Desktop assessment of Starvation Hill Fault hazard in relation to a land parcel comprising parts of Lots 2 and 3, DP 51992, Oxford, North Canterbury

DJA Barrell

GNS Science Consultancy Report 2023/44
March 2024

DISCLAIMER

Use of Data:

Date that GNS Science can use associated data: March 2024

BIBLIOGRAPHIC REFERENCE

Barrell DJA. 2024. Desktop assessment of Starvation Hill Fault hazard in relation to a land parcel comprising parts of Lots 2 and 3, DP 51992, Oxford, North Canterbury. Lower Hutt (NZ): GNS Science. 19 p. Consultancy Report 2023/44.

CONTENTS

FIGURES

TABLES

EXECUTIVE SUMMARY

The Starvation Hill Fault is an active geological fault, aligned west-east, in the Oxford area. The Waimakariri District Council has released a Proposed District Plan that includes placing an area of land on the eastern margin of Oxford township (parts of Lot 2 and Lot 3, Deposited Plan (DP) 51992) in a Large Lot Residential (LLR) Zone. This area of land lies within a ‘fault awareness area’ associated with the Starvation Hill Fault. Commissioned by Waimakariri District Council, this report presents a desk-based assessment of the potential risks associated with the Starvation Hill Fault for any future development arising from the proposed land re-zoning. The assessment uses existing publicly-available information, including aerial photography and satellite imagery, and in particular the examination and analysis of high-resolution lidar (laser radar) datasets that provide a very precise picture of ground topography.

Information gathered as part of this assessment supports previous interpretations that the Starvation Hill Fault is likely to be an active fault. For this report, the fault is taken as being active, with interpretations presented in terms of active faulting, without further caveats.

The fault-related landform features associated with the Starvation Hill Fault in the vicinity of Lots 2 and 3, DP 51992 are classified as fault scarps (well-defined deformation), broad fault scarps (distributed deformation), slightly to moderately tilted ground and slightly tilted ground (uncertain deformation – constrained). The broad fault scarps are interpreted to have formed from diffused deformation from the main fault rupture, perhaps 50 to 100 m underground. The fault scarps are interpreted as more focused ground-surface offsets on subsidiary fault break-outs from the main fault. The tilted ground is interpreted to have been produced by progressive changes in height along the line of the fault scarps. In addition to the vertical deformation registered in the fault-related landforms, there may be a component of sideways deformation. It is possible that in the next fault rupture, the well-defined deformation zones might lengthen, or new ones break out in the distributed deformation zones. The well-defined and distributed deformation zones are therefore recommended to be treated in the same way in regard to fault avoidance zonation.

There is no direct information on the recurrence interval of the Starvation Hill Fault. Based on various geological inferences, it is possible that the recurrence interval may be somewhat less than 5000 years. It is recommended that recurrence interval class III (>3500 to ≤5000 years) be used for applying the MfE active guidelines to the Starvation Hill Fault. A targeted geological investigation may be able to obtain data to improve the estimation of the fault’s recurrence interval.

Applying the recommended recurrence interval class III to the Starvation Hill Fault indicates that, in the ‘greenfield’ setting of the property under assessment, construction of single-story timber-framed dwellings of less than 300 m^2 area may be a permitted activity within the fault avoidance zones. Other types of larger dwellings are indicated as non-complying. However, the guidelines are not binding and it is for a council to determine what activities to allow.

The northern parts of Lots 2 and 3, DP 51992 that are proposed to be rezoned from Rural Zone to Large Lot Residential (LLR) Zone lie almost entirely on ground that has previously experienced deformation as a result of ruptures of the Starvation Hill Fault. The central and southern parts of Lots 2 and 3, DP 51992, which are proposed to retain rural land-use zoning (General Rural Zone) are on ground classed as having ‘no ground deformation hazard’. If consideration were given to instead placing the northern parts of Lots 2 and 3 in the General Rural Zone and creating a LLR zone on the central to southern parts of the lots, there would be no active fault hazard to consider for building in the revised LLR zone.

1.0 INTRODUCTION

A geological fault passes through part of Oxford township. The Starvation Hill Fault is recognised from geological relationships in the subsurface (Forsyth et al. 2008); as explained in detail by Barrell and Begg (2013). Topographic steps at the general location of the subsurface fault have characteristics suggesting they formed from fault-related deformation of the ground surface. However, it is possible that these steps were produced by ancient river action rather than fault activity. This led to the Starvation Hill Fault being classified as a 'likely', rather than 'definite', active fault (Barrell and Begg 2013).

The Waimakariri District Council (WDC) is reviewing the current (operative) Waimakariri District Plan and released a Proposed District Plan in September 2021 for consultation. The Proposed District Plan includes the rezoning of an area of land (parts of Lot 2 and Lot 3, Deposited Plan (DP) 51992) on the eastern margin of Oxford township (Figure 1.1) from Rural Zone to Large Lot Residential (LLR) Zone. The land proposed to be rezoned (henceforth in this report, the 'land parcel') lies within a 'fault awareness area' (Barrell et al. 2015) associated with the Starvation Hill Fault, created by Environment Canterbury (Jack 2020; see Figure 2.1). WDC engaged the Institute of Geological and Nuclear Science Limited (GNS Science) to assess the potential risks associated with the Starvation Hill Fault for any future development arising from the proposed land re-zoning. This report presents the results of the assessment. The report is intended to provide a foundation of scientific evidence to assist WDC in determining the suitability of the land parcel for the proposed rezoning, and in formulating provisions (if any) for the development of the land parcel.

The assessment is desk-based and draws upon publicly-available information. No site visit was made but the writer is familiar with the geology and landforms of the wider Oxford area, having done geological field surveys there in the mid-2000s. This assessment applies the Ministry for the Environment (MfE) guidelines for planning for development of land on or close to active faults (Kerr et al. 2003; hereafter in this report, the MfE active fault guidelines), and mirrors a similar assessment previously undertaken for the Ashley Fault Zone, about 30 km east of Oxford (Barrell and Van Dissen 2014).

Specific components used in the assessment were:

- Examination of aerial photography and satellite imagery accessed through the GNS Science ArcMap geographic information system (GIS) platform.
- Examination and interpretation of high-resolution topographic information from a lidar (airborne laser radar) dataset for Waimakariri District, surveyed in 2005. Use was made of a lidar-derived digital elevation model (DEM) composed of grid cells at 1 m spacing. Each 1 m diameter grid cell assigned an elevation value in metres above sea level.
- Generation of detailed topographic contours in the GIS system, from the lidar DEM.
- Examination of archival black and white aerial photos taken in 1942, held by GNS Science (photo run SN117, photos 14–18).
- Examination of ground-based photos from roads, accessed via Google Street View.
- Online inspection of the operative and the proposed new Waimakariri District Plan <https://www.waimakariri.govt.nz/planning/district-plan/district-eplan2 >.

An active fault is one which occasionally experiences a sudden slip event ('rupture'), initiated deep in the Earth's crust. If sufficiently large, the rupture may extend up to the ground surface. 'Surface rupture' is expressed as a sudden offset (faulting) or buckling (folding) of the ground surface of as much as several metres. Buildings or other infrastructure situated within a zone of sudden offset and/or buckling are likely to suffer serious damage. This may pose a significant threat of injury or death to building occupants. Determining and managing active fault hazards is among the activities undertaken by territorial and regional authorities.

