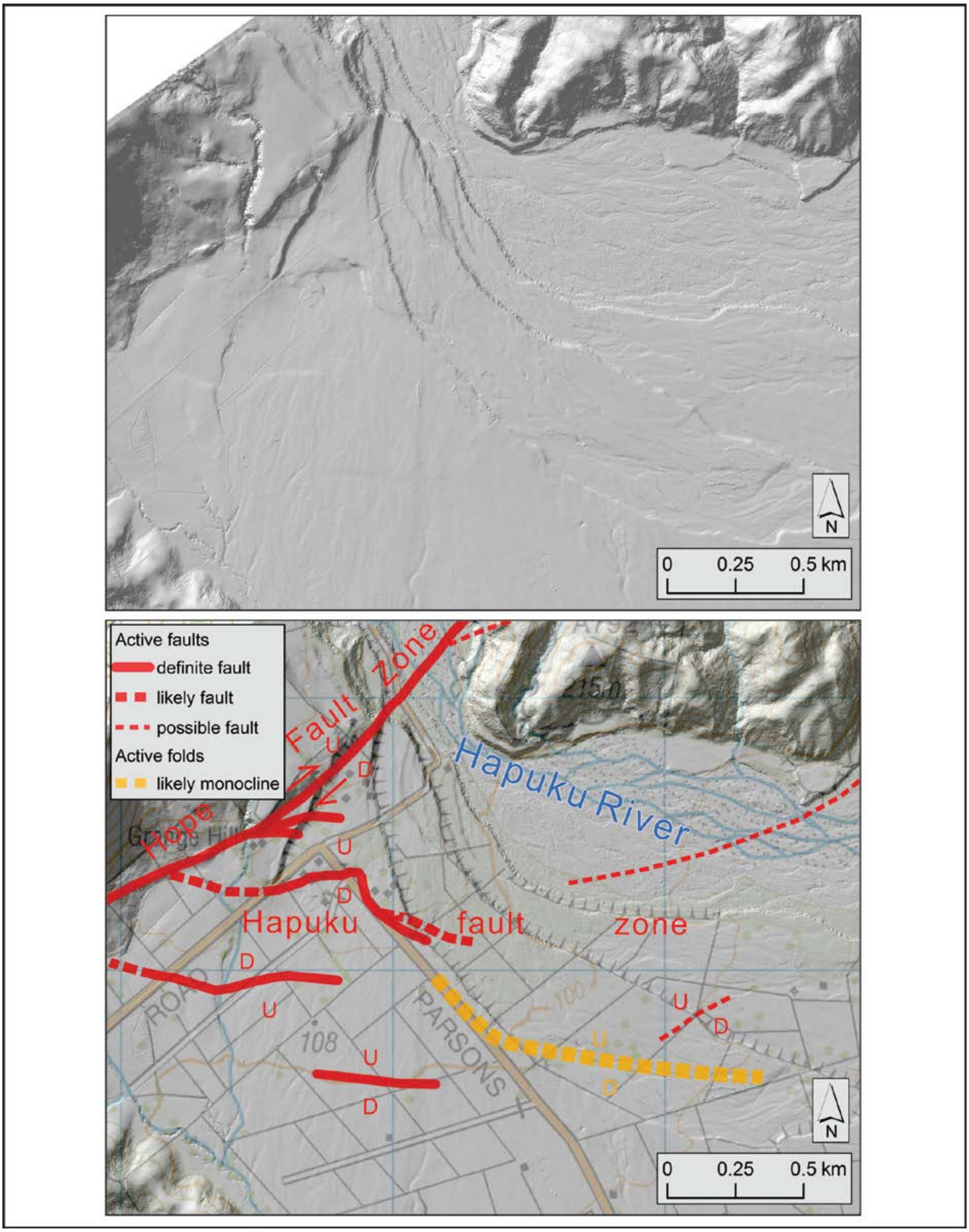

Figure 12 A lidar DEM with hillshade effect showing the area near the junctions of Grange Road (left) and Parsons Road, near the intersection of the Hapuku fault zone and the Hope Fault Zone. The lower image shows a topographic location map (NZ Topo50) draped on the DEM, and the active fault and fold interpretation plotted from the database accompanying this report.

6.0 CONCLUSIONS

1. Regional geological mapping has identified a number of active faults and folds (monoclines, synclines and anticlines) in the Kaikoura District. In total, 14 areas of known or suspected active faults and/or folds are delineated. Most of these were already known about, but several features are newly identified.
2. A GIS dataset of information on the active faults and folds accompanies this report. For each mapped fault and fold, an attribute of ‘certainty’ indicates the level of confidence in the mapping of the feature, whether ‘definite’, ‘likely’ or ‘possible’. Also included is a classification of ‘surface form’, whether ‘well expressed’, ‘moderately expressed’, ‘not expressed’ or ‘unknown’. The surface form classification 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 information presented here is not sufficiently precise for site-specific hazard assessment. Instead, the information is intended to highlight those areas which, at our current state of knowledge, are potentially affected by active fault or fold hazards. The information may help to target site-specific investigations that may be desirable, or required, prior to development, and allow identification of lifeline vulnerabilities and emergency management response plans.

7.0 ACKNOWLEDGEMENTS

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

8.0 REFERENCES

Bacon, S.N.; Chinn, T.J.; Van Dissen, R.J.; Tillinghast, S.F.; Goldstein, H.L.; Burke, R.M.; 2001. Paleo-equilibrium line altitude estimates from late Quaternary glacial features in the Inland Kaikoura Range, South Island, New Zealand. New Zealand Journal of Geology and Geophysics 44: 55–67.

Barnes, P.C.; Audru, J.-C. 1999. Recognition of active strike-slip faulting from high-resolution marine seismic reflection profiles: Eastern Marlborough fault system, New Zealand. Geological Society of America Bulletin 111 (4): 538–559.

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

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

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

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

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

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

Barrell, D.J.A.; Litchfield, N.J.; Townsend, D.B.; Quigley, M.; Van Dissen, R.J.; Cosgrove, R.; Cox, S.C.; Furlong, K.; Villamor, P.; Begg, J.G.; Hemmings-Sykes, S.; Jongens, R.; Mackenzie, H.; Noble, D.; Stahl, T.; Bilderback, E.; Duffy, B.; Henham, H.; Klahn, A.; Lang, E.M.W.; Moody, L.; Nicol, R.; Pedley, K.; Smith, A. 2011. Strike-slip ground–surface rupture (Greendale Fault) associated with the 4 September 2010 Darfield Earthquake, Canterbury, New Zealand. Quarterly Journal of Engineering Geology and Hydrogeology 44: 283–291.

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

Brown, L.J. 1988. Water well data, geohydrology and Quaternary geology, southern Marlborough. New Zealand Geological Survey Report 111. Lower Hutt, NZ Geological Survey. 57 p.

Campbell, J.; Tonkin, P.; Bradshaw, J. 2005. Field Trip 5A – Structure and tectonics of the Kaikoura Peninsula. Pages 112–127 In Pettinga, J.R.; Wandres, A.M. (eds.) Field Trip Guides, Geological Society of New Zealand 50th Annual Conference, Kaikoura, New Zealand. Geological Society of New Zealand Miscellaneous Publication 119B. Available for download at www.gsnz.org.nz.

Grapes, R.H.; Holdgate, G.R. 2014. Earthquake clustering and possible fault interactions across Cook Strait, New Zealand, during the 1848 and 1855 earthquakes. New Zealand Journal of Geology and Geophysics (in press).

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

Kerr, J.; Nathan, S.; Van Dissen, R.; Webb, P.; Brunsdon, D.; King, A. 2003. Planning for development of land on or close to active faults: A guideline to assist resource management planners in New Zealand. Ministry for the Environment, July 2003. ME Number: 483; also identified as Institute of Geological and Nuclear Sciences Client Report 2002/124. Available for download at www.mfe.govt.nz.

Kieckhefer, R.M. 1979. Late Quaternary tectonic map of New Zealand 1:50,000. Sheets M31D, N31A, N31C, parts M32A & M32B Leader Dale; Sheets N31B & N31D Dillon; Sheets 030C & 031A Lake McRae. Wellington, Department of Scientific and Industrial Research. 3 maps + 1 booklet.

Knuepfer, P.L.K. 1992. Temporal variations in late Quaternary slip across the Australian-Pacific plate boundary, northeastern South Island, New Zealand. Tectonics 11: 449–464.

Langridge, R.M.; Campbell, J.; Hill, N.L.; Pere, V.; Pope, J.; Pettinga, J.; Estrada, B.; Berryman, K.R. 2003. Paleoseismology and slip rate of the Conway Segment of the Hope Fault at Greenburn Stream, South Island, New Zealand. Annals of Geophysics 46: 1119–1139.

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

McFadgen, B.G. 1987. Beach ridges, breakers and bones: late Holocene geology and archaeology of the Fyffe site, S49/46, Kaikoura Peninsula, New Zealand. Journal of the Royal Society of New Zealand 17: 381–394.

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

Ota, Y.; Pillans, B.; Berryman, K.; Beu, A.; Fujimori, T.; Miyauchi, T.; Berger, G.; Climo, F.M. 1996. Pleistocene coastal terraces of Kaikoura Peninsula and the Marlborough coast, South Island, New Zealand. New Zealand Journal of Geology and Geophysics 39: 51–73.

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

Rattenbury, M.S.; Townsend, D.B; Johnston, M.R. (compilers) 2006. Geology of the Kaikoura area. Institute of Geological & Nuclear Sciences 1:250 000 Geological Map 13. Lower Hutt, New Zealand. GNS Science. Map (1 sheet) + 70 p.

Reay, M.B. 1993. Geology of the middle part of the Clarence Valley. Institute of Geological & Nuclear Sciences Geological Map 10. Map (1 sheet) + 144 p.

Robinson, R.; Van Dissen, R.; Litchfield, N. 2011. Using synthetic seismicity to evaluate seismic hazard in the Wellington region, New Zealand. Geophysical Journal International 187: 510–528.

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

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

URS 2007. Mt Ross Subdivision active fault hazard assessment. Report prepared by URS New Zealand Limited for Winston Gray, 5 March 2007. 9 p. plus map (Figure 1).

URS 2008. Wairimu Station Subdivision – geotechnical assessment. Report prepared by URS New Zealand Limited for Pritchard Group Limited, 15 May 2008. 43 p.

Van Dissen, R.J. 1989. Late Quaternary faulting in the Kaikoura region, southeastern Marlborough, New Zealand. Master of Science thesis, Oregon State University. Accessible at Oregon State University library, http://osulibrary.oregonstate.edu/, Scholars Archive, search word < Van Dissen >. 72 p. and map (Plate 1).

Van Dissen, R.J.; Nicol, A. 2009. Mid-Late Holocene paleoseismicity of the eastern Clarence Fault, Marlborough, New Zealand. New Zealand Journal of Geology and Geophysics 52: 195–208.

Van Dissen, R.J.; Yeats, R.S. 1991. Hope Fault, Jordan thrust, and uplift of the Seaward Kaikoura Range, New Zealand. Geology 19: 393-396.

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

Van Dissen, R.; Little, T.; Nicol, A. 2005. Field Trip 4 – Faults of eastern Marlborough: Picton, Awatere and Kekerengu. Pages 85–110 In Pettinga, J.R.; Wandres, A.M. (eds.) Field Trip Guides, Geological Society of New Zealand 50th Annual Conference, Kaikoura, New Zealand. Geological Society of New Zealand Miscellaneous Publication 119B. Available for download at www.gsnz.org.nz.

APPENDICES

APPENDIX 1: GIS LAYERS

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

- KDC_faults.shp
- KDC_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 Kaikoura (Rattenbury et al., 2006). 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:

- KDC_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. The geographic coordinate system for the data is New Zealand Map Grid 1949.

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

APPENDIX 2: DETAILED COMMENTARY ON THE MAPPING OF ACTIVE FAULT/FOLD FEATURES IN THE KAIKOURA DISTRICT

Regional-scale (i.e., 1:250,000) topographic maps, on which the faults and folds are plotted, are provided at the end of the Appendix (Figures A2-1a-e), to assist the reader in locating the geographic features mentioned in this appendix. Not all of the geographic locations (e.g., names of minor streams) are shown on these maps, and a reader requiring more information may also wish to refer to 1:50,000 topographic maps from the NZ Topo50 series, which can be viewed via the internet from sites such as http://www.topomap.co.nz/.

Clarence Fault (feature 1a, Figure 8)

This feature is continuous with the Clarence Fault of the Hurunui District. The sector of the Clarence Fault in the Kaikoura District is described in detail by Van Dissen & Nicol (2009), and interested readers should refer to that paper for further information. In the Kaikoura District fault dataset, the scarp of the Clarence Fault is for the most part classified as 'definite' and 'moderately expressed', and 'not expressed' across stream valley floors. The reason for selecting 'moderately expressed' is because the fault runs along the foot of the Inland Kaikoura Range, and the scarp varies over short distances from sharply defined, to considerably obscured by slope debris.

Van Dissen & Nicol (2009) found that recent scarps of the Clarence Fault could not be traced northeast of the area between Dee Stream and Mead Stream. There is no doubt that the fault continues to the northeast as a geological feature, but there is a question-mark over whether it is an active fault. Accordingly, in this dataset, the fault northeast of that area is classified as 'likely', in order to highlight an uncertainty as to whether the activity of the fault continues to the northeast.

Clarence Fault – subsidiary faults (feature 1b, Figure 8)

Four faults close to the Clarence Fault are referred to collectively as subsidiary faults of the Clarence. This is just for geographic convenience, and no direct connection is implied between any of these faults, or necessarily any direct connection to the activity of the Clarence Fault.

On the northern side of Bluff River, just upstream of the Inland Kaikoura range-front, a topographic step high up a mountain-side is classed as 'likely', 'moderately expressed', and was interpreted by Rattenbury et al. (2006; unpublished record sheets) to be a fault scarp. On the published map, the fault was interpreted to extend southwest to meet the Clarence Fault. This continuation is classified here as 'likely', 'not expressed'; it may simply be a gravitational movement feature (i.e., 'ridge rent').

