Land damage and natural hazards in the Mt Lyford Village area following the 2016 Kaikōura earthquake

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EXECUTIVE SUMMARY

A team led by GNS Science and including engineers from Golder Associates (NZ) Ltd. has been tasked with assessing land damage at Mt Lyford Village, north Canterbury caused by the November 14th, 2016 M_w 7.8 Kaikōura earthquake.

Several houses within the village were given red or yellow Rapid Building Assessment (RBA) placards on the grounds of structural and/or land damage conditions. Seven of these houses within the village were later issued with section 124 notices. A post-earthquake reconnaissance was undertaken in August 2017 following the transition from RBA placarding to section 124 notices on buildings within the village. The reconnaissance confirmed the presence of co-seismic and ongoing ground failure related to slope instability. Where slopes were very steep, the land (including slopes above these areas) was prone to cracking, extension, and shallow to moderately deep slumping (landsliding). In some cases, extension, slumping and erosion was ongoing and exacerbated by post-earthquake rainfall.

Airborne Light Detection and Ranging (LiDAR) datasets were used for geomorphic mapping, fault mapping and to generate slope maps. From these digital maps, a very steep slope (>25°) category was defined, which extended the definition of Mt Lyford slopes in an earlier report by Hancox et al. (2006), with greater precision. Very steep slopes correspond with areas where intense landsliding and erosion has occurred during the Holocene period (last c. 11,700 years), particularly where creeks and streams have incised deep gullies in the area. Geomorphic mapping was used to help define the age of geologic surfaces, faulting and erosion across the wider area. This study notes a strong correlation between the very steep slopes, the land damage during and after the 2016 Kaikōura earthquake, and major structural damage to buildings.

Active faults were remapped across the area using the LiDAR-derived digital surface models. Fault trace data were used to develop Fault Avoidance Zones (FAZs) for several distinct fault traces here including the Tinline, Hedgerows, Avenue, Airstrip and Terako Station faults (informal names), and the Hope Fault. Based on revised paleoseismic trench and slip rate data the Hope, Tinline, Hedgerows, and Avenue faults have been defined as Recurrence Interval Class I (RI ≤2000 yr) faults, while the Airstrip and Terako Station faults have been defined as Recurrence Interval Class II (RI >2000-≤3500 yr) faults. Fault Avoidance Zones around these faults range from 60 to 140 m width, generally in relation to the mapped accuracy of the fault traces.

Other observations related to the Kaikōura earthquake in the Mt Lyford area include: evidence that accelerations of >1.0 g were experienced in the village; regional uplift of 1-2.5 m occurred based on differential LiDAR data and LINZ re-surveys; translation of the area by c. 1 m to the NNE from LINZ re-surveys; and possible co-seismic rupture on the NNW-striking Avenue fault in the village. In light of the earthquake, GNS has reassessed the Conditional Probability of failure of the Conway segment of the Hope Fault at c. 28% in 50 years (Goded et al., 2017).

This report is science-based and provides some recommendations regarding current and future land use planning. Planning Recommendations will follow in a separate report that will be subject to ongoing consultation between GNS and its partners, Hurunui District Council (HDC), Environment Canterbury and the landowners at Mt Lyford Village.

Results from this study should be used by HDC toward considering current and future land use practice at Mt Lyford Village. Four classifications of land considering slope and another regarding the presence of active faulting have been developed from this study. These are:

(1) Areas with gentle, moderate and steep slopes (all <25°); these are common throughout the village and provide good land for building and potential for future development. These areas may be limited by the presence of FAZs or other features that require investigation (such as ridge-parallel extensional features, formerly described by Hancox et al. 2006). For these reasons, a geotechnical study is suggested for future development of these areas.

(2) Areas with consistently very steep slopes (>25°) are not recommended to be used for further development.

(3) Areas that are within 20 m of very steep slopes. We recommend that a buffer of 20 m is applied to the upper edge of very steep slopes (2 above). A geotechnical report would be required in order for such areas to be developed in future to consider the issue of slope instability.

(4) Areas that have a mixed or terraced slope (i.e. having very steep slopes mixed with slopes <25°). For future development, a geotechnical report is recommended because of the potential for slope instability issues.