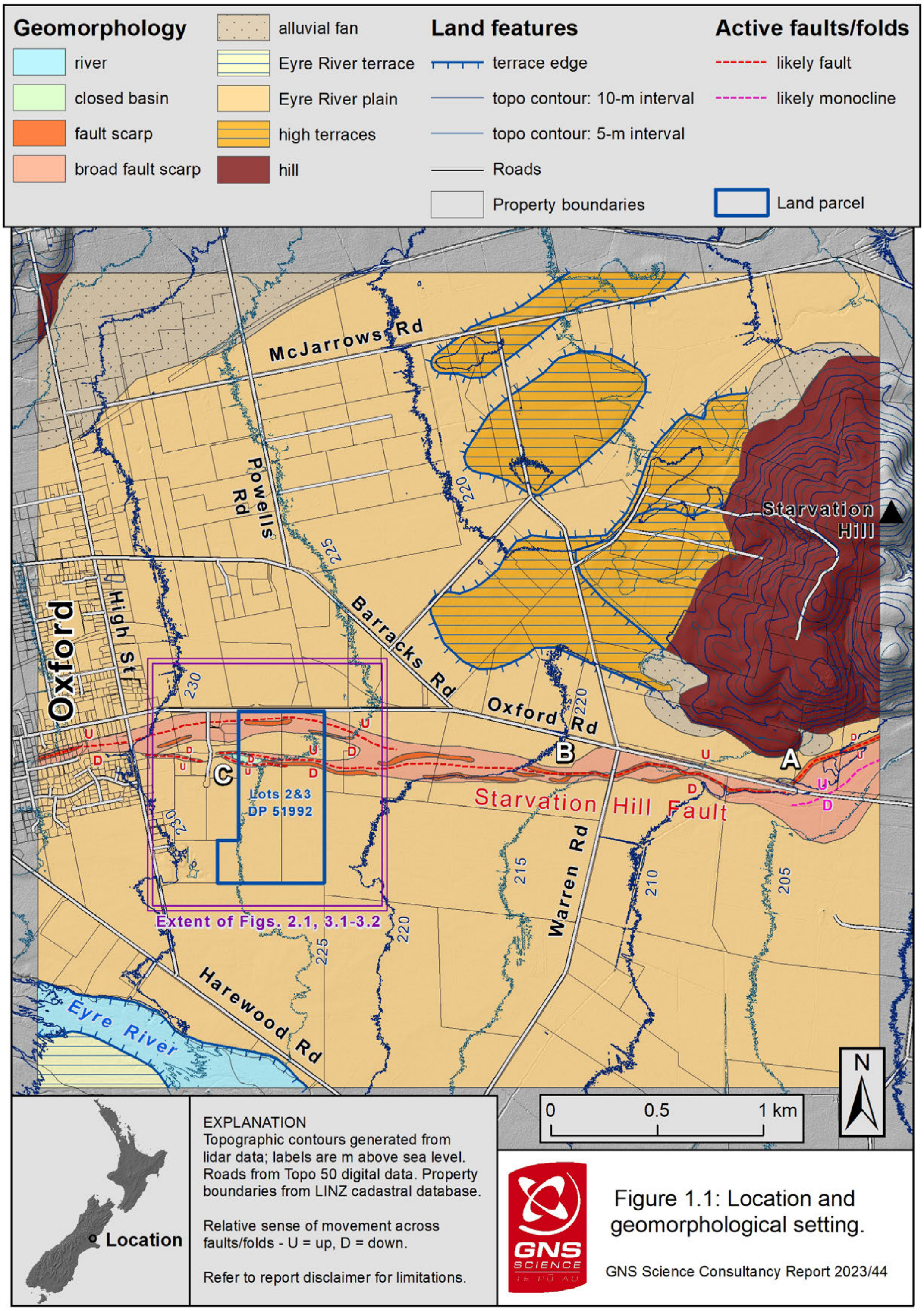

Figure 1.1 Location and geomorphological setting of the Starvation Hill Fault east of Oxford. Refer to Section 2.0 for description of the landform (geomorphological) units and other features. Lettered locations A–C are places discussed in the text. The diffuse nature of the topographic (topo) contours is due to their generation from a lidar DEM with 1 m^2 grid cells.

2.0 DESCRIPTION AND INTERPRETATION OF LANDFORM FEATURES

The information resources listed in Section 1.0 were used to prepare the ~4 km by ~4 km geomorphological map presented in Figure 1.1, encompassing the land parcel. This wider view of landforms in the area provides essential context for interpreting the specific landforms at the land parcel. The main landform feature at Oxford township is an alluvial plain (Eyre River plain), formed when the Eyre River flowed in a more easterly direction than it does now. Based on the considerable degree of soil development on the river plain, it is confidently interpreted to be relatively old, likely last occupied by the river during the latter part of the Last Glaciation (Forsyth et al. 2008; Barrell et al. 2011a). A nominal age of ~18,000 years was assigned to the river plain by Barrell and Begg (2013). Rising above the plain is Starvation Hill, composed of Miocene-age volcanic rock (Forsyth et al. 2008). The hill is flanked by remnants of elevated river terraces (high terraces), localised accumulations of stream sediment (alluvial fans) that have built out onto the plain, and terraces from gullies draining the hill terrain (Figure 1.1).

The Starvation Hill Fault is aligned west-east and was classified as a 'likely' active fault by Barrell and Begg (2013; see that report for definitions). The Eyre River has formerly flowed parallel to the fault, making it difficult to interpret whether topographic steps are due to fault offset of the ground, or a product of river erosion (Appendix 1 of the Barrell and Begg (2013) report). The interpretation that the fault is active was emphasised as very likely by Barrell (2019b), and further evaluation of geomorphological information during the present assessment (see below) reinforces that interpretation. Without direct evidence of fault activity, such as exposure of faulted sediments in an investigation trench, I do not classify it as a 'definite' active fault. However, for this report, the working assumption is made that these topographic features near the Starvation Hill Fault result from fault-related ground deformation, with relative upthrow to the north. Accordingly, these topographic features are referred to in this report as fault-related landforms on Figure 1.1, with Figure 2.1 showing the map at larger scale in proximity to the land parcel.

Total vertical deformation across the fault zone increases from ~4 m at Oxford township to ~7 m south of Starvation Hill, as shown by eastward progressively greater deflection of topographic (in diagrams abbreviated to topo) contours (Figure 1.1). At Location B, total vertical deformation across the fault zone is about 5 m. The amount of fault-related deformation is why travellers on this part of Oxford Road have a commanding view south across the plains. Interested readers can examine this in Google Street View, especially looking south from the intersection of Oxford Road (also called the Inland Scenic Route 72) and Warren Road.

Distinction is made in Figures 1.1 and 2.1 between relatively sharp topographic steps (fault scarp) and more gentle changes in ground elevation (broad fault scarp). Each broad fault scarp feature is also identified by a line, at about the middle of the broad fault scarp. All the fault features have relative upthrow (U) to the north, with three exceptions. A well-expressed fault scarp at location A in Figure 1.1 is up to the southeast. Two short topographic steps at location C in Figure 1.1 are up to the south and are interpreted as likely active fault features. They may possibly have been formed by prehistoric river action, but their location, and because the eastern step forms one margin of a closed basin depression on the river plain (Figure 2.1), leads me to prefer their interpretation as broad fault scarps.

The landform features along the Starvation Hill Fault illustrate a complex expression of ground surface deformation (Figure 1.1). This is not unusual and has similarities with the recent example of ground deformation produced along the 4th of September 2010 Greendale Fault, rupture, which generated the Darfield Earthquake (Barrell et al. 2011b). The broad fault scarps of the Starvation Hill Fault are interpreted as zones where distributed fault deformation has emerged at the ground surface from more focused offset on the main fault at depth (e.g. maybe 50 to 100 m below the ground surface). These zones of broad deformation may relate to warping/tiling of the ground, to incremental strain, or a combination of both. The relatively sharp fault scarp landforms have a discontinuous and somewhat arcuate character. These are interpreted as localised subsidiary faults that have broken out from the main fault at depth. Near location A in Figure 1.1, the considerable (~300 m) width of the broad fault scarp landform led me to interpret it as a monoclinal (one-sided) fold of the ground surface (Figure 1.1). The formation of broad fault scarps via distributed ground deformation in combination with localised rupture break-outs resulting in well-defined fault scarps is a demonstrated characteristic of some active faults in New Zealand, with examples shown in Figure 2.2.