About 2 km southeast of and parallel to the Clarence Fault, between Cow Stream and Dead Horse Gully, a topographic step on the northwest edge of a limestone outcrop was mapped as a fault scarp by Rattenbury et al. (2006; unpublished record sheets). Geological relationships indicate that this step lies at the location of a fault in bedrock. The section where the topographic step is present is classified here as 'likely', 'moderately expressed'. Those parts of the bedrock fault to the northeast and southwest, attributed as 'active' by Rattenbury et al. (2006), are classified as 'likely', 'not expressed'. This highlights the possibility that the topographic step may be a result of differential erosion, or gravitational movement, rather than fault movement.

An approximately 2 km long fault mapped as active by Rattenbury et al. (2006) as branching south-southwest from the Clarence Fault between Dart Stream and Trolove Stream is classified here as ‘possible’. The topographic step is not well defined, and it is in a position where it could well be the result of slope movement rather than fault movement.

A sharply defined topographic step, up to the east, crosses a stream terrace between Branch Stream and Whisky Stream, and is classified as ‘definite’, ‘well expressed’. To the southwest lies deeply eroded and scrub covered terrain, and the active fault is extrapolated along a fault mapped in bedrock (Rattenbury et al., 2006). The fault here is classified as ‘likely’, ‘not expressed’. To the northeast of the definite fault scarp, is eroded terrain, and this sector is marked as ‘definite’, ‘not expressed’.

At the time of writing, the NZ Active Faults Database shows five active faults in the catchment of Ouse Stream, on the southeast side of Chalk Range. They are attributed as being sourced from the original 1:250,000-scale compilation of the Active Faults database, and thus are highly generalised. They appear to have been taken from the 1st Edition 1:250,000 scale geological map of Kaikoura (Lensen 1962), and were not shown on the 2nd edition geological map of Rattenbury et al. (2006). Having examined aerial photos of this area as part of the present project, I am of the opinion that these suspected fault scarps are related to slope instability, or are the expressions of hard layers within the geological sequence. Their interpretation as active faults is considered unjustified, and I recommend that they be removed from the Active Faults database.

Elliott Fault (feature 2, Figure 8)

For the most part, the Elliott Fault lies west of Kaikoura District, within the Hurunui District and Marlborough District. In the far west corner of Kaikoura District, the Elliott Fault passes beneath low terraces on the south side of the Clarence River, 4 km upstream of its junction with Palmer Stream. Although the fault scarp is prominent on higher terraces on the north side of the river, it is not evident on the low-level terraces, which presumably were formed after the most recent rupture of the fault at this location. To the SW and NE, the fault lies just beyond the boundary of the District.

Fidget Fault (feature 3, Figure 8)

A fault offset of a flight of terraces of the Clarence River, downstream of its confluence with Limestone Stream, is identified by Rattenbury et al. (2006; unpublished record sheets). That offset is classified here as ‘definite’, ‘well expressed’. Southwest of Limestone Stream, the extrapolated line of the fault crosses eroded hill terrain and no scarp is evident; it is classified as ‘likely’, ‘not expressed’. North of the faulted river terrace, the fault crosses out of the district, but returns on the eastern side of Red Hill Stream. There, there is a vague topographic step classified here as a ‘likely’, ‘moderately expressed’ active fault. From there, east-northeast to near Muzzle homestead, the fault projects beneath the Clarence River bed, or across irregular hill terrain, and is classed as ‘likely’, ‘not expressed’, to highlight that the exact location of the fault is uncertain in this area. Between Roaring Meg Stream and Bluff River is a prominent topographic step, up to the east, that is interpreted to be the fault scarp. It is classified as ‘definite’, ‘well expressed’. East from there, the fault is marked by moderately to sharply defined topographic steps across hill terrain, and is classed ‘definite’, and differentiated into well, moderately or not expressed, as befits its topographic prominence from place to place.

East of Dubious Flat, the fault loses any topographic expression, at least as far as can be discerned in aerial photos and satellite imagery, and is classed as ‘likely’, ‘not expressed’, to highlight that its exact location is uncertain. East from Chimney Stream as far as Jam Stream, topographic steps are present to varying degrees along the hill slopes, and are interpreted as being fault scarps and classified as ‘definite’, ‘moderately expressed’. From Jam Stream through to the inferred junction of the Fidget Fault with the Kekerengu Fault, on the north side of George Stream close to its confluence with the Clarence River, the line of the fault crosses eroded mountain terrain, in places with bush cover. No convincing fault scarps have been identified, although there is a series of aligned saddles which may indicate the presence of a fault crush zone in bedrock. Through this section, the fault is classified as ‘likely’, ‘not expressed’. At one location on the southern bank of George Stream, about 1.3 km south-southwest of Black Hill, Van Dissen (1989) reported an exposure of the fault zone, in which the fault displays a vertical dip. The sector of the fault in this immediate vicinity is classified as ‘well expressed’ on account of the fault being exposed, but a classification of ‘likely’ is retained, because there is no direct evidence, at this location, that the exposed fault has been recently active.

Litchfield et al. (2014) assessed the Fidget Fault as having a right-lateral strike slip sense of motion, at a slip rate of 2 ± 1 mm/yr. If one assumes two nominal alternative values of 2 m and 5 m for the mean amount of slip per surface rupture event on the Fidget Fault, these imply recurrence intervals of between 700 and 2,000 years (2 m per event, 1 and 3 mm/yr slip rates respectively) and between 1700 and 2,000 years (5 m per event, 1 and 3 mm/yr slip rates respectively). These estimates span recurrence interval classes I to III.

Kekerengu Fault (feature 4, Figure 8)

The Kekerengu Fault, for the most part, has a well-defined location as it juxtaposes different rock types. It is divided according to the degree of expression. At its SW end it is inferred to have a three-way intersection with the Jordan Thrust and Fidget Fault.

On the southwestern side of McLean Stream, about 600 m west of Waiautoa farm buildings, Van Dissen (1989) describes stream terraces that have been horizontally offset across the Kekerengu Fault. The fault here is classified as ‘well expressed’. Using weathering-rind dates of these offset terraces determined by Knuepfer (1988, 1992), Van Dissen (1989) calculated a slip rate of between 3 and 10 mm/yr for the Kekerengu Fault at that location. The smallest offset reported by Van Dissen (5.6 ± 2 m) affords a maximum estimate for single event displacement. Assuming between 2 and 5 m to be representative single-event displacements, the larger and smaller slip rate bounds imply a recurrence interval in the range of 200 to 1670 years. However, R. Van Dissen (personal communication, 2014) now regards those weathering rind ages as being of doubtful validity, and therefore considers that the estimated slip rates and any derived recurrence interval estimates to be of poor reliability.

Northeast of the Clarence River, the fault is positioned along an offset of bedrock geological units, with basement rock to the northwest of the fault and cover rocks to the southeast, indicating an overall sense of downthrow to the southeast. However, over a 3 km stretch of the mapped fault between the Clarence River and the headwaters of Deadman Stream, the landscape is mostly actively eroding hill terrain, and no fault scarps are evident. Within this area, the fault passes through two saddles, where the landforms are more stable, but even so there are no convincing fault scarps. Where the fault passes through each saddle, it is classified as ‘moderately expressed’ to indicate the existence of these saddles, but the lack of obvious fault scarps has led to this section of the Kekerengu Fault, including the ~4 km long stretch farther southwest between Big Stream and Boundary Stream, being classed as

'likely'. This acknowledges a possibility that the adjacent section of the Heaver's Creek fault, from the Clarence River to Mole Hill (see next section) could conceivably be the active segment of the Kekerengu Fault, and that the fault activity then steps left onto the Kekerengu Fault northeast of Mole Hill.

Northeast of Deadman Stream, the Kekerengu Fault crosses smoother hill terrain, although disrupted by landslides on the northwestern side of the fault. There is a straight and prominent topographic step, up to the southeast, in the western sector of the Valhalla Stream catchment, at the location of the mapped fault. This is interpreted to be a fault scarp, though it has undoubtedly been accentuated by erosion or landsliding. It is classed as 'definite', 'well expressed'. To the northeast, any topographic expression of the fault is obscured by eroded hill terrain in the catchment of Valhalla Stream, and farther northeast, across the catchment of a tributary of Kekerengu River that has no formal name but is known locally as Heaver's Creek. Throughout this area, the fault is classed as 'not expressed'.

Between the Heaver's Creek catchment and the Kekerengu River is a set of landforms along the line of the fault that are described in detail by Van Dissen et al. (2005). They suggest that a set of terraces and channels were formed by Glencoe Stream, and have subsequently been offset dextrally by as much as 700 m. Based on age estimates for the terraces derived from soil and terrace cover sediment characteristics, Van Dissen et al. (2005) proposed that this offset has occurred over the past ~30,000 to 40,000 years, implying a maximum slip rate for the Kekerengu Fault of between 18 and 23 mm per year. This interpretation was adopted as the preferred slip rate for the fault by Litchfield et al. (2014; 20 ± 2 mm/yr). I agree that this is one interpretation, and indeed provides an approximate maximum estimate of fault offset. However, other interpretations are possible and should be evaluated. The following discussion should be read in conjunction with pages 100 to 108 of the Van Dissen et al. (2005) article (see reference list for the download location of that article).

- The first point to note is that the Kulnine/Winterholme terrace riser west of Glencoe Stream need not have been formed at the present location of Glencoe Stream. Streams can easily cut wider beds at localities where they debouch from hill terrain. It is by no means inconceivable that at the debouchment point, Glencoe Stream swung southwest along the line of the fault, leading to the cutting of the terrace riser where the stream swung to a more downvalley trend. Thus, the alternative consideration is that the offset of the riser may be as little as 0 m. The offset is unlikely to be more than 500-550 m, as pointed out by Van Dissen et al. (2005), but it could be very much less.
- The second point to note relates to the so-called 'beheaded channel', inferred to have been offset dextrally by about 700 m from the location of Glencoe Stream. This channel represents a stream incision below the level of the Kulnine terrace west of the Glencoe Stream, but was this channel incision necessarily formed by Glencoe Stream? Could it instead have been formed by an east-flowing distributary from the nearby Heaver's Creek catchment? The answer remains unclear, but it is important to note that the terrain in this area is in highly erodible strata, and may have the facility to evolve rapidly, as seen for example by the deep post-glacial incision of most of the stream valleys. Many uncertainties attend the reconstruction of hydrological patterns in relation to older parts of the landscape, and in my view there is some ambiguity in the interpretation of the 'beheaded channel'.
- Last, in many places, the fault scarp is not sharply expressed in the landscape, even at locations across ridges or high terraces, where a frequently-rupturing fault might be anticipated to have relatively good expression

The points raised above do not call into dispute the analysis of Van Dissen et al. (2005) that defines a maximum estimate of slip rate for the Kekerengu Fault at this location. That remains a valid estimate, but not to be overlooked is that there are potentially valid alternative interpretations of these landforms, that would enable the estimation of other, lesser, slip rate values.

Northeast of the Kekerengu River, the Kekerengu Fault traverses hill terrain, that in the upper reaches of the southwest fork of the Tirohanga Stream valley, is quite gentle and subdued, and accordingly the fault scarp is prominently expressed in the landscape. West of there, the fault is obscured under deeply gullied and landslipped terrain. At one location, the geological map of Rattenbury et al. (2006) shows the Kekerengu Fault as being concealed beneath uplifted beach deposits which, if true, would suggest that the fault has not moved during the late Quaternary, and therefore is not active. I consider that this relationship shown on the geological map was an accident of cartographic generalisation. The unpublished record sheets tentatively indicate the presence of two nearby areas of beach gravels, one either side of the fault, and in compiling the published map, these two areas were combined into one, and the call was made to show the fault as concealed under the gravels. As there is a distinct fault scarp at this location, classified here as ‘definite’, ‘well expressed’, showing the fault as concealed under old beach gravels is clearly incorrect.

Comments on Kekerengu Fault slip rate: The overall tectonic model proposed for this part of Marlborough by Van Dissen & Yeats (1991) is that the large slip rate of the Hope Fault is transferred northward along the Jordan Thrust and then onto the Kekerengu Fault. Therefore the Kekerengu Fault should have a slip rate similarly large to that of the Hope Fault. However, account now needs to be taken of the suspected additional active tectonic features identified in the present report, the Hapuku fault zone and Mangamaunu fault, near the northeastern end of the Hope Fault. If these features are confirmed to be active faults, they presumably accommodate some of the motion expressed on the Hope Fault farther southwest, and thus would reduce the proportion of Hope Fault displacement that is expressed on the Kekerengu Fault.

Noting the maximum slip rate in the range of 18 – 23 mm/yr, and the faster bound of slip rate at McLean Stream (10 mm/yr), although its robustness is doubted, a slip rate in the range of 10 to 20 mm/yr is adopted in this report as a working estimate for the Kekerengu Fault. If one assumes two nominal alternative values of 2 m and 5 m for the mean amount of dextral strike-slip per surface rupture event on the Kekerengu Fault, these imply recurrence intervals of 200 and 100 years (2 m per event, 10 and 20 mm/yr slip rates respectively) and 500 and 250 years (5 m per event, 10 and 20 mm/yr slip rates respectively). These lesser slip rates still place the Kekerengu Fault in recurrence interval Class 1 (<2,000 years).

Heaver’s Creek fault (feature 5, Figure 8)

This fault was first depicted as active on the map of Lensen (1962), and the name Heaver’s Creek fault was applied by Van Dissen et al. (2005). The diagrams of Van Dissen et al. (2005) identify Heaver’s Creek as a tributary that drains from the west into the Kekerengu River, 1 km upstream of State Highway 1. This name does not appear on published topographic maps, so presumably is a local name for this tributary. Within the QMAP dataset, the fault is attributed as being downthrown to the SE. While this is generally correct in regard to the relative offset of bedrock geological units, it is not true of the surface scarp which, from Mole Hill northeast to the Kekerengu area, is downthrown to the northwest. Accordingly, the database attribute for downthrown direction has been revised in this section of the fault, to reflect the character of the surface scarp.

