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Assessment of active fault ground deformation hazards associated with the Ashley Fault Zone, Loburn, North Canterbury

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EXECUTIVE SUMMARY

The Ashley Fault Zone is a system of active geological faults and folds that passes through the Loburn area, a few kilometres north of Rangiora. Loburn has many „rural lifestyle" small holdings and potential for further rural subdivision. This report provides an assessment of hazards and risks posed by the Ashley Fault Zone to existing and future buildings and infrastructure in the Loburn area. The main hazard associated with active faults is the occurrence of a sudden slip event („rupture") on the fault, initiated deep in the Earth"s crust, which generates a large earthquake and causes strong ground shaking across a wide area around the fault. If sufficiently large, the fault slip movement will extend up to the ground and cause „surface rupture", which involves a sudden offset (faulting) or buckling (folding) of the ground surface by up to several metres. Buildings or other infrastructure situated within a zone of sudden offset and/or buckling are likely to suffer serious damage or even destruction. This poses a significant threat of injury or death to occupants of any such buildings, and may make the building unusable.

This report is based on the assessment of existing publicly-available information on the Ashley Fault Zone, including aerial photography and satellite imagery, examination of a high-resolution lidar (laser radar) dataset that provides a very precise picture of ground topography, and a one-day reconnaissance inspection of landforms in the vicinity of the Ashley Fault Zone, from public roads.

For this report, considerable effort was directed towards using the lidar data for detailed mapping of landforms in the general vicinity the fault zone, in order to characterise the surface deformation. This enabled estimation of the amounts of offsets of landforms. In turn, this provided a basis for estimating the recurrence interval for fault ground-surface rupture.

In overall character, the Ashley Fault Zone consists of a broad upward bulge (anticlinal fold) aligned roughly east-west, accompanied by three overlapping fault strands, each at least ~4 to 6 km long. Two of these strands, Ashley Fault and Ashley Fault (East), are upthrown to the north, while the Loburn Fault is upthrown to the south. The surface expressions of these fault strands are steps in the ground surface („fault scarps"). The fault scarps represent „well-defined" deformation. In addition, there are some localised bends in the ground („monoclinal flexures") that are classified as distributed deformation. Broader areas of gently tilted ground associated with the fault scarps or monoclinal flexures are classed as „uncertain deformation". A future large, ground surface rupturing earthquake on the Ashley Fault Zone would result in localised severe ground deformation at the fault scarps, lesser amounts of deformation in the general vicinity and severe earthquake shaking in the wider region.

The fault strands are characterised as having approximately equal components of up-down (dip-slip) and sideways (strike-slip) movement, with a contractional (reverse) sense of up-down movement, and a clockwise (right-lateral) sense of sideways movement. The most recent surface ruptures are estimated to have each involved a „single-event" vertical component of offset typically between ~1 and ~2 m, but over short distances varied from as little as ~0.5 m to as much to ~3 m. The western end of the Loburn Fault strand did not experience surface rupture during the most recent surface rupture of the Ashley Fault strand.

The Ashley Fault Zone is assessed as having an average recurrence interval for surface-rupture earthquakes of between 7,000 and 15,000 years, with a small possibility that it could be as short as approximately 5,000 years.

Ministry for the Environment guidelines on “Planning for development on or close to active faults” (Kerr et al., 2003) provide a risk-based approach for evaluating active fault hazards. There are three key inputs for implementing the guidelines; an estimate of how often surface rupture occurs on a fault (recurrence interval), delineation of how concentrated the surface deformation is (fault complexity), and the life-safety significance of human constructions across the fault (Building Importance Category – BIC).

The Ashley Fault Zone is assigned to Recurrence Interval Class IV (>5,000 to ≤10,000 years) according to MfE active fault guidelines. There is considered to be a small possibility that the recurrence interval **could** be as short as 5,000 years, and therefore fall within Recurrence Interval Class III (>3,500 to ≤5,000 years).

Detailed mapping of the fault zone enabled the delineation of fault complexity according to three categories; well-defined fault deformation, distributed deformation and uncertain ground deformation. The areas of well-defined deformation and distributed deformation should be regarded as fault avoidance zones for any structures of significant importance in regard to the recurrence interval. In addition, 20-m-wide buffers have been applied to well-defined and distributed deformation areas. The buffers form an integral part of the fault avoidance zone and their purpose is twofold. First, they provide some contingency against uncertainties in defining the limits of the deformation areas. Second, they make some allowance for the possibility that the deformation area may expand slightly in the next deformation event(s). The precision of mapping is not sufficient to warrant defining a set-back on the 'uncertain' deformation areas.

Based on a Recurrence Interval Class of IV, the MfE guidelines indicate that critically important structures (BIC 4 buildings) should be sited outside the fault avoidance zones of the Ashley Fault Zone, as should any important (BIC 3 buildings) in a new („greenfield“) development. Residential dwellings and industrial/commercial buildings (BIC 2) are allowable within any part of the fault zone. However, if the Recurrence Interval Class is III, the MfE guidelines indicate restrictions on large residential dwellings and industrial/commercial buildings (BIC 2b) within the fault zone at greenfield locations, and on important buildings (BIC 3) in existing or greenfield developments. Any limitations or land-use or development in this regard are matters for the territorial authority to determine. Nonetheless, land owners and developers could choose to avoid placing buildings or other valuable infrastructure within well-defined or distributed deformation zones.

Future geological investigations may allow the extents or the classifications of hazard avoidance areas to be refined. Further investigations targeting the history of movement of the Ashley Fault Zone may be able to confirm when surface rupture(s) last occurred, and may yield more precise estimates of the recurrence interval. Dating of offset river terrace landforms would also aid the refinement of the recurrence interval estimates. Such information would afford better constraint on the risk of future fault rupture, and aid land-use planning and hazard mitigation.

1.0 INTRODUCTION

A system of active geological faults, referred to here as the Ashley Fault Zone, passes through the Loburn area, a few kilometres north of Rangiora township, North Canterbury (Figure 1). The Loburn area is rural land, but includes many „rural lifestyle" small holdings. The rural setting on relatively flat land with hill and mountain backdrops, and proximity to Christchurch city and large towns such as Rangiora, makes Loburn a prospective area for further rural subdivision. It is therefore desirable that the nature and extent of potential hazards associated with the Ashley Fault Zone be delineated, so that risks to existing and future buildings and infrastructure can be determined and minimised.

The main potential hazard associated with active faults is the occurrence of a sudden slip event („rupture") on the fault, causing a large earthquake. Ruptures commonly begin deep in the Earth's crust and, if of large size, may extend up to the ground and cause „surface rupture", which involves a sudden offset (faulting) or buckling (folding) of the ground surface by up to several metres. Although violent ground shaking is the most widespread effect of an earthquake, surface rupture is a significant localised hazard. Buildings or other important structures situated within a zone of sudden offset and/or buckling are likely to suffer serious damage or even destruction. This poses a significant threat of injury or death to occupants of buildings, and may affect the post-earthquake functionality of the building or other structures.

Guidelines for planning to mitigate the threat to life safety due to active fault ruptures are presented in a Ministry for the Environment report on "Planning for development on or close to active faults" (Kerr et al., 2003). To aid in the implementation of these guidelines, a number of active fault hazard assessments have been undertaken elsewhere in New Zealand, such as Wellington City (Perrin & Wood 2003), Kapiti Coast District (Van Dissen and Heron 2003, Van Dissen et al., 2004, 2006) and at Twizel in inland South Canterbury (Barrell 2010).

Canterbury Regional Council (Environment Canterbury) engaged the Institute of Geological and Nuclear Sciences Limited (GNS Science) to provide an assessment of active fault hazards in relation to the Ashley Fault Zone in the vicinity of Loburn, including a fault-rupture hazard avoidance zonation for the fault zone. The assessment area extends between the Okuku River approximately 12 km north-northwest of Rangiora, and Boundary Road, approximately 5 km north of Rangiora (Figure 1). This report presents the results of that hazard assessment.

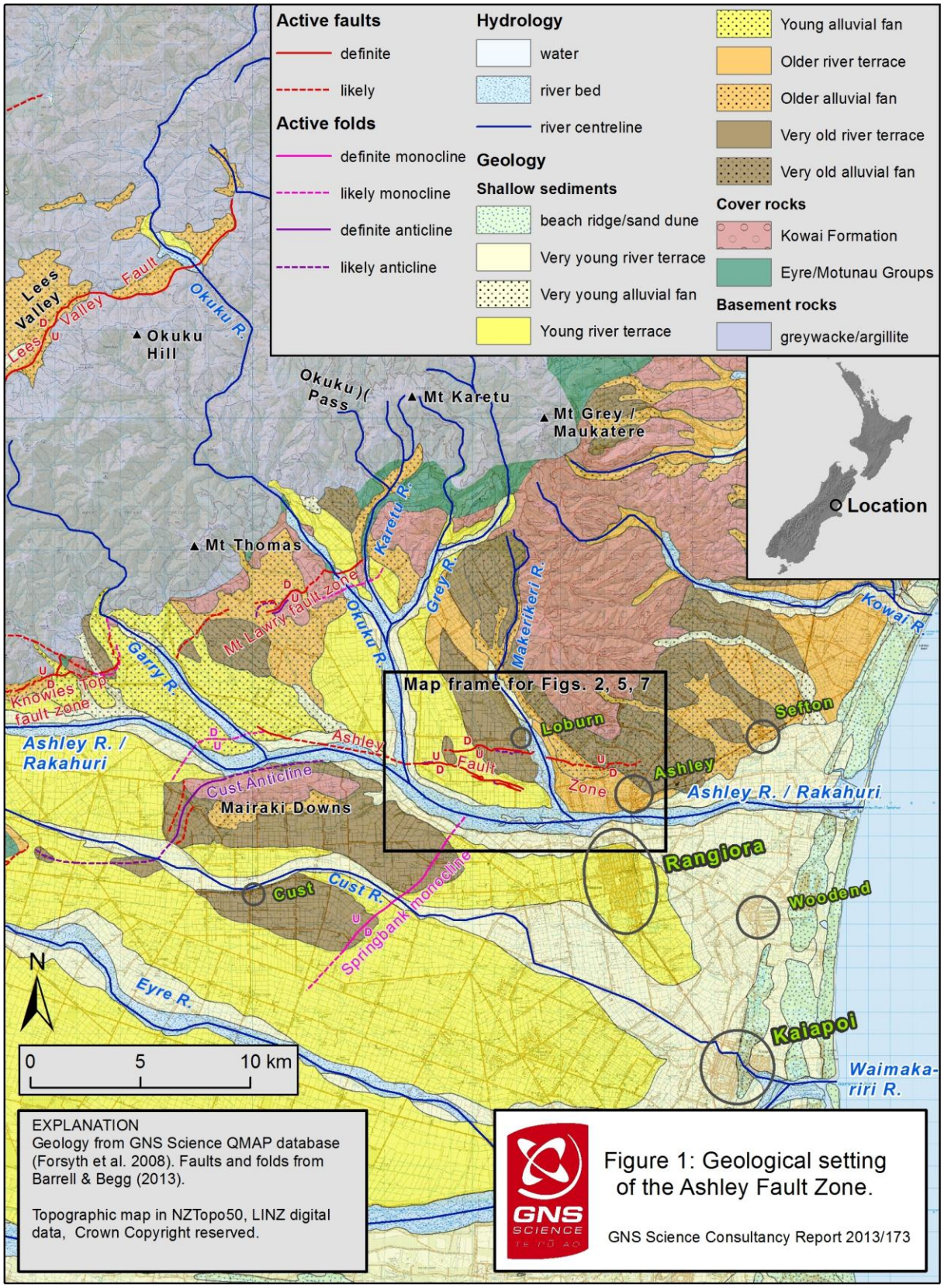

Figure 1 Geological setting of the Ashley Fault Zone.

2.0 INVESTIGATION METHODS

This assessment of Ashley Fault Zone hazards is based on:

- examination of existing, publicly-available, information on the Ashley Fault Zone, including aerial photography and satellite imagery;
- results from a one-day site examination of landforms in the vicinity of the Ashley Fault Zone east of Okuku River, from public roads;
- examination and interpretation of a high-resolution lidar[1] dataset for Waimakariri District, surveyed in 2005 and supplied by Environment Canterbury. The lidar dataset was used to generate a digital elevation model (DEM) composed of grid cells at 1 m spacing, with each 1 m diameter grid cell assigned a representative elevation value in metres above sea level. Although the elevation value is given to millimetre precision, for the purposes of the assessment in this report, it is considered accurate only to the nearest ten centimetres. The DEM was then used to map the fault and terraces and topographic transect profiles were generated across the Ashley Fault Zone.

The investigations were confined to surface observations and measurements. No excavations or other subsurface investigations were undertaken.

[1] Lidar is similar to radar, but uses light (lasers) rather than radio waves.

3.0 GEOLOGICAL ASSESSMENT OF THE ASHLEY FAULT ZONE

3.1 INTRODUCTION

The Loburn area lies on the lower reaches of the terraced plains of the Okuku and Makerikeri rivers. A few kilometres south of Loburn, these rivers join the Ashley River (Figure 1). The hills to the north and west are cored by cover rocks, while the underlying basement rock is exposed in the ranges to the northwest that form the foothills of the Southern Alps. What are termed here „shallow sediments" underlie the river terraces and plains (Figure 1). The hills and ranges have been formed as a result of tectonic uplift, produced by movement of faults (fractures) and folds (buckles). As the land has risen, erosion has shaped the terrain, in particular by carving numerous valleys and gullies.

The active faults and folds in Figure 1 are all components of a belt of tectonic deformation known as the Porters Pass to Amberley Fault Zone, which extends from the headwaters of the Rakaia River east-northeast towards Amberley in coastal North Canterbury. The Ashley Fault Zone has three named components, The Ashley Fault, the Loburn Fault, and what is termed here the Ashley Fault (East) (Figure 2).

A detailed evaluation of the geological and landform information relevant to the Ashley Fault Zone is provided in Appendix 1.

3.2 LANDFORM MAP

This report places considerable emphasis on the mapping and interpretation of landforms. River terrace landforms are particularly useful for assessing active fault ground deformation hazards. This is because the amounts of offset or buckling of river plains or terraces of various ages provides a geological record of prehistoric fault movements, and indicates the level of activity of a fault. Also of great advantage is that the river terrace surfaces usually are planar and almost flat, so the heights of the offsets or buckles are readily measureable. An important value to obtain, where possible, is the amount of offset that typically occurs during a ground-surface rupture event (single-event displacement, or SED). Another key parameter to estimate is the recurrence interval, which is the amount of time that typically elapses between surface rupture events. The recurrence interval is the main measure of fault activity used to assess risks to buildings and infrastructure. Determining the recurrence interval depends on having reliable estimates of the ages of offset geological deposits or landforms.

Using topographic maps, detailed topographic elevation models derived from lidar, and field observations, we made a map of the landforms in the vicinity of the Ashley Fault Zone (Figure 2), with a particular focus on river terraces and topographic steps or rises (scarps) produced by fault or fold movement. The relationship of this map to previous maps in this area is discussed in Appendix 1.

Topographic relations between different river terraces indicate their ages relative to one another. Older terraces stand at higher levels than younger terraces. In general, the older the terrace, the more subdued and irregular is its surface, due largely to the long-term effects of erosion and gullying by minor streams. „Terrace edge" symbols mark boundaries between two adjacent terrace levels, with ticks pointing to the lower terrace. Table 1 sets out the mapped landform units, along with estimates of their ages. The age estimation methods and the basis on which ages are assigned are described in Appendix 1.

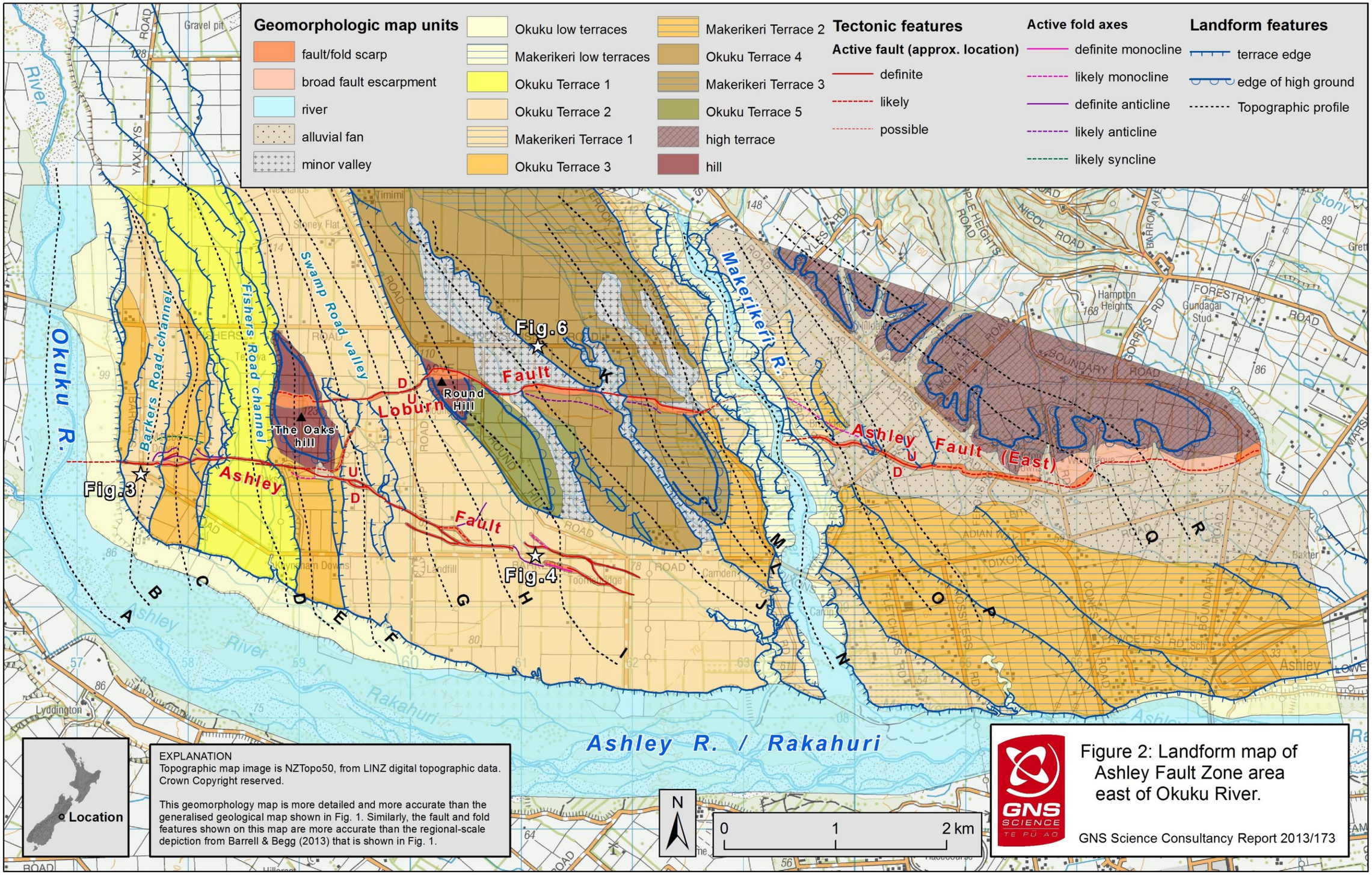

Figure 2 Landform map of the Ashley Fault Zone area, east of Okuku River. The topographic profiles are presented in Appendix 1.

Table 1 Mapping of shallow sediments and associated landforms in the Loburn area.

Geological map unit (Figure 1)	Landform map unit (Figure 2)	Estimated landform age ± uncertainty (years)
river bed	river	modern
very young river terrace deposits	low terraces	younger than Okuku Terrace 1 and Makerikeri Terrace 1
young river terrace deposits	Okuku Terrace 1	14,000 ± 4,000
	Okuku Terrace 2, Makerikeri Terrace 1	16,000 ± 4,000
	Okuku Terrace 3	23,000 ± 5,000
older river terrace deposits, older alluvial fan deposits	Makerikeri Terrace 2 (including alluvial fans)	20,000 ± 8,000
very old river terrace deposits, very old alluvial fan deposits	Okuku Terrace 4, Makerikeri Terrace 3	160,000 ± 30,000
	Okuku Terrace 5	>130,000 & <380,000
	„hill"	320,000 ± 60,000
	high terrace	480,000 ± 90,000

Two isolated hills are the oldest elements of the landscape of the central to western part of the investigation area. The high terrace on the eastern side of the Makerikeri River valley (Figure 2) is considered to be somewhat older, as it stands at a higher elevation than the hills.

Set lower in the landscape is a succession of river terraces (Figure 2). Terraces formed by the Makerikeri River are distinguished (horizontal line pattern) from terraces of the Okuku River (no pattern). The terrace numbering system counts back, starting with the youngest terraces, so that terrace 2 is older than terrace 1. Colour is used to reinforce the interpretation of terrace ages, for example the orange background applied to Okuku Terrace 3 and Makerikeri Terrace 2 indicates that these terraces are thought to be approximately the same age.

The oldest component of the Okuku/Makerikeri terrace sequence is identified as Okuku Terrace 5. This comprises isolated remnants of an old terrace of the Okuku River, lying southeast of Round Hill (Figure 2). Set at a lower level is Okuku Terrace 4, which is adjoined to the north by Makerikeri Terrace 3. Both of these terraces are extensively dissected by numerous gullies, and by larger inset drainages, which are mapped as „minor valley" (Figure 2).