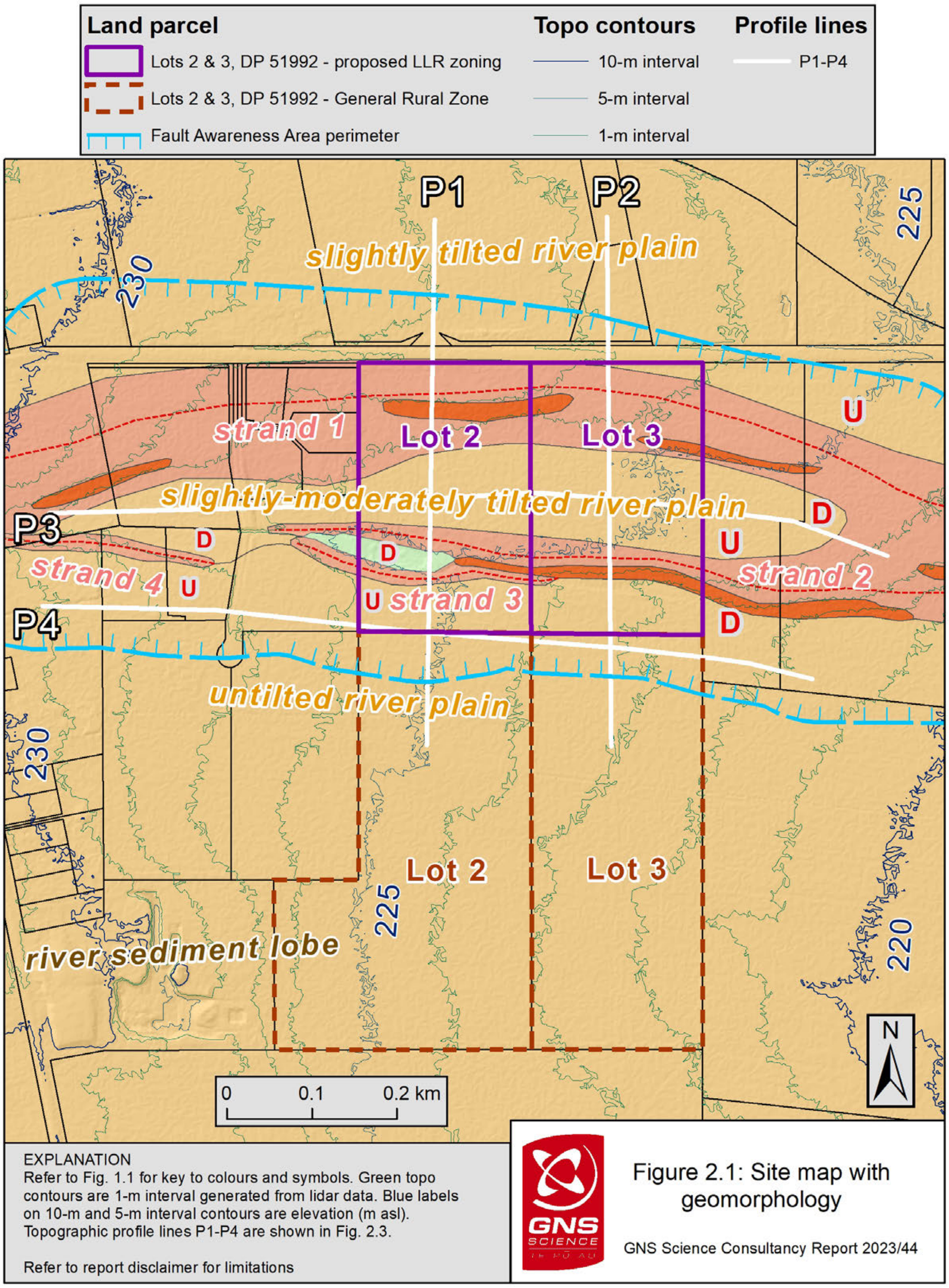

Figure 2.1 Site map with geomorphology. Topographic profiles P1-P4 are presented in Figure 2.3. Different elements of the fault-related landforms are identified as strands, which are discussed in the text.

Figure 2.2 Illustrative fault scarp photos. **A**: View of a ~100-m-wide, broad fault scarp, or monoclinal fold, in the Clarence River valley, North Canterbury, formed during rupture of the Papatea Fault in the 2016 Kaikōura Earthquake (Van Dissen et al. 2019). Prior to the 2016 rupture, the ground here was flat, and was level with the road (arrowed in green). Tilting of the formerly vertical pine trees illustrates the 2016 ground deformation. Photo: DJA Barrell, November 2017. **B**: A localised fault scarp (green arrow) marking a small fault break-out associated with a broad monoclinal fold west of Twizel, South Canterbury. The ~150-m-wide monocline runs left to right across this river plain, and the fence and lower parts of the distant pine trees disappear from view beyond the crest of the fold. Subsequent trenching showed that the fault scarp is formed over a ~0.6 m near-vertical fault offset of the river plain deposits (Barrell 2019a). Photo: DJA Barrell, April 2019.

To examine in closer detail the land parcel proposed for LLR zoning, four topographic profiles were generated from the lidar DEM (Figure 2.1) and are presented in Figure 2.3. The profiles together with topographic contours derived from the lidar data (see Figures 1.1 and 2.1) greatly assist in the interpretation of landform features at the location of the land parcel.