The scarp of the Heaver's Creek fault is most prominent where it crosses the catchment of Valhalla Stream, about 3 km west of Kekerengu village. Aerial photos suggest that over an approximately 1.5 km long section of the fault, the scarp, upthrown to the south, is as much as 10 m high across hill landforms. At a road called East Lane, the Heaver's Creek fault has offset the northeastern margin of a broad channel of presumed Kulnine age, as much as ~25 m dextrally, and by several metres up to the southeast, indicating a ratio of horizontal to vertical movement of ~4:1 (D. Townsend, personal communication, 2014). The Kulnine Terrace is at least ~30,000 years old, as indicated by the presence of the 25.4 ± 0.2 ka Kawakawa/Oruanui tephra (Vandergoes et al., 2013) occurring as disseminated glass shards within the loess cover beds overlying the terrace gravels (Van Dissen et al., 2005). This implies a horizontal component of slip of as much as ~0.8 mm/yr. Van Dissen et al. (2005) show the fault to have a very steep southeast dip, at an exposure west of Kekerengu River; this means that the vertical component of most recent offsets (those which produced the surface scarp) has a reverse sense of dip-slip movement.

From the western side of Valhalla Stream southwest to Mole Hill is an area of irregularly eroded hill terrain. Across this area, the fault scarp is not recognisable and thus is classified as 'not expressed', except for two spurs in the Deadman Stream catchment where there is an up-to-the-south step at the location of the fault.

In the 2 km stretch of mapped fault from Mole Hill west to the Clarence river bed is some rather irregular terrain, but on the projected line of the fault are several semi-closed basins, and their closure is interpreted here to indicate the presence of an up-to-the-northwest fault scarp. There are at least two en-echelon steps here, and the overall landforms suggest the possibility of a substantial, and perhaps dominant, dextral strike-slip offset. Several of these basins have been utilised for on-farm water storage by the construction of low embankments across the closures. The fault here is classed as 'definite', 'moderately expressed'. As part of this data set, a 'likely', 'not expressed' connection is drawn across the Clarence River between the end of the Heaver's Creek fault and Kekerengu Fault on the west bank of the river. This is one inference; alternatively the fault may extend farther southwest along the line of the river bed, towards Shag Bend.

Northeast of Valhalla Stream, the fault scarp is moderately well expressed across an irregular ridge, but thereafter is not clearly expressed. A low terrace on the western side of Kekerengu River comprises overlapping alluvial fans from the mouth of 'Riser Gully' (informal name applied by Van Dissen et al., 2005) and Glencoe Stream. At the western side of this terrace, an up-to-the-southeast step is evident on old aerial photographs, marked by ponds/swaps on its northwest side. This is attributed as a 'likely', 'moderately expressed' fault scarp. No step is evident on the eastern side of the terrace remnant, suggesting that the alluvial fan comprising that part of the terrace is younger than the most recent surface rupture of the Heaver's Creek fault at this location.

On the eastern side of the Kekerengu River valley, the projected location of the fault crosses eroded hill terrain with a number of landslide features. Overall, the physical evidence for fault activity on the mapped line of the Heaver's Creek fault east of the Kekerengu River is very limited. It is, for example, not inconceivable that the active fault motion has diverted northward off the line of the Heaver's Creek fault to the Kekerengu Fault. For that reason, the Heaver's Creek fault east of the Kekerengu River has been classified as 'likely' throughout this area. In three places along the mapped line of the Heaver's Creek fault, there are broad topographic steps on ridges that could reflect fault displacement, and are classified as 'moderately expressed'. Otherwise the fault is classified as 'not expressed'.

In the Valhalla Stream and Heaver's Creek catchments, a north-northeast striking fault is mapped from an intersection with the Heaver's Creek fault, to the Kekerengu Fault. Although the geological map of Van Dissen et al. (2005) indicates a throw (in bedrock) that is up to the west, the surface scarp is consistently up to the east. The scarp is as much as several metres high on the Kulnine terrace. It is named in the GIS dataset as a subsidiary fault of the Heaver's Creek fault. Another similar fault crosses the western branch of Valhalla Stream, and is also identified as a subsidiary fault of the Heaver's Creek fault.

A northeast-trending fault scarp on the 'Winterholme' terrace on the northern side of the Kekerengu River mouth, called Winterholme Fault by Van Dissen et al. (2005), is also identified in the GIS dataset as a subsidiary fault of the Heaver's Creek fault.

It is worth noting that east of the Clarence River and south of the Heaver's Creek fault, a multitude of faults have been mapped by Rattenbury et al. (2006) but classed as 'inactive'. The faults, and the geological strata between them, appear to have steep dips and the faults clearly relate to very complex deformation. Across this general area there is an 'accordance' of hill crest heights at around 200 m above sea level. This represents the remains of an erosion surface, probably marine, and is thought likely to date from the penultimate interglacial period, about 200,000 years ago (Ota et al., 1996). As there are no indications of disruption of that hill summit accordance by any of the numerous mapped faults, this provides a basis for classing them as inactive. For that reason, they are not included in this data set.

Jordan Thrust (feature 6, Figure 8)

Identified by Van Dissen (1989) and Van Dissen and Yeats (1991) as an active fault that runs along the eastern end of the high part of the Seaward Kaikoura Range, the Jordan Thrust is interpreted as accommodating a substantial component of motion on the Hope Fault. It is noted, and in fact clear, that the displacement on the Hope Fault is markedly less north of the Hapuku River, and the transfer of motion along the Jordan Thrust provides an explanation for this. There is however, very limited evidence of surface scarps along the Jordan Thrust, which reflects the combination of its location in mountainous country, and the low angle of dip on the fault plane, towards the west. Van Dissen (1989; Plate 1 map) shows that in many places northeast of Clinton River, the thrust plane was exposed, and its attitude measured, in rock exposures in many of the stream valleys draining off the Seaward Kaikoura Range. Between the stream valleys, it is assumed with confidence that the fault lies close to the prominent transition from steep mountain slope to gentler lowland terrain along the northeastern foot of the mountain range. However, for the purposes of this report, the lack of a clear scarp means that the fault is classified as 'not expressed'.

The fault is classed as definite in regard to its activity, as young gravel has been seen incorporated along the fault plane in several places (Van Dissen, 1989; Van Dissen & Yeats, 1991). However, southwest of Clinton River, there are no documented identifications of the fault plane, and there are no convincing landform offsets. Thus the location of the Jordan Thrust in that area is uncertain, and there is no clear evidence of its degree of activity. Accordingly, southwest of the terraces of the south fork of Clinton River, the fault is marked as 'likely', 'not expressed'.

Van Dissen (1989; Figure 11) described offset terraces of the south fork of Clinton River; these fault scarps are mapped as ‘definite’, ‘well expressed’. The same classification was applied to a short section of the fault in Happy Valley Stream, where Van Dissen (1989; Figure 14) described an exposure where the Jordan Thrust has pushed greywacke rock up and over stream gravel deposits.

Near the southern branch of Miller Stream, Van Dissen et al. (2006) noted a topographic step across a landslide deposit (Millar Stream landslide) that may be a scarp of the Jordan Thrust. Accordingly, that step is mapped as moderately expressed, but because it is not certain that it is a fault scarp, rather than for example being some other landform feature that was overridden by the landslide debris, or a topographic irregularity associated with the debris, it is classed as ‘likely’.

In the northern headwaters of Miller Stream, on the southeast side of George Spur, there are some well-expressed fault scarps, mostly up to the SE. Although included as part of the Jordan Thrust by Rattenbury et al. (2006), their straightness and sharpness (when viewed in high-altitude aerial photos) suggests they are on a steeply dipping fault or faults, and differences in sense of throw along strike suggests a significant strike-slip component. Accordingly in the Kaikoura District dataset, they were renamed as part of the Kekerengu Fault. A ‘likely’, ‘not expressed’ connection is drawn between these faults and the Kekerengu Fault, as mapped in the QMAP dataset on the north side of George Stream.

Van Dissen (1989) used weathering-rind dating of the faulted terraces at Clinton River south fork to estimate the activity of the Jordan Thrust. He reported evidence for at least three surface rupture events over the past ~3500 years, which implies a maximum recurrence interval of ~1200 years. However, it should be noted that the reliability of these weathering-rind ages is unknown. Differences in fault scarp heights and terrace riser heights suggest maximum single-event vertical displacement of between 1.2 and ~2 m. In combination with the age estimates, Van Dissen (1989) calculated horizontal and vertical (northwest side up) slip rates of 2.2 ± 1.3 mm/yr and 2.1 ± 0.5 mm/yr, respectively. Thus the sense of movement comprises an approximately 1:1 ratio of reverse and dextral strike-slip motion.

A potential difficulty arises from the hypothesis that the Jordan Thrust transfers most of the motion on the Hope Fault northwards onto the Kekerengu Fault (Van Dissen 1989; Van Dissen & Yeats 1991). These authors accounted for the discrepancy between the Hope Fault having a much large slip rate than the Jordan Thrust by suggesting that a large part of the Hope Fault motion was diffused by way of fold-related uplift of the Seaward Kaikoura Range, and by distributed shear within the greywacke bedrock. Therefore, although regional interpretations of fault activity have assigned the Jordan Thrust a slip rate of 17 mm/yr (Stirling et al., 2012) or 20 mm/yr (Robinson et al., 2011; Litchfield et al., 2014), these values relate to the fault structure as a whole, at depth, and thus represent a maximum for slip rate at the ground surface. However, even the much smaller, field-based, estimate of ground-surface slip rate of ~2 mm/yr determined for the Jordan Thrust by Van Dissen (1989) implies that the fault has a recurrence interval of Class 1.

Hope Fault Zone (feature 7; Figure 8)

The Hope Fault is a major right-lateral (dextral) strike-slip fault extending from the western side of the Southern Alps near Arthurs Pass through the Hanmer area to offshore of Kaikoura. It accommodates a substantial component (as much as ~50%) of the plate boundary motion through that part of New Zealand. That sector of the Hope Fault extending northeast from the Hanmer basin, has been referred to as the ‘Conway segment’ (Langridge

et al., 2003), which in the Kaikoura area has also been referred to as the 'Kahutara segment' (Van Dissen 1989, 1991). Van Dissen (1989, 1991) defined a segment boundary at the Kowhai River, between the Kahutara (aka Conway) segment to the southwest, and the Mt Fyffe segment to the northeast. The Mt Fyffe segment was defined as extending northeast to the Hapuku River, beyond which is the Seaward segment which has been mapped as extending northeast to meet the coast at Half Moon Bay. Farther offshore, seismic profiling has identified what is believed to be the offshore continuation of the Hope Fault Zone (Hope Fault – offshore; Barnes & Audru, 1999). Some information is available on the fault character and movement history from the Green Burn trench sites reported by Langridge et al. (2003). Detailed mapping of the Mt Fyffe Segment, including radiocarbon dating of materials obtained from trench exposures, is reported by Coulter (2007). Van Dissen (1989, 1991) also provides some estimates of fault activity between Sawyers Creek and the Hapuku River, based on mapping of surface offsets of fluvial terraces accompanied by weathering-rind dating of terrace surfaces, using data from Knuepfer (1988). As part of the work undertaken for this report, interpretations were aided by lidar along the Seaward Kaikoura range-front east of the Kahutara River, and across the general location of the Seaward segment to Half Moon Bay.

Hope Fault Zone – eastern section (feature 7a; Figure 8)

The Hurunui District fault report (Barrell & Townsend 2012) referred to the Hope Fault Zone northeast of the Hanmer basin as 'eastern section', and this same term is used for the Kaikoura District. It encompasses both the Conway and Mt Fyffe segments.

In general, the eastern section fault trace is quite complex, with minor step-overs and bulges (e.g., Eusden et al., 2005a,b). In most cases, these would be adequately encompassed by a ~250 m wide buffer either side of the mapped fault trace. No amendments were made to the QMAP line positions, they were simply cut in places to aid 'Surface form' attribution.

East of Middle Creek, there are several places where the location of the fault trace is not clear, likely because it sits at the foot of the rangefront, and may be partly obscured by young fans, or is obscured by landslide terrain. There is a prominent scarp on the high terraces on the southwest side of the Hapuku River, near Grange Hill farm.

Several definite or likely fault scarps close to the Hope Fault main trace were detected aided by the lidar imagery. These are identified by name as 'Hope Fault Zone – subsidiary faults'. Several have not been previously reported.

One of these features is mapped along the foot of low hills just southeast of the base of the range-front, between Cribb Creek and Kowhai River, in the headwaters of Humbug Stream, immediately west of Swyncombe farm. The sharpness of the southeastern face of the hills, in a setting where streams drain southeast, thus away from the foot of the low hills and not along them, makes it unlikely that the face of the hills have been trimmed by river or stream action. There appear to be at least two instances in the headwater branches of Humbug Stream where there is a terrace upstream of the hillfront, but not downstream. The terrace is about 7 m high, judging from lidar elevation data. On this evidence, a fault is drawn along the foot of the hills, and classed as 'likely'. The southwestern extent of the fault is uncertain. A possible extension is drawn to the west to the edge of the Cribb Creek floodplain, across low hill terrain that displays diffuse lineaments. Freund (1971) indicated the presence of fault scarps at about the location of the fault mapped in this data set.

A prominent fault scarp, as much as 4 m high, is evident in the lidar as much as 100 m southeast of the foot of the range on the east bank of Waimangarara River. This was also mapped by Van Dissen (1989), and mapped and described by Coulter (2007), with the same information from Coulter's work provided by URS (2007). Coulter (2007) interpreted the fault as continuing to the eastern bank of the Waimangarara River, but the lidar shows that it broadens and takes a more westerly trend – this sector is mapped as a monocline in this data set. Coulter (2007) and URS (2007) interpreted this to be the trace of the Hope Fault, and considered that erosion by the Waimangarara River has trimmed the rangefront, and that the scarp represents the fault movements subsequent to that trimming. In order to preserve the position of the Hope Fault as depicted in the QMAP dataset, this fault scarp and monocline are named as 'subsidiary faults' of the Hope Fault Zone.