Next youngest are Okuku Terrace 3 and Makerikeri Terrace 2. We have interpreted these two terraces as being of similar age because both are trimmed by the inset Okuku Terrace 2 (Figure 2). Okuku Terrace 2 appears to adjoin Makerikeri Terrace 1. Areas of Okuku Terrace 2 include the floors of the Swamp Road valley and Barkers Road channel (Figure 2). One of the sectors of Okuku Terrace 2 subsequently carried Okuku River water and was cut

to a deeper level than adjacent parts of the Okuku Terrace 2. This inset channel is referred to here as the Fishers Road channel, and its floor is identified here as Okuku Terrace 1. This channel equates to the Loburn 3 channel of Sisson et al. (2001).

Subsequently, the rivers have cut one or more lower terraces (identified here as „low terraces") before attaining their present floodplains.

Near the high terrace, alluvial fans have been built out from streams draining off the terrace and have encroached over Makerikeri terraces 1 and 2.

Where the Ashley Fault Zone has broken or buckled the surfaces of the terraces or alluvial fans (Figure 3), the resulting step in the ground („scarp") is depicted in two ways (Figure 2). A line is used to represent the approximate position of each fault or fold scarp, which is how faults and folds are usually depicted on maps. However, even the narrowest and sharpest of fault–related features are, from top to base, at least several metres wide when viewed from above (i.e., in map or plan view). Therefore, in addition, the faults and monoclines were also mapped as zones, or areas, termed „fault/fold scarp" (Figure 2). At the eastern end of the investigation area, where the Ashley Fault (East) runs along the southern end of the „high terrace", the exact location of the fault is unclear, and so the entire step up to the high terrace is mapped as a „broad fault escarpment" (Figure 2). The line depiction is useful at generalised scales, while the mapped areas suit more detailed map scales and describe more accurately the likely width of the active fault ground deformation hazard.

Figure 3 View of a step in the ground surface, running left-right, that marks the scarp of the Ashley Fault where crossed by Barkers Road, looking north. The scarp is ~1.7 m high. Photo: D.J.A. Barrell, May 2013.

3.3 GROUND DEFORMATION CLASSIFICATION MAP

The detection of past fault rupture breakage (Figure 3) or flexure-related buckling or bulging of the ground (Figure 4) rely largely on the steepness and orientation of the ground slope, as a means of interpreting locations and extents of fault scarps, monoclinal flexures and anticlines. The ground deformation classification map shown in Figure 5 and explained in Table 2 is based on physical characteristics of the ground surface (e.g., slope angle) within a context of ground surface age and the origin of its form. The map illustrates the overall character of deformation across the Ashley Fault Zone. Topographic profiles generated from the lidar elevation model greatly assisted in the interpretation. Those profiles are presented and discussed in Appendix 1.

The general features of the Ashley Fault Zone ground surface deformation are the overall slight regional tilt of the wider area and the more focused fault and fold scarps. Near the eastern end of the Ashley Fault strand, where its surface expression peters out, the delineation of the margin of regionally tilted ground is a tentative estimate, guided largely by the easternmost extent of the preserved older terraces.

Figure 4 This view west along Barkers Road, about 800 m west of the Round Hill Rd intersection, shows the carriageway rising over an anticline associated with the Ashley Fault. This is classed as slightly tilted ground (Figure 5). Photo: D.J.A. Barrell, May 2013.

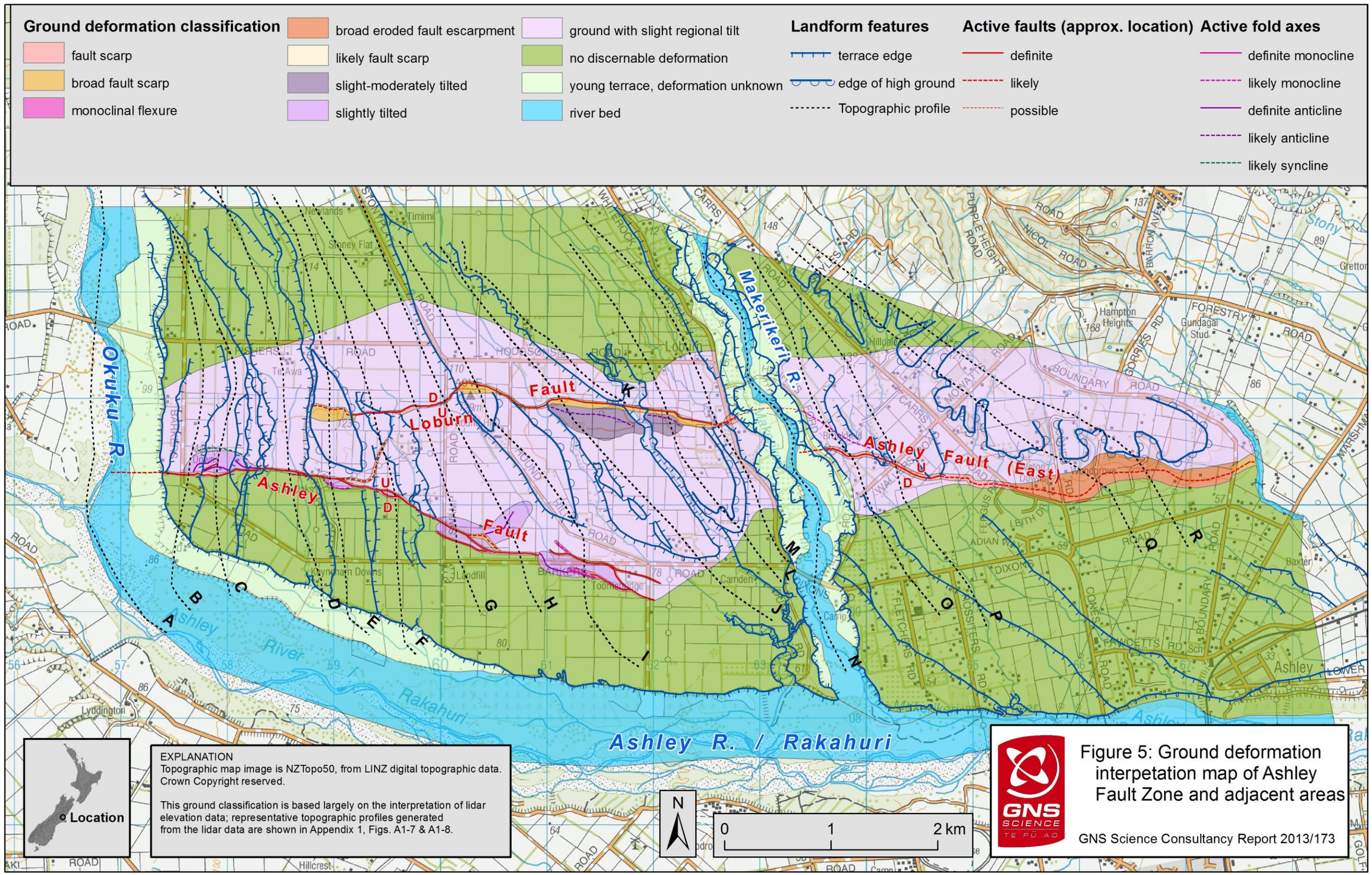

Figure 5 Ground deformation classification map of Ashley Fault Zone. The topographic profiles are presented in Appendix 1 (Figures A1-7 and A1-8).

Table 2 Ashley Fault Zone ground deformation classification (see Figure 5), along with the likely effects of fault rupture, and relationship to fault complexity class (Kerr et al., 2003).

Ground classification	Description (slope angles are relative to original ground slope of ~0.5°)	Likely effects on buildings in a ground-deforming earthquake	Fault complexity class
Older land surfaces (sufficient age to exhibit effects of past surface fault-rupture events)			
Fault scarp (including likely fault scarp)	Well expressed topographic step attributed to physical breakage of the ground by fault movement. Associated warping or tilting. Slope generally at least 10° steeper than original ground slope.	Very severe damage or destruction; life safety threat to occupants.	Well-defined deformation
Broad fault scarp	Broad, though still well expressed topographic step, typically situated on older, higher terraces adjacent to well expressed fault scarps on lower terraces. Interpreted to be an eroded fault scarp, with locus of past ground breakage somewhere within the broad topographic step.	If sited across the exact location of the fault breakage, very severe damage or destruction; life safety threat to occupants.	Well-defined deformation
Monoclinal flexure	Broad well-defined topographic step with tilting (generally 2 to 10° slope) of the original ground surface. Possibly affected by diffuse ground breakage as well as tilting.	Slight to severe damage; possible life safety threat to occupants.	Distributed deformation
Broad, eroded fault escarpment	Broad topographic step due to fault deformation, but has been eroded to the extent that the exact location(s) of the fault are obscured.	If sited across the exact location of the fault, very severe damage or destruction; life safety threat to occupants.	Uncertain deformation – constrained
Slightly - moderately tilted ground	Slight but noticeable tilt (typically 0.5 to 3°) relative to the original ground slope.	Building out of plumb. Ground shaking effects dominate life safety hazard to occupants.	Uncertain deformation – poorly constrained
Slightly tilted ground	Slight tilt (typically <0.5°) relative to the original ground slope.		
Ground with slight regional tilt	Slight tilt (typically <0.3°) relative to the original ground slope.	Building slightly out of plumb. Ground shaking effects dominate life safety hazard to occupants.	No significant ground deformation hazard
No discernible deformation	As far as can be determined, the ground surface has not been deformed or tilted by fault-related movements.	Ground shaking the main source of damage and life safety hazard to occupants.	No ground deformation hazard
Younger land surfaces			
Young terrace, deformation unknown	The terrace appears to be younger than the most recent ground-surface fault deformation event.	Characteristics of adjacent older ground surfaces assumed to apply.	As per adjacent zone(s). Relative youth prevents reliable assessment of deformation
River bed	Active land surface feature.		

3.4 FAULT ZONE CHARACTERISATION

In this assessment, the Ashley Fault Zone as a whole is characterised as an approximately west-east striking contractional structure. The Ashley Fault and Ashley Fault (East) have a sense of upthrow to the north, while upthrow on the Loburn Fault is to the south. Trench investigations have shown that both the Ashley Fault and Loburn Fault are moderately to steeply dipping reverse faults, and the Ashley Fault (East) is inferred to be a reverse fault. The geometry of the surface trace of the Ashley Fault suggests that the fault has a component of right-lateral strike slip motion. It is interpreted here to have sub-equal components of reverse motion and right-lateral strike slip motion, and the Loburn Fault and Ashley Fault (East) are inferred to also have that sense of motion. The surface faults are considered to be „break-out" features from a fault or faults at depth whose movement has produced a broad anticlinal upfold, the extent of which is registered by the area of „slight regional tilt" shown in Figure 5.

A fault surface rupture history has been deduced from relationships between river terraces and the height of the Ashley Fault scarp (Appendix 1). The second-to-most-recent metre-scale surface rupture occurred during formation of Okuku Terrace 2, and an age of 16,000 ± 4,000 years is inferred for that terrace. This implies that the fault rupture occurred sometime between 12,000 and 20,000 years ago. The most recent surface rupture occurred sometime after the formation of Okuku Terrace 1, and radiocarbon dating indicates that the rupture occurred approximately 5,000 years ago. At face value this suggests a recurrence interval for surface rupture of the Ashley Fault of somewhere between 7,000 to 15,000 years. However, if one were to speculate that the ground surface offsets were the result of three rupture events, rather than the two ruptures that are the preferred interpretation of the available evidence, than the recurrence interval would be shorter. Therefore, there is a possibility that the recurrence interval could be as short as 5,000 years, which is the elapsed time since the most recent surface rupture. Also, it is important to note that the time of occurrence of the earlier surface rupture(s) is not well established. On the Ashley Fault there is reasonable basis for inferring that the two most recent surface ruptures each had single-event vertical components of offset typically between ~1 and ~2 m, but with considerable variations along the length of the fault („along-strike„), from minima of ~0.5 m to maxima of ~3 m. Notably, the size and locations of along-strike variation was somewhat different in each of those ruptures.

Towards the western end of the Loburn Fault, the most recent surface rupture had a vertical component of offset of ~0.5 m, and occurred during formation of Okuku Terrace 2 (estimated age of 16,000 ± 4,000 years). Although it occurred at approximately the same time as the second-to-most-recent rupture on the Ashley Fault, it is unclear whether or not they were simultaneous. Also, it is possible that subsequent surface rupture(s) have occurred on the Loburn Fault, but did not break the western sector of the surface trace. If the 0.5 m vertical component of offset is the typical single event displacement, it suggests that at locations where the fault scarp is several metres high (Figure 6), the scarp at those locations represents the cumulative product of several surface ruptures.

For maximum simplicity and conservatism, the surface rupture history deduced for the Ashley Fault is also assumed to apply to the Loburn Fault and Ashley Fault (East).

Figure 6 A telephoto view south from Hodgsons Road, about 0.5 km east of Round Hill Road, towards a ~5 m high scarp of the Loburn Fault, running left-right through the background of the scene. This location is approximately at the position of profile J (see Appendix 1, Figure A1-7; also see Figures 2 and 5 for location). On the upthrown side of the fault is a remnant of Okuku Terrace 4 while the foreground is mapped as a younger landform, „minor valley" (Figure 2). This topographic step is mapped as a „broad fault scarp" (Figure 5), which is likely a product of at least several surface rupture events, with the scarp having been progressively smoothed by erosion during its evolution. Despite its breadth (~60 m), it is likely that the locus of fault movement is concentrated on a relatively narrow zone somewhere on this step, probably in the mid to lower half of the slope. Photo: D.J.A. Barrell, May 2013.

4.0 HAZARD ASSESSMENT

4.1 FAULT GROUND DEFORMATION HAZARD

4.1.1 Fault avoidance zones

„Fault complexity" is a useful way of defining fault surface rupture ground deformation hazard (Table 2). Where fault-related deformation is distributed over a wide area, the amount of deformation at a specific locality within the distributed zone is less, compared with localities where the deformation is concentrated on a single well-defined sharp fault scarp. The relative fault rupture hazard is therefore less within a zone of distributed deformation than within a narrow, well defined zone. Following the approach used for the Kapiti Coast District (Kerr et al., 2003; Van Dissen & Heron 2003; Van Dissen et al., 2004), the Twizel area of the Mackenzie District (Barrell, 2010) and for the Greendale Fault, Selwyn District (Villamor et al., 2011, 2012), the categories of fault complexity used in this report are :

a. „Well-defined" deformation zones. These result from fault rupture (sudden physical displacement or deformation of the ground due to a fault breaking through to the ground surface and forming a fault scarp, or increasing the size of an existing scarp), along with flexing (sudden physical buckling or tilting of the ground, over a fairly narrow zone, probably including localised subsidiary ground rupture).

b. „Distributed" deformation zones. These result from significant flexing or tilting (sudden physical buckling or tilting of the ground over a fairly wide area, possibly including localised subsidiary ground rupture).

c. „Uncertain" deformation zones. These include areas where there is uncertainty about the presence or location of a fault or fold, uncertainty about nature of the deformation, such as whether it is faulting or folding, and areas where the deformation comprises a general tilting of the ground rather than breakage (faulting) or distinct bending (folding). We distinguish between „constrained" and „poorly constrained" sub-classes (Table 2).

In this report, fault scarps are classified as well-defined deformation because their boundaries are well expressed on the ground surface. The broad fault scarps are also classified as well-defined deformation, because we think it likely that their broadness is due to erosion or sediment deposition having smoothed the appearance of the scarp, rather than them having formed as a result of distributed deformation. We envisage that somewhere within each area mapped as broad fault scarp, there will be a zone of well-defined deformation, but its exact location is uncertain (see Figure 6). Monoclinal flexures are identified as distributed deformation (Table 2). The feature mapped as „broad fault escarpment" (Figure 5) is classified as „uncertain – constrained" deformation, because it is unclear whether this landform is the product of fault breakage, monoclinal folding, or some combination of both.

Areas of tilted ground associated with anticlines are mapped as „uncertain – unconstrained". Although a distinction is made in Figure 5 and Table 2 between slightly and slightly-moderately tilted ground, the slightly-moderately tilted ground is associated with older terraces, and we consider it likely that that these areas of slightly-moderately tilted ground have been produced by a number of slight tilting events. Therefore, no hazard distinction is drawn between slight or slightly-moderately tilted, and both are classified as „uncertain deformation – poorly constrained", following the concepts developed in Section 12 of Kerr

et al. (2003) and also explained by Van Dissen et al. (2004). Finally, in places where a fault scarp cannot be traced along-strike due to the presence of landforms that appear to be younger than the most recent surface deformation, a representative area of „uncertain deformation – poorly constrained" is mapped to indicate that the fault may extend in that direction, but its location is unknown.

Fault (surface rupture) hazard avoidance zonation in the MfE active fault guidelines (Kerr et al., 2003) involves a risk-based approach that takes account of the significance of buildings („Building Importance Categories" (BIC), Table 3), and surface-rupture recurrence interval (Table 4). A distinction is made between previously subdivided and/or developed sites, and undeveloped „greenfield" sites, and allow for different conditions to apply to these two types of sites (Table 4).

Table 3 Building Importance Categories and representative examples. From the MfE active fault guidelines (Kerr et al., 2003).

Building Importance Category	Description	Examples
1	Temporary structures with low hazard to life and other property	• Structures with a floor area of <30 m^2 • Farm buildings, fences • Towers in rural situations
2a	Timber-framed residential construction	• Timber framed single-story dwellings
2b	Normal structures and structures not in other categories	• Timber framed houses with area >300 m^2 • Houses outside the scope of NZS 3604 "Timber Framed Buildings" • Multi-occupancy residential, commercial, and industrial buildings accommodating <5000 people and <10,000 m^2 • Public assembly buildings, theatres and cinemas <1000 m^2 • Car parking buildings
3	Important structures that may contain people in crowds or contents of high value to the community or pose risks to people in crowds	• Emergency medical and other emergency facilities not designated as critical post disaster facilities • Airport terminals, principal railway stations, schools • Structures accommodating >5000 people • Public assembly buildings >1000 m^2 • Covered malls >10,000 m^2 • Museums and art galleries >1000 m^2 • Municipal buildings • Grandstands >10,000 people • Chemical storage facilities >500 m^2
4	**Critical structures** with special post disaster functions	• Major infrastructure facilities • Air traffic control installations • Designated civilian emergency centres, medical emergency facilities, emergency vehicle garages, fire and police stations

Table 4 Relationships between recurrence interval and Building Importance Category. From the MfE active fault guidelines (Kerr et al., 2003).

<table>
<tr><th rowspan="2">Recurrence interval class</th><th rowspan="2">Average recurrence interval of surface rupture</th><th colspan="2">Building Importance Category (BIC) limitations (allowable buildings)</th></tr>
<tr><th>Previously subdivided or developed sites</th><th>'Greenfield' sites</th></tr>
<tr><td>I</td><td>≤2000 years</td><td>BIC 1
temporary buildings only</td><td rowspan="2">BIC 1
temporary buildings only</td></tr>
<tr><td>II</td><td>>2000 years to ≤3500 years</td><td>BIC 1& 2a
temporary and residential timber-framed buildings only</td></tr>
<tr><td>III</td><td>>3500 years to ≤5000 years</td><td>BIC 1, 2a, & 2b
temporary, residential timber-framed and normal structures</td><td>BIC 1& 2a
temporary and residential timber-framed buildings only</td></tr>
<tr><td>IV</td><td>>5000 years to ≤10,000 years</td><td rowspan="2">BIC 1, 2a, 2b & 3
temporary, residential timber-framed, normal and important structures
(but not critical post-disaster facilities)</td><td>BIC 1, 2a, & 2b
temporary, residential timber-framed and normal structures</td></tr>
<tr><td>V</td><td>>10,000 years to ≤20,000 years</td><td>BIC 1, 2a, 2b & 3
temporary, residential timber-framed, normal and important structures
(but not critical post-disaster facilities)</td></tr>
<tr><td>VI</td><td>>20,000 years to ≤125,000 years</td><td colspan="2">BIC 1, 2a, 2b, 3 & 4
critical post-disaster facilities cannot be built across an active fault with a recurrence interval ≤20,000 years</td></tr>
<tr><td colspan="4">Note: Faults with average recurrence intervals >125,000 years are not considered active</td></tr>
</table>

Recurrence interval class, fault complexity and BIC are the three key parameters that, when brought together, enable a risk-based approach to be taken when making planning decisions about development of land on, or close to, active faults. Understanding the interrelationships between these parameters is important when developing consistent, risk-based policies and methods for guiding development of land that may be affected by surface rupture faulting.

The fault complexity classes translate directly into „fault avoidance zones" for different types of built structure, depending on the assessed recurrence interval for surface deformation. The fault avoidance zones based on fault complexity are shown in Figure 7. In places where the landforms are too young to show recognisable deformation, we have interpolated or extrapolated from places where the deformation is recognisable. These interpolations or extrapolations are identified as „extended" avoidance zones (Figure 7). In addition, in accordance with the principles of the guidelines, a 20 m wide buffer is suggested as an appropriate set-back from well-defined and distributed fault avoidance zones. These buffers are integral parts of each fault avoidance zone. The precision of mapping is not sufficient to warrant defining a set-back on the „uncertain" deformation areas.