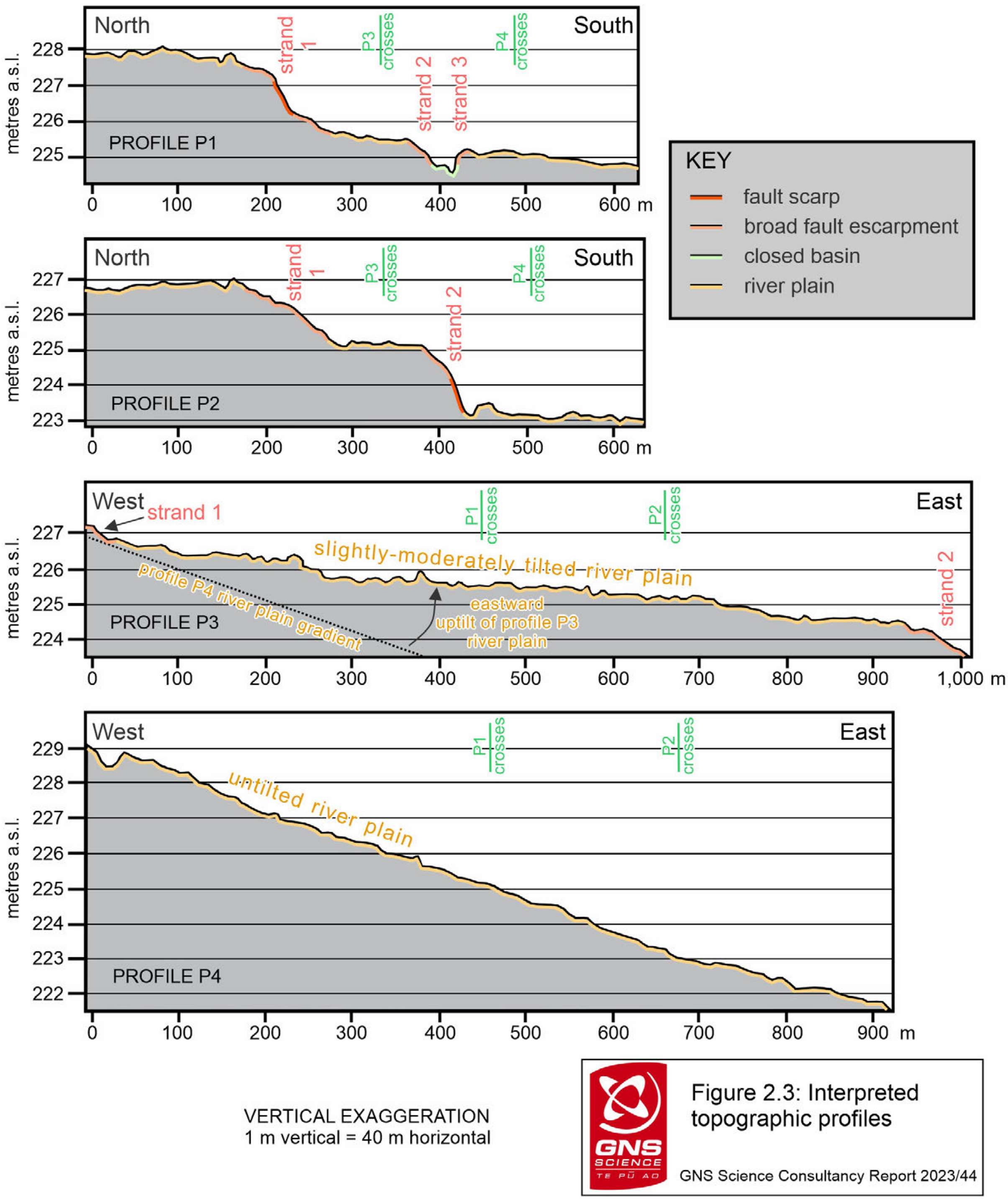

Figure 2.3 Interpreted topographic profiles. Profile locations are shown in Figure 2.1. The subsurface is shown in grey, with a black line for the ground profile. Lines below the ground profile correspond in colour to the units on the geomorphological map (Figures 1.1 and 2.1). Profile intersection locations are denoted in green. All profiles are the same scale, with the vertical dimension exaggerated 40 times relative to the horizontal scale to accentuate the subtle landform features.

In proximity to the land parcel, the fault landforms are identified as 'strands' to aid description and discussion (Figures 2.1 and 2.3). The strand 1 fault scarp decreases in height from west to east, while the strand 2 scarp begins immediately west of the land parcel and increases in height towards the east. Strands 3 and 4 are short broad fault scarps that are up to the south. If correctly interpreted as faults, strands 3 and 4 probably represent short extensional fault features within the overall zone of the Starvation Hill Fault, as discussed further in Section 3.

The gradient of the Eyre River plain in the vicinity of the land parcel south of the Starvation Hill Fault is typical for this part of the Canterbury Plains, with a fall (elevation change in the direction of former river flow) of 1 m in about 120 m distance (Figure 2.3, profile P4). The Eyre River plain immediately south of the Starvation Hill Fault is regarded as 'untilted' and taken as representing the original natural gradient of the river plain in this area (Figures 2.1 and 2.3). The section of river plain at the land parcel between fault strands 1 and 2 is anomalously flat, with a fall of 1 m in about 460 m distance. This is difficult, though not impossible, to reconcile as being a natural river gradient on this part of the Canterbury Plains, and instead provides further indication that the ground here has been affected by fault-related deformation. It is identified as 'slightly-moderately tilted river plain' in Figure 2.1 and illustrated in profile P3 (Figure 2.3). The Eyre River plain immediately north of the Starvation Hill Fault falls at 1 m per 180 m and is interpreted as 'slightly tilted' (Figure 2.1).

Drawing together the information above, the landform history in the vicinity of the land parcel can be summarised as follows. During the Last Glaciation (approximately between 65,000 and 18,000 years ago), rivers of the Canterbury Plains, including the Eyre River, had wide-ranging courses across the plains (Barrell et al. 2011a). The glacial episode ended about 18,000 years ago, with rapid warming of climate (Denton et al. 2021). The climatic improvement reduced the river sediment load, with most rivers adopting more stable courses, incised slightly below the main surface of the plains. On this basis, 18,000 years ago is adopted as the time when river action ceased across much of the plains (Barrell and Begg 2013). Since then, movement on the Starvation Hill Fault has deformed the surface of the Eyre River plain. The vertical component of deformation increasing towards the east accounts for the slight tilt of the river plain north of the fault (westward tilt reducing the original eastward gradient of the plain). Emergence of the strand 2 fault, and its rapid height increase towards the east accounts for a distinct westward tilt on the river plain section between strands 1 and 2, which has reduced the original eastward gradient of the river plain to almost flat (Figures 2.1 and 2.3).

3.0 HAZARD ASSESSMENT

3.1 Active Fault Characterisation

Two common ways of characterising the degree of activity of a fault are slip rate and recurrence interval[1]. The behaviour of an active fault generally comprises a relatively long period of no movement, during which strain slowly builds up in the subsurface rock, until the fault moves (ruptures) in a sudden slip event, causing an earthquake. For faults where the largest slip events are sufficient to produce ground-surface rupture (as applies to the Starvation Hill Fault), each slip event can be expected to involve sudden ground-deforming movement on the fault of as much as several metres. Average recurrence interval for ground-surface fault rupture is the parameter that forms the basis for the risk-based evaluation of fault rupture hazard defined in the MfE active fault guidelines (Kerr et al. 2003). The most active of New Zealand's faults experience a surface rupture once every few hundred years, but for most faults, up to several thousand years elapse between ruptures (e.g. Stirling et al. 2012). This means the historically-documented record of New Zealand earthquakes (~200 years) is too short to be useful. Instead, the geological record of deformation of young deposits and landforms is the main source of evidence needed to define a recurrence interval for a specific active fault.

The degree of activity of a fault is usually assessed by excavating a trench across a zone of displaced ground above a fault to obtain a history of movement by measuring previous offsets and geological dating of sediment layers. The Starvation Hill Fault has not been trenched and the information presented below is based on geological inference. Although the Starvation Hill Fault is classified as only a 'likely' active fault, it has been included in national active fault data compilations. Litchfield et al. (2014) regarded it as part of the 'Cust' active fault zone, which they characterised as being a reverse (contractional) fault, with a fault plane dipping (inclined) towards the northwest at an angle of between 40° and 60° from horizontal, and a slip rate of between 0.1 and 0.3 mm/year. An updated compilation (Seebeck et al. 2022, 2023) proposes a link between the Ashley Fault Zone (Barrell and Van Dissen 2014, and references therein) and the Starvation Hill Fault, as an entity named the 'Starvation – Ashley' fault. It is assigned a fault plane dip of between 60° and 80° from horizontal towards the north, and a slip rate of between 0.4 and 0.8 mm/year (0.6 mm/year as the most likely value). Its sense of movement is proposed to be partly contractional (reverse) and partly sideways (strike-slip). This sense of movement acknowledges the regional setting of North Canterbury's active faults (Campbell et al. 2012; Jongens et al. 2012), wherein a fault that is aligned east-west (such as the Starvation Hill Fault) is likely to carry a small to substantial component of right-lateral strike slip. A component of right-lateral slip would be compatible with the array of discontinuous small sinuous fault scarp break-outs along the Starvation Hill Fault, although such break-outs are not necessarily diagnostic of there being a component of strike slip. If the 'likely' broad fault scarps of strands 3 and 4 are fault-related in origin, they are strongly indicative of a substantial (e.g. 50%) component of strike-slip motion on the Starvation Hill Fault, due to the opposite sense of upthrow between these strands and strands 1 and 2.