Trench investigations and radiocarbon dating near Green Burn, at the western edge of the Kaikoura District, indicate a maximum horizontal slip rate of 23 ± 4 mm/yr, an estimated single-event displacement of between 5 and 6 m, and average recurrence interval of between 180 and 310 years (Langridge et al., 2003; also summarised by Eusden et al., 2005b). Three km farther northeast at Sawyers Creek, Van Dissen (1989) estimated a minimum horizontal slip rate of 28 ± 8 mm/yr, and at Goldmine Creek, on the My Fyffe segment immediately northeast of the Kowhai River, Van Dissen and Yeats (1991) reported a minimum horizontal slip rate of 16 ± 5 mm/yr. At the northeastern end of the Mt Fyffe segment, on the southwest bank of the Hapuku River, Van Dissen (1989) estimated a horizontal slip rate of between 2.8 and 7.5 mm/yr (see discussion in 2nd to last paragraph on the section on the Hapuku fault zone later in this Appendix). These estimates form a basis for the interpretation that the displacement on the Conway segment of the Hope Fault Zone is progressively transferred onto other faults farther north, including the Kowhai and Fyffe faults, and in particular onto the Jordan Thrust (Van Dissen & Yeats 1991). It is worth noting that in all cases, there are substantial uncertainties involved in these estimates, first that much of the dating of offset features is indirect, utilising the weathering rind method whose validity is a matter of debate, and second that many of the landform features whose offsets have been measured may not necessarily have been part of a single continuous landform. Of the offset features, the Sawyers Creek terraces and the Hapuku River boulder bar are the most robust for reconstructing offsets, but neither site is robustly dated. However, even if the estimated slip rates were wrong by a large amount, say 25%, the recurrence interval would still lie in Class I.

Whether the indicated lesser slip rate at Hapuku River is a reflection of the single-event displacement being less in that area, or a result of not all surface rupture events on the fault farther west have propagated as far northeast as Hapuku River, is unknown. The latter interpretation is implied by Robinson et al. (2011) who modelled a recurrence interval of 1700 years for the Seaward segment/offshore section, which is much longer than the recurrence interval indicated for the Conway segment.

At Waimangarara River (see Figure 6 and Figure 7 in the report), Van Dissen (1989) described a substantial (~18 m high) tectonic warp (i.e., monocline) on the western bank, at the foot of the Seaward Kaikoura Range. This monocline has notable vertical offset but appears to lack prominent lateral offset. However, the sharpness of the foot of this feature is such that it is probably better classified as a fault scarp, and indeed that is how it is defined in the QMAP dataset. Along strike on the east bank of the river, on a higher, and thus older, terrace, is a broad ~26 m high fault scarp. As the strike of these features is more northerly than that of the Hope Fault, and this location is close to where the Jordan Thrust intersects

the Hope Fault, the question arises as to whether these tectonic features are developed on the Jordan Thrust rather than the Hope Fault. They are retained as part of the Hope Fault Zone in the present data set, but future workers may wish to examine this possibility.

Hope Fault Zone – Seaward segment (feature 7b; Figure 8)

This feature comprises the Hope Fault's Seaward segment described by Van Dissen (1989, 1991). A problem acknowledged by most previous workers is that northeast of the Hapuku River, no well-defined fault scarps have been recognised, and as a result, it is not clear exactly where the active traces of the Hope Fault are. Previous mappers have identified topographic lineaments, in the form of aligned spurs, saddles, etc, as possible fault-related features (e.g., Freund 1971). Van Dissen (1989; Plate 1) mapped several fault zones in the bedrock, but did not identify any surface fault scarps. On regional-scale geological maps (Lensen 1962; Rattenbury et al., 2006), the active trace of the Hope Fault is drawn northeast of the Hapuku River along a presumed faulted boundary between greywacke basement rock to the south and the lower part of the cover rock sequence, to the north. Northeast of the valley of Blue Duck Creek, the fault is drawn across greywacke rock terrain out to the coast at Half Moon Bay.

For part of its length, the mapped position of the Seaward Segment underlies the active bed of Puhi Puhi River, and then is mapped as swinging east across the eastern side of the river valley. At that location, there are terraces at the eastern margin of the valley, and there are no visible indications, in satellite imagery or lidar, of a fault offset of those terraces. However, about 100 m south of the mapped location of the fault, the lidar reveals that there is a vague right step of two adjacent terrace risers. This is identified in the dataset as a 'possible' fault scarp. It is designated 'possible', rather than 'likely', because there are no other compelling other indications of a fault crossing the terrace surfaces at this location visible in the lidar.

Simpson (1995; Figures 3.7–3.9) describes two exposures of the Hope Fault in the lower reaches of Blue Duck Creek. In these exposures, the fault appears to offset Quaternary landslide debris or colluvial sediments, although the exposure was not quite good enough to be certain that it is a faulted relationship. In one exposure, the debris is radiocarbon-dated to approximately 2000 years old (Simpson 1995; Figure 3.13). This may approximate the timing of a surface rupture of the fault at this location. However, it is conceivable that the geological relationships described by Simpson (1995) simply relate a sequence of events, comprising stream erosion that created a stream-eroded cliff along the plane of the fault, after which a landslide event occurred, and its debris accumulated against the eroded fault plane. For that reason, a classification of 'likely' is applied to the section of the fault in the vicinity of these exposures, along with 'well expressed' which acknowledges the occurrence of these exposures.

Prominent topographic steps trending northeast on the eastern side of the Irongate Stream valley were mapped by Van Dissen (1989) and by Simpson (1995). Simpson inferred that these steps mark an active fault and applied the name 'Patutu Fault' to these features. As much as 300 m east of the Patutu Fault are some more northerly-trending topographic lineaments that Simpson named Clematis Fault. Although there can be little doubt that these topographic features are the result of displacement of the ground surface, the question remains as to whether they are due to fault movement, or gravitational movement associated with slope instability. In the general area of these two inferred faults, Simpson (1995) mapped two large areas of gravitational slope movement, referred to as the Wairimu collapse complex and Irongate collapse complex. It is notable that the areas where these inferred

faults are most clearly expressed are within these collapse complexes. This suggests the possibility that these topographic steps which have been inferred to be fault scarps may instead be related to slope movement, rather than faulting.

URS (2008) undertook a geotechnical assessment of an area of land on Wairimu Station for a proposed rural residential subdivision, in an area that includes both proposed branches of the Hope Fault, as well as the Patutu and Clematis faults, and both collapse complexes. The mapping and interpretation of Simpson (1995) appears to have been adopted directly by URS (2008), and they undertook Fault Avoidance Zonation in relation to the mapped faults. The URS report notes that on the Patutu Fault, there is as much as 20 m right-lateral offset of ridges, but none was observed on the Clematis Fault. Having examined the lidar closely in this area, as well as satellite imagery, the case for lateral offsets is not convincing. In one or two places, one could argue for a lateral offset, but in other places along the identified fault, there are no offsets in places where the landforms ought to show it, if the 20 m offset elsewhere is in fact a fault offset. As an aside, URS (2008) took the interpreted presence of noteworthy fault scarps on the Patutu Fault, where it crosses the collapse complexes, to infer that the collapse complexes have long been inactive. This reasoning is flawed because there is at least some possibility that the presumed fault offsets are the product of movement in the collapse complexes.

The approach to classification taken with the present dataset is as follows. From east bank of the Hapuku River to the east side of Puhi Puhi River in the upper reaches of Blue Duck Creek, the fault (as defined in the QMAP dataset) is mapped as ‘likely’, ‘not expressed’. Discontinuous topographic lineaments between Hapuku and Puhi Puhi rivers, on the east bank of Puhi Puhi River, and in the hills southwest of the headwaters of Blue Duck Creek have been mapped as part of the present report as ‘possible’, ‘moderately expressed’, and identified by name as ‘subsidiary faults’ of the Seaward Segment.

In the middle reaches of Blue Duck Creek, QMAP showed the fault breaking into two branches; these are identified in this dataset as ‘north branch’ and ‘south branch’.

The south branch was identified as a fault in bedrock by Van Dissen (1989), and includes the exposures described by Simpson (see earlier paragraph), which are classed as ‘likely’, ‘well expressed’. Because of this ‘likely’ assignation, adjacent parts of the south branch are also classed as ‘likely’, but are attributed as ‘not expressed’. At Irongate Stream, there is a presumed intersection between the Patutu Fault and the south branch. East of there, the south branch is classified as ‘possible’, ‘moderately expressed’, because although there are vague topographic features across the hill terrain there that could be interpreted as fault-related features, they are far from compelling. The interpretive model adopted in this dataset is that the presumed activity on the south branch is transferred northeast along the Patutu Fault (if it is in fact an active fault).

The north branch from Blue Duck Creek to Irongate Stream is classified as ‘possible’, because despite the fault passing beneath a medium-level terrace of Irongate Stream near Wairimu Station homestead, there is no indication, in imagery or lidar, of any fault scarp crossing this terrace. Nor is there any convincing indication of offset valleys or hill landforms. The fault in QMAP is drawn on the basis of topographic features, with higher ground to the north, and because in places, parts of the Blue Duck Creek and Irongate Stream valleys are aligned along the fault (D. Townsend, personal communication, 2014). Van Dissen (1989; Plate 1) identified a fault crush zone in bedrock at the approximate location of the mapped fault, but in general there is no indication that this fault is active. East of the presumed intersection with the Patutu Fault, the north branch is shown as ‘likely’, ‘not expressed’.

Although there are no compelling indications of landform offsets along the line of the north branch fault east of Irongate Stream, the ‘likely’ assignation reflects the tentative interpretation that displacement (if any) from the ’likely’ active Patutu Fault would be transferred eastward onto the north branch. There is one possible exception in the valley of Rakautara Stream, where the fault projects across terraces in the valley floor. Lidar suggests that there is a topographic anomaly in the terrace form. This is at a place where the valley axis swings parallel to the trend of the fault, and the topographic features could easily be due to stream erosion, and most probably are. However, in order to highlight this location as worthy of a closer look should any further work be done on trying to evaluate the faulting in this area, this topographic anomaly is identified in the dataset as ‘likely’, ‘moderately expressed’.

A speculative possible offshore extension is drawn from where the mapped location (in QMAP) of the north branch fault reaches the coastline at Half Moon Bay, out to the nearest strand of the offshore Hope Fault mapped by Barnes and Audru (1999).

Overall, it is apparent that the locations and character of active fault strands along the presumed Seaward segment of the Hope Fault are not well established. In part, previous interpretations of the nature of the Hope Fault through this area probably reflect an expectation that active fault deformation should extend through this area. However, the identification in this report of previously unreported active fault features farther southwest, named here as the Hapuku fault zone and Mangamaunu fault (features 10 and 11 in this Appendix), provide an explanation as to where at least part of the deformation from the northeast end of the Mt Fyffe segment of the Hope Fault may be distributed. Although there is no doubt about the existence of faults in bedrock along the line of the Seaward segment, as mapped in the QMAP dataset, it is conceivable that these faults are no longer active, and instead recent activity is focused farther south, on the Hapuku and Mangamaunu features. This issue would require further field investigation if there is a need to clarify the status and nature of the Seaward segment of the Hope Fault, and its relation, if any, to the Hapuku fault zone and the Mangamaunu fault.

Hope Fault (offshore) (feature 7c; Figure 8)

The offshore Hope Fault shows evidence for a vertical component of the deformation ranging from about 0.15 ± 0.05 mm/yr to 1.6 ± 0.4 mm/yr (Barnes & Audru 1999). It also reveals evidence for a component of strike-slip motion in the overall style of deformation, but how much is unknown, because it is rarely possible to quantify the strike-slip component of offset using seismic profiles. A strike-slip rate of 5 mm/yr is inferred by Robinson et al. (2011) and Litchfield et al. (2014), and Robinson et al. (2011) calculated a recurrence interval of ~1700 years.

Upper Kowhai, Kowhai, & Fyffe faults (feature 8, Figure 8)

Three relatively long faults have been mapped in the mountainous terrain on the southeast side of the range crest, and classified as active faults by Rattenbury et al. (2006). Field studies by Van Dissen (1989) identified these faults from geological exposures of fault planes and crushed zones. The extent of each fault is based on interpolation between and extrapolation beyond the scattered exposures of the fault zones, aided by topographic features such as saddles and alignments of landforms (topographic lineaments). For two of these faults, named Kowhai Fault (feature 8b) and Fyffe Fault (feature 8c) by Van Dissen & Yeats (1991), there is scattered evidence that they are active, as outlined below. For the third

fault, informally named the upper Kowhai fault (feature 8a) by Van Dissen (1989) and that name is adopted in this report, there is no direct evidence that it is active. Nonetheless, all three were shown as active by Rattenbury et al. (2006).

As a whole, the Kowhai Fault (feature 8b) is classified as 'likely', because no direct evidence has been reported for offset late Quaternary deposits. However, Van Dissen (1989) noted that about 700 m northeast of the confluence of Kowhai River and Snowflake Stream, at the projected location of the Kowhai Fault, there are what look like right-laterally offset drainages, beheaded streams, and shutter ridges. This area is therefore denoted in this dataset as 'well expressed'. Lensen's (1962) map depicted a fault at the approximate location of the Kowhai Fault, drawn in a way that indicated that Lensen regarded it as an extension of the Kekerengu Fault. Lensen's map showed a section of the fault (referred to here as Kowhai Fault) southwest of Snowflake Stream as being active, in an area where there is a line of knolls and saddles along the valley side. While these landforms highlight the presence of a fault zone in bedrock, with differing erosion characteristics either side of the fault, they do not necessarily provide direct evidence of activity, and a classification of 'not expressed' is maintained through this area. Lensen (1962) also showed an active trace at Kowhai saddle, but there is no compelling topographic evidence, as judged in aerial photographs, so this implied fault scarp is not included in this dataset, and the Kowhai Fault is mapped through the saddle as 'not expressed'.