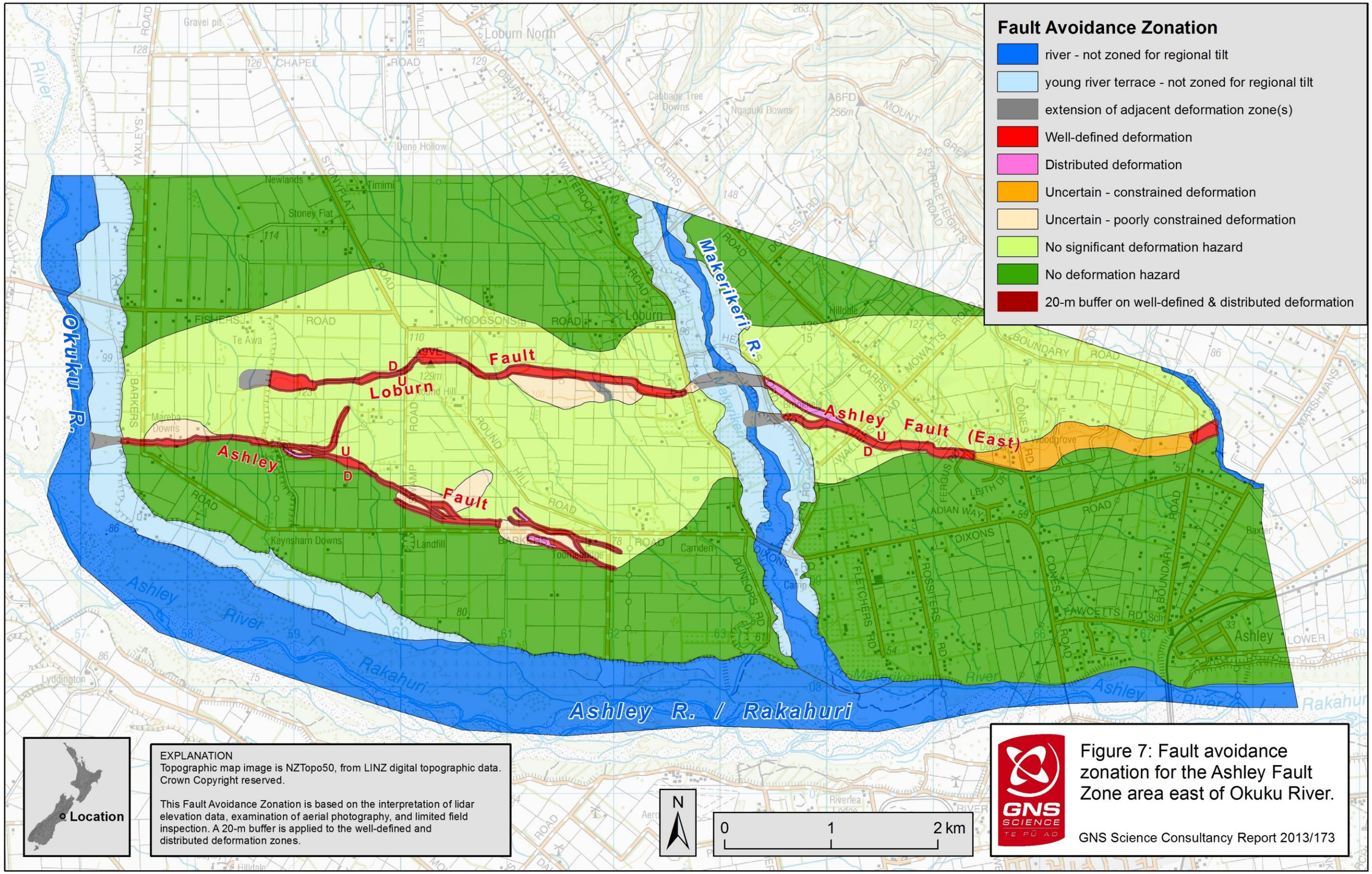

Figure 7 Fault avoidance zonation for the Ashley Fault Zone. Although the buffers are shown separately for illustrative purposes, they comprise an integral part of the fault avoidance zones.

4.1.2 Resource consent category

Determining an appropriate resource consent category for different combinations of recurrence interval, fault complexity and BIC, and development status, is a complex task. As the significance of what is at risk increases, the resource consent category becomes more restrictive, and the range of matters that a Council may wish to consider increases.

The recurrence interval for surface rupture on the Ashley Fault Zone is assessed as most likely being between 7000 and 15,000 years (Section 3.4 and Appendix 1). We are moderately confident that the Ashley Fault Zone has a recurrence interval of not less than Recurrence Interval (RI) Class IV (>5000 to ≤10,000 years). It is, however, not inconceivable that it is Class III (>3500 to ≤5000 years) or V (>10,000 to ≤20,000 years). We think that the most readily justifiable approach, given the available knowledge as well as the numerous uncertainties, is to adopt a RI Class IV assignation for the Ashley Fault Zone. Table 5a sets out proposed resource consent categories for the Ashley Fault Zone assuming RI Class IV. However, we think it appropriately conservative to also provide a scenario assuming an RI Class III (Table 5b), given that the most recent surface rupture of the Ashley Fault was ~5,000 years ago, the previous surface rupture has not directly constrained by dating, and the age estimate for that previous rupture is based on geomorphic inference.

4.1.3 Areas not subject to fault deformation hazard

Areas identified as „no deformation hazard" and „no significant deformation hazard" in Figure 7, are considered to be free from fault rupture or significant tectonic ground deformation hazards. From a fault deformation hazard avoidance perspective, these areas are considered suitable for the construction of any type of residential, commercial or industrial building that conforms to New Zealand building codes. The „no significant deformation hazard" category represents the area where there has been minor „regional" tilt of the ground over time. This would only be of relevance to certain types of major structures, such as large canals, wind turbine towers or power stations. Such structures would require a range of consents for reasons other than ground deformation hazards, and would warrant in-depth engineering assessments as well as specific evaluation of ground deformation hazards.

4.1.4 Development considerations

The information and evaluations presented in this report have led us to assign the Ashley Fault Zone to RI Class IV (Table 5a), while acknowledging a small possibility that it may be RI Class III (Table 5b). According to the Kerr et al. (2003) guidelines, taking the more likely scenario (given present data) of RI Class IV, this implies (Table 5a) that the construction of BIC 2a or 2b buildings within or across the Ashley Fault Zone could, from a risk perspective, be a permitted activity, in both previously-subdivided sites and greenfield developments. Critical structures (BIC 4) would be non-complying in all cases, and important structures (BIC 3) would be non-complying or discretionary for greenfield sites (Table 5a). There would be a case for assigning a controlled or discretionary status to BIC 2 structures in locations where the deformation is well defined, for example not having dwellings straddling a fault scarp. If assuming RI Class III (Table 5b), construction of BIC 2b buildings within or across the fault zone would be a non-complying to discretionary activity in greenfield developments, and important structures (BIC 3) would be non-complying or discretionary for both previously-subdivided and greenfield sites. These are all matters for the territorial authority to determine.

Nonetheless, the information presented in this report also provides property owners with the opportunity to make voluntary choices not to place high-value buildings or other important infrastructure across fault scarps.

Areas classified as „uncertain deformation" should be subjected to detailed site assessment should any major development be proposed, with emphasis on determining precise locations of faults, and the style of deformation. Examples of „major development" may include plan changes to allow intensification of housing density, or construction of buildings of BIC 3 or greater. In all cases, detailed site investigations may provide a technical basis for refining the extent or the classification of the hazard avoidance areas.

Table 5a Suggested resource consent categories in relation to fault complexity for the Ashley Fault Zone, assuming a RI Class of IV. Refer to Figure 7 for fault avoidance zonation (FAZ) in relation to well-defined and distributed deformation. The FAZ area, which includes set-back buffers, would apply to all categories except „permitted".

ASHLEY FAULT ZONE (based on fault Recurrence Interval Class IV, >5000 to ≤10,000 years)					
	Previously subdivided or developed sites				
Building Importance Category	**1**	**2a**	**2b**	**3**	**4**
Fault complexity	**Resource consent category**				
Well-defined and distributed	Permitted	Permitted*	Permitted*	Permitted*	Non-Complying
Uncertain – constrained	Permitted	Permitted	Permitted	Permitted	Non-Complying
Uncertain – poorly constrained	Permitted	Permitted	Permitted	Permitted	Non-Complying
	Greenfield sites				
Building Importance Category	**1**	**2a**	**2b**	**3**	**4**
Fault complexity	**Resource consent category**				
Well-defined and distributed	Permitted	Permitted*	Permitted*	*Non-Complying*	Non-Complying
Uncertain – constrained	Permitted	Permitted	Permitted	*Discretionary*	Non-Complying
Uncertain – poorly constrained	Permitted	Permitted	Permitted	*Discretionary*	Non-Complying
* Indicates that the resource consent category is permitted, but could be controlled or discretionary given that the fault location is well-defined. Italics: Italics indicate that the resource consent category could be more flexible. For example, where non-complying is indicated, discretionary may be considered more suitable by the Council, or vice versa.					

Table 5b Suggested resource consent categories in relation to fault complexity for the Ashley Fault Zone, assuming a RI Class of III. Refer to Figure 7 for fault avoidance zonation (FAZ) in relation to well-defined and distributed deformation. The FAZ area, which includes set-back buffers, would apply to all categories except „permitted".

ASHLEY FAULT ZONE (based on fault Recurrence Interval Class III, >3500 to ≤5000 years)					
	Previously subdivided or developed sites				
Building Importance Category	**1**	**2a**	**2b**	**3**	**4**
Fault complexity	**Resource consent category**				
Well-defined and distributed	Permitted	Permitted*	Permitted*	*Non-Complying*	Non-Complying
Uncertain – constrained	Permitted	Permitted	Permitted	*Discretionary*	Non-Complying
Uncertain – poorly constrained	Permitted	Permitted	Permitted	*Discretionary*	Non-Complying
	Greenfield sites				
Building Importance Category	**1**	**2a**	**2b**	**3**	**4**
Fault complexity	**Resource consent category**				
Well-defined and distributed	Permitted	Permitted*	*Non-Complying*	*Non-Complying*	Non-Complying
Uncertain – constrained	Permitted	Permitted	*Discretionary*	*Discretionary*	Non-Complying
Uncertain – poorly constrained	Permitted	Permitted	*Discretionary*	*Discretionary*	Non-Complying
* Indicates that the resource consent category is permitted, but could be controlled or discretionary at locations where the fault location is well-defined. Italics: Italics indicate that the resource consent category could be more flexible. For example, where non-complying is indicated, discretionary may be considered more suitable by the Council, or vice versa.					

4.1.5 Making use of the fault avoidance zonation

The following approach is recommended for putting the fault avoidance information presented in this report into practice. The GIS layer representing the fault avoidance zonation shown in Figure 7 should be overlaid on cadastral map information in order to identify which land parcels coincide with fault avoidance zones. For any such land parcel, a Land Information Memorandum (LIM) and Property Information Memorandum (PIM) should include information that a fault avoidance zone or zones have been mapped on the land, and the types of zone (whether well-defined, distributed or uncertain) should be stated. A map showing the zones on the land parcel could be included. Additional information in relation to development constraints (if any) could be included, although we reiterate that it a matter for the territorial authority to decide on what those constraints may be, particularly in regard to construction of dwellings.

In the event of concerns about the safety of a proposed development in relation to fault rupture, there are avenues for further inquiry, such as determining more accurately the recurrence interval of the fault, or defining the location the fault more exactly, which may allow a reduction in the extent of the area that should be avoided. An example of this would be a broad fault scarp, where determining the exact location of fault rupture zones could provide a basis for reducing the size of the avoidance zone.

Finally, because recurrence interval is a key criterion for assessing risk, further detailed investigation to obtain more robust estimates of recurrence interval of the Ashley Fault strand would provide better constraint on the risk of future fault rupture, and attendant implications for land-use, planning and hazard mitigation. Determining precise ages for Okuku Terraces 2 and 3 would help to tie down when the second-to-last rupture event occurred on the Ashley Fault, and would clarify whether the recurrence interval is RI Class IV or III.

4.2 OTHER HAZARDS

4.2.1 Permanent elevation change hazard

Permanent, differential, changes in ground elevations may occur in the future across the area mapped as „ground with slight regional tilt" in Figure 5, and classified as „no significant ground deformation hazard" in Figure 7. Although further slight regional tilting does not pose a significant hazard to most types of buildings, it could be potentially hazardous to precisely engineered structures, such as gravity drainage systems. We do not know, however, whether the development of this tilt proceeds in association with large earthquakes, or proceeds more steadily over time.

4.2.2 Earthquake shaking hazard

In the event of a future ground surface-rupturing earthquake on the Ashley Fault Zone, all areas in the general vicinity of the fault (i.e., Rangiora, and other nearby towns or settlements), will be subjected to severe ground shaking. Severe earthquake ground shaking is a common potential hazard in many parts of New Zealand. The primary mitigation is to ensure that all constructions conform to the relevant New Zealand building codes. More general mitigation measures include locating buildings on relatively flat ground with good foundation conditions, and the securing of water tanks, heavy furniture, etc.

4.2.3 Liquefaction

Ground liquefaction is a potential hazard in areas underlain by wet sandy deposits (Brackley 2012). However, there are likely to be few if any such areas in the general vicinity of the Ashley Fault Zone, because the unconsolidated deposits are mainly gravelly river sediments. Some cracking (lateral spreading) is likely close to the margins of incised stream or river channels.

4.2.4 Slope instability hazards

Close to active faults, steep slopes such as hill sides or river terrace faces are potentially subject to slope instability (landslip) hazards, especially in the event of a major earthquake on the fault. It is prudent to avoid situating buildings either directly on, or at the crest or foot, of steep slopes. A set-back distance equal to the height of the slope is a useful rule-of-thumb for defining a slope instability hazard avoidance zone at the top and base of the slope.

5.0 CONCLUSIONS

1. The ground-surface expression of the Ashley Fault Zone east of Okuku River comprises a broad upward bulge (anticlinal fold) aligned roughly east-west, accompanied by three overlapping fault strands, each at least ~4 to 6 km long. Two of these strands, the Ashley Fault and Ashley Fault (East), are upthrown to the north, while the Loburn Fault is upthrown to the south. These strands are interpreted to be localised surface breakouts from deeper-seated fault(s) underlying the anticline. Whether or not surface ruptures occur simultaneously on all three fault strands has not been determined.

2. The fault strands are characterised as having a composite dip-slip/strike-slip sense of motion, with approximately equal components of reverse and right-lateral (dextral) throw. The single-event vertical component of surface displacement is estimated to be typically between ~1 and ~2 m, but there is some localised along-strike variation, from ~0.5 m to ~3 m. The western end of the Loburn Fault strand did not experience surface rupture during the most recent surface rupture of the Ashley Fault strand.

3. The Ashley Fault Zone is assessed as having an average recurrence interval for surface-rupture earthquakes of between 7000 and 15,000 years. On this basis it is assigned to Recurrence Interval Class IV (>5000 to ≤10,000 years) according to MfE active fault guidelines, while acknowledging a possibility that it may be Recurrence Interval Class III.

4. A large, ground-surface rupturing earthquake on the Ashley Fault Zone would result in localised severe ground deformation at the fault scarps, lesser amounts of slight tilting deformation in the general vicinity and severe earthquake shaking in the wider region.

5. Using the approach set out in the MfE active fault guidelines, the risks of future ground-surface fault rupture have been addressed by mapping the fault zone and classifying it into areas of well-defined fault deformation, distributed deformation and uncertain ground deformation.

6. A 20 m set-back has been applied to well-defined and distributed deformation areas to define a fault avoidance buffer for those areas likely to be subject to the most concentrated deformation in a future surface-rupture event. The precision of mapping is not sufficient to warrant defining a set-back on the „uncertain" deformation areas.

7. Based on the most likely Recurrence Interval Class (IV), the MfE guidelines indicate that Building Importance Category (BIC) 4 buildings should be sited so as to avoid the fault zone, as should BIC 3 buildings in any greenfield development. BIC 2 buildings are allowable within any part of the fault zone, although these are all matters for the territorial authority to decide. If the Recurrence Interval Class is III, the MfE guidelines indicate that BIC 2b buildings in greenfield developments should avoid the fault zone, as should BIC 3 buildings. In any case, land owners and developers could choose to avoid placing buildings or other valuable infrastructure across well-defined or distributed deformation zones.

8. Future geological investigations may allow the extents or the classifications of hazard avoidance areas to be refined. Further investigations targeting the history of movement of the Ashley Fault Zone may be able to confirm when surface rupture(s) last occurred, and may yield more precise estimates of the recurrence interval. Such information would afford better constraint on the risk of future fault rupture, and aid land-use planning and hazard mitigation.

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APPENDICES

APPENDIX 1: DETAILED ASSESSMENT OF GEOLOGICAL FEATURES IN THE LOBURN AREA RELEVANT TO THE EVALUATION OF ACTIVE FAULTING

A1.1 INTRODUCTION

This Appendix contains a detailed review and evaluation of river terrace and fault scarp landforms of the Ashley Fault Zone assessment area. It provides detailed documentation that provides a foundation for the geological and geomorphological interpretations in the body of the report. It is of a more technical nature than the main report.

A1.2 GEOLOGICAL SETTING

A general outline of the geological setting of the Waimakariri District, including the Loburn area, is provided by Barrell & Begg (2013). By way of overview, the Loburn area lies near the northeastern edge of the Canterbury Plains, within a broad zone of geologically young faulting and folding known as the Porters Pass to Amberley Fault Zone (Cowan et al., 1996). The rates of tectonic movement have been sufficient, over the past million years or so, to have uplifted the ground along the lines of upward-thrusted faults or upward-buckled folds (anticlines). Rivers and streams have forged paths around or across the rising land, but hills or ridges of the uplifted ground survive. Of the geological formations of the Canterbury region (see Figure 1 of the main report), cover rocks form the core of some of the uplift zones, except in places where the uplift has been sufficient to expose the underlying basement rock.

The youngest deposits are poorly consolidated shallow sediments, which include gravels, sands and silts laid down by rivers and streams (see Figure 1 of the main report). The land surfaces developed on those deposits are river plains and alluvial fans. The river plains of Canterbury typically have a broad fan shape, in other words the river plain spreads out downstream rather like an open fan, or a segment of a cone cut lengthwise. Alluvial fans form where smaller streams emerge from the hills onto the plain or valley of a larger river. Alluvial fans are steeper than river plains and have a more strongly expressed fan shape. In both instances, where the river or stream has cut a valley into its plain or fan, one of more terrace levels may have formed during the valley incision. River terraces or fan terraces provide useful age markers in a landscape. At any particular location, the highest terrace is older than the next lowest terrace, and each successively lower terrace is younger than the one before. Although in most cases the exact ages of terraces are not known, the sequence of relative ages is valuable in its own right, when it comes to estimating the degree of activity of faults or folds.

As explained in more detail by Barrell & Begg (2013), episodes of cool conditions (glaciations, or „ice ages"), separated by periods of warmer climate („interglaciations"), such as exists today, have been an important influence on the deposition of river and stream sediments. Cooler temperatures during glaciations pushed the treeline much lower than it is today, and erosion rates increased in the hills and mountains. The excess sediment tended to choke the rivers and streams, and accumulated within river and stream valleys, and on the Canterbury Plains. Much lower sea level during glaciations meant that in the Waimakariri-Ashley sectors of the Canterbury Plains, the ice-age coast lay as much as 60 km east

from where it is today, and the rivers occupied wide-ranging, ever-changing, courses across the plains. Riverbed silt picked up by the wind accumulated on abandoned river terraces and hill slopes, forming deposits of yellow-brown loess.

The most recent episode of ice age climate, commonly known as the „Last Glacial Maximum" (LGM), occurred between about 28,000 and about 18,000 years ago. The LGM ended quite abruptly, after which atmospheric temperatures rose rapidly. Studies of glacier moraines in the Southern Alps (Kaplan et al., 2013; Putnam et al., 2013) indicate that atmospheric temperature was about 6° cooler than today around 18,000 years ago, but by 15,600 years ago had warmed to about 2° cooler than today, and by about 12,000 years ago was only about 1° cooler than late 19th century temperatures (i.e., prior to the onset of global warming attributed to greenhouse gases). Consequences of the warming post-glacial climate after 18,000 years ago included glacier recession in the Southern Alps, the spread of woody vegetation to higher altitudes and the stabilisation of hill slopes. The improved slope stability and reduced sediment load caused the rivers to gradually cut down into the plains, leaving flights of terraces.

A1.3 RIVER LANDFORMS

A1.3.1 Introduction

In this assessment, considerable emphasis is placed on the mapping and interpretation of river terrace landforms. River terraces are particularly useful for assessing active fault ground deformation hazards. This is because the amounts of offset or buckling of river terraces of various ages provides a geological record of prehistoric fault movements, and indicates the level of the activity of a fault. Of particular importance is information on the amount of offset that typically occurs during a ground-surface rupture event (single-event displacement, or SED), and on the recurrence interval, which is the amount of time that typically elapses between surface rupture events. The recurrence interval is the main measure of fault activity used to assess risks to buildings and infrastructure. Determining the recurrence interval depends on having reliable estimates of the ages of offset geological deposits or landforms. Their ages can be measured by laboratory methods such as radiocarbon dating. However, this requires expensive investigations, usually involving the excavation of trenches, to obtain the samples for dating, in addition to the cost of the laboratory work For that reason, dating is rarely done in the preparation of geological maps. Instead a geologist usually relies on various lines of indirect evidence for estimating river terrace ages.