---

[1] The **slip rate** is the long-term average rate of movement on a fault across multiple earthquakes. This is usually calculated from the amount of fault offset of a land surface feature, such as a river plain, divided by the estimated age of the land surface feature and expressed in mm per year. This does not mean that the fault moves a certain amount each year but is simply a way of expressing its degree of activity. A large (high) average slip rate (e.g. 2 mm/year) indicates that a fault can be expected to experience a ground-surface rupture event more frequently than a fault with a small (low) slip rate (e.g. 0.2 mm/year). Average **recurrence interval** is the average length of time (expressed in years) that can be expected to elapse between ground-surface rupturing events.

For the Ashley Fault Zone, a previous trenching and dating investigation indicates its most recent surface rupture was about 5000 years ago (Sisson et al. 2001). An earlier rupture is registered by a larger offset of adjacent, slightly higher (and thus older) river terraces, for which an age of 16,000 ± 4000 years was inferred by Barrell and Van Dissen (2014). Assuming that the offset of the older river terraces was from just two ruptures of the fault, Barrell and Van Dissen (2014) calculated a recurrence interval range of between 7,000 years (time elapsed between the 12,000-year minimum age of the older terrace and the most recent rupture ~5000 years ago) and 15,000 years (time elapsed between the 20,000-year maximum age of the older terrace and the most recent rupture ~5000 years ago). They also considered the possibility that the older terrace offset may have been the result of three rather than two ruptures, in which case the recurrence interval could be as short as ~5000 years.

Despite the connection implied by Seebeck et al. (2022, 2023) between the Ashley Fault Zone and Starvation Hill Fault, whether the two faults share identical rupture histories, or degrees of activity, remains an open question. It is possible, for example, that even if they are structurally connected, they do not always rupture in the same earthquake.

The slip rate assigned to the Starvation – Ashley fault entity by Seebeck et al. (2022, 2023) of 0.6 ± 0.2 mm/year was estimated by me, based on the ~7 m of vertical deformation of the inferred 18,000-year-old river plain south of Starvation Hill[2]. The slip-rate range encompasses end-member possibilities that the landform-registered vertical deformation relates to purely reverse movement on a near-vertical fault (0.4 mm/year) or was produced by a substantial component of strike-slip motion on a moderately steep fault (0.8 mm/year). I consider that the breadth of this range adequately accounts for uncertainties in the estimated amount of deformation and age of the river plain. The lack of trenching or dating information for the Starvation Hill Fault means that its recurrence interval is unknown. I provisionally adopt the estimates for the Ashley Fault Zone (Barrell and Van Dissen 2014), and thus there is a possibility that the Starvation Hill Fault recurrence interval may be somewhat less than 5000 years. I consider that an appropriately conservative approach is to assume, for the purposes of hazard evaluation, that the recurrence interval is in the range of 3500 to 5000 years (recurrence interval class III of Kerr et al. 2003), as discussed further in Section 3.4.

3.2 Ground Deformation Classification

Following the approach of Barrell and Van Dissen (2014), a ground deformation classification map has been produced for the land parcel (Figure 3.1). For maximum context, the map encompasses the two entire properties, not just the parts of each that are proposed for LLR zoning. The ground deformation map units are described in Table 3.1, along with an indication of the likely effects of a ground-deforming fault rupture, and the relationship of the deformation map units to fault complexity class.

[2] The Seebeck et al. (2022, 2023) fault entities are characterized in relation to movement at depth. As some movement may be diffused as it approaches the ground surface, places where ground surface deformation is greater may be more indicative of the fault's overall movement (with some exceptions).

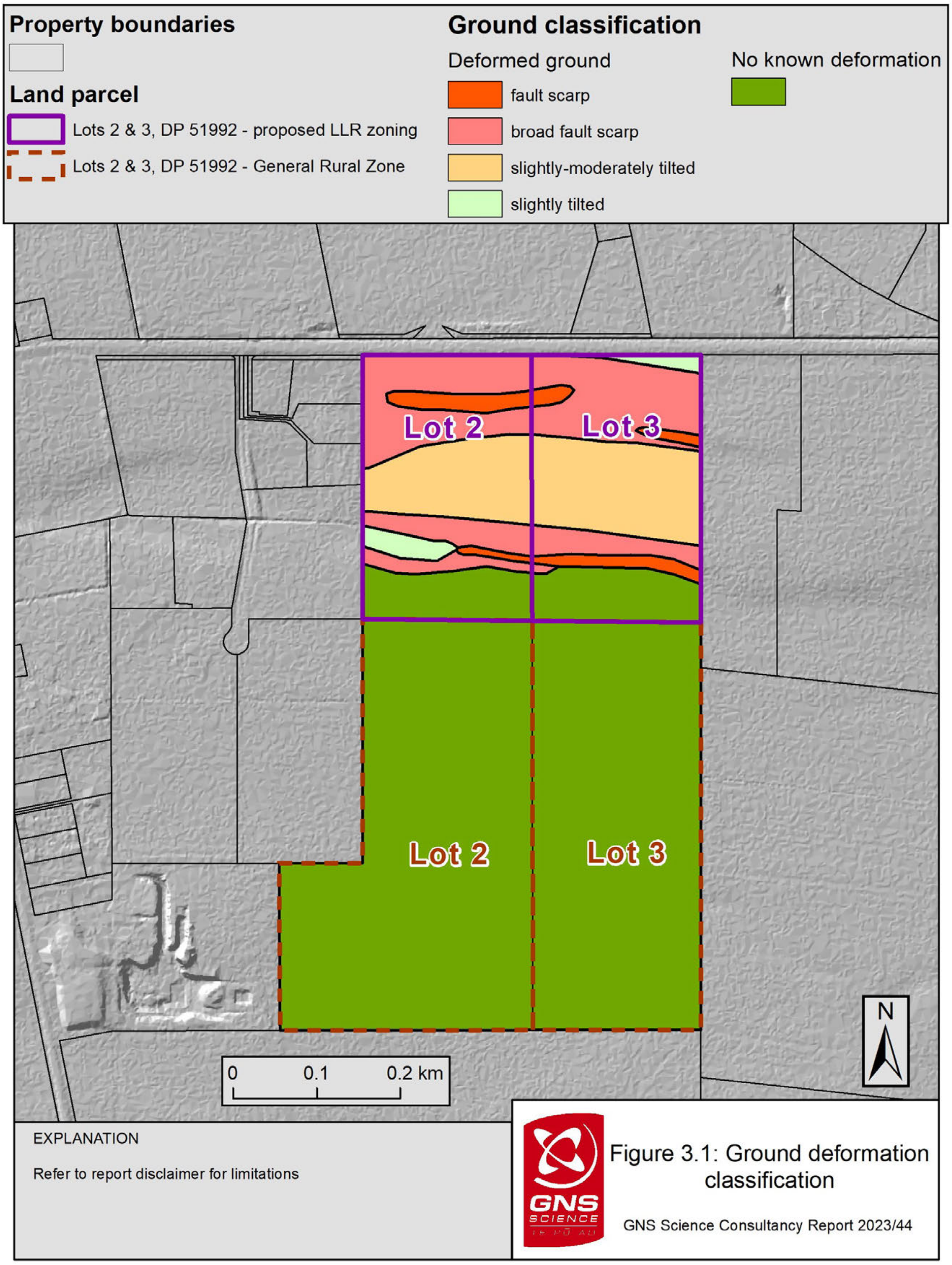

Figure 3.1 Ground deformation classification. Map units are described in Table 3.1.