An exposure of the Fyffe Fault (feature 8c), at a knoll called Big Hau, shows what appear to be scree deposits offset above the fault which is expressed as a crushed zone in the bedrock (Van Dissen, 1989). Van Dissen (1989) discussed other alternative explanations for the geological relationships at this locality, but considered faulting to be the most likely explanation. Overall, the activity of the fault is classed as 'definite', although a classification of 'likely' was considered, because the only direct evidence for activity is at the Big Hau exposure, and other explanations for the apparent fault offset have not been completely discounted. In this dataset, the fault at Big Hau is classified as 'well expressed'. Elsewhere, although the presence of a fault is not in doubt, as its crushed zone and fault plane are identified at several locations, it is classed as 'not expressed' due to a lack of any reported surface offset scarps.

The upper Kowhai fault (feature 8a) is also classified as likely, although there is no direct evidence for fault scarps. In particular, in the headwaters of the Kowhai River, 2.3 km south-southeast of Mt Saunders, there is a thick accumulation of sediments, possibly colluvium or glacial deposits, that lie across the fault zone and appear not to have been displaced by fault movement (Van Dissen 1989). The age of these sediments is not known, and so they do not discount the upper Kowhai fault being active, but do tend to create uncertainty as to whether the upper Kowhai fault would be better classified as 'possible' rather than 'likely'.

A 'possible' northeastern extension of the upper Kowhai fault has been drawn along a series of benched spurs, as far as the splinter fault in Happy Valley Stream associated with the Jordan Thrust. Although a fault was not shown here by Van Dissen (1989) or Rattenbury et al. (2006), Lensen (1962) showed an active trace of his Kekerengu Fault (see 2nd paragraph of this section) at about this location, and most likely he was representing these benched spurs. While there is no evidence for fault offset of these landforms, identification of these benched spurs as representing a 'possible' fault is adopted here as an appropriate action.

There are no convincing landform offsets across any of these three faults, so no direct estimates of slip rate or recurrence interval can be made. Van Dissen et al. (2003) assigned a recurrence interval of less than 2,000 years to the Fyffe Fault, but none of these faults are included in the active fault catalogue of Litchfield et al. (2014), because they were regarded as being much less important than the nearby Hope Fault Zone (R. Van Dissen, personal communication, 2014). Van Dissen (1989) noted that the slip rate on the Hope Fault is relatively large both southwest and northeast of the location where it is met by the Fyffe Fault, suggesting that the slip rate on the Fyffe Fault is relatively small. For the purpose of this report, a slip rate of 2 mm/yr is inferred for the Fyffe Fault, with rates of 1 mm/yr and 0.5 mm/yr inferred for the Kowhai Fault and upper Kowhai fault respectively. Assuming single event displacements of between 2 m and 5 m for each fault, this implies recurrence intervals in the ranges of 4,000 to 10,000 years (upper Kowhai fault), 2,000 to 5,000 years (Kowhai Fault) and 1,000 to 2,500 years (Fyffe Fault).

Stewart Creek fault (feature 9, Figure 8)

Located in steep hill terrain west of the lowest reaches of the Clarence River, and named after the stream catchment in which it lies, this feature is sharply defined at its northern end, and is downthrown to the southwest. It is conceivably a gravitational feature, and its extrapolation to the south may involve connection with unrelated topographic lineaments, rather than being a single feature. It is classed as ‘likely’.

Hapuku fault zone (feature 10; Figure 8)

A number of previously unreported tectonic features have been identified on the western side of the Hapuku River, and are described below. For reference, they are referred to in this report collectively as the Hapuku fault zone.

Two previously unreported fault traces were identified in lidar and Google Earth Street View southwest of where the Hapuku River exits the range-front. The most pronounced is a broad east-west trending step, down to the south, that passes through the Grange Rd – Parsons Rd intersection. Its surface trace shows considerable variation in strike, suggesting that it is probably mainly dip-slip, but it is not clear whether it is a thrust fault or normal fault. The scarp is about 5 m high, and does not displace the lowest terraces of the Hapuku River. This feature has been mapped as a river terrace edge by Rattenbury et al. (2006), but the lidar shows conclusively that this topographic step is transverse to stream channels on the alluvial fan, and therefore is tectonic.

About 500 m southwest of the Grange Rd – Parsons Rd intersection is a less well-defined east-west step, up to the south, that also is transverse to stream channels and therefore classified as a ‘definite’ fault scarp. It is crossed by a northeastern fork of Harnetts Creek, and where the stream crosses the scarp, it has cut a 1 to 2 m deep valley. There is no fault scarp across the floor of this valley, indicating that the valley floor is younger than the most recent surface rupture of this fault. The valley depth matches the height range of the fault scarp. This latter feature was shown as a fault scarp on the unpublished record sheets of Rattenbury et al. (2006), but not on the published 1:250,000 scale map, presumably because it is too short, and of too uncertain an extent, to show at that map scale.

About 800 m south of the Grange Rd – Parsons Rd intersection is an east-west trending step, about 1 m high and down to the south, that also is transverse to stream channels and accordingly is classed as a ‘definite’ fault scarp. It is worth noting that its detection was only possible because of the high-precision of the lidar data.

East of Parsons Rd, topographic profiles drawn using the lidar data reveal a broad east-west trending topographic step, between 2 and 3 m high and about 100 m wide, and down to the south. At its western end, it swings to a more northwesterly trend, almost parallel to Parsons Rd. The high ground associated with this topographic step is also evident in Google Earth Street View. This feature is classified as a likely monocline. A small topographic step, trending east-northeast and between 1 and 2 m, down to the south-southeast, is evident in the lidar ~1.3 km southwest of the State Highway 1 bridge over the Hapuku River. Along part of its length it coincides closely with a fence, and so there is some possibility of a human origin. Accordingly, it is classified as a 'possible', 'moderately expressed' fault.

The age of this part of the alluvial plain of the Hapuku River (Hapuku Fan of Brown 1988) has not been established directly. Brown (1988) and Van Dissen (1989) map the Hapuku Fan in the vicinity of Parsons Road as Burnham Formation and in part Springston Formation. In order to try and establish an estimate of the age of the alluvial surfaces that appear to have been deformed by the suspected faults and folds of the Hapuku fault zone, soil development and topographic information is reviewed below. Regional-scale soil maps (i.e., very generalised) show 'Hapuku loam' on the Hapuku Fan (Gibbs & Beggs, 1953), which is described as varying in its profile from place to place, suggesting that the fan, at least in places, is of composite age. An exposure of the terrace deposits was described by Chandra (1968; lithological section 13) where the Hapuku Fan meet the costal cliff on the southwest side of the Hapuku River mouth, at Trig A794 shown on the NZTopo50 map series. Chandra (1968) described notable weathering colouration of the matrix of the river gravels down to as much as 8 m below the terrace surface, but not a strongly developed surface soil. In contrast, Chandra's section 12, from a ~5 m high exposure in the banks of Harnetts Creek, about 1 km upstream of the Bay Paddock Rd bridge over the creek, comprises a ~1 m thick brightly coloured and well developed soil on the gravel deposits. These contrasts in the degree of soil development reinforce the interpretation that the fan surface is of composite age.

Notably, Luke Creek and the Kowhai River have active beds that are scarcely incised into their plains near the rangefront, and not at all in their middle to lower reaches. Also, there is no coastal cliff near their mouths, and so the toes of their plains have not been eroded by the sea during post-glacial time. In contrast, there is an up-to-30 m high coastal cliff eroded into the seaward edge of the Hapuku Fan, and the Hapuku River flows in an incised, terraced, valley cut below the level of the fan. The differences in form of these river systems are readily attributable to the presence, or not, of post-glacial coastal erosion. The effect of coastal erosion is to shorten the river course, and steepen its lower reaches, as the river bed must inevitably grade to the shoreline. A common characteristic of rivers whose incision is due to coastal erosion is that the depth of their valley incision decreases steadily upstream; this is the case of the Hapuku River, where it is incised into its plains by ~30 m at the coast, but within 4 km upstream, the incision has reduced to ~20 m.

Assuming that the coastal cliff at the seaward edge of the Hapuku Fan began to form ~7,000 years ago, at the culmination of the post-glacial sea level rise (Gibb, 1986), this age also represents the beginning of post-glacial downcutting of the Hapuku River into its fan. Some parts of its fan may be about that age, if the river was flowing across those parts just before the onset of incision. Any parts of the plain that had fortuitously been free of river activity for some time prior to that are thus somewhat older, and are likely to be characterised by relatively older soils. This would account for the contrasts in degree of soil development on different parts of the fan.

Where the Hapuku Fan is crossed by the Hope Fault, about 450 m north-northeast of the Grange Rd – Parsons Rd intersection, the terrace riser that marks the western margin of the main surface of the Hapuku Fan is offset with a dextral component of 30 ± 10 m and a vertical component of 11 ± 1 m, up to the north (Van Dissen 1989). On the lower terrace surface, a distinctive boulder bar has been offset by movement of the fault, and the age of this boulder deposit has been estimated using the 'weathering rind' dating method (Knuepfer 1988, Van Dissen 1989). Weathering rind dating is a 'relative' method that depends on calibration of rind thicknesses at sites where there is independent dating. Therefore, weathering rind dating is an indirect method of age estimation. There is considerable debate about the accuracy and reliability of weathering rind age estimates. Knuepfer (1988) estimated the age of the boulder deposit as 6,290 ± 950 years. The calibration of the rinds would have been done relative to 'raw' radiocarbon ages, because the calibration system for radiocarbon used today was not in existence at that time. Therefore the weathering rind age reported by Knuepfer (1988) translates to about 7,000 calendar years before present. Although many geologists harbour suspicions about the validity of the weathering rind method, in this case, it accords well with the independent age estimate for the incision of the Hapuku River, and the consequent abandonment of the main surface of its fan, derived from geomorphic interpretation of the effects of coastal erosion on the river system.

Based on all of this, there is a reason for some confidence in the reliability of the Hope Fault slip rate estimates at this locality provided by Knuepfer (1988) and Van Dissen (1989). In this same regard, those age estimates can be used to infer slip rates for the Hapuku fault zone. Thus the fault scarp close to the Grange Rd/Parsons Rd intersection is about 5 m high, on a ~7,000 year old surface, implying a vertical component of slip of 0.7 mm/year. This is a minimum rate for the fault zone as a whole, because there are at least two other, smaller, fault scarps farther southeast. A working estimate of the vertical component of slip of ~1 mm/yr is adopted for the calculation of recurrence interval (Table 2 of main report). Whether or not there is a lateral component of displacement is yet to be established.

It is very likely that the Hapuku fault zone continues along strike in an approximately northerly or easterly direction, but the intervention of the broad young floodplain of the Hapuku River has obscured any surface expressions of the tectonic features. On the northeastern side of the river is an extensive high terrace, part of the Hapuku Fan, and suspected by Brown (1988) to be a relatively old part. This terrace lies within the zone of lidar coverage, and there is no sign of any tectonic features crossing this terrace. Therefore, any continuation of the Hapuku fault zone goes either to the north or the south of this terrace (or perhaps both). On account of the typical northeasterly strike of faults in the Kaikoura District, a continuation to the northeast rather than the east seems more likely. Accordingly, a possible extension of the Hapuku fault zone, denoted as 'possible', 'not expressed' has been drawn, heading northeast towards the area where the Mangamaunu fault has been identified.

Mangamaunu fault (feature 11; Figure 8)

This feature comprises an east-northeast topographic anomaly running across alluvial fan terraces in the Mangamaunu area. There are at least two localised areas of higher ground along the line of this feature, and right-hand steps in the courses of minor stream valleys. Collectively, these features are interpreted to mark the location of a dextral strike-slip fault, which is classified here are 'likely', 'well expressed'. Fault traces are drawn either side of the areas of higher ground, on the inference that the ground has been 'bulged' up in association with fault movement.

There is a rural residential development at Mangamaunu, through which this suspected fault passes. Geotechnical investigations for the proposed development were undertaken by Connell Wagner Ltd (2005). During the consent application process for the development, the landform features described above were identified as possibly related to movement on an active fault (Geotech Consulting Ltd 2005a). An assessment of the Geotech Consulting Ltd (2005a) interpretation by GNS Science concluded that these landform features most likely had origins unrelated to active faulting (GNS Science 2005). Geotech Consulting Ltd continued to take the view that these features are most likely related to active faulting (Geotech Consulting Ltd 2005b). Ahead of a formal hearing of the resource consent application under the Resource Management Act 1991, further inspection of these landform features was undertaken by representatives from Geotech Consulting Ltd (Dr Mark Yetton) and Connell Wagner Ltd (Dr Jan Kupec), both expert witnesses at the hearing. They reached agreement on the scope and nature of further geotechnical investigations needed in regard to questions of slope instability and active faulting at the proposed subdivision (Geotech Consulting Ltd 2005b, 2005c). Subsequently, Kaikoura District Council decided in early 2006 to grant resource consent for the development subject to several conditions (KDC, 2006), which included a requirement for further investigation of possible fault-related features. The further investigation (Connell Wagner Ltd, 2007), which included the excavation and examination of trenches, concluded that there was no evidence for the presence of active faults.

Lidar survey data for the coastal sector of the Kaikoura District was acquired in July 2012, and its coverage includes the Mangamaunu area. The lidar has imaged the land surface in unprecedented detail, and was examined closely as part of the assessment that is the subject of this report. The lidar highlights the continuity and consistency of form of the features identified by Geotech Consulting Ltd (2005a-c), providing substantial reinforcement for the suggestion that they are related to active fault deformation. As a result, I consider it likely that there is an active fault passing through the Mangamaunu area.