The first line of evidence is the arrangement of the river terraces. Topographic relations between different river terraces indicate their ages relative to one another. Older terraces stand at higher levels than younger terraces. In general, the older the terrace, the more subdued and irregular is its surface, thanks to the long-term effects of erosion and gullying by minor streams, and the accumulation of loess. Another useful line of evidence is whether or not the gravels forming a river terrace are capped by wind-blown loess. The silt that forms loess is regarded as being generated most prolifically during episodes of ice-age climate. This means that river terraces that carry a cap of loess can be interpreted, with reasonable confidence, as having formed prior to the most recent ice-age episode. In contrast, river terraces formed during and after the most recent ice age commonly have stony surfaces. There are, of course, always exceptions, such as where floodwaters have overtopped river terraces and left sheets of river silt. The subdivision by age of the stony terraces is more difficult, and is usually based on the maturity of the soils developed on the terraces.

Usual geological practice is to assume that older terraces relate to earlier episodes of ice-age climate, and that during episodes of warmer climate, the rivers cut down their beds, stranding the older terraces. Areas subject to tectonic uplift commonly have flights of progressively older terraces, carried over time to higher levels as the land has risen. Overall, the estimation of river terraces ages relies heavily upon the opinion of the geologist, and the way in which he/she has weighed up the various lines of indirect evidence. However, even informed guesses of the ages of fault-deformed river terraces are helpful.

A1.3.2 Previous mapping

The terraces and fans in the general vicinity of Loburn have been mapped geologically at differing scales by different workers (Table A1-1). On regional geological maps presented at a scale of 1:250,000 (Gregg 1964, Forsyth et al., 2008), where 1 cm on the map represents 2.5 km on the ground, many details are omitted in order to provide a clear general picture of the geology of a wide area. The Forsyth et al. (2008) map represents an updated and revised edition of Gregg"s (1964) map. A more detailed 1:50,000-scale geological map (1 cm on the map represents 500 m on the ground) by Brown (1973) was the first geological map to identify and depict the Ashley Fault. A detailed study of the Ashley Fault by Sisson et al. (2001) included a 1:17,500-scale geological and geomorphological map (1 cm on the map represents 175 m on the ground). Finally, as part of the present report, we have drawn our own interpretation of the terrace landforms in the vicinity of the Ashley Fault Zone using a lidar dataset not available to the previous workers. The landform map (Figure A1-1; also presented in slightly different form in Figure 2 of the main report), compiled at approximately 1:10,000 scale and presented at 1:35,000 scale, emphasises the sequence of river terraces formed by the Okuku, Makerikeri and Ashley rivers.

Each of the maps described above shows a somewhat different interpretation of the river terraces of the Loburn area, as summarised in Table A1-1. Sisson et al."s (2001) map (Map 1 in Appendix 2) is the most detailed one published so far, and includes invaluable on-the-ground surveying of the Ashley and Loburn fault scarps. For the most part, we agree with the main elements of their mapping of the river terraces. The naming of channels by Sisson et al. (2001) is, however, somewhat unclear. Conceptually, their channels denote areas where the river(s) flowed in former times, but their „Loburn 1 Channel", for example, is today an area of high ground, whereas intuitively a channel lies lower than adjacent areas. Instead, this report differentiates the terrace sequence according to the river that formed a particular terrace, as set out in Table A1-1 and Section A1.3.4. In addition, three channel features are delineated, the Barkers Road channel, the Fishers Road channel (Loburn 3 channel of Sisson et al., 2001), and the Swamp Road valley (Loburn 2 channel of Sisson et al., 2001) (Figure A1-1).

D. Barrell was one of the compilers of the Forsyth et al. (2008) map, and during preparation of that map, examined the various lines of indirect evidence for river terraces ages in the Okuku/Ashley sector of the Canterbury Plains, and concluded that the Loburn 2 and Loburn 3 terraces are most likely older than was indicated by Sisson et al. (2001). Accordingly, Forsyth et al. (2008) mapped the Sisson et al. (2001) Burnham terraces, together with their Loburn 2 and 3 channels, as undifferentiated „Last Glacial Maximum", equating to a span of time between about 28,000 and 12,000 years ago (see Table A1-1 and Figure 1 of main report). Farther to the east, Forsyth et al. (2008) suspected that the broad terraces of the Makerikeri River are older than the stony terraces nearer the Okuku River, and so mapped those Makerikeri terraces as undifferentiated „Late Quaternary", equating to a much wider span of time between about 125,000 years ago and the present day. One reason for that interpretation was that soil maps (Kear et al., 1967) indicate a cover of at least 1 m of silt on

the Makerikeri terraces. Although the soil maps imply that the silt is loess, Forsyth et al. (2008) thought it likely that the silt, at least in part, is a floodwater deposit of minor streams draining off the high terrace to the east, those streams having constructed an apron of alluvial fans near the foot of the high terrace (Figure A1-1). The wide age range assigned by Forsyth et al. (2008) highlights that the Makerikeri terraces may not necessarily be as old as would be indicated if the silt were purely loess.

There are two isolated hills in the investigation area, Round Hill, and an unnamed hill that we refer to informally as „The Oaks" hill after a nearby farm (Figure A1-1). On the geological maps of Gregg (1964) and Sisson et al. (2001; see Appendix 2 – their Map 1), both hills were shown as being composed of Kowai Formation. However, Forsyth et al. (2008) chose to map these hills as being underlain by unconsolidated river deposits of middle Quaternary age (older than about 130,000 years – see Table A1-1 and Figure 1 of the main report), because the hills resemble eroded remnants of buckled river terraces. Whichever interpretation is more correct has no particular bearing on the assessment of hazards related to the Ashley Fault Zone.

Table A1-1 Mapping classification of Quaternary-age deposits and landforms in the Loburn area.

<table>
<tr><th>‘Hurunui’ geological map (Gregg 1964)</th><th>Ashley/Loburn Fault study (Sisson et al., 2001; Map 1 in Appendix 2)</th><th>‘Christchurch’ geological map (Forsyth et al., 2008)</th><th>This report, Figure 1: geological setting map</th><th>This report, Figure 2 and Figure A1-1: landform map</th></tr>
<tr><td>Shingle river beds</td><td>River Gravels (currently active)</td><td>Active floodplain („Q1a" stippled)</td><td>river bed</td><td>rivers</td></tr>
<tr><td>Holocene river gravels („f")</td><td>River Gravels (stabilised and farmed)</td><td>Holocene river alluvium („Q1a")</td><td>very young river terrace deposits</td><td>low terraces</td></tr>
<tr><td>Springston Formation („sp")</td><td>Springston Formation (in Loburn 3 Channel)</td><td rowspan="2">„Last Glacial Maximum" river alluvium („Q2a")</td><td rowspan="2">young river terrace deposits</td><td>Okuku Tce 1</td></tr>
<tr><td rowspan="3">Burnham Formation („bu")</td><td>Loburn 2 Channel Deposits</td><td>Okuku Tce 2, Makerikeri Tce 1</td></tr>
<tr><td rowspan="2">Burnham Formation</td><td>Okuku Tce 3</td></tr>
<tr><td>undifferentiated „late Quaternary" river alluvium („JQa") and „late Quaternary" fan alluvium („JQa" stippled)</td><td>older river terrace deposits, older alluvial fan deposits</td><td>Makerikeri Tce 2 (including alluvial fans)</td></tr>
<tr><td>Woodlands Formation („wo")</td><td>Woodlands Formation (comprising Loburn 1 Channel)</td><td rowspan="2">undifferentiated „middle Quaternary" river alluvium („mQa") and „middle Quaternary" fan alluvium („mQa" stippled)</td><td rowspan="2">very old river terrace deposits, very old alluvial fan deposits</td><td>Okuku Tce 4 & 5, Makerikeri Tce 3</td></tr>
<tr><td>Hororata Formation („ho")</td><td>[outside Map 1 area]</td><td>high terrace</td></tr>
</table>

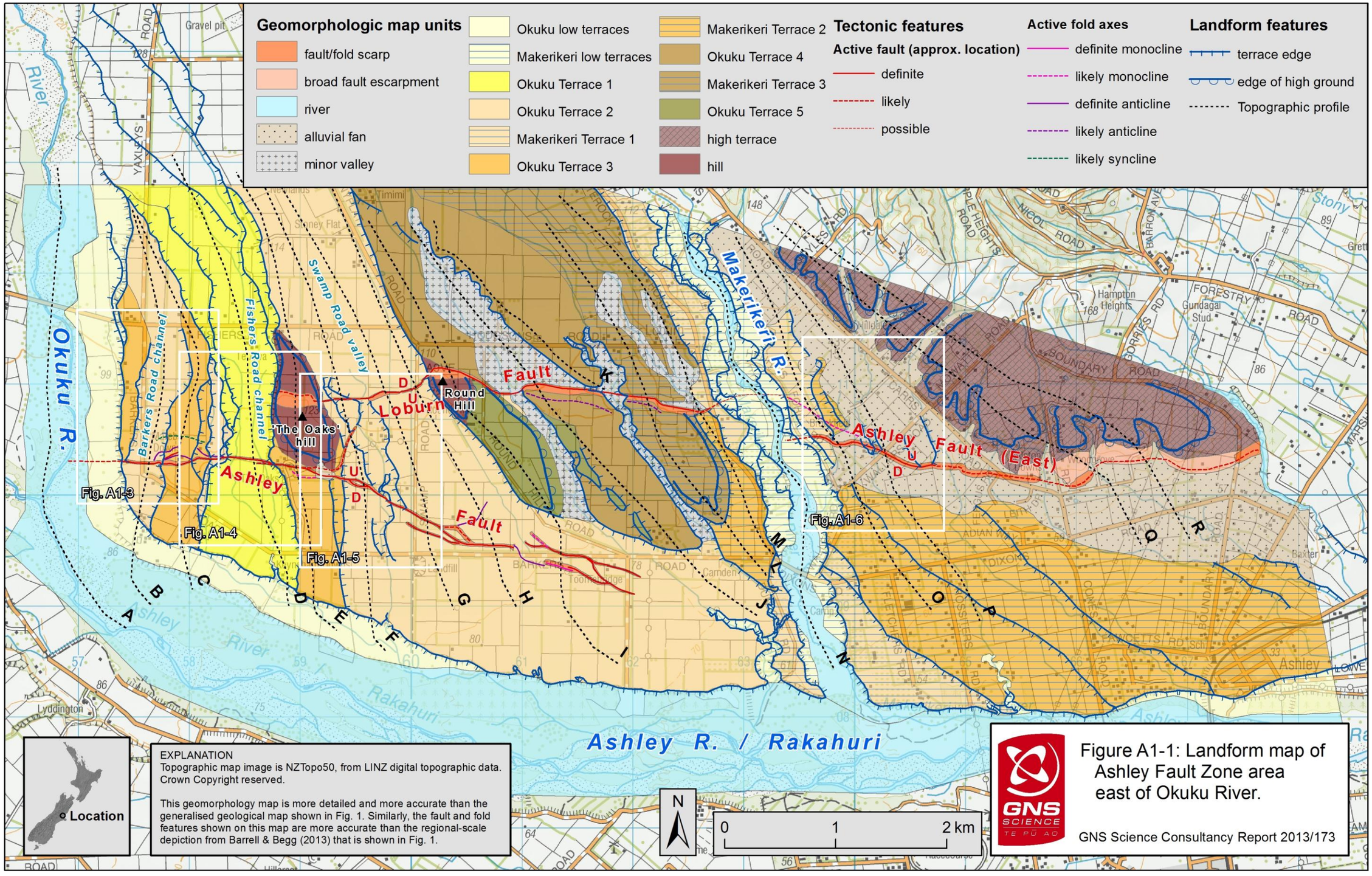

Figure A1-1 Landform map of the Ashley Fault Zone area, east of Okuku River. This map is presented in slightly different form in Figure 2 of the main report.

The ages that Sisson et al. (2001) assigned to their mapped terrace sequence are generally compatible with the regional-scale soil maps of the Canterbury Plains (Kear et al., 1967; scale of 1:126,720, equating to one inch on the map representing 2 miles on the ground). The Kear et al. (1967) maps show relatively young „Eyre" soils on the terraces identified by Sisson et al. (2001) as Loburn 2 and Loburn 3. However, Landcare Research, as part of their online „S-map" national soils database (see reference list), have recently revised the soil mapping of this sector of the Canterbury Plains. The soils on the stony terraces of the Okuku River, corresponding to Sisson et al."s (2001) Loburn 3, Loburn 2 and (in part) Burnham terraces, Forsyth et al."s (2008) „Q2a" (rendered as „young river terrace deposits" in Figure 1; main report), and the Okuku 1–3 terraces (Figure A1-1), are now classified in S-map as having predominantly Darnley and Pahau soils, of the „Argillic Pallic" New Zealand soil group. Those soils are generally regarded as characteristic of river terraces at least as old the „Last Glacial Maximum". This is discussed further in Section A1.3.4.

A1.3.3 River behaviour

The courses of rivers on the Canterbury Plains have changed over time, as each river occupied different sectors of its plain. One particularly important change in the Loburn area is that the Grey River formerly flowed into the Makerikeri valley via a now-abandoned channel mapped as „older river terrace" in Figure 1 of the main report (see the series of schematic block diagrams in Figure A1-2). The Grey River drains a large hill to mountain catchment between Mt Karetu and Mt Grey, whereas the modern Makerikeri River drains a small catchment in low hills north of Loburn (see Figure 1; main report). Following the Grey River"s capture by the Okuku River, the input of water and sediment to the Makerikeri valley near Loburn would have been much reduced, and we think it likely since that time, the Makerikeri River has cut a narrow channel, forming the Makerikeri Terrace 1, and low terraces, whereas the Okuku River, enhanced by the water and sediment of the Grey River, maintained a wide-ranging course over its plains, forming Okuku Terrace 2 (Figure A1-2, panel B).

An important influence on the terrace sequence is past interaction between the east-flowing Ashley River and the south-flowing Okuku and Makerikeri rivers (Figure 1; main report). It is likely that the architecture of the terrace sequence reflects, at least to some degree, the behaviour of the Ashley River. The plains of the Ashley River also extend down the Cust River valley (young river terrace in Figure 1; main report), and at times in the past, the main stream of the Ashley would have flowed down that valley. At other times, the Ashley River would have flowed down its present course. When the Ashley flowed down the Cust valley, the Okuku and Makerikeri rivers, deprived of the power of the Ashley River that normally helps distribute their gravel coastwards, would have constructed fans of gravel out into the area where the Ashley River normally flows (Figure A1-2, panel A). When the Ashley main stream returned to near its present course, it would have eroded the lower reaches of the fans, causing the Okuku and Makerikeri rivers to cut channels in the lower reaches of their fans (Figure A1-2, panel B).

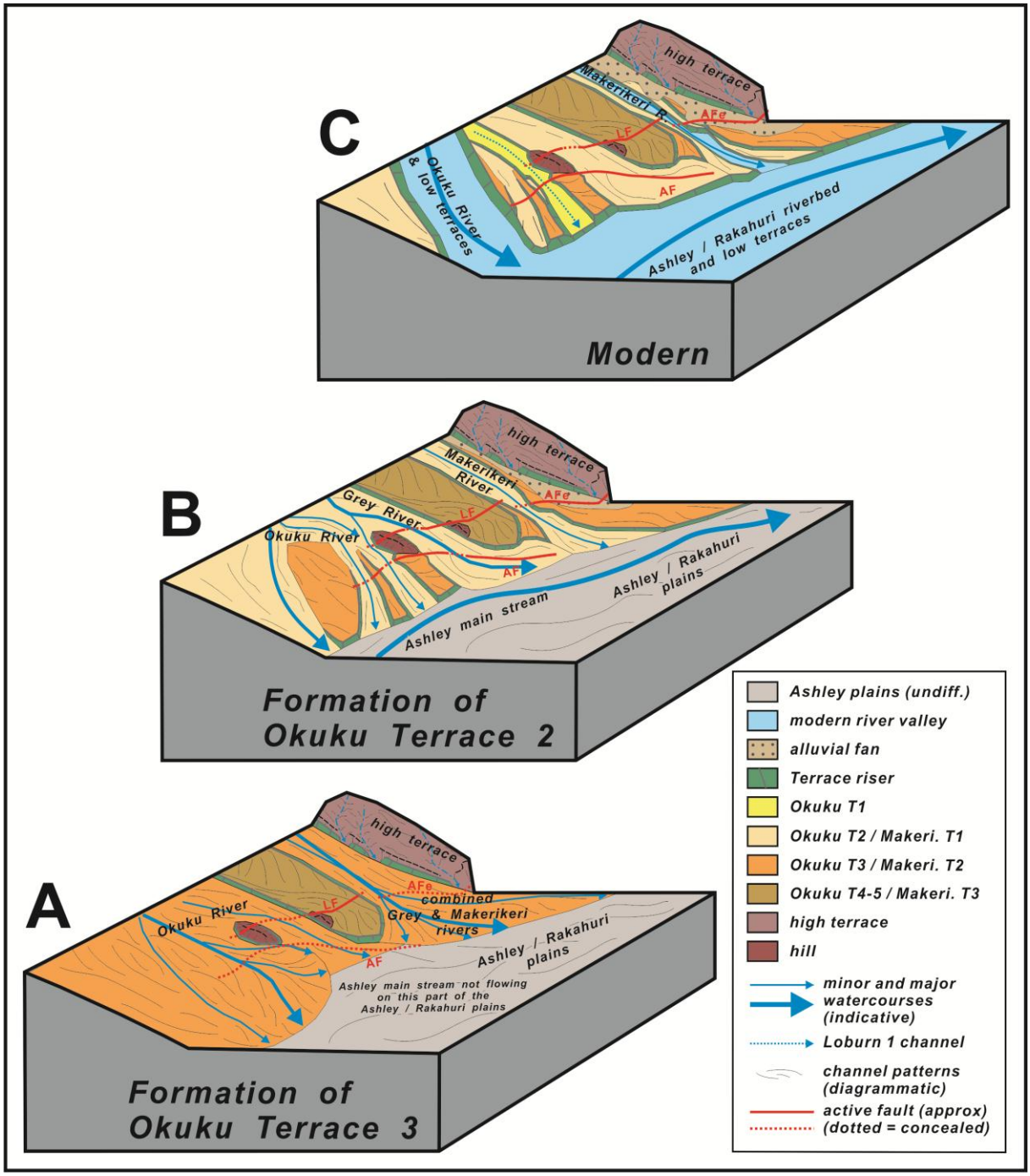

Figure A1-2 Conceptual diagrams showing an interpretation of the evolution of the Ashley and Okuku river plains in the vicinity of the Ashley Fault Zone (viewed looking northeast). During formation of Okuku Terrace 3 (panel A), the Grey and Makerikeri rivers were joined, and together with the Okuku River, built fans of gravel out onto the Ashley/Rakahuri River plains. Return of the Ashley main stream (panel B) eroded the toes of the fans, and Okuku Terrace 2 was formed, by which time the Grey River had formed a new path closer to the Okuku River. Okuku Terrace 1, (panel C) was formed by the combined Okuku and Grey rivers. Since then, the Okuku and Makerikeri rivers have cut more deeply into their plains, and the Ashley main stream has continued to wash the gravel from those rivers downstream, preventing the build-up of gravel fans.

The effect on rivers of climate-induced change is shown by the modern rivers of the Canterbury Plains. Since the end of the last glaciation, most rivers have cut terraced valleys below the general level of the plains. These valleys increase in depth upstream, highlighting that the river gradients were steeper when the rivers flowed on the surface of the plains than they are today. For example, the floor of the modern Okuku River valley at its confluence with the Ashley River is 8 m below the general level of the plains, but the valley deepens

progressively upstream. Near Whiterock, 10 km upstream of the Ashley confluence, the Okuku valley floor lies 35 m below the level of the plains. The post-glacial river incision is thought to be due to warmer climate, which in turn encouraged the spread of forest to higher elevations in the catchments than was the case during the last glaciation. Better vegetation resulted in less erosion, and therefore less sediment generation, in the catchments. The effects of decreased sediment load would have been registered first in the upper reaches of each river, causing the river to start cutting down into its bed. However, the sediment contributed by bed erosion would have been delivered to the middle and lower reaches of the river system, lessening the impact of reduced sediment input from the catchment. The onset of bed erosion would have progressively migrated downstream as the river systems tried to equilibrate with the warmer climate and reduced sediment supply. Therefore, it is likely that there was some delay between the onset of climatic warming, and the appearance of its effects in downstream reaches of a river system. The delay would have been influenced by the individual characteristics of each river system, but could conceivably have been of the order of several hundreds of years to several thousands of years.

These considerations provide a conceptual basis for distinguishing river terraces that were produced by short-term changes in the courses of nearby rivers, from those terraces related to longer-term climate changes. In the assessment area, terraces on the Okuku River plains resulting from trimming of the toe of the Okuku plains by the Ashley River are likely to have relatively steep gradients, and the risers at their margins will steadily decrease in height upstream. Conversely, terraces related to the onset of post-glacial incision are likely to have relatively gentle gradients, and the risers at their margins are likely to maintain height, or increase in height, upstream. This provides a way of identifying terraces that were formed as a result of post-glacial incision after the end of the last glaciation, from terraces formed prior to that, as a result of river course changes. The age of climate-related terraces can be estimated from regional and global knowledge of past climate changes.

A1.3.4 River terrace age estimates

In this section, the relative age relationships between the terraces are examined, followed by an evaluation of the various lines of evidence that can be used to assign age ranges to landforms in the assessment area, starting with the younger parts of the terrace sequence. The most useful information comes from the Okuku river terraces. The estimates and logical considerations from that area are extrapolated to other terraces and landforms of the assessment area.