3.3 Fault Avoidance Zonation

'Fault complexity' is a useful way of defining fault rupture ground deformation hazard (Table 3.1). 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 deformation zone. Following the approach recommended in the

MfE active fault guidelines (Kerr et al. 2003), and previously applied for the Ashley Fault Zone (Barrell and Van Dissen 2014), the categories of fault complexity used in this report, and illustrated in Figure 3.2, are:

- Well-defined deformation, where previous deformation has been concentrated across a narrow area.
- Distributed deformation, where previous deformation has been distributed across a wider area.
- Uncertain deformation – constrained, which is applied to areas where the ground has experienced previous tilting related to fault rupture.

Table 3.1 Starvation Hill Fault ground deformation classification for the Lots 2 and 3 DP 51992 land parcel. Description is provided for each deformation class, along with likely effects of a ground-deforming fault rupture and relationship to fault complexity class. After Barrell and Van Dissen (2014).

Ground Classification	Description (slope angles are relative to original ground slope of ~0.5°)	Likely Effects on Buildings in a Ground-deforming Fault Rupture	Fault Complexity Class
Fault scarp	Well expressed topographic step attributed to physical breakage of the ground by fault movement in an earthquake. There may be associated warping or tilting. Slope generally at least 10° steeper than original ground slope.	Serious damage or destruction; life safety threat to occupants.	Well-defined deformation.
Broad fault scarp	Broad, moderately clearly expressed topographic step. Interpreted to be a result of distributed strain or tilting/warping of the ground, or some combination.	Slight to serious damage; possible life safety threat to occupants.	Distributed deformation.
Slightly – moderately tilted ground	Slight but identifiable tilt (up to 0.4°) relative to the original ground slope.	Building out of plumb. Ground shaking effects dominate life safety hazard to occupants.	Uncertain deformation – constrained.
Slightly tilted ground	Slight tilt (typically <0.2°) relative to the original ground slope.		
No known 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 identified ground deformation hazard.

An additional component of fault avoidance zonation is an appropriate set-back distance. The set-back ('buffer') accounts for small uncertainties in defining the limits of the deformed ground and an allowance for some expansion in the extent of deformed ground in the next fault rupture. In accordance with the MfE active fault guidelines, a 20-m-wide buffer has been generated around the well-defined and the distributed deformation zones. The buffers together with the fault complexity mapping of well-defined and distributed deformation areas form a fault avoidance zonation map (Figure 3.2). In relation to the tilted ground on the land parcel, buffering was not done for the 'uncertain – constrained' deformation areas, because the buffers would lie within the areas already encompassed by the well-defined and distributed deformation zones, and their buffers.

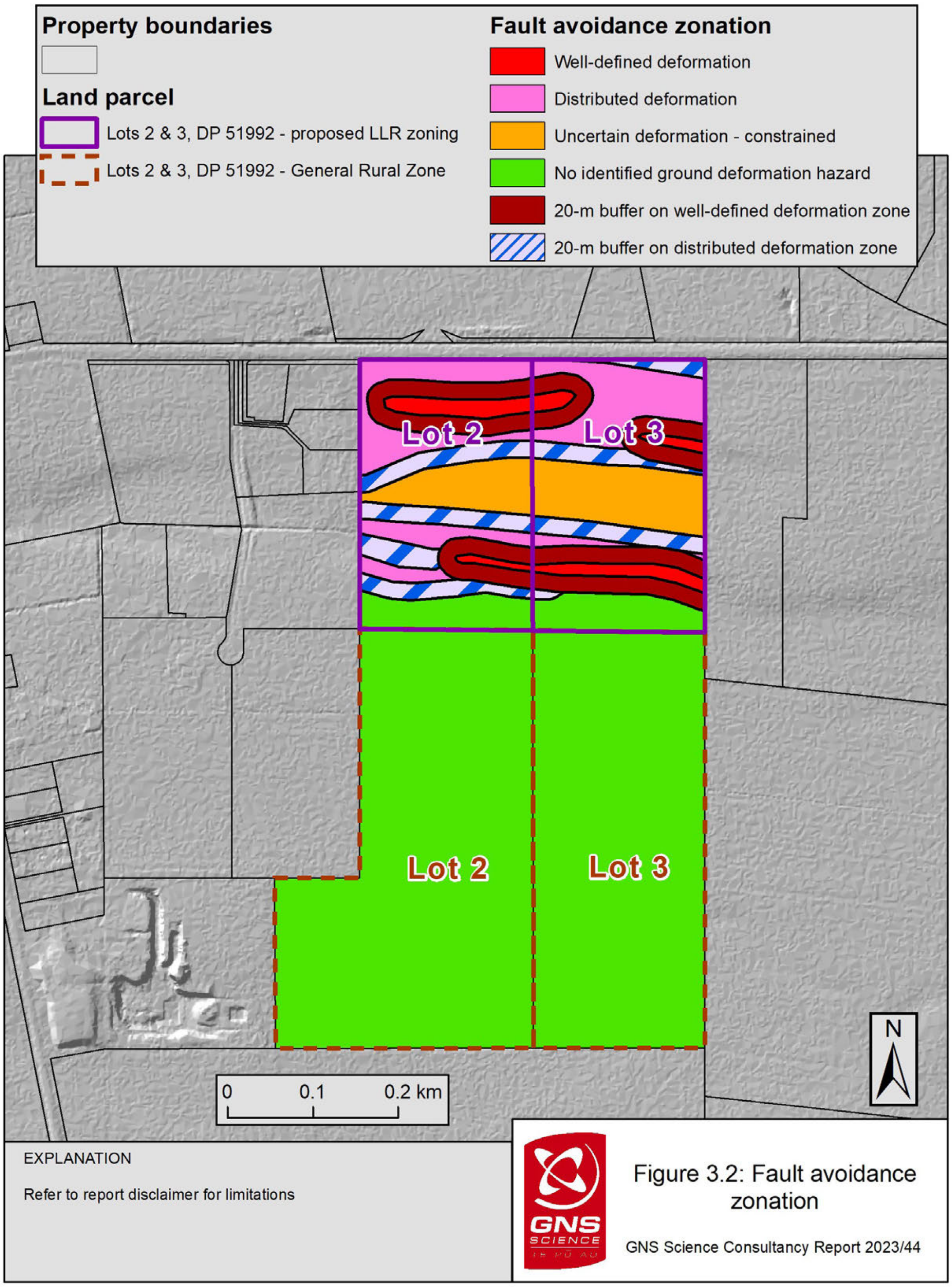

Figure 3.2 Fault avoidance zonation. The map shows the components of deformed ground, as well as the buffers on those components. Collectively, those components, and their buffers, make up the fault avoidance zones See text for discussion.

3.4 Building Importance Categories and Consent Categories

Surface-rupture fault avoidance zonation in the MfE active fault guidelines (Kerr et al. 2003) involves a risk-based approach that accounts for the significance of buildings (Building Importance Category (BIC), Table 3.2), and recurrence interval (Table 3.3). Distinction is made between previously subdivided and/or developed sites, and undeveloped 'greenfield' sites, allowing for different conditions to apply to these two types of sites (Table 3.3).

Table 3.2 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 3.3 Relationships between recurrence interval (RI) and Building Importance Category (BIC). From the MfE active fault guidelines (Kerr et al. 2003).