This contrasts with the conclusions of the Connell Wagner Ltd (2007) investigation, which found no evidence for active faulting. Having examined the Connell Wagner Ltd (2007) report in detail, it is my opinion that only two of the trenches were sited at or across the fault features identified here as ‘likely’. One of them, Trench 1 on Lot 21 of the development, was excavated across a ‘likely’ fault trace and onto the margins of one of the areas of higher ground. Although the trench log does not identify any fault offsets, where the trench excavation rises onto the higher ground, the sediment layering also rises up, parallel to the ground slope. This is compatible with the idea that the rise onto higher ground is a product of fault-related tilting of the ground. The other trench, Trench 4 on Lot 22, was described by Connell Wagner Ltd (2007) as being located “on the downhill side of the linear feature”. The trench itself is very short (9 m) and its shortness combined with its reported location downhill of the feature, raises doubt as to whether the trench did in fact cross the suspected fault feature. My assessment is that the trench information is not sufficient to disprove a fault origin for the landform features described above. Accordingly, I consider their classification as ‘likely’ remains justified on present evidence. Further, more detailed, investigations would be needed in order to prove whether or not the features do in fact mark the location of an active fault, and if so, to assess its degree of activity.

Near the farmpark pavilion site, there is an area of high ground on the fan terrace, on the south side of a ‘likely’ fault trace. Based on a suspicion that this area of higher ground may have been elevated by fault-related movement, I have drawn a ‘possible’ fault around the southern side of this higher ground. This ‘possible’ fault lies as close as ~60 m northwest of

the pavilion building. In a geotechnical assessment for the pavilion and associated facilities, Connell Wagner Ltd (2006) excavated a trench across the location of this feature, extending onto the higher ground (Trench II of that report). I generated detailed topographic profiles from the lidar at the location of this trench, and the profiles show that the ground rises up by as much as 3 m. The sediment layering recorded in the trench also rises up, parallel to the ground surface. Thus, it is conceivable that the trench log does show fault-related tilting of the ground at that location. Further assessment of these topographic features may be worthwhile if future work is done on the question of active faulting in the Mangamaunu area.

To the west of the alluvial fan terraces lies eroded hill terrain, and it is unclear exactly where this suspected fault is located in that area. There are a number of topographic anomalies, comprising various combinations of saddles and topographic steps or benches, and each of these is denoted in this data set as a ‘possible’ fault. On-site investigations would be needed to establish which, if any, of these features are related to active faulting. Trenches were excavated across several linear features on Lots 1, 2, 8 and 9 of the proposed rural residential subdivision (Connell Wagner Ltd 2007), but the exact locations of the trenches on those lots is not recorded in the report. No fault features were identified in the trench logs, but information on the trench locations is insufficient to assess whether or not the trenches crossed any of the features identified in this report as ‘possible’ faults.

To the east, the alluvial fan terraces are truncated by a ~25 m to ~45 m high post-glacial coastal cliff. The ‘likely’ fault on the alluvial fan terraces projects across the coastal cliff and beach ridges, but no fault offsets of these landforms are evident either in the lidar data, or in Google Earth Street View taken along State Highway 1. But it is likely that these landforms are very young (e.g., a few hundred years old). Eastward from there, two alternative possible directions for the trend of the suspected fault are drawn. One is directly east-northeast to the southern end of the Hope Fault – offshore, mapped by Barnes and Audru (1999). The other is drawn northeast along the coast, back onshore at the mouth of Blue Duck Creek, and up the valley of Irongate Creek to the approach the intersection of the Hope Fault – Seaward segment – South Branch and Patutu Fault. The reasoning for drawing the second alternative is that there is a marked contrast in shoreline morphology either side of Blue Duck Creek; extensive rocky shore platforms to the north and a gravel-dominated beach to the south. This potentially may indicate Holocene tectonic uplift north of the Blue Duck Creek mouth, but relatively less uplift, if any, to the south.

At Mangamaunu, the alluvial fan across which the fault runs is dissected by several stream gullies. The alluvial fan surface is relatively steep and if its gradient is projected seawards, it intersects present sea level about 100 m seaward of the current shoreline. The post-glacial sea level rise culminated about 7,000 calendar years ago (equating to ~6500 ^{14}C years BP), at approximately its modern level. It is assumed for the purposes of this report that the formation of the coastal cliff commenced ~7,000 calendar years ago, and that also marks the time of initiation of what are now the deep gullies that have dissected the fan. There could of course have been other factors at play leading to the formation of these gullies and so the estimate of 7,000 years for the attainment of their general form is simply one possibility. But that is the only possibility at present that enables a reasoned age to be inferred for the landforms at this location.

The edges of the fan terraces, at the margins of the gullies, have apparent lateral offsets of between 10 m and 30 m, measured at the outer margins of each gully using the resolution of the lidar data. Running these values through a calculation, the assumed 7,000 year age of onset of gullying coupled with a 10 m lateral offset implies a slip rate of 1.4 mm per year and

if the offset is 30 m then the implied slip rate is 4.3 mm per year. If one assumes a mean single event displacement of 3 m dextral strike slip, this implies a recurrence interval of 2,100 and 700 years respectively. Given the uncertainties of the age estimates of the gullies as outlined above, it is difficult to know the reliability of these estimates of recurrence interval. They do however imply that the Mangamaunu fault may be recurrence interval Class I or II. However, it is important to bear in mind that this fault is classed as 'likely' and so in the first instance it would be desirable to establish for certain whether or not it is an active fault.

Kaikoura Fault (feature 12; Figure 8)

Barnes & Audru (1999) propose a late Quaternary vertical separation rate and fold amplitude growth rate for the Kaikoura Fault of as much as 0.9 ± 0.2 mm/yr. They also identified indications of a component of strike-slip displacement. The uplift estimates are broadly similar to that of the Kaikoura Peninsula fault, and the Hapuku fault zone, noting that the two latter fault features are suspected rather than definite. . It is not known whether these three fault features are separate entities, or whether one or more of these fault features are linked.

Subsequent compilations of active fault data have placed a horizontal slip rate of 0.13 mm/yr on the Kaikoura Fault (Stirling et al., 2007; Litchfield et al., 2014), doubtless arising from efforts to try and balance the regional distribution of slip across the various active faults of the wider area (e.g., Robinson et al., 2011). As this value is at odds with the findings of Barnes & Audru (1999), and because there is reason to think the fault has a substantial, and probably dominant, component of dextral strike-slip, the issue of the slip rate of the Kaikoura Fault appears to require re-evaluation.

Kaikoura Peninsula fault and folds (feature 13; Figure 8)

The presence of an uplifted Holocene shore platform around Kaikoura Peninsula, and a flight of uplifted marine terraces on and northwest of the peninsula forms a basis for inferring an active fault lying offshore southeast of the peninsula (Ota et al., 1996; Campbell et al., 2005). Litchfield et al. (2014) infer that this fault is the northeast continuation of the Hundalee Fault. However, the evidence that the Hundalee Fault is active is not persuasive (see Barrell & Townsend 2012, and Section on Hundalee Fault below). Therefore the step is taken in this report of drawing a tentative location for the inferred fault responsible for having uplifted the Kaikoura Peninsula. It is drawn on an east-northeast – west-southwest strike, and called 'Kaikoura Peninsula fault'. It is positioned at a zone of relatively closely spaced bathymetric contours. Whether it is an emergent fault, or perhaps a monocline, is not known. What relationship, if any, this suspected fault has to the Kaikoura Fault to the north, or the Hundalee Fault to the south, remains unknown.

A feature of the marine terrace flight that form much of the land surface of the peninsula is a notably expressed tilt, with the terraces standing at a higher level at the southeast end of the peninsula than to the northwest where the peninsula adjoins the mainland (Ota et al. 1996). Terrace 3 is the most extensively preserved terrace remnant, and stands at between 60 and 70 m above sea level (asl) at the southeast end of the peninsula, but only between 30 and 40 m asl at the edge of the mainland, about 3 km to the northwest. Long-term uplift rate of Kaikoura Peninsula, based on ages assigned to the raised marine terraces is ~1.2 mm/yr (Ota et al., 1996). On account of the northwesterly down-tilt, the uplift rate varies depending on location. Thus, using extensive Terrace 3, its age is inferred to be about 80,000 years, at which time sea level was about 20 m lower than present. In the southeast, the terrace stands

about 65 m asl, thus has been uplifted by about 85 m, with an average uplift rate there of about 1.1 mm/yr. In the northwest, the terrace stands about 35 m asl, thus has been uplifted by about 55 m, with an average uplift rate there of about 0.7 mm/yr.

There is a prominent Holocene raised shore platform around much of the peninsula, clearly due to one of more recent uplift events. McFadgen (1987) proposed that there had been 4 uplift events, at about 1900, 1400, 400 and 200 ^{14}C years BP. It is likely that the latter two represent just one uplift event, because radiocarbon dates, after calibration, tend to overlap markedly at those young age ranges. Typically 1 m uplift per event is suggested by McFadgen (1987). Campbell et al. (2005) suggested that the uplifted Holocene shore platform stands higher in the southeast, indicating that the tilting has continued in the most recent uplift events.

Based on data in McFadgen's (1987) study near Fyffe House at the southeastern end of Kaikoura township, I make the following comments. McFadgen (1987) expressed altitudes above the crest of the modern beach ridge (ambrc). He mapped two uplifted wave-cut limestone rock platform surfaces, the higher at ~4 m ambrc, the lower at ~1 m ambrc. He described results from radiocarbon dating of stratigraphic exposures of sediments at the margins of these exposed rock platforms. Shelly sand overlying a rock platform at ~3 m ambrc has a radiocarbon age of ~3,000 radiocarbon years BP, equating to ~3,150 calendar years BP. As no ~3 m ambrc platform was mapped in the area, I assume that this shelly sand rests on a low point on the ~4 m ambrc platform. A working assumption is that this sand, and the underlying rock platform, was raised above marine influence by an earthquake uplift event which presumably occurred ~3,000 years ago. Immediately seaward, beach gravel and sand deposits overlie a rock platform surface at ~1 to ~2 m ambrc. I assume this rock platform equates to the nearby exposed ~1 m ambrc rock platform. The beach gravel laps up on the edge of the ~3 m ambrc buried rock platform and its shelly sand cover. The beach gravel and shelly sand returned radiocarbon ages ranging from ~1,600 to ~1,300 radiocarbon years BP. I assume that this platform and overlying beach sediments were raised above marine influence by an earthquake uplift event which presumably occurred ~1,300 years ago. Nearby, a beach gravel ridge deposit drapes the seaward margins of the older sediments and associated ~1 to ~ 2 m ambrc rock platform. The crest of the highest part of the ridge is ~1.9 m ambrc. Shells within the gravels of this beach ridge are ~500 calendar years BP. I assume that this ridge, and the adjacent narrow coastal plain on which the modern road runs, was uplifted ~500 years ago. Collectively, these geological relationships at this location can be interpreted as the result of at least three uplift events. An uplift of between ~1 m and ~3 m occurred ~3,000 years ago. An uplift of between ~1 m and ~2 m occurred ~1,300 years ago, followed by an uplift of as much as ~2 m that occurred ~500 years ago. While some of these three suggested uplifts may have been the result of two or more smaller uplift events, there is good evidence for at least three uplift events in the past ~3,000 years. This implies a maximum average recurrence interval of ~1,000 years for uplift events in the recent past. Taken at face value, recurrence intervals have ranged from ~800 years to ~1,700 years. An uplift rate of at least 1 mm/yr is implied. It is difficult to be more specific about uplift rate, because there is no direct information on the altitudes at which the various rock platforms, and beach ridges, were formed.

For the purpose of this report, the long-term uplift rate of 1.1 mm/yr is taken as an approximation for estimating the vertical slip rate on the Kaikoura Peninsula fault. Two metres per event implies an average recurrence interval of ~1,800 years per event. This is broadly compatible with the findings of McFadgen (1987).

There is a set of northeast-southwest trending anticlines and synclines within the cover rock sequence exposed on the peninsula, and it has been suggested that the folds may have caused slight deformation of the marine terraces (Campbell et al., 2005). The indications that these folds remain active are tentative, however, because there is considerable natural irregularity in the form of the terrace surfaces, which makes it difficult to confidently identify the presence or otherwise of fold growth, especially over short wavelengths. For the purposes of this report, the folds are classified as 'possible'. Any activity that they have undergone is subtle at best, and any growth event would have little impact on land-use. No attempt is made to infer growth rates for these features. Onland, these folds are designated 'moderately expressed', because the locations of the fold axes can be determined from the dips of bedding layers in the bedrock. Their offshore extensions are 'not expressed'. Names for the folds are from Campbell et al. (2005).

Hundalee Fault (feature 14; Figure 8)

The Hundalee Fault is without doubt a notable geological feature, whose past movements have brought greywacke basement rock into contact with much younger cover rocks (Rattenbury et al., 2006). However, there is no compelling evidence that it is currently active. For example, there are no prominent uplifted marine terraces at the location where the fault crosses the coastline. In particular, the absence of a notable difference in Holocene coastal terrace height at the fault's projected location at the coast counts against the implication that it is the fault responsible for the prominently uplifted Holocene coastal platform on Kaikoura Peninsula.

Litchfield et al. (2014) classify the Hundalee Fault as a northwest-dipping reverse fault with a slip rate of 1.22 mm/yr. This may reflect the presumption that the fault is responsible for uplift of the Kaikoura Peninsula, an explanation that I do not favour, for the reason given above. In this dataset, the Hundalee Fault is identified as a 'possible' active fault. Furthermore, it is assigned a provisional minimum recurrence interval of between 5,000 and 10,000 years, because there is no indication of offset Holocene landforms on the line of the fault, particularly the Holocene coastal landforms. Following Ota et al. (1996), a 'possible' offshore extension is drawn in this dataset just offshore of the coast northeast of Oaro, and across the head of the Kaikoura submarine canyon, to approach the Kaikoura Peninsula fault. This offshore extension of the Hundalee Fault is a speculative interpretation. No connection necessarily implied with the Kaikoura Peninsula fault. The Hundalee Fault and its possible extensions are worthy of consideration, and perhaps further investigation, in future studies. It would be useful to assess the hypotheses offered in the dataset accompanying the present report.