The surface gradients of the few surviving remnants of Okuku Terrace 3 indicate that the gravels forming Okuku Terrace 3 were emplaced in a fan-building event (Figure A1-2, panel A). Cross-cutting relationships demonstrate that Okuku Terrace 2 is younger than Okuku Terrace 3. The Barkers Road channel is occupied by a remnant of Okuku Terrace 2. The risers on either side of the channel die out upstream, indicating that the Barkers Road channel formed in response to trimming of the toe of Okuku plains by the Ashley River (Figure A1-2, panel B). If the Barkers Road channel had been formed during post-glacial incision of the Okuku River, the risers should increase in height upstream, rather than dying out in that direction. Therefore, Okuku Terrace 2 in the Barkers Road channel is interpreted to be older than the onset of post-glacial incision of the Okuku plains. In contrast, the Fishers Road channel is incised all the way upstream to where it is cut out by the modern Okuku valley. Therefore, the Fishers Road channel, and the Okuku Terrace 1 which floors the channel, is interpreted to have formed during the early stages of post-glacial downcutting, prior to the Okuku River becoming established in its present location (Figure A1-2, panel C).

This defines the relative-age sequence of those terraces, and also indicates that only Okuku Terrace 1 has formed since the onset of post-glacial river incision into the Okuku plains. This means that some well-constrained inferences can be made about the age of Okuku Terrace 1. Furthermore, the only direct dating in the assessment area is from a trench across the Ashley Fault on Okuku Terrace 1 in the Fishers Road channel (Sisson et al., 2001; see Figure A1-4; Trench 1). A radiocarbon date of 4805 ± 505 calendar yrs BP, from the base of a 2 m thick deposit of peat overlying the river terrace gravels represent a minimum age for the underlying river gravels, and is considered to closely approximate the time of the most recent rupture of the Ashley Fault. This is described and discussed in more detail in Section A1.4. This ~5,000 year age estimate also affords an approximate maximum age for river terrace surfaces that lie across the line of the Ashley Fault, but which have not been offset.

There are two considerations from which to infer an age for Okuku Terrace 1. First is the geomorphic evidence that the terrace formed after the onset of post-glacial river incision. The end of the Last Glacial Maximum commenced at ~18,000 cal. yrs BP, and climate warmed progressively over the next ~6,000 years, attaining interglacial conditions by ~12,000 cal. yrs BP (e.g., Barrell et al., 2013). Okuku Terrace 1 is unlikely to be older than 18,000 years, because post-glacial incision would not have begun until after the end of the Last Glacial Maximum. There is no easy way to estimate how long it took for the post-glacial reduction in river sediment load to have migrated downstream in the Okuku catchment, but some indication can be taken from the degree of soil development on Okuku Terrace 1, and adjacent older terraces, notably the presence of mature Darnley and Pahau soils. These soils are thought to be characteristic of terraces dating from the Last Glacial Maximum, but specific ages, and whether those soil types may span a range of ages is uncertain. To be conservative, one could speculate that the terraces on which they occur are no younger than the attainment of interglacial conditions, say 10,000 to 12,000 years ago. From these considerations, an age of somewhere between 18,000 and 10,000 cal. yrs BP is inferred for Okuku Terrace 1, which can be expressed as 14,000 ± 4,000 cal. yrs BP. This is simply an indirect estimate, and doubtless it could be successfully tested by further geological investigation and dating. But for the purpose of this assessment, it provides a starting point from which to estimate the ages of nearby older terraces (Table 2).

Okuku Terrace 2a predates the post-glacial incision, and is cut by Okuku Terrace 1, and is therefore older than Okuku Terrace 1. Allowing for the possibility that post-glacial incision may have taken several thousand years to reaches the downstream part of the Okuku Plains, an indicative age of as 16,000 ± 4,000 cal. yrs BP is assigned. The same age range is assigned to Okuku Terrace 2c-b and Makerikeri Terrace 1, on the grounds that there is no reason to think that they are significantly different in age from Okuku Terrace 2a. As Okuku Terrace 3 is associated with a fan-building event, it is assigned the age range of the Last Glacial Maximum (23,000 ± 5,000 cal. yrs BP). Makerikeri Terrace 2 is also assigned to the LGM, except that a younger bound age of 12,000 cal. yrs BP is applied in order to account for the onlapping alluvial fans. Okuku Terrace 4 and Makerikeri Terrace 3 are loess covered and have been substantially dissected by erosion, and so are judged to be significantly older than the terraces described above. They are assigned to the previous glaciation (160,000 ± 30,000 cal. yrs BP). Based on height and dissection, the hill landform is inferred to be about twice as old as Okuku Terrace 4, and the high terrace is inferred to be half as old again as the hill landform. Clearly, all of these age estimates are just generalised inferences based on geomorphology. If it were important to define the ages to a better level of confidence, some geological dating would need to be applied.

Table A1-2 Age estimates for river terraces in the Loburn area. See Section A1.5 for discussion of estimates of the timing of fault rupture events included in this table.

Terrace (Figures A1-1 and A1-3 to A1-6)	Key observations	Estimated age (cal. yrs BP)	Comments
Okuku low terraces (eastern bank)	No fault scarp; terrace is younger than the most recent rupture of the Ashley Fault	<4,300	Terrace is ~1 m above modern river, 6-8 m below Okuku Tce 3
Makerikeri low terraces	No scarp recognised on projections of Loburn Fault or Ashley Fault (East); younger than most recent rupture(s)	Younger than Makerikeri Tce 1	No discrete age estimate possible
Okuku Tce 1	Cut by a rupture on Ashley Fault, ~5,000 years ago	18,000 – 10,000 (14,000 ± 4,000)	Channel formed during early stage of post-glacial river incision into plains
Okuku Tce 2a	Cut by a rupture on Ashley Fault, ~5,000 years ago	20,000 – 12,000 (16,000 ± 4,000)	Product of fan-trimming, prior to post-glacial incision
Okuku Tce 2c-b	Cut by at least 2 ruptures on Ashley Fault, and at least 1 rupture on Loburn Fault	20,000 – 12,000 (16,000 ± 4,000)	Product of fan-trimming, prior to post-glacial incision
Makerikeri Tce 1	Cut by at least 1 rupture on Ashley Fault (East) and possibly warped by Loburn Fault	20,000 – 12,000 (16,000 ± 4,000)	Product of fan-trimming, prior to post-glacial incision
Okuku Tce 3	Cut by at least 2 ruptures on Ashley Fault	28,000 – 18,000 (23,000 ± 5,000)	Product of fan-building, during last glaciation
Makerikeri Tce 2 (incl. alluvial fans)	Cut by at least two ruptures on Ashley Fault (East)	28,000 – 12,000 (20,000 ± 8,000)	Product of fan-building, during last glaciation
Okuku Tce 4, Makerikeri Tce 3	Loburn Fault scarp ~5 m high across these terraces. Terraces dissected, extensive loess cover	190,000 – 130,000 (160,000 ± 30,000)	Age range corresponds to the second-to-most recent major glaciation
Okuku Tce 5	Not crossed by any fault scarps	>130,000 & <380,000	Older than Okuku Tce 4, younger than „hill"
„hill" landforms	Loburn Fault scarp ~12 - 15 m high across these landforms	380,000 – 260,000 (320,000 ± 60,000)	Assumed to be twice as old as Okuku Tce 4, Makerikeri Tce 3
high terrace	Eroded scarp of Ashley Fault (East) is ~50 – 70 m high adjacent to high terrace	570,000 – 390,000 (480,000 ± 90,000)	Assumed to be half as old again as „hill" landforms

A1.4 PREVIOUS FAULT TRENCHING INVESTIGATIONS

Fault investigation trenches excavated across the Ashley Fault (two trenches, 1 and 3) and the Loburn Fault (one trench, 4) were described by Sisson et al. (2001). Trench locations are plotted on Figures A1-4 and A1-5. The log of Trench 1 (Figure 11 of Appendix 2) is difficult to interpret. The trench exposed an apparent broad warp within sediments on the northern (upthrown) side of the fault scarp, and a peat sequence on the downthrown side, that

appears to have accumulated since the last deformation event. There was no clearly expressed fault in the trench exposure. Trench 2 collapsed before it could be examined, so there is no record of what was exposed in its walls. Trench 3 exposed a fault zone dipping steeply to the north, and upthrown to the north, indicating a reverse component of displacement (Figure 12 of Appendix 2). This log is also difficult to interpret, particularly the lack of a well-defined fault scarp. Trench 4 (Figure 13 of Appendix 2) exposed a fault zone dipping at a moderate angle (~50°) to the south, and upthrown to the south, also indicating a reverse component of displacement. There is also evidence for some buckling of the alluvial deposits, as well as a distinct offset. This trench illustrates that buckling is a significant component of the scarp height, and that the scarp has been considerably smoothed by erosion and soil accumulation since the most recent surface rupture/deformation event.

Collectively, Trench 1 across the Ashley Fault and Trench 4 across the Loburn Fault show that both faults are of contractional character. The following paragraphs discuss in detail the exposures of Trench 1 and its implications for surface rupture history of the Ashley Fault.

The only direct dating that places constraint on the timing of surface ruptures of the Ashley Fault Zone comes from Trench 1 of Sisson et al. (2001) (see Figure 11 and Table 1 of Appendix 2), excavated across the fault scarp that displaces the floor of the Fishers Road channel (Figure A1-4). The trench log indicates that the deeper part of the stratigraphy on the upthrown side of the fault scarp records at least one earlier deformation event, including buckling of gravel layers, etc, and thus the floor of the Okuku 1 Terrace channel here is essentially an erosion surface cut on those older, more deformed, deposits. We concur with Sisson et al. (2001) that because the trench lies adjacent to a minor graben on the downthrown side (Figure A1-4), peat sedimentation on the downthrown side most likely commenced shortly after formation of the scarp. Overall, though, the trench stratigraphy is difficult to interpret. The most problematic aspect is that despite the trench having been excavated across a morphologically very well expressed fault scarp, there is no clear expression of the most recent offset(s) in the eastern face of the trench.

There are at least two possible explanations for the relationships recorded in Trench 1. One is simply that the surface deformation associated with formation of the fault scarp at this location involved buckling rather than sharp rupture, and a free face, of sufficient steepness to shed colluvium, was not formed. An alternative possibility is that there was partial erosion of the fault scarp, subsequent to its formation. In regard to the erosion scenario, we note that the trench was sited adjacent to where a minor stream has incised a gully into the upthrown side of the fault (visible in Figure A1-4). A challenging implication of this scenario is that powerful fluvial erosion occurred shortly after scarp formation, but there has been little further input of stream sediment at this site since the onset of peat deposition. One could speculate that strong ground shaking associated with the most recent metre-scale fault rupture at this location induced widespread expulsion of groundwater, similarly to that observed close to the Greendale Fault during the 2010 Darfield earthquake (Cox et al., 2012). That could provide a means for the minor stream to have incised its channel into the scarp, and caused lateral erosion of the scarp, under stronger hydrologic forcing than has prevailed subsequently with rainfall-driven flows. However, which if either of these two possible explanations is more correct has no particular bearing on assessment of hazards in this report.

The trench exposed up to 2 m of peat overlying the river terrace gravels on the downthrown side of the fault (Figure 11 and Table 1 of Appendix 2). Four radiocarbon dates were obtained from the peat deposits. All are in correct stratigraphic order (older ages from deeper in the sequence) and all represent a minimum age for the underlying river gravels. The

radiocarbon age of the stratigraphically deepest sample (Tr1/2; Table 1 of Appendix 2; 4280 ± 170 ^{14}C yrs BP) was recalibrated using the latest calibration curves (CALIB programme; Stuiver et al. (2013) in conjunction with SHCal13 (Hogg et al., 2013). This returned an age of 4805 ± 505 calendar yrs BP, at 95% confidence, for this radiocarbon sample[2]. This age, specifically its younger bound of 4300 cal. yrs BP, is a minimum for the deposition of the underlying river gravel, and formation of the Fishers Road channel (Table A1-1). As discussed above, the deposition of the peat is suspected to have been initiated by a fault rupture of the ground surface, which created a localised depression on the terrace, in which peat was able to accumulate. Thus, the radiocarbon date for the base of the peat is considered to be a close minimum for the most recent metre-scale surface rupture of the Ashley Fault at that location, but does not necessarily provide a close limit on the age of the underlying river gravel. An age of ~5,000 cal. yrs BP is inferred for that rupture, which acknowledges that the peat deposition began after the rupture that deformed the terrace surface and provided a depocentre for peat accumulation. This ~5,000 year age estimate also affords an approximate maximum age for river terrace surfaces that lie across the line of the Ashley Fault, but which have not been offset. There is no age control on the older events preserved deep in the trench stratigraphy. Thus, the available evidence points towards the most recent rupture of the Ashley Fault at this location having occurred more than 4300 years ago (the younger bound of the calibrated radiocarbon age). We adopt a working value, in round numbers, of 5000 years ago for the most recent metre-scale surface rupture of the Ashley Fault.

Sisson et al. (2001) suggested that the silty peat and gravelly colluvium within the peat sequence at Trench 1 may indicate the occurrence of further, younger, earthquake events. In considering this suggestion, we first note that the silty and gravelly layers do not relate to surface rupture on the fault at this location, because there is no deformation where the interpreted fault plane intersects the base of the peat sequence in the eastern face of Trench 1. Instead, it seems more likely that the presence of these sediment layers can satisfactorily be explained by minor slope erosion of the fault scarp and input of silty water from the minor stream. While it is possible that slope erosion or silt sedimentation occurred in response to ground shaking from nearby large earthquakes, these may not necessarily have produced surface rupture. Finally, there remains the puzzling distribution of the green silty clay layer in either face of the trench (Figure 11 in Appendix 2). We can offer no explanation, other than wondering if this layer was emplaced by some sort of soft-sediment deformation (e.g., liquefaction).

A1.5 EVALUATION OF FAULT SCARP AND RIVER TERRACE RELATIONSHIPS

Where river terraces cross the line of an active fault, the heights of the fault scarp across a succession of river terraces, and the heights of a terrace riser (the step between two adjacent terrace levels, denoted by „terrace edge" symbol on maps) either side of the fault, collectively provide valuable information on the history of fault movement events. There are several such important localities in the investigation area, and measurements of fault scarp height and river terrace riser heights made from the lidar dataset provide an unprecedented level of information.

[2] Natural atmospheric radiocarbon (^{14}C) content has varied over time. The measured ^{14}C content of carbon-bearing sub-fossil material (e.g., peat), and the radioactive decay rate of ^{14}C yields an age in ^{14}C years before present (^{14}C yrs BP). This needs calibrating to obtain a true age, in calendar years (cal. yrs BP).

However, a broad view needs to be taken of the measurements, because of the natural irregularity of gravel-bed rivers, where the crests of bars typically stand 1 m or more above the floors of channels. For example, during the formation of a lower terrace, the river may coincidentally scour out a channel alongside a pre-existing bar on the higher terrace, thus over-accentuating the height difference. Such river-bed irregularity may potentially confound the estimation of scarp height on faults that have a component of strike-slip movement, if a bar were to be shifted to a position adjacent to a channel, for example.

Very useful information on the activity of the Ashley Fault is preserved in the relationships between Okuku Terrace 3, 2, and 1, and the variations in fault scarp height across those terraces, in the area up to 2 km east from the Okuku River (Figure 2; main report). To illustrate these interrelationships, we subdivided the Okuku 3 and 2 terrace groups into individual terrace levels (Figures A1-3 to A1-6) using letters, where terrace „a" is younger than terrace „b", and terrace „b" is younger than terrace „c". This is described in more detail in the following subsections.

A1.5.1 Barkers Road channel

The north-south trending part of Barkers Road, south of Fishers Road, runs along a shallow channel between two remnants of Okuku Terrace 3 (Figures A1-1 and A1-3). This channel is mapped as part of Okuku Terrace 2, and is referred to in this report as the Barkers Road channel. It is labelled „T2a" in Figure A1-3 (see discussion in Section A1.5.2).

A key finding from interrogation of the lidar data is that the riser on the eastern side of the Barkers Road channel, cut against the T3b terrace, changes in height at the Ashley fault scarp, and decreases in height at the axis of a syncline (green dotted line in Figure A1-3). This indicates that a fault rupture occurred prior to, or during, the formation of the Barkers Road channel. In other words, the Barkers Road channel was cut into the already-deformed T3b surface, which accounts for the different riser heights. The anticlinal and synclinal buckling north of the fault is related to the pop-up bulge („flower structure" of Sisson et al., 2001) that is prominent on the T3b terrace remnant east of Barkers Road (Figure A1-3, also see Figure 9 in Appendix 2).

Where the fault scarp crosses the Barkers Road channel, at one place the fault scarp is ~2.2 m high, in contrast to the ~1.6 to ~1.7 m high fault scarp across the remainder of the Barkers Road channel (Figure A1-3). One possibility is that the ~2.2 m high scarp occurs at an imperfectly eroded remnant of the channel floor that was displaced during the rupture event. Conversely, the location where the scarp is ~2.2 m high may be a localised bulge associated with an anticline axis that trends south towards the fault scarp at that location (Figure A1-3).

In summary, the Barkers Road channel has been displaced by at least one surface-rupture event, with vertical offset of no more than ~1.6 to 1.7 m. At least one previous rupture has deformed the T3b terrace, where the maximum fault scarp of ~3.9 m is the product of at least two ruptures, the one(s) that deformed the Barkers Road channel, plus the earlier rupture(s). Despite a need for caution because of the marked along-strike changes in vertical offset on the fault scarp, and the uncertainties from natural variability in the river terrace landforms, these observations suggest that in this area, the earlier rupture(s) had a slightly greater vertical offset than the later one(s).

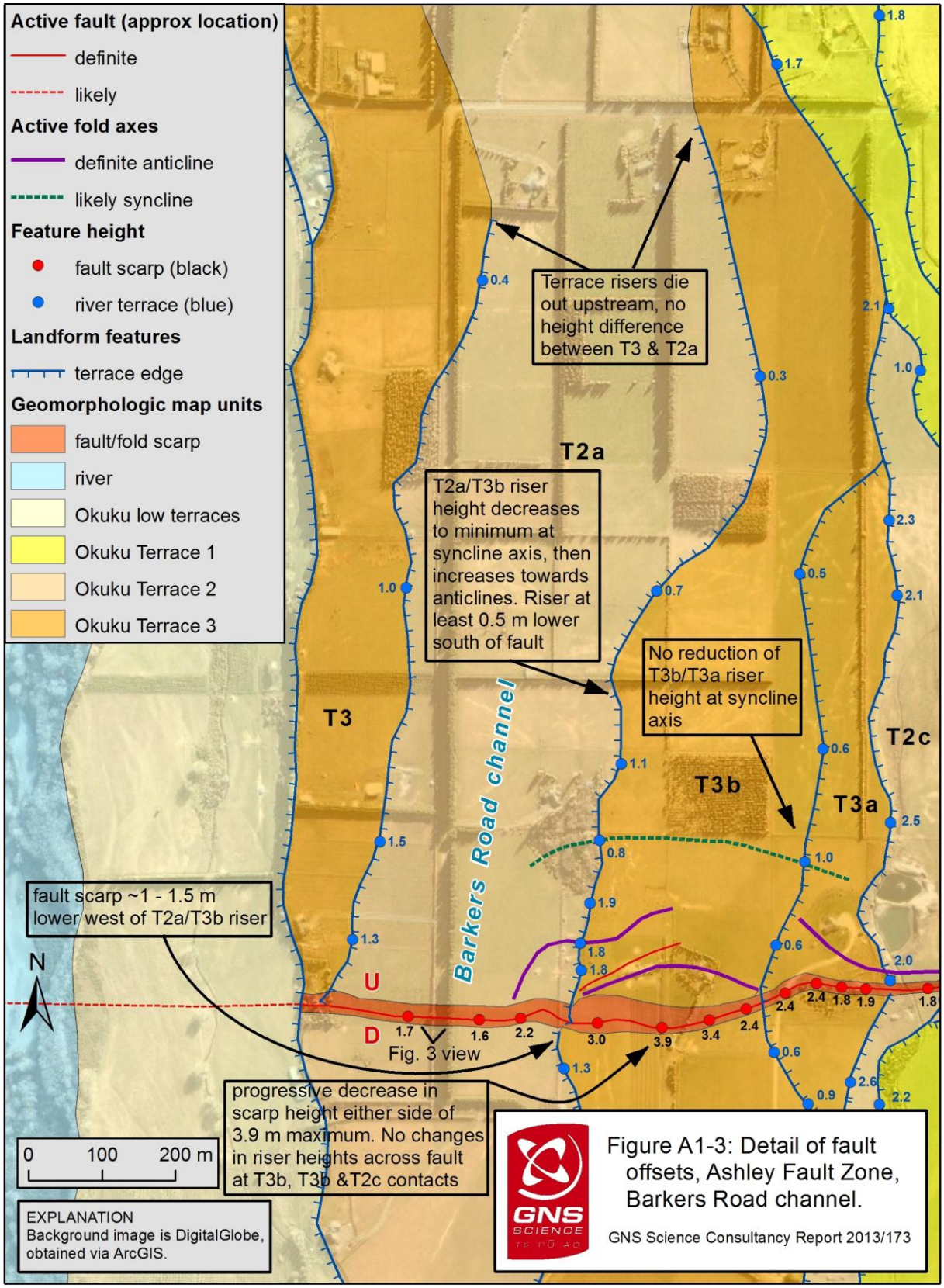

Figure A1-3 Detail of fault offsets, Ashley Fault Zone at Barkers Road, east of Okuku River. See Figure A1-1 for location.