RI Class	Average RI for Surface Rupture	BIC Limitations (allowable buildings): Previously Subdivided or Developed Sites	BIC Limitations (allowable buildings): 'Greenfield' Sites
I	≤2000 years	BIC 1 temporary buildings only.	BIC 1 temporary buildings only.
II	>2000 years to ≤3500 years	BIC 1 and 2a temporary and residential timber-framed buildings only.	
III	>3500 years to ≤5000 years	BIC 1, 2a, and 2b temporary, residential timber-framed and normal structures.	BIC 1 and 2a temporary and residential timber-framed buildings only.
IV	>5000 years to ≤10,000 years	BIC 1, 2a, 2b and 3 temporary, residential timber-framed, normal and important structures (but not critical post-disaster facilities).	BIC 1, 2a, and 2b temporary, residential timber-framed and normal structures.
V	>10,000 years to ≤20,000 years		BIC 1, 2a, 2b and 3 temporary, residential timber-framed, normal and important structures (but not critical post-disaster facilities).
VI	>20,000 years to ≤125,000 years	BIC 1, 2a, 2b, 3 and 4 critical post-disaster facilities cannot be built across an active fault with a recurrence interval ≤20,000 years.	
Note: Faults with average recurrence intervals >125,000 years are not considered active.			

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. As discussed in Section 3.1, the lack of direct data on Starvation Hill Fault activity means that a conservative adoption of a surface-rupture recurrence interval class III (>3500 to ≤5000 years) is my recommended approach. Table 3.4 sets out suggested resource consent categories for the Starvation Hill Fault in relation to the fault avoidance zonation of the land parcel. Because the proposed rezoning of parts of Lots 2 and 3, DP 51992 to LLR equates to a greenfield development, resource consent categorisation for previously subdivided and/or developed sites, such as Barrell and Van Dissen (2014) provided for the Ashley Fault Zone, is not included in Table 3.4.

Under the class III categorisation, construction of BIC 2a buildings within the Starvation Hill Fault avoidance zones could, from a risk perspective, be a permitted activity, in a greenfield development. Construction of BIC 2b buildings within the fault avoidance zones would be a non-complying activity. Critical structures (BIC 4) and important structures (BIC 3) would be non-complying (Table 3.4). Construction of BIC 2b buildings on the tilted ground (uncertain – constrained deformation) is indicated as a discretionary activity. Assigning a controlled or discretionary status to BIC 2 structures could be considered in locations where the deformation is well defined, for example not having dwellings straddling a fault scarp. It should be noted that the MfE active fault guidelines (Kerr et al. 2003) is not binding, and the determination of what is permitted or otherwise is a matter for the territorial authority to decide.

Table 3.4 Suggested resource consent categories for the land parcel in relation to the Starvation Hill Fault. The fault complexity avoidance zonation, including the set-back buffers, would apply to all categories except 'permitted'. After Barrell and Van Dissen (2014). BIC = Building Importance Category; RI = recurrence interval.

Starvation Hill Fault at Lots 2 and 3, DP 51992 Greenfield Setting, RI Class III, >3500 to ≤5000 years					
BIC	**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
* Indicates that the resource consent category is permitted but could be controlled or discretionary at locations where the fault location is well-defined. Italics: Indicates 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.					

3.5 Discussion

The fault scarps (well-defined deformation) represent discontinuous zones of previous fault break-outs within the broad fault scarps (distributed deformation). In future ruptures, it is conceivable that the existing fault scarps might lengthen, or new ones might break out in other locations within the broad fault scarps (distributed deformation zones). While a case might be made for treating the well-defined fault avoidance zones with greater caution, for example by making them exclusion areas for dwellings, I recommend a more cautious approach where the well-defined and distributed fault avoidance zones are treated equally in regard to siting of buildings. For that reason, the well-defined and distributed zones are combined in Table 3.4.

The anticipated consequences of a future rupture of the Starvation Hill Fault include focused differential deformation of the ground in the well-distributed deformation areas, broader differential change in ground elevation in the distributed deformation areas, and accrual of further tilt of the ground in areas of uncertain – constrained deformation. Thus, differential change in ground elevation would be the main hazard to any future buildings within the fault avoidance zone the land parcel. If the proposed rezoning were to proceed, a mitigation to reduce adverse effects of a future fault rupture, and associated differential land movement, may be a condition that in the fault avoidance zones, dwellings be designed so that they could be relevelled relatively easily, for example by using a piled foundation.

Fault surface-rupture recurrence interval is a key criterion for assessing risk to buildings. There is currently no direct information on the rupture history, or recurrence interval, of the Starvation Hill Fault. A trenching and dating investigation of the Starvation Hill Fault may be able to obtain geological information on the fault rupture history and recurrence, which would help refine the assessment of future fault rupture hazard and risk. Such investigations need to target fault offsets of the ground and near-surface sediments; tilted ground or tilted sediments will not provide definitive information. Therefore, only the well-expressed fault scarps would be suitable for such an investigation. It would be advantageous to consider commissioning a trenching and dating investigation of the Starvation Hill Fault ahead of making any final decision on the suitability of rezoning the land as currently proposed.

The extent of the proposed LLR rezoning of Lots 2 and 3, DP 51992, is almost entirely within the fault avoidance zones of the Starvation Hill Fault (Figure 3.2). The remainder of those lots, representing well over half of their land areas, is entirely outside the fault avoidance zones, in the area of ground classed as having ‘no ground deformation hazard’. That area is considered to be free from fault rupture or significant tectonic ground deformation hazards. From a fault deformation hazard avoidance perspective, those parts of the lots would be suitable for the construction of any type of residential, commercial or industrial building that conforms to New Zealand building codes. If the proposed zoning change was amended to retain the northern parts of Lots 2 and 3 as General Rural Zone and create a LLR zone on the central to southern parts of the lots, beyond the fault avoidance zones, with an access easement from Oxford Road, there would be no active fault hazard to consider for building in the revised LLR zone.

A final consideration is that in the event of a future ground surface-rupturing earthquake on the Starvation Hill Fault, all areas in the general vicinity of the fault (i.e. Oxford and other nearby 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.

4.0 CONCLUSIONS

1. Information gathered as part of this desk-based assessment has reinforced previous assessments that the Starvation Hill Fault is likely to be an active geological fault.
2. The northern parts of Lot 2 and Lot 3, Deposited Plan (DP) 51992, that are proposed to be rezoned from Rural Zone to Large Lot Residential (LLR) Zone, lie almost entirely on ground that is interpreted to have previously experienced deformation as a result of ruptures of the Starvation Hill Fault.
3. The fault-related landform features are classified as fault scarps (well-defined deformation), broad fault scarps (distributed deformation), and slightly to moderately tilted ground and slightly tilted ground (uncertain deformation – constrained).
4. The broad fault scarps are interpreted to have formed by diffused deformation from the main fault rupture, perhaps 50 to 100 m underground. The fault scarps are interpreted as more focused ground-surface offsets on subsidiary fault break-outs from the main fault at depth. The tilted ground is interpreted to have been produced by progressive changes in height along the line of the fault scarps. In addition to the vertical deformation registered in the fault-related landforms, there may be a component of sideways deformation.
5. Buffers of 20-m width have been generated around the outer perimeters of the mapped zones of well-defined deformation and distributed deformation. These buffers together with the deformation zones constitute fault avoidance zones, for various combinations of Building Importance Category and average recurrence interval for surface rupture on the Starvation Hill Fault.
6. There is no direct information on the recurrence interval for surface rupture on the Starvation Hill Fault. Based on geological inference, the recurrence interval may possibly be somewhat less than 5000 years. It is recommended that recurrence interval class III (>3500 to ≤5000 years) be used for applying the Ministry for the Environment (MfE) guidelines for planning for development of land on or close to active faults (Kerr et al. 2003). A targeted geological trenching and dating investigation of the Starvation Hill Fault may be able to obtain data to improve the estimation of recurrence interval for the fault.
7. The MfE active fault guidelines indicate that for a class III recurrence interval active fault, in a greenfield setting, construction of single-story timber-framed dwellings of less than 300 m^2 area may be a permitted activity within the fault avoidance zones. However, the guidelines are not binding and it is for a council to determine what activities to allow.
8. The central and southern parts of Lots 2 and 3, DP 51992, which are proposed to retain rural land-use zoning (General Rural Zone) are on ground classed as having ‘no ground deformation hazard’. Instead, if the zoning proposal was amended to place the northern parts of Lots 2 and 3, encompassing the fault avoidance zones, in General Rural Zone, and create a LLR zone on the central to southern parts of the lots, there would be no active fault hazard to consider for building in the revised LLR zone.