Additional references not listed in the body of the report

Chandra, S., 1968, Geomorphology of the Kaikoura area. Master of Science thesis, University of Canterbury. Available from University of Canterbury < www.canterbury.ac.nz >, Research repository, search terms 'theses and dissertations, 1968, Chandra'. 90 p. and 3 maps.

Connell Wagner Ltd 2005. Proposed Mangamaunu Subdivision – General Geotechnical Assessment. Revision 2 – Issued 12th September 2005 (document control panel). Prepared for Cedar Properties Kaikoura Ltd. 16 p. plus photographs (4 pages).

Connell Wagner Ltd 2006. Section 127 application – 05/28 & 05/29 – Cedar Properties Kaikoura Ltd. Letter to Kaikoura District Council dated 31st July 2006. 5 p. plus 8 p. of appended photo, maps and trench logs.

Connell Wagner Ltd 2007. Resource consent ·Cedar Properties Limited - addressing resource consent conditions 8 and 9. Letter report to Kaikoura District Council, 26th February 2007. 31 p., including appended maps, photos and trench logs.

Coulter, R.F. 2007. Tectonic Geomorphology and Seismic Hazard of the Mt Fyffe Section of the Hope Fault. Master of Science thesis, University of Canterbury. Available from University of Canterbury < www.canterbury.ac.nz >, Research repository, search terms 'theses and dissertations, 2007, Coulter'. 211 p. and map.

Cowan, H.A. 1990. Late Quaternary displacements on the Hope Fault at Glynn Wye, North Canterbury. New Zealand Journal of Geology and Geophysics 33: 285–293.

Eusden, J.D.; Pettinga, J.R.; Campbell, J.K. 2005a. Structural collapse of a transpressive hanging-wall fault wedge, Charwell region of the Hope Fault, South Island, New Zealand. New Zealand Journal of Geology and Geophysics 48: 295-309.

Eusden, J.D.; Pettinga, J.R.; Langridge, R.M. 2005b. Field Trip 7 – Structural geomorphology and paleoseismicity of the Hope Fault. Pages 157-177 In Pettinga, J.R.; Wandres, A.M. (eds.) Field Trip Guides, Geological Society of New Zealand 50th Annual Conference, Kaikoura, New Zealand. Geological Society of New Zealand Miscellaneous Publication 119B.

Freund, R. 1971. The Hope Fault – a strike slip fault in New Zealand. New Zealand Geological Survey Bulletin 86. 49 p. and maps (2 sheets).

Geotech Consulting Ltd 2005a. Cedar Properties – Mangamaunu Subdivision: Peer Review of Geotechnical Assessment. Letter report to Kaikoura District Council, 10th October 2005. Comprises formal submission of peer review report that was originally transmitted by fax on 8th August 2005. 10 p. including two maps.

Geotech Consulting Ltd 2005b. Re: Cedar Properties Kaikoura Ltd - Proposed subdivision of Lot 2 DP 11880, Lots 1 & 2 DP 11892 Pt Mangamaunu Secs 10A & 10B of 2 & pt Mangamaunu Sec 10B2 of 2. Letter report to Kaikoura District Council, 6th December 2005. 6 p.

Geotech Consulting Ltd 2005c. Re: Cedar Properties Kaikoura Ltd – Proposed subdivision of Lot 2 DP 11880, Lots 1 & 2 DP 11892 Pt Mangamaunu Secs 10A & 10B of 2 & pt Mangamaunu Sec 10B2 of 2. Letter report to Kaikoura District Council, 10th December 2005. 4 p.

Gibb, J.G. 1986. A New Zealand regional Holocene eustatic sea-level curve and its application to determination of vertical tectonic movements. Royal Society of New Zealand Bulletin 24: 377-395.

Gibbs, H.S.; Beggs, J.P. 1953. Soils and agriculture of Awatere, Kaikoura and part of Marlborough counties. New Zealand Soil Bureau Bulletin 9. Wellington, Department of Scientific and Industrial Research. 55 p. and map (1 sheet).

GNS Science 2005. RE: Active faulting at Maungamanu site, Letter to Connell Wagner Ltd, 29th August 2005. 4 p.

Kaikoura District Council 2006. Notice of Decision, Resource Management Act 1991: Cedar Properties Kaikoura Limited: Consent application for farmpark subdivision and associated land-use. 1st February 2006. 23 p.

Knuepfer, P.L.K. 1988. Estimating ages of late Quaternary stream terraces from analysis of weathering rinds and soils. Geological Society of America Bulletin 100: 1224-1236.

Lensen, G.J., 1962. Sheet 18 – Kaikoura. Geological map of New Zealand 1:250 000. Wellington, New Zealand, Department of Scientific and Industrial Research. 1 sheet.

Rattenbury, M.S.; Townsend, D.B; Johnston, M.R. 2006. hand-drawn record sheets for the Geology of the Kaikoura area 1:250 000 Geological Map 13. Accessible through the GNS Science Regional Geological Mapping Archive http://rgmad.gns.cri.nz/publish/index.html

Simpson, R.J. 1995. The Seaward segment of the Hope Fault, Seaward Kaikoura Range, southeast Marlborough. Unpublished B.Sc (Hons) thesis, Department of Geological Sciences, University of Canterbury. 82 p. and map (1 sheet).

Stirling, M.W.; Gerstenberger, M.; Litchfield, N.J.; McVerry, G.H.; Smith, W.D.; Pettinga, J.; Barnes, P. 2007. Updated probabilistic seismic hazard assessment for the Canterbury region. GNS Science Consultancy Report 2007/232. ECan Report Number U06/6.

Van Dissen, R.J. 1991. An evaluation of seismic hazard in the Kaikoura region, southeastern Marlborough. New Zealand Geological Survey Record 43: 93-99.

Van Dissen, R.J.; Sutherland, D.G.; Bowers, R.J.; Redwine, J.L. 2006. Forest burial by large rock avalanche in Miller Stream, Seaward Kaikoura Range, New Zealand, c. 1700 years ago. New Zealand Journal of Geology and Geophysics 49: 151-157.

Vandergoes, M.J., Hogg, A.G., Lowe, D.J., Newnham, R.M., Denton G.H., Southon J., Barrell D.J.A., Blaauw, M., Wilson, C.J.N., McGlone, M.S., Allan, A.S.R.., Almond, P.C., Petchey, F., Dabell, K., Dieffenbacher-Krall, A.C. 2013. A revised age for the Kawakawa/Oruanui tephra, a key marker for the Last Glacial Maximum in New Zealand. Quaternary Science Reviews 74: 195-201.

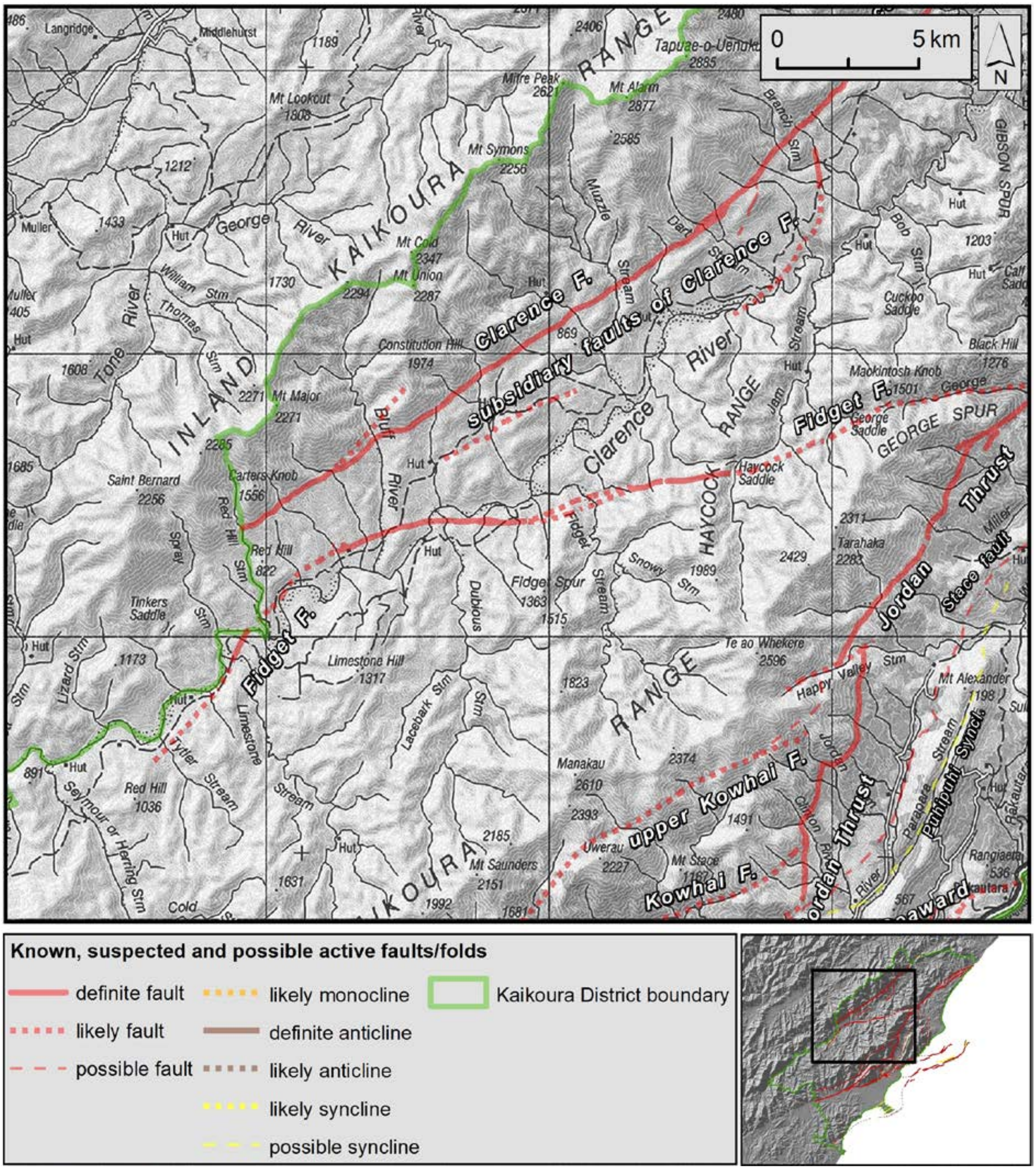

Figure A2-1a The known, suspected and possible active faults/folds of the northwestern sector of the Kaikoura District plotted on a greyscale version of topographic map NZTopo 250 (Land Information NZ, Crown Copyright reserved). The map area is shown in the context of the Kaikoura District in the index map at lower right. Fault or fold entities that consist only of 'possible' features are labelled in smaller font than fault or fold entities that include 'definite' or 'likely' features.

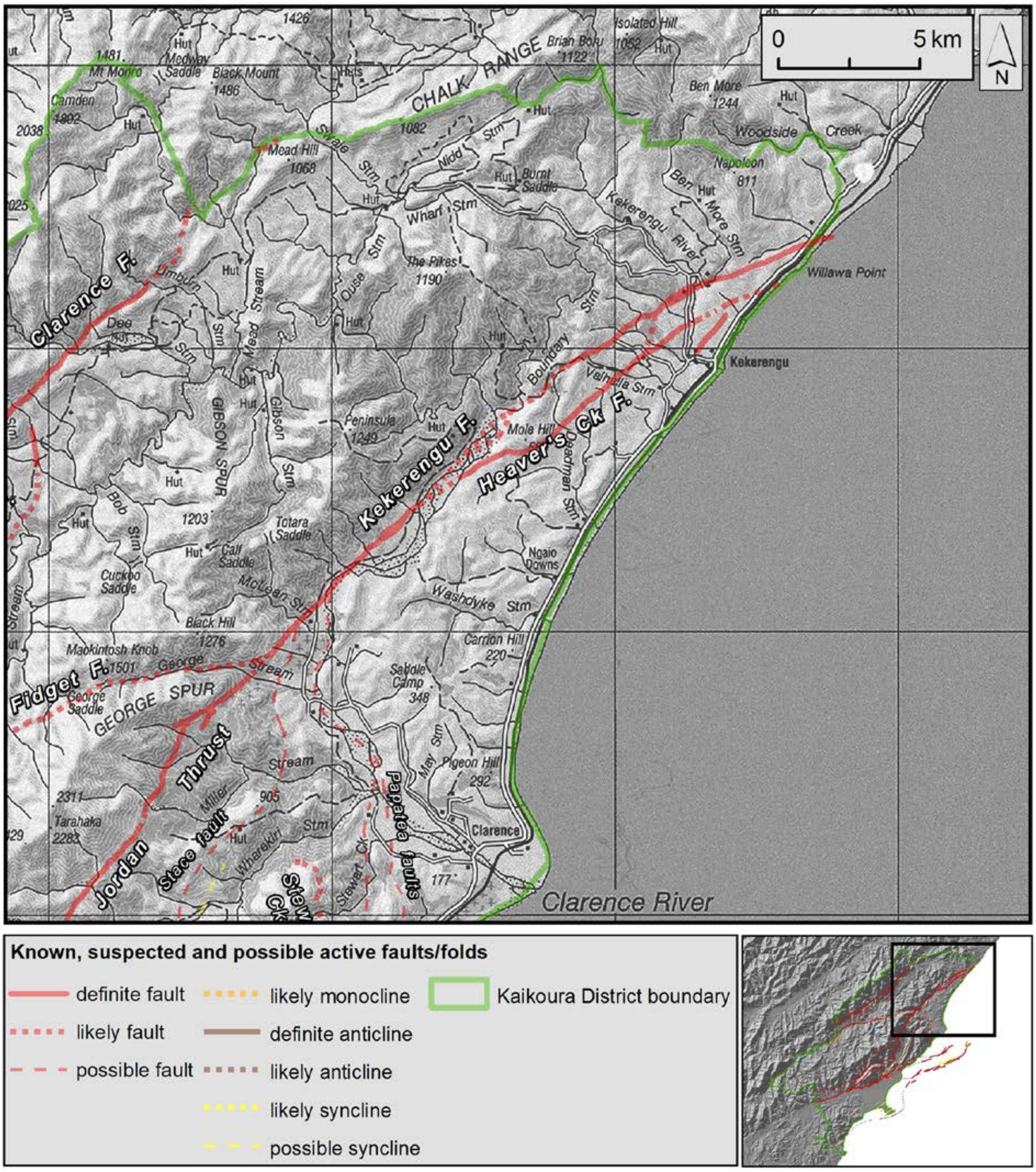

Figure A2-1b The known, suspected and possible active faults/folds of the northeastern sector of the Kaikoura District plotted on a greyscale version of topographic map NZTopo 250 (Land Information NZ, Crown Copyright reserved). The map area is shown in the context of the Kaikoura District in the index map at lower right. Fault or fold entities that consist only of 'possible' features are labelled in smaller font than fault or fold entities that include 'definite' or 'likely' features.