A1.5.2 Fishers Road channel

The Ashley Fault crosses a flight of river terraces on the western side of the Fishers Road channel (Figs. A1-1 and A1-4). Risers between terraces T3b and T3a, between T3a and T2c, and between T2c and T2b (Figure A1-4) show no discernible difference in height either side of the fault. This indicates strongly that during the formation of these terraces, there was no decimetre or metre-scale surface rupture on the fault that caused uplift on one side or other of the fault. We consider it very likely that the fault did not experience a measurable vertical surface rupture during the period that those terraces formed.

In contrast, the riser between T2b and T1a is ~0.6 m high south of the fault, and between ~1 and 1.5 m high north of fault. This indicates that there was a fault rupture, which resulted in uplift of the north side of the fault relative to the south side by as much as ~1.0 m, between formation of T2b and T1a. T1a itself is cut by a fault scarp of between ~0.8 and 1.4 m high, which attests to at least one subsequent fault rupture.

Notably, the height of the fault scarp across the flight of terraces on the western side of the channel increases from ~1.8 m to ~2.4 m, not at the riser between T2b and T2c, as suggested by Sisson et al. (2001; see Figure 9 in Appendix 2), but rather at the place where the fault changes from an ~E-W strike, to an ~ENE-WSW strike, midway across terrace T3a. This suggests the change in height is natural variability of the fault scarp height, not indicative of a rupture event during formation of the terrace flight.

On the eastern side of the Fishers Road channel, the T1a terrace is cut against a T3 terrace. It is not clear whether this T3 terrace equates in age with T3a or T3b, because the fan-shaped geometry makes the correlation of isolated terrace remnants impossible based simply on height (see Figure A1-2, panels A and B). The T3/T1a terrace riser is between ~1.5 and 2 m higher on the northern, upthrown, side of the fault, and the fault scarp is similarly higher on the T3 terrace than on the T1a terrace. This indicates that at least one rupture occurred between formation of T3 and T1a, and at least one rupture occurred subsequently.

On the western side of the Fishers Road channel, no surface fault rupture occurred during formation of terraces T3b, T3a, T2c, T2b. This indicates that the floor of the Barkers Road channel is the youngest component of the Okuku Terrace 2 in this area (Section A1.5.1), and therefore has been designated as terrace T2a. The Barkers Road channel stands at a relatively high elevation, and Sisson et al. (2001) mapped it as a paleochannel on their Burnham Formation terrace (Map 1 of Appendix 2) (Okuku Terrace 3 of this report). This is understandable if the mapping is based on a simple reading of topographic elevations. However, we consider that the relative differences in deformation across this flight of terraces are more persuasive age indicators than relative heights of the terraces. An explanation that accounts for these observations emerges if one takes account of the overlapping fan-like architecture of the Okuku plains (Figure A1-2, panel B). At the time of formation of the Okuku Terrace 2, the Okuku River had built a relatively steep and strongly fan-shaped alluvial plain, whereas the Grey River had constructed a low-gradient, less fan-shaped set of channels, one of which extended through the area that was later to become the Fishers Road channel. On that basis, we mapped the Barkers Road channel as T2a, and the terrace flight on western side of the Fishers Road channel as T2b and T2c, representing slightly older parts of the Okuku Terrace 2 system, formed by a relatively low-gradient distributary of the Grey River. Thus, in our mapping farther east, we have used the presence of deformation resulting from more than one surface rupture to differentiate Okuku Terrace 2 into T2c and T2b, from T2a which has experienced at least one less surface rupture (see Section A1.5.3).

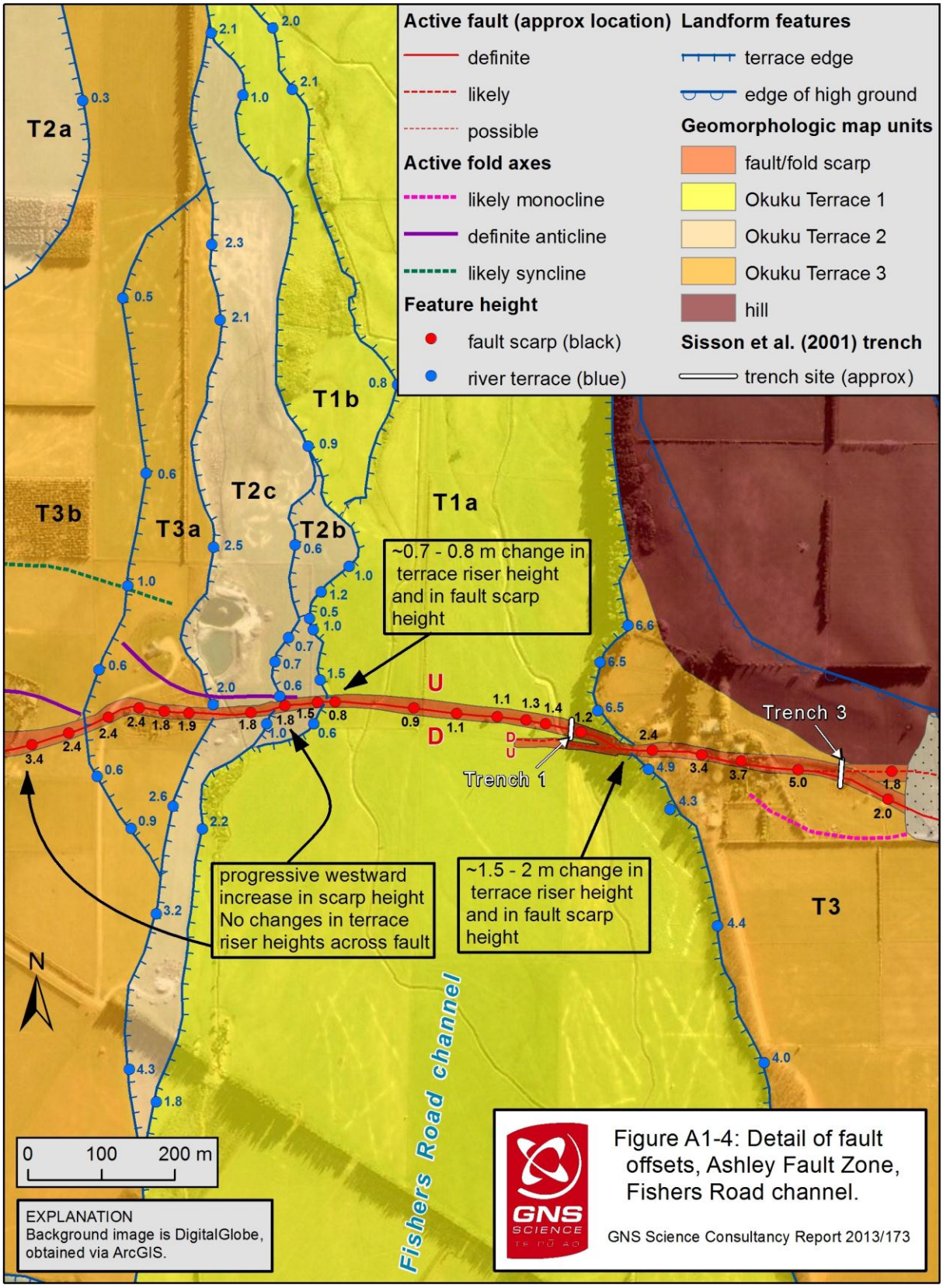

Figure A1-4 Detail of fault offsets, Ashley Fault Zone in the Fishers Road channel. See Figure A1-1 for location.

A1.5.3 Okuku Terrace 2 in the Swamp Road area

An extensive remnant of Okuku Terrace 2 occupies a valley between „The Oaks" hill and Round Hill (Figure A1-1). This valley was referred to as the „Loburn 2 channel" by Sisson et al. (2001), and they applied the same term to the river deposits underlying the channel floor. But because we recognise this as part of a more extensive terrace surface, with correlatives elsewhere in the assessment area, we have applied the term „Swamp Road valley" to this geographic area, which is traversed by Swamp Road. The Swamp Road valley is crossed by both the Ashley Fault and the Loburn Fault (Figure A1-5). Looking first at the Ashley Fault, a pair of terrace risers, defining a slightly inset channel mapped as T2a, occur only on the upthrown side (north) of the fault. The absence of these risers on the downthrown side of the fault indicates strongly that the Ashley Fault ruptured while river water was still flowing down the Swamp Road valley and, following a fault surface rupture event, the river cut the incised (T2a) channel across the uplifted ground north of the Ashley Fault. The assignation of this incised channel as T2a is based on the relationships farther west on the fault described in the sections above, and similarly the terraces either side of the channel are mapped as T2b-c. North of the Loburn Fault and south of the Ashley Fault, we cannot differentiate these terrace levels (Figure A1-5). On the western side of the valley, the riser between the T3 terrace and the T2b-c terrace is the same height either side of the Ashley Fault, indicating that no measurable surface rupture occurred during the formation of those two terraces.

In the east (Figure A1-5), the fault scarp adjoining the T2b-c terrace is ~2.5 to ~2.7 m high, but drops in height to ~1.8 m at the terrace riser down to the T2a terrace. That riser is ~0.8 m high. Collectively, these observations indicate that uplift of ~0.8 m occurred at this location, during the rupture that preceded the cutting of the T2a channel, and there was at least one subsequent rupture which produced a vertical offset of ~1.8 m of the T2a terrace. In contrast at the western side of the T2a channel, the riser up to the T2b-c terrace is at least 2 m high, and the fault scarp adjoining the T2b-c terrace is between 2.5 and 3 m higher than it is on the T2a terrace, at that location. A little farther west, the fault breaks into a double scarp, the more southerly scarp being between 2.8 and 3 m high, while the northern strand is between 1.3 and 1.5 m high. The scarp height then decreases rapidly westward, close to where a northerly trending fault scarp splays off from the line of the Ashley Fault (Figure A1-5).

In summary, the fault pattern in this area is quite complicated, with multiple strands and some uncertainties of interpretation, particularly in regard to the „possible" strand of the Ashley Fault that strikes north towards the Loburn Fault. Collectively, we interpret our mapping observations as representing an earlier surface rupture(s) of the Ashley Fault, in which the vertical offset increased westward across the „Swamp Road valley" from ~0.8 m to as much as 3 m, before decreasing westward. A subsequent rupture had a relatively large vertical offset in the east, of about 1.8 m, that declined westward to 1.3 m or less, and is represented in the northerly strand of the double scarp. Thus, it appears that the vertical offset distribution was rather different in each of these surface-rupture events. We cannot discern from fault scarp/terrace riser relationships whether the northerly-trending splay southeast of „The Oaks" hill ruptured in either one or more of those previous ruptures of the Ashley Fault (or indeed independently of those ruptures).

Where the Loburn Fault crosses the Swamp Road valley, terrace T2b-c is present on the upthrown (south) side of the fault scarp, which is typically ~0.5 m high. There is no discernible offset of the T2a terrace surface. There are three localised, approximately 20 m wide, breaches of the Loburn Fault scarp on the eastern side of the valley, near Trench 4

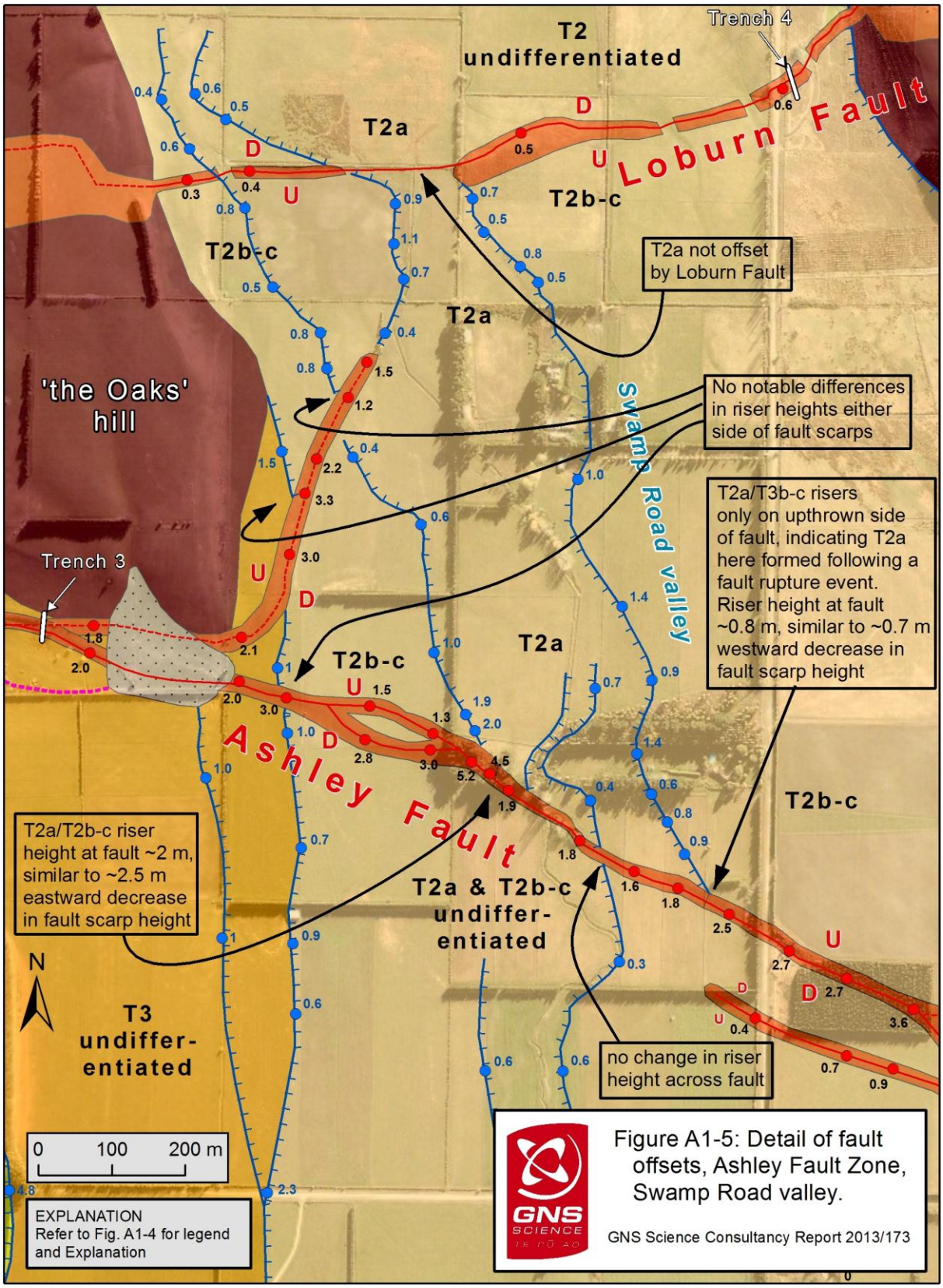

Figure A1-5 Detail of fault offsets, Ashley Fault Zone at the Swamp Road valley. See Figure A1-1 for location and Figure A1-4 for legend. The red lines depicting the faults show the fault location, rather than whether or not the fault has displaced geomorphic features at that location. That information is provided by the „fault/fold scarp" map unit.

(Figure A1-5). These may have formed shortly after the most recent surface rupture, as the river flow within the valley at that time attempted to forge a path across the scarp, prior to establishing the T2a channel.

These relationships indicate that the most recent surface rupture of the Loburn Fault occurred prior to formation of the T2a terrace. Because the T2a terrace is offset across the Ashley Fault, and the T2a surface formed after the penultimate surface rupture of the Ashley Fault across Swamp Road valley, it suggests that the most recent surface rupture of the Loburn Fault at this location occurred at approximately the same time as the penultimate rupture of the Ashley Fault. Whether those ruptures were simultaneous, or occurred independently with some time gap in between, cannot be determined from landform information alone.

A1.5.4 East of Makerikeri River

A fault scarp east of the Makerikeri River, upthrown to the north and identified here as the Ashley Fault (East) crosses terraces of the Makerikeri River and the alluvial fans that have encroached over those terraces (Figs. A1-1 and A1-6). A short distance north of the northwestern end of this scarp, the lidar dataset reveals a very slight flexure (monocline), up to the south, that may be a continuation of the Loburn Fault, as is indicated in Figure A1-1.

The scarp of the Ashley Fault (East) is ~1.5 m high on the Makerikeri 1 Terrace, and commonly is as much as 3 m high on the alluvial fans that have encroached over the terrace. In places where there are incised fan terraces across the line of the fault, the scarp is smaller, between ~1 and ~1.5 m. At one locality, the scarp is as much as ~6 m high against an older, higher, fan remnant. Altogether, these observations suggest that at least two surface-rupture events are represented in the Ashley Fault (East) scarp on the eastern side of the Makerikeri River, with at least one rupture additional to that represented by the localised higher fan remnant immediately north of the fault (Figure A1-6).

A1.5.5 Discussion

The fault scarps provide additional (event) „time markers" in the landscape. At the Barkers Road channel (Figure A1-3), Okuku Terrace 3 has experienced at least one more surface-rupture event than Okuku Terrace 2. To the east, the fault scarp descends a flight of terraces (T3a, T2c, T2b) into the „Fishers Road channel" (Figure A1-4). That terrace flight appears to have experienced the same number of surface-rupture events as Okuku Terrace 3. In other words, that terrace flight is older than the Okuku Terrace 2 surface that floors the „Barkers Road channel". The last key interrelationship is that Okuku Terrace 1 is cut into the north end of the terrace (Okuku Terrace 2) that forms the „Barkers Rd channel" (Figure A1-1). Fishers Road channel has been offset by at least one surface-rupture event on the Ashley Fault. Collectively, these observations indicate that a metre-scale fault rupture occurred during formation of Okuku Terrace 2, with terraces 2b-c pre-dating the rupture and terrace 2a post-dating the rupture. Another metre-scale surface rupture post-dates formation of Okuku Terrace 1. The detailed analysis of fault scarp heights and river terrace heights using lidar indicates that there have been as few as two metre-scale surface-rupture events on the Ashley Fault since formation of Okuku Terrace 3. But because there are at least 6 identifiable individual terrace levels spanning that period, it suggests that surface-rupture events on the Ashley Fault Zone had a fairly minor impact on the evolution of the overall terrace sequence during and since formation of Okuku Terrace 3. Factors related to river-course changes and natural climate changes have had a more important impact on terrace formation.

It is unlikely that surface rupture of the Ashley Fault Zone induced the formation of the Barkers Road channel, because the channel is incised both upstream and downstream of the fault.

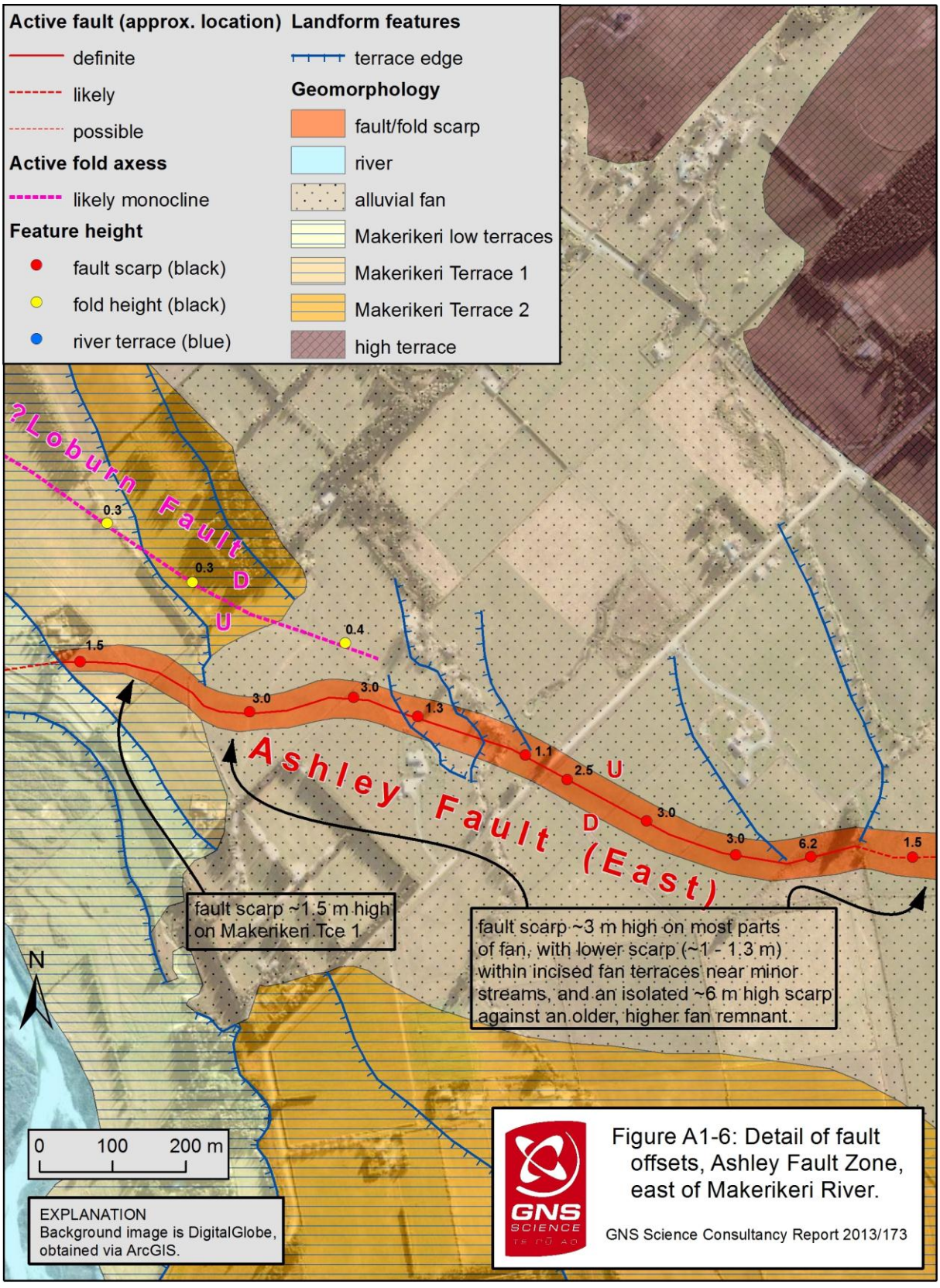

Figure A1-6 Detail of fault offsets, Ashley Fault Zone east of Makerikeri River. See Figure A1-1 for location.