5.0 ACKNOWLEDGEMENTS

This report has benefitted from technical reviews by Nicola Litchfield and Genevieve Coffey of GNS Science.

6.0 REFERENCES

Barrell DJA. 2019a. Assessment of fault location for the proposed subdivision of Lots 16 & 17 DP 82890, Manuka Terrace, Twizel, South Canterbury. Lower Hutt (NZ): GNS Science. 35 p. Consultancy Report 2019/59. Prepared for McKenzie Downs (2004) Limited.

Barrell DJA. 2019b. Review of active fault information for the Waimakariri District. Lower Hutt (NZ): GNS Science. 10 p. Consultancy Report 2019/141LR. Prepared for Environment Canterbury.

Barrell DJA, Begg JG. 2013. General distribution and characteristics of active faults and folds in the Waimakariri District, North Canterbury. Lower Hutt (NZ): GNS Science. 53 p. Consultancy Report 2012/326. Prepared for Environment Canterbury.

Barrell DJA, Van Dissen RJ. 2014. Assessment of active fault ground deformation hazards associated with the Ashley Fault Zone, Loburn, North Canterbury. Lower Hutt (NZ): GNS Science. 59 p. Consultancy Report 2013/173. Prepared for Environment Canterbury.

Barrell DJA, Andersen BG, Denton GH. 2011a. Glacial geomorphology of the central South Island, New Zealand. Lower Hutt (NZ): GNS Science. 81 p. + 6 sheets (GNS Science monograph; 27).

Barrell DJA, Litchfield NJ, Townsend DB, Quigley M, Van Dissen RJ, Cosgrove R, Cox SC, Furlong K, Villamor P, Begg JG, et al. 2011b. Strike-slip ground-surface rupture (Greendale Fault) associated with the 4 September 2010 Darfield Earthquake, Canterbury, New Zealand. *Quarterly Journal of Engineering Geology and Hydrogeology*. 44(3):283–291. https://doi.org/10.1144/1470-9236/11-034

Barrell DJA, Jack H, Gadsby M. 2015. Guidelines for using regional-scale earthquake fault information in Canterbury. Lower Hutt (NZ): GNS Science. 30 p. Consultancy Report 2014/211. Prepared for Environment Canterbury.

Campbell JK, Pettinga JR, Jongens R. 2012. The tectonic and structural setting of the 4th September 2010 Darfield (Canterbury) earthquake sequence, New Zealand. *New Zealand Journal of Geology and Geophysics*. 55(3):155–168. https://doi.org/10.1080/00288306.2012.690768

Denton GH, Putnam AE, Russell JL, Barrell DJA, Schaefer JM, Kaplan MR, Strand PD. 2021. The Zealandia switch: ice age climate shifts viewed from Southern Hemisphere moraines. *Quaternary Science Reviews*. 257:106771. https://doi.org/10.1016/j.quascirev.2020.106771

Forsyth PJ, Barrell DJA, Jongens R. 2008. Geology of the Christchurch area [map]. Lower Hutt (NZ): GNS Science. 1 fold. map + 67 p., scale 1:250,000. (Institute of Geological & Nuclear Sciences 1:250,000 geological map; 16).

Jack H. 2020. Using earthquake fault information in the Waimakariri District Plan review [memo]. Christchurch (NZ): Environment Canterbury. 12 p. Prepared for Waimakariri District Council.

Jongens R, Barrell DJA, Campbell JK, Pettinga JR. 2012. Faulting and folding beneath the Canterbury Plains identified prior to the 2010 emergence of the Greendale Fault. *New Zealand Journal of Geology and Geophysics*. 55(3):169–176. https://doi.org/10.1080/00288306.2012.674050

Kerr J, Nathan S, Van Dissen R, Webb P, Brunsdon D, King, A. 2003. Planning for development of land on or close to active faults: a guideline to assist resource management planners in New Zealand. Wellington (NZ): Ministry for the Environment. 67 p. ME 483. Accessible from the Ministry for the Environment website: https://environment.govt.nz/; search term < active faults guidelines >

Litchfield NJ, Van Dissen RJ, Sutherland R, Barnes PM, Cox SC, Norris R, Beavan RJ, Langridge RM, Villamor P, Berryman KR, et al. 2014. A model of active faulting in New Zealand. *New Zealand Journal of Geology and Geophysics*. 57(1):32–56. https://doi.org/10.1080/00288306.2013.854256

Seebeck H, Van Dissen RJ, Litchfield NJ, Barnes PM, Nicol A, Langridge RM, Barrell DJA, Villamor P, Ellis SM, Rattenbury MS, et al. 2022. New Zealand Community Fault Model – version 1.0. Lower Hutt (NZ): GNS Science. 97 p. (GNS Science report; 2021/57). https://doi.org/10.21420/GA7S-BS61

Seebeck H, Van Dissen RJ, Litchfield NJ, Barnes PM, Nicol A, Langridge RM, Barrell DJA, Villamor P, Ellis SM, Rattenbury MS, et al. 2023. The New Zealand Community Fault Model – version 1.0: an improved geological foundation for seismic hazard modelling. New Zealand Journal of Geology and Geophysics. https://doi.org/10.1080/00288306.2023.2181362

Sisson RJ, Campbell J, Pettinga J, Milner D. 2001. Paleoseismicity of the Ashley and Loburn faults, North Canterbury, New Zealand. Christchurch (NZ): University of Canterbury. 31 p. EQC Research Project 97/237. Prepared for Earthquake Commission Research Foundation. Accessible from the Toka Tū Ake EQC website: https://www.eqc.govt.nz/; search term < Ashley Fault >

Stirling M, McVerry G, Gerstenberger M, Litchfield N, Van Dissen R, Berryman K, Barnes P, Wallace L, Bradley B, Villamor P. et al. 2012. National seismic hazard model for New Zealand: 2010 update. *Bulletin of the Seismological Society of America*. 102:1514–1542. https://doi.org/10.1785/0120110170

Van Dissen RJ, Stahl T, King AB, Pettinga JR, Fenton C, Little TA, Litchfield NJ, Stirling MW, Langridge RM, Nicol A, et al. 2019. Impacts of surface fault rupture on residential structures and rural infrastructure during the 2016 M_W Kaikōura earthquake, New Zealand. *Bulletin of the New Zealand Society for Earthquake Engineering*. 52(1):1–22. https://doi.org/10.5459/bnzsee.52.1.1-22

www.gns.cri.nz

Principal Location

1 Fairway Drive, Avalon
Lower Hutt 5010
PO Box 30368
Lower Hutt 5040
New Zealand
T +64-4-570 1444
F +64-4-570 4600

Other Locations

Dunedin Research Centre
764 Cumberland Street
Private Bag 1930
Dunedin 9054
New Zealand
T +64-3-477 4050
F +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road
Private Bag 2000
Taupo 3352
New Zealand
T +64-7-374 8211
F +64-7-374 8199

National Isotope Centre
30 Gracefield Road
PO Box 30368
Lower Hutt 5040
New Zealand
T +64-4-570 1444
F +64-4-570 4657