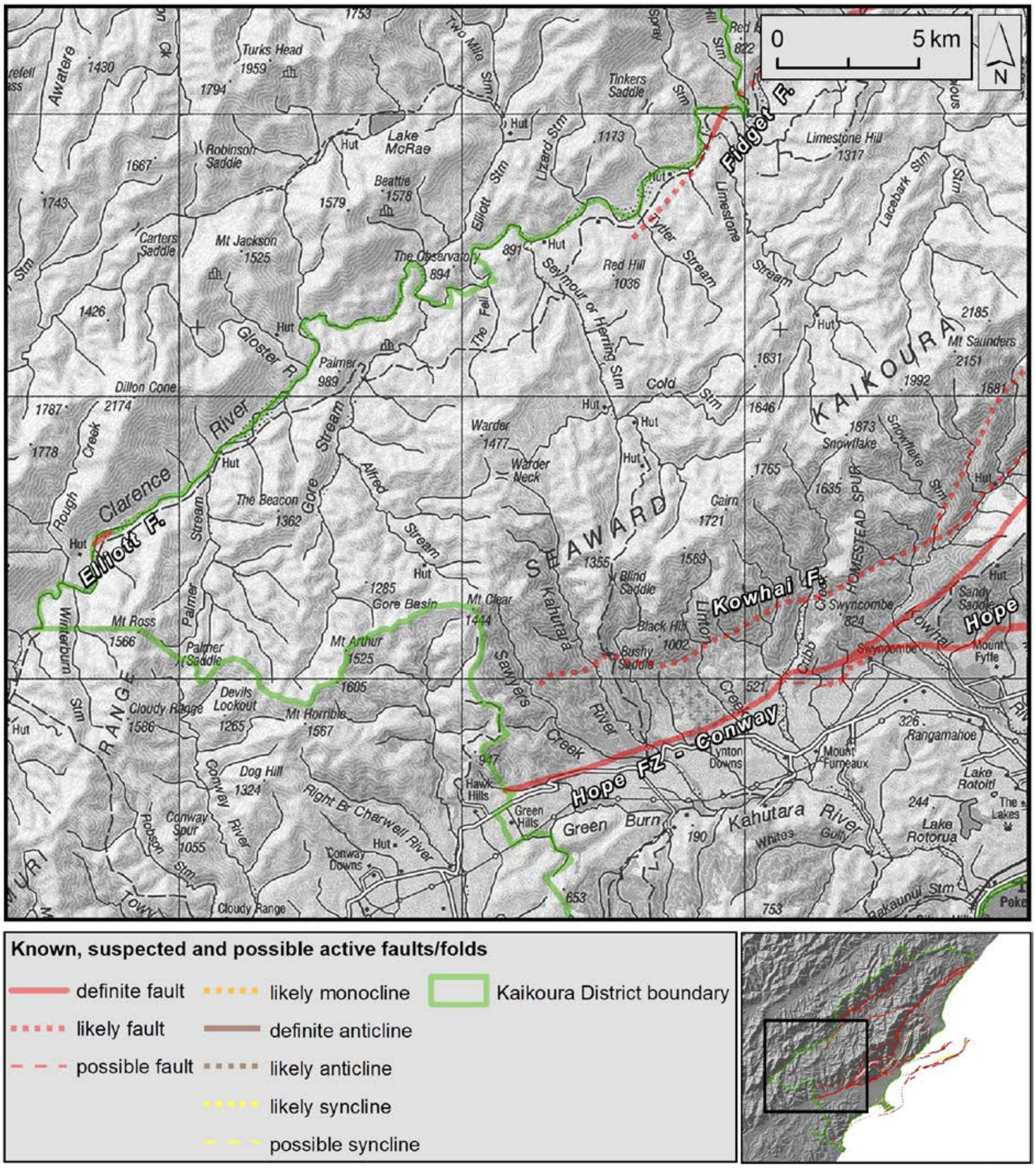

Figure A2-1c The known, suspected and possible active faults/folds of the southwestern sector of the Kaikoura District plotted on a greyscale version of topographic map NZTopo 250 (Land Information NZ, Crown Copyright reserved). The map area is shown in the context of the Kaikoura District in the index map at lower right. Fault or fold entities that consist only of 'possible' features are labelled in smaller font than fault or fold entities that include 'definite' or 'likely' features.

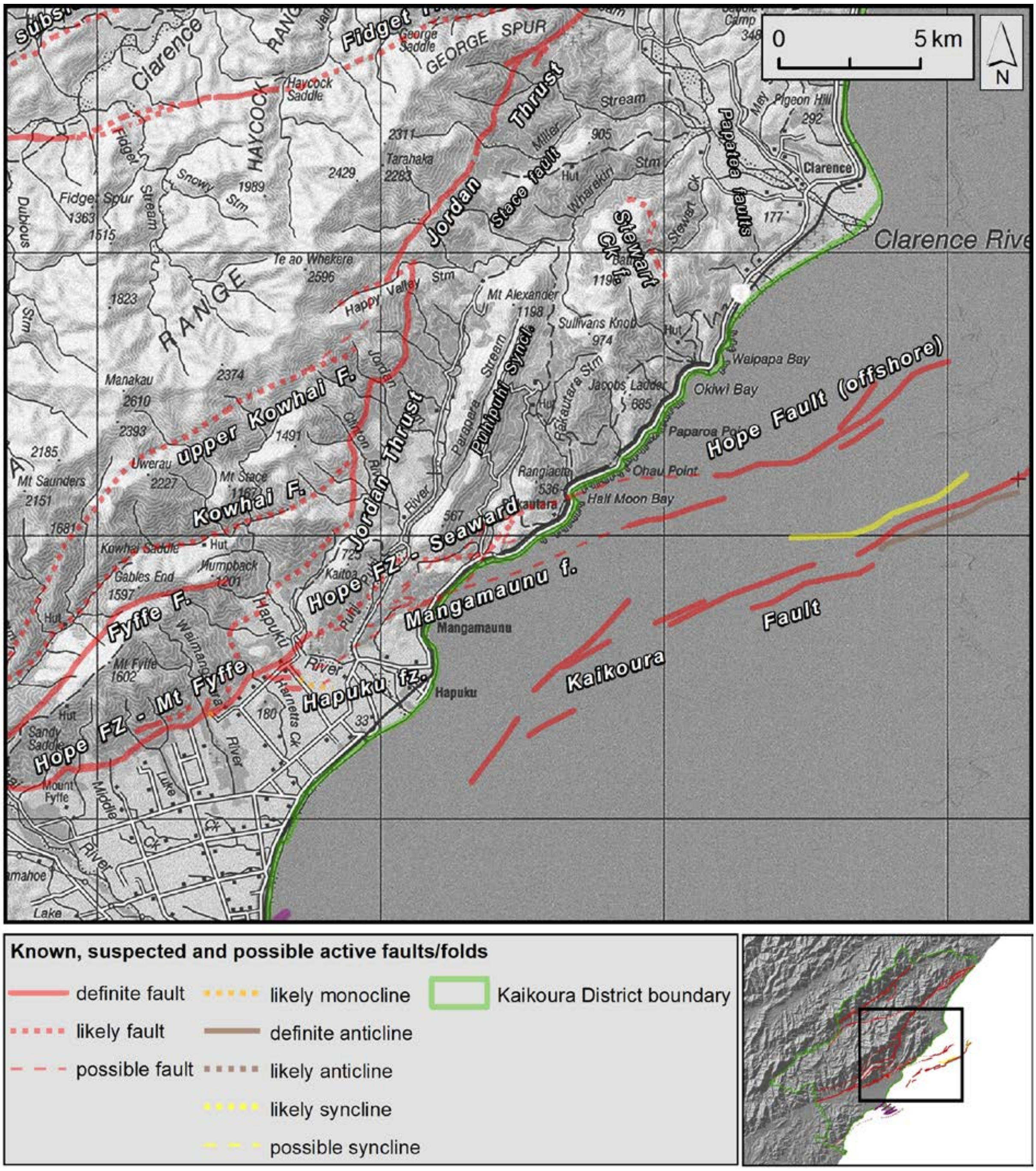

Figure A2-1d The known, suspected and possible active faults/folds of the eastern sector of the Kaikoura District plotted on a greyscale version of topographic map NZTopo 250 (Land Information NZ, Crown Copyright reserved). The map area is shown in the context of the Kaikoura District in the index map at lower right. Fault or fold entities that consist only of 'possible' features are labelled in smaller font than fault or fold entities that include 'definite' or 'likely' features.

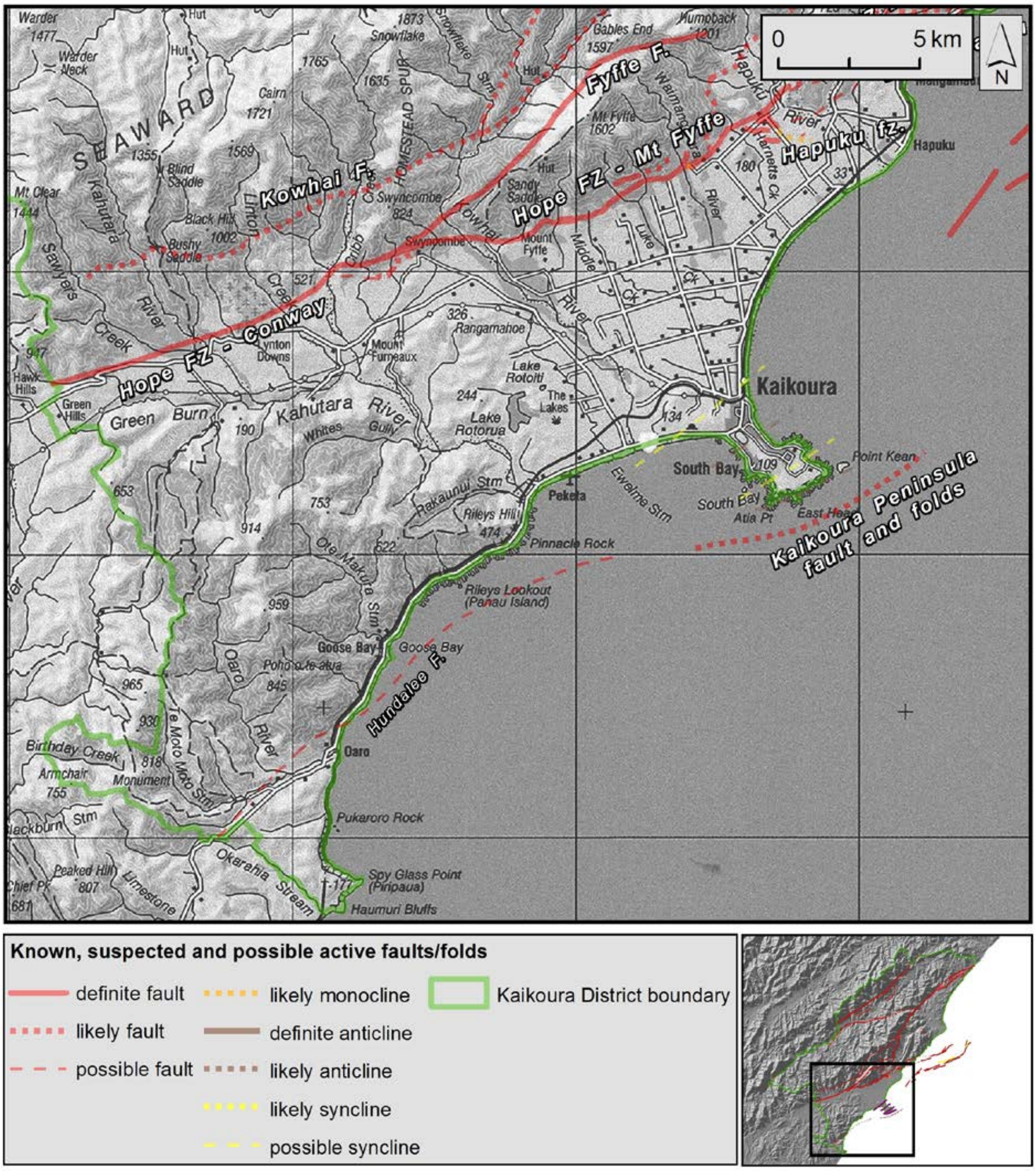

Figure A2-1e The known, suspected and possible active faults/folds of the southern sector of the Kaikoura District plotted on a greyscale version of topographic map NZTopo 250 (Land Information NZ, Crown Copyright reserved). The map area is shown in the context of the Kaikoura District in the index map at lower right. Fault or fold entities that consist only of 'possible' features are labelled in smaller font than fault or fold entities that include 'definite' or 'likely' features.

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