A1.6 FAULT DEFORMATION EVALUATION

A1.6.1 Nature and extent of deformation

Fault investigation trenches excavated across the Ashley Fault and Loburn Fault (Sisson et al., 2001) revealed moderately to steeply dipping fault planes, with a vertical component due to contractional (reverse) movement (Figs. A1-1, A1-4, A1-5; see trench logs in Appendix 2).

The Ashley Fault Zone has long been suspected to have an oblique sense of movement, judging by the form of its surface trace, notably the presence on the Ashley Fault of several grabens and one prominent pop-up (Sisson et al., 2001). Also, its approximately east-west strike is favourable for dextral motion under the present stress regime. Sisson et al. (2001) did not find conclusive evidence for horizontal offsets, but in our view that is not surprising, because the fault scarp is at most a few metres high. Although the vertical component is obvious on the near-flat river terrace surfaces, recognising horizontal components relies on features such as channels or terrace risers, both of which are commonly wavy in form, and rather ill-defined on a scale of several metres. We think that a horizontal component similar to the vertical component would be impossible to discern in the terraced landscape that the Ashley Fault crosses. On the other hand, if the horizontal component were several times greater than the vertical component, we think that would be identifiable by terrace riser offsets. On balance we think it likely, based on the form of the fault trace, particularly that of the Ashley Fault, that the fault has an oblique reverse-dextral sense of movement, with the horizontal component similar to that of the vertical component.

In order to assess the overall deformational nature of the Ashley Fault Zone, we generated numerous topographic profiles from the lidar data, with profile lines shown in Figure A1-1 (as well as Figures 2 and 5 of the main report) and profiles displayed in Figures A1-7 and A1-8. For interpreting these profiles, we used the modern gradients of the Okuku and Makerikeri rivers, and the overall gradient of the Okuku Plains on the western side of the river (i.e., beyond the study and away from the vicinity of the Ashley Fault Zone) as a guide for interpreting gradient anomalies on terraces across the Ashley Fault Zone. The profiles demonstrate that there is a broad zone of very subtle, but distinctive, uplift and/or warping, associated with the Ashley Fault Zone (Figure 5 of main report). We emphasise that the tilting, even of the older terraces, is very slight, of the order of one degree or less, and so does not present a significant hazard to most types of land-use activity, but rather simply highlights aspects of the overall deformational character of the fault zone.

On balance, we consider that the overall structure of the Ashley Fault Zone is a broad, approximately E-W trending, anticline, with the Ashley Fault, Loburn Fault and Ashley Fault (East) representing localised surface breakouts from a fault (or faults) at depth that have contributed to the growth of the anticline. We also note that the overall lengths of the Loburn Fault and Ashley Fault (East) are quite short, only a few kilometres, and we think it quite plausible that surface ruptures may be interlinked and occur simultaneously on all these fault strands. We further note that this may not necessarily occur during every rupture event, especially on the evidence that the most recent surface rupture(s) on the Ashley Fault was not accompanied by discernible surface rupture on the adjacent sector of the Loburn Fault. It is also important to note that the Ashley Fault Zone is interpreted to be a pre-existing normal fault that has been reactivated as a contractional fault, and is likely to be still developing and evolving (Campbell et al., 2012; Jongens et al., 2012), which may, at least in part, explain its complicated surface expression.

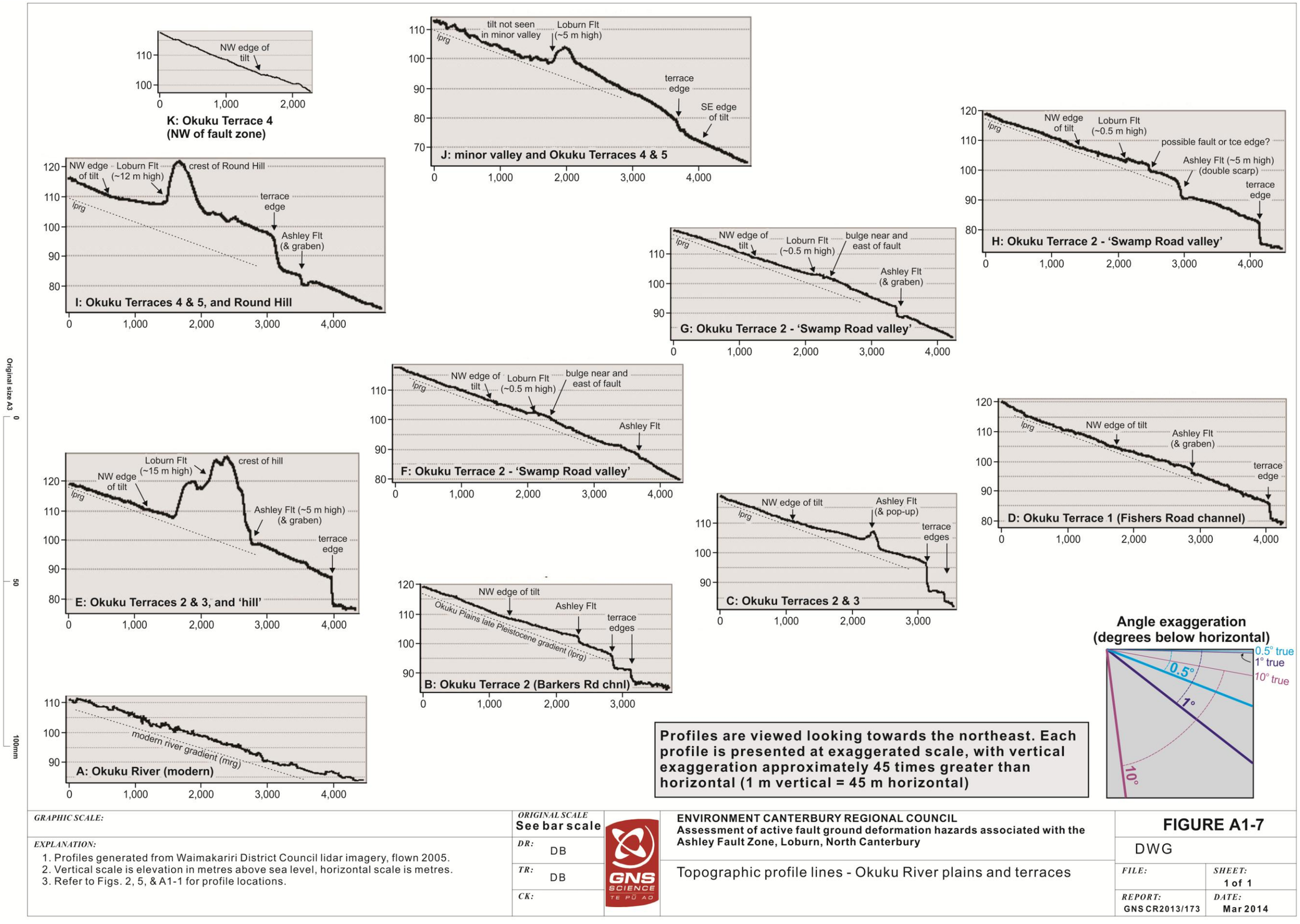

Figure A1-7 Topographic profile lines, Okuku River plains and terraces. See Figure A1-1 for profile locations.

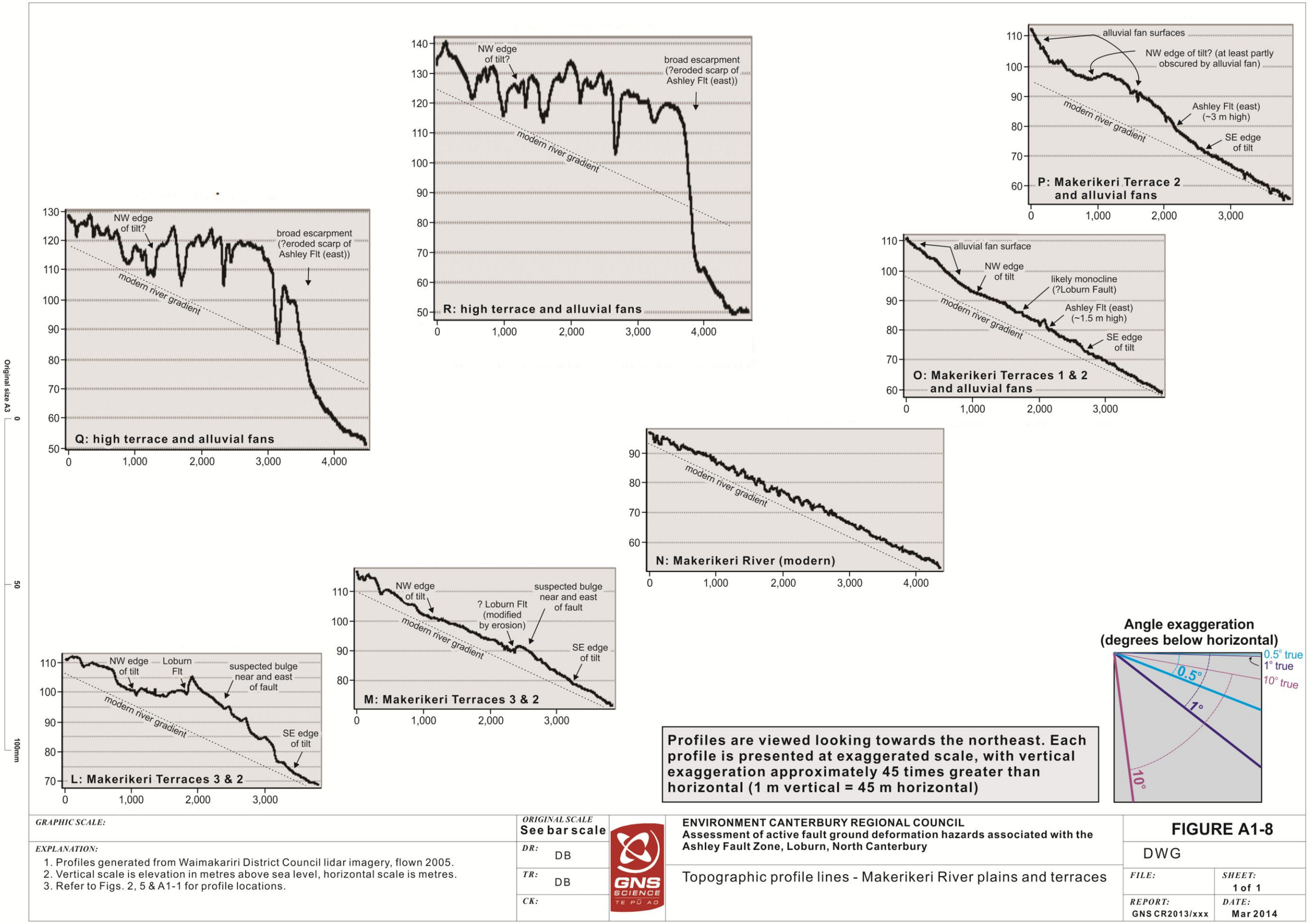

Figure A1-8 Topographic profile lines, Makerikeri River plains and terraces. See Figure A1-1 for profile locations.

Sisson et al. (2001) proposed the existence of several NW-SE trending anticlinal folds, affecting the older terraces at and east of Round Hill (Figure 10 and Map 1 of Appendix 2). However, we are unconvinced of the existence of these folds, because we consider that the topographic ridges and slopes that Sisson et al. (2001) attributed to the effects of folding can as just as easily be attributed to the effects of overlapping river fan surfaces, dissection by erosion, and superimposed effects of the broad E-W anticlinal arch on those fluvially formed terrace, gully and minor valley topographic features. While not disproving the existence of the NW-SE trending folds proposed by Sisson et al. (2001), we think that non-tectonic explanations for those topographic features are adequate, and the mapping of folds cannot be justified on present evidence. Finally, based on our evaluation of lidar, we have interpreted the „Loburn wedge structure" of Sisson et al. (2001) (Figure 10 and Map 1 of Appendix 2) as localised anticlinal bulges on the upthrown side of the Loburn Fault (Figure 5 of main report) rather than a faulted „pop-up", as shown by Sisson et al. (2001) and Forsyth et al. (2008).

A1.6.2 Size of single-event surface-rupture fault displacements

Along the Ashley Fault, relationships between the heights of fault scarps and river terrace risers, as described in Sections A1.5.1–A1-5.3, are consistent with the occurrence of at least two metre-scale surface-rupture events during and since the formation of the preserved river terrace sequence. Assuming that this interpretation is correct, and noting that there is no evidence that undermines it, the two most recent surface ruptures each had single-event vertical components of offset typically between ~1 and ~2 m, but with considerable along-strike variations, from minima of ~0.5 m to maxima of ~3 m. Notably, the size and locations of along-strike variation was somewhat different in each of those ruptures.

The surface form of the fault trace suggests a component of strike-slip motion, but there are no recognisable strike-slip offsets of terrace risers. An explanation for this is that the fault movement comprises approximately equal components of vertical and strike-slip motion. That would provide enough strike-slip motion to account for the surface form of the fault trace, but not enough strike-slip motion to discernibly offset the terrace risers. Although one could argue that the vertical component is prominent at the ground surface and therefore could be assumed to be the dominant component, the assumption of sub-equal amounts of horizontal and vertical motion seems preferable to inferring some other ratio (e.g., 2/3 vertical, 1/3 horizontal), for which no observational evidence exists.

The most recent surface rupture of the Loburn Fault in the Swamp Road valley had a single-event vertical component of displacement of ~0.5 m, with the scarp height diminishing westward to ~0.3 m at the western side of the valley. We do not know how far east that surface rupture extended, or whether the displacement was greater, or smaller, farther east. We therefore adopt 0.5 m as a minimum single-event vertical displacement for the Loburn Fault. About 1 km along strike to the west of the Swamp Road valley, the Loburn Fault projects across remnants of Okuku Terrace 3b, 3a and 2c, but there is no discernible fault offset of those terraces. Either the surface rupture did not extend that far or, just west of „The Oaks" hill, the Loburn Fault swings south and, if so, would intersect the Ashley Fault trace within ~0.6 km. Both scenarios place a definite western limit on the most recent surface rupture of the Loburn Fault.

Although no detailed investigations such as trenching have been undertaken on the Ashley Fault (East), the predominance of scarp heights of either between ~1 and ~1.5 m, or ~3 m, leads us to infer provisionally that the ~1 to ~1.5 m scarp represents a single-event vertical

component of displacement, and that where the scarp is ~3 m high, at least two rupture events are represented. For consistency, we assume approximately sub-equal amounts of vertical and horizontal motion on the Ashley Fault (East).

We do not know whether the broad anticlinal arch associated with the Ashley Fault Zone has grown in bursts during ground-surface rupture events on the fault zones, during non-surface-rupturing blind fault ruptures, or has grown steadily over time.

A1.6.3 History of fault deformation events

The most recent identified rupture near the western end of the Loburn Fault occurred after formation of the Okuku Terrace 2c-b, and before formation of Okuku Terrace 2a (Table 2). It is possible, however, that subsequent ruptures occurred on other strands of the fault zone. The most recent rupture on the Ashley Fault occurred ~5,000 years ago.

Only on the Ashley Fault is there a good basis for constraining the timing of an earlier surface-rupture event. This occurred before formation of Okuku Terrace 2a, and after formation of Okuku Terrace 2c-b, both of which are assigned an age range of 16,000 ± 4,000 years (Table 2). We adopt this as the estimated age of the second-to-last surface rupture of the Ashley Fault, and of the most recent surface rupture of the Loburn Fault, at least at the Swamp Rd channel.

As there is only one „inter-event" period, whose age range is not well defined, only broad limits can be placed on the recurrence interval. A recurrence interval range of 7000 to 15,000 years is implied. As a sensitivity test, one can hypothesise that ~1 m high scarp across the Fishers Road channel is the result of two ~0.5 m rupture events. This scenario would imply an average recurrence interval in the range of ~4000 to ~7000 years. There is, however, no direct evidence for the three-rupture scenario, so we adopt two-rupture scenario (recurrence interval of 7000 to 15,000 years) as the most likely estimate, based on present information. In contrast, previous recurrence interval estimates are 2,000–3,500 years (Pettinga et al., 2001; Van Dissen et al., 2003).

A1.7 APPENDIX 1 REFERENCES

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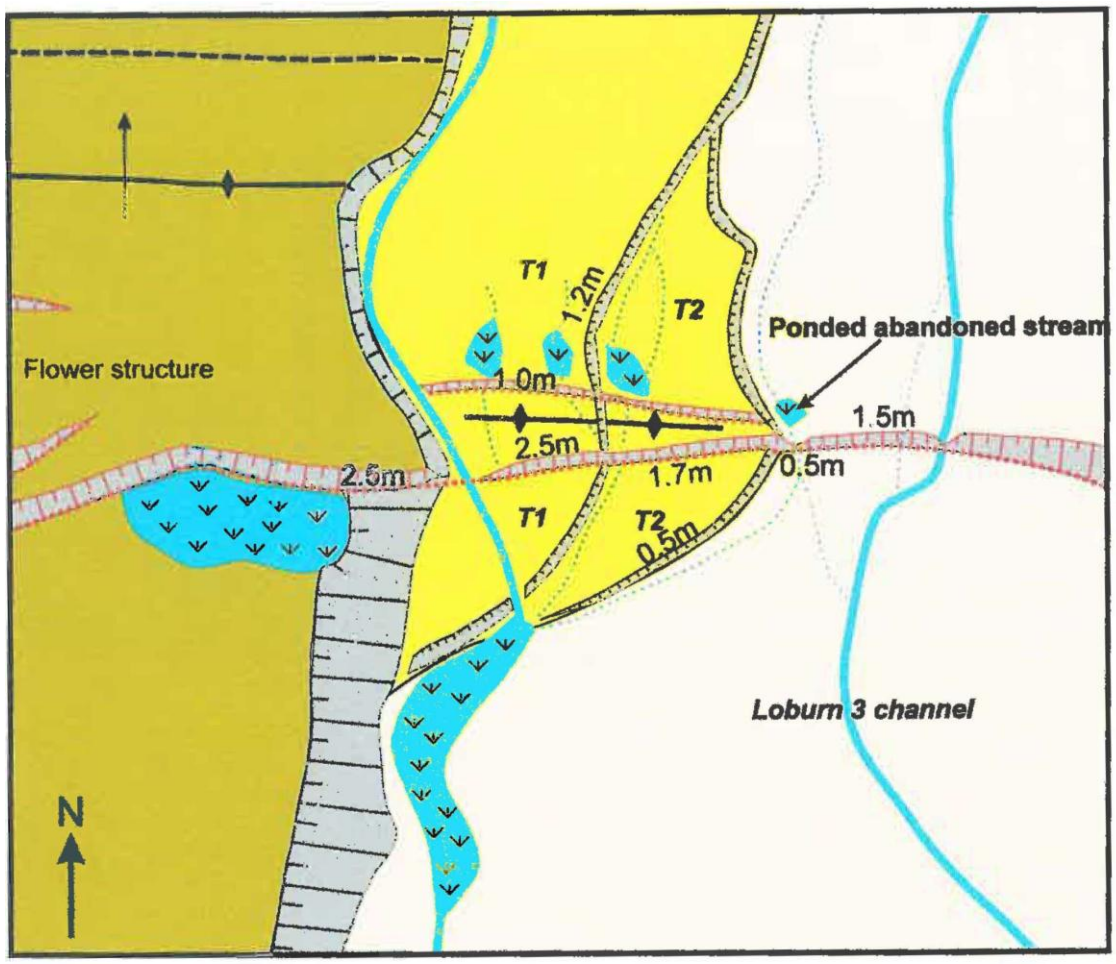
APPENDIX 2: FIGURES, TABLE AND MAP FROM SISSON ET AL. (2001)

The following items are appended from that report, used with permission from EQC.

- Figures 9, 10, 11, 12 and 13
- Table 1
- Map 1



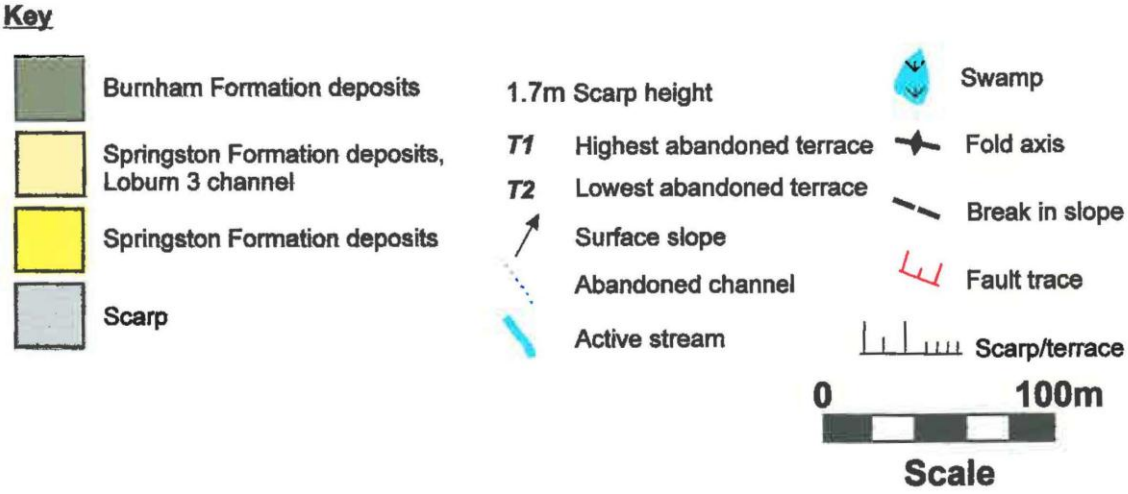


Fig. 9. Fault offsets, abandoned terrace and stream channel, western side of the Loburn 3 channel.

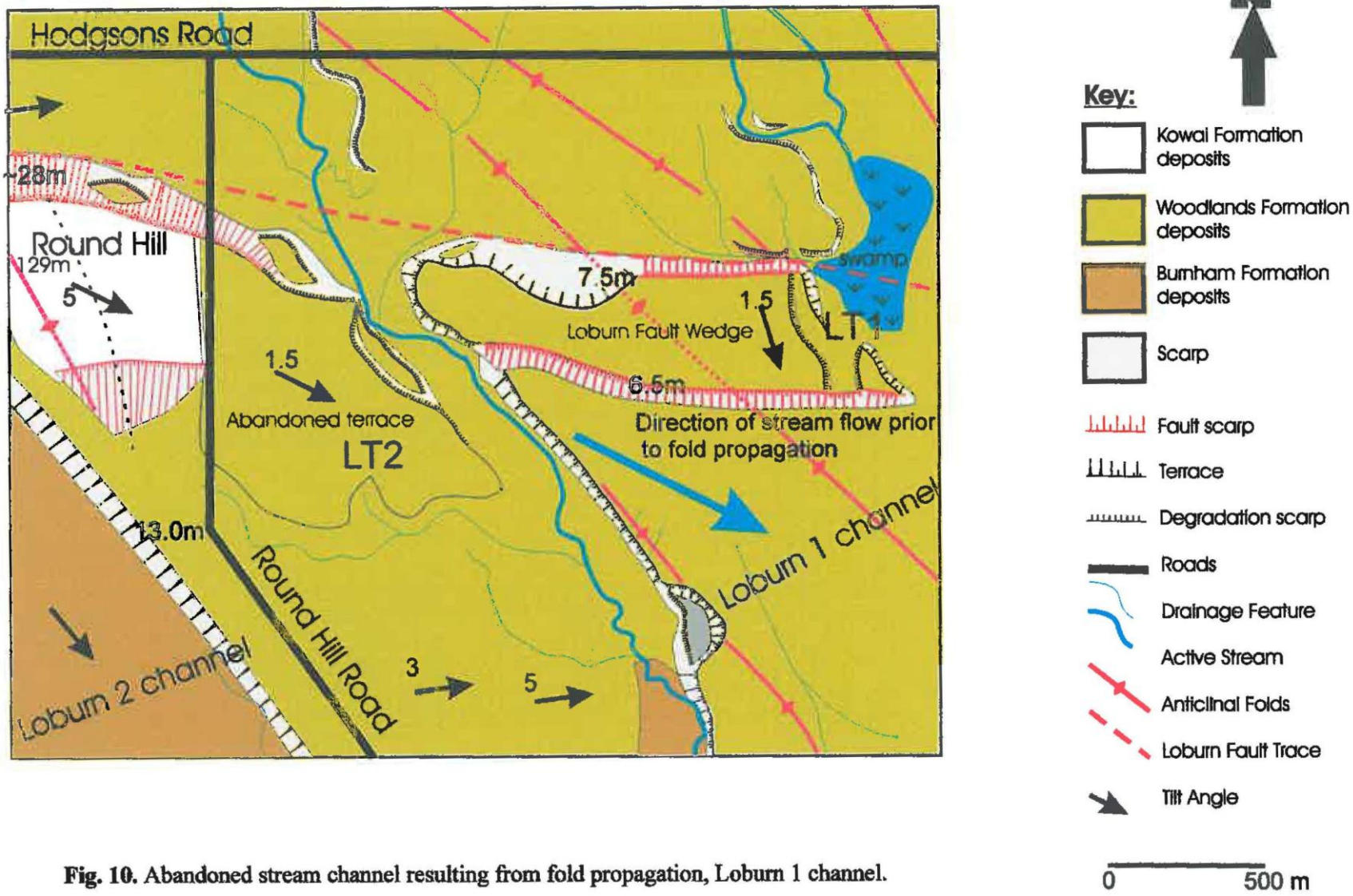


Fig. 10. Abandoned stream channel resulting from fold propagation, Loburn 1 channel.

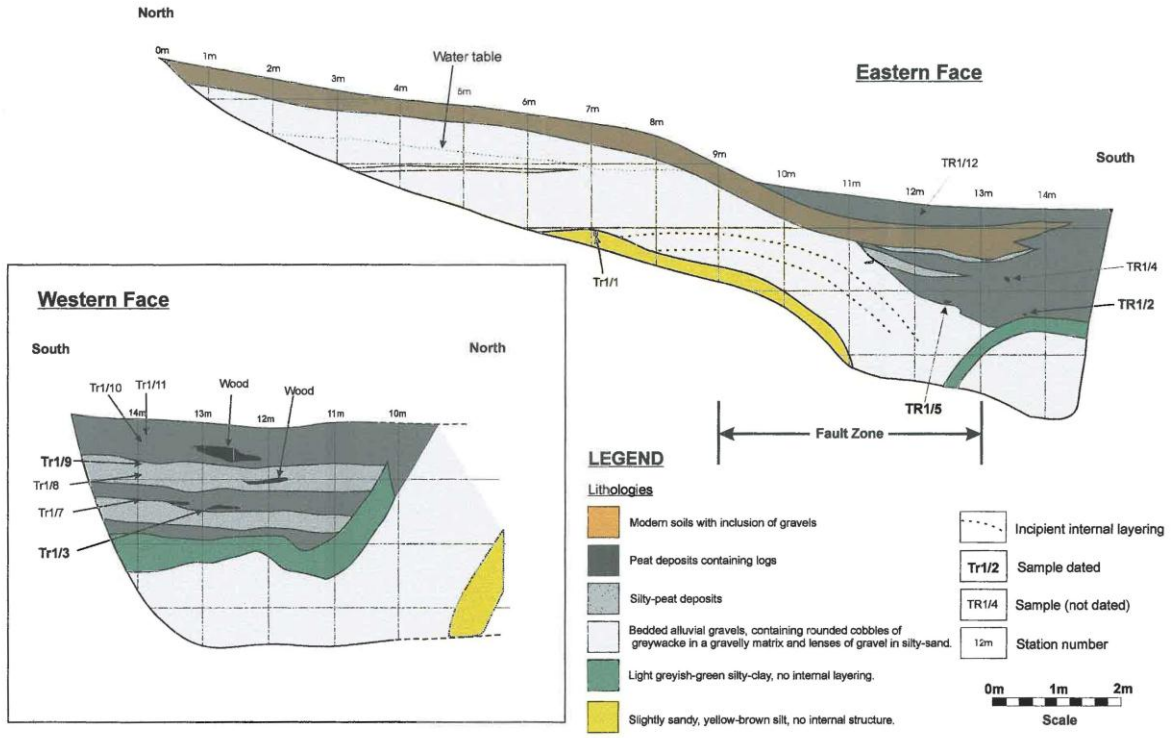


Fig. 11. Trench 1, Ashley Fault, Loburn 3 channel. NZMS260, M34/687719.

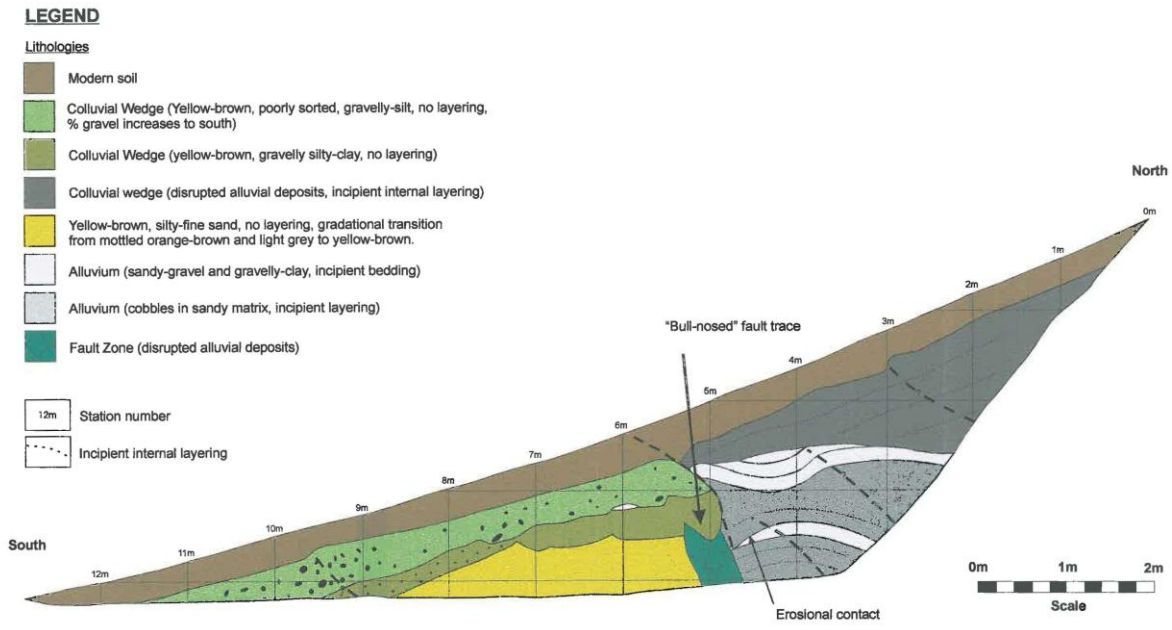


Fig. 12. Trench 3, Ashley Fault, 'the Oaks', western face. NZMS260 M34/691718

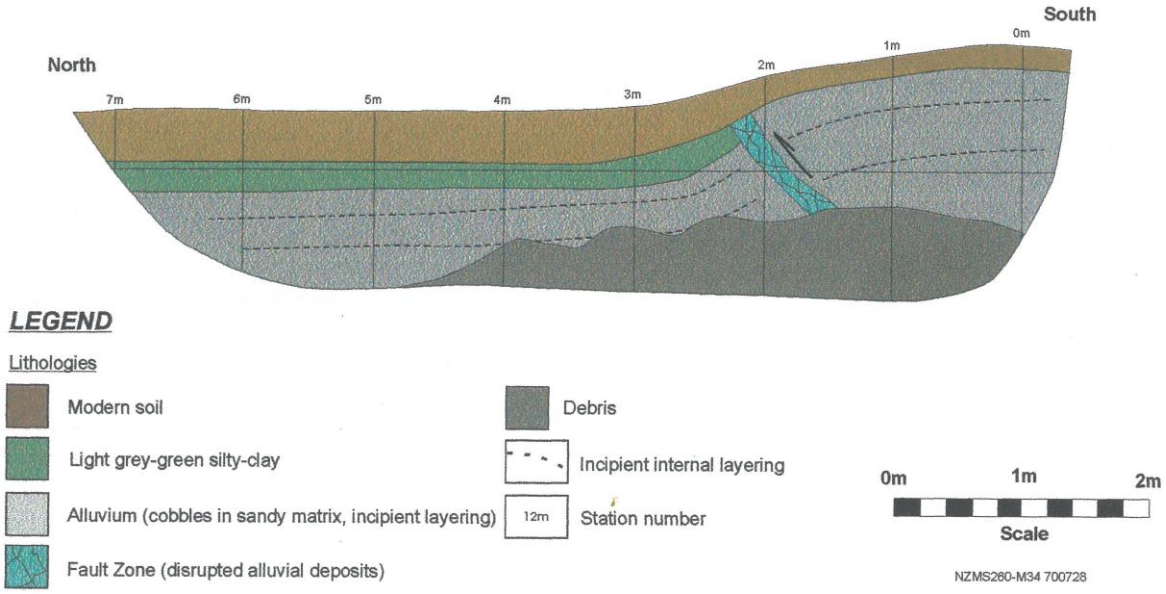
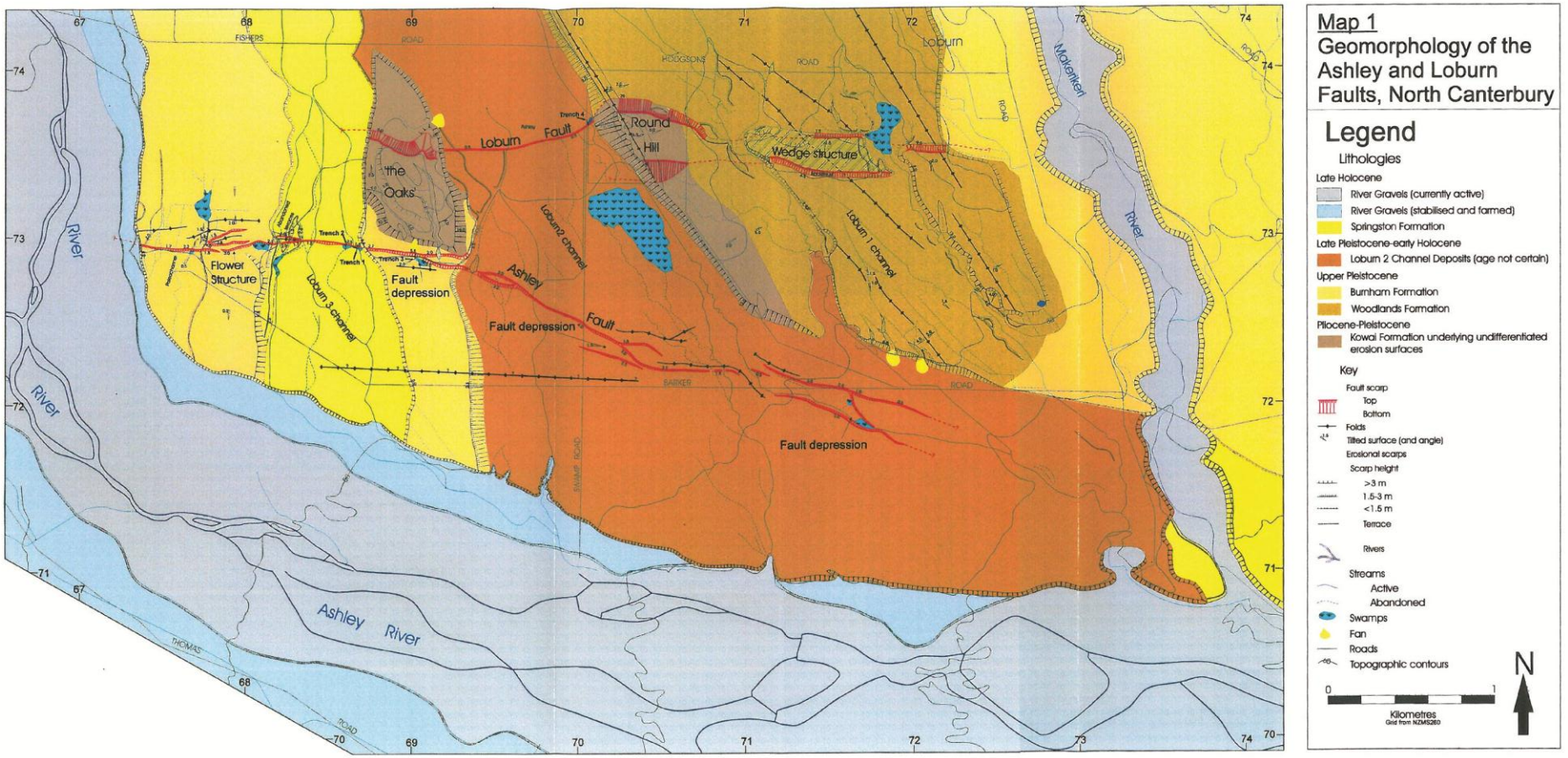


Fig. 13. Trench 4, Loburn Fault, Loburn 2 channel, west of Round Hill, eastern face.

Trench Code	dC13	% Modern	Depth (m)	Radiocarbon dates	Calibrated C_{14} results	Stratigraphic location	Comments
Tr1/2	-26.6±0.2	58.7±1.2	1.55	4280±170 years BP	**4785±255 years BP**	Above silty-clay in lowest peat, eastern face.	Probably represents the minimum age of Loburn 3 channel surface and the oldest datable rupture event.
Tr1/3	-24.0±0.2	64.4±0.5	1.30	3530±60 years BP	**3765±75 years BP**	Bottom of second peat above the first silty-peat layer, western face.	Probably represents the second youngest event on the Ashley Fault.
Tr1/5	-25.5±0.2	59.6±0.5	1.40	4160±60 years BP	**4675±155 years BP**	Interface between alluvium and peat, eastern face.	As for Tr1/2 above.
Tr1/9	-25.0±0.2	66.9±0.6	0.65	3240±70 years BP	**3420±60 years BP**	Interface between the most recent peat deposit and the uppermost silty-peat.	Probably represents the youngest event preserved before the formation of the recent peat deposits.

Table 1. Results from four samples extracted from Trench 1.



Map 1
Geomorphology of the Ashley and Loburn Faults, North Canterbury

Legend

Lithologies

Late Holocene
- River Gravels (currently active)
- River Gravels (stabilised and farmed)
- Springston Formation

Late Pleistocene-early Holocene
- Loburn 2 Channel Deposits (age not certain)

Upper Pleistocene
- Burnham Formation
- Woodlands Formation

Pliocene-Pleistocene
- Kowai Formation underlying undifferentiated erosion surfaces

Key
- Fault scarp
  - Top
  - Bottom
- Folds
- Tilted surface (and angle)
- Erosional scarps
  - Scarp height
    - >3 m
    - 1.5-3 m
    - <1.5 m
  - Terrace
- Rivers
- Streams
  - Active
  - Abandoned
- Swamps
- Fan
- Roads
- Topographic contours

0 1
Kilometres
Grid from NZMS260

N

APPENDIX 3: DIGITAL DATA

The Geographic Information System (GIS) data sets referred to in this report, and used to display geological or landform features in Figures 2, 5, and 7 of the main report, as well as in diagrams in Appendix 1, are archived on a data disk that forms a companion to this report.

People seeking more information about the digital data files or wishing to gain access to the data should contact Environment Canterbury.

A3.1 CONTENTS OF THE DATA DISK

GIS layers (see below)

GNS Science Consultancy Report CR2013-173_Ashley Fault Zone ground deformation hazards.pdf (PDF format) – print resolution

GNS Science Consultancy Report CR2013-173_Ashley Fault Zone ground deformation hazards_low resolution.pdf (PDF format) – screen resolution

Figures 2, 5 and 7 of the report as high-resolution images
GNS CR2013-173_Fig 2_Ashley Fault Zone_landform map.jpg
GNS CR2013-173_Fig 5_Ashley Fault Zone_ground classes.jpg
GNS CR2013-173_Fig 7_Ashley Fault Zone_fault avoidance zones.jpg

A3.2 THE GIS LAYERS

The GIS layers referred to in the report consist of the following shapefiles:

Fig2_geomorphologic_map_units.shp

Fig5_deformation_classes.shp

Fig7_Fault_avoidance_zones.shp

Fig7_Well_defined_and_distributed_FAZs_with_20m_buffer_added.shp

Figs2-5_active_fault_lines_approx.shp

Figs2-5_landform_feature_lines.shp

Descriptive metadata accompany the fault and fold datasets.

A3.3 ACCURACY

These datasets are presented at a scale of 1:35,000 in the report, but the data were compiled at more detailed scales.

The river-related and hill landform areas of the geomorphologic map, and the landform feature lines, were mapped on-screen at a scale of approximately 1:10,000. Locations of the boundaries of those map units and landform lines are considered to be accurate to about +/- 30 m. The lesser precision and greater generalisation applied to the mapping of these features allowed more effort to be focused on mapping the fault-related features.

The fault-related landform area and the fault lines were mapped in more detail on-screen, at a scale of approximately 1:5,000. The locations of the fault lines and the boundaries of fault-related geomorphologic map units are considered to be accurate to +/- 10 m at best on the younger river terraces (Okuku Terrace 3/Makerikeri Terrace 2 and younger), but are no better than +/- 20 m on older terrace or hill landforms.

Lines representing the fold axes are less precise because those features are less clearly defined in the landscape than the fault scarps. Lines representing monoclines are considered to be accurate to +/- 20 m at best, while syncline or anticline axis positions are considered to be accurate to +/- 40 m at best.