(5) or areas that fall within FAZs we recommend that any plans for future development of these areas apply the MfE guidelines (see Kerr et al. 2003) for building on or near active faults, as prescribed in this report.

In general, the areas classified and buffered due to very steep slopes have axes parallel to the drainage network (typically NW) while FAZs have axes parallel to the fault network (typically NE-SW). This means that, given our recommendations, there is effectively a grid or mesh of higher hazard versus lower hazard land. The usable land corresponds well with the ridgeline on the main part of the Mt Lyford Village where the building and land damage during the 2016 Kaikōura earthquake was less severe.

The mapping outcomes described above are presented as GIS data as part of the report. This data has been delivered to Hurunui District Council. Individual figures within this report are for illustrative purposes only.

1.0 INTRODUCTION

1.1 BACKGROUND

The M_w 7.8 Kaikōura earthquake struck at 12:03 a.m. on the 14th November 2016. The epicentre of the earthquake was south of the town of Waiau, north Canterbury (**Figure 1.1**; Kaiser et al., 2017). Strong to extreme seismic shaking causing extensive damage to both land and built structures, experienced over a large region spanning north Canterbury, Marlborough and Wellington City (Bradley et al., 2017). The earthquake ruptured an unprecedented number of faults in the region, with rupture propagating from the epicentral area in the southwest, toward the northeast, as far as Cook Strait (Hamling et al., 2017; Litchfield et al., in review). One of the major effects of the earthquake was to cause very extensive small-to-moderate landslides, interspersed with several very large landslides, and at least 200 landslide-dammed lakes in the hillier terrain (Dellow et al., 2017; Massey et al., 2018). Damage occurred to houses and other buildings in the main towns of North Canterbury and widespread damage occurred to infrastructure including roads, bridges, railways and utility networks (Stirling et al., 2017; Stringer et al., 2017). Ground motions from seismic shaking were variable across the affected regions (Figure 1.2). Some recorded ground motions exceeded 1.0 g (i.e. greater than the acceleration due to Earth's gravity), and possibly up to 3.0 g near Waiau (Kaiser et al., 2017). Ongoing aftershock activity occurred across the region and was particularly clustered near Kaikōura, and near the towns of Ward and Seddon in Marlborough, both of which are close to the epicentres of two moderate-to-large earthquakes that occurred in 2013 (Figure 1.1).

This report reviews the natural hazards and land damage at Mt Lyford Village (Hurunui District) following the November 14, 2016 Kaikōura earthquake. Along with other towns in North Canterbury, including Waiau, Cheviot and Kaikōura, the village suffered considerable damage to built structures and utilities. Mt Lyford Village is a rural-lifestyle village with a house construction covenant centred around the concept of log cabin building design. Within Mt Lyford Village, the impacts of the earthquake were variable. There is no doubt that intense co-seismic shaking was experienced throughout the village with anecdotal evidence suggesting that ground motions exceeded 1.0 g (a road grader in the village was apparently lifted off the ground and moved c. 2 m away).

As part of the earthquake response, Hurunui District Council (HDC) dispatched engineers to the village to assess and categorise the damage to built structures. The result of this assessment was a standard classification of red/yellow/white placarding being assigned to each dwelling in the village (Figure 1.3). These designations were later reviewed as part of the shift from post-earthquake response to council-led Section 124 notices under the Building Act 2004 (dangerous building, prohibited access) being placed on houses. The log cabins in the village had a variable response to the strong shaking. Seven of the buildings within the village were given red placards (dangerous building, no access) and four yellow placards (damaged building, limited access) for a variety of reasons. Forty-five other dwellings were given a white placard designation (undamaged building, no access restrictions). A preliminary assessment of the performance of the log cabin buildings was undertaken by PTL (NZ), a private log cabin engineering company (Buchanan and Moroder, 2017; Appendix 5). Dr. Daniel Moroder of PTL (NZ) was invited to be part of the project team to provide advice on the performance of log cabins relative to land damage and ground conditions (see Appendix 5).

In response to significant concern from Mt Lyford villagers for reassurance and a way forward in terms of life safety, way-of-life, and property value, HDC consulted with Environment Canterbury (ECan) to develop a medium-term response to the damage that resulted from the Kaikōura earthquake. One of the two fatalities from the Kaikōura earthquake occurred in the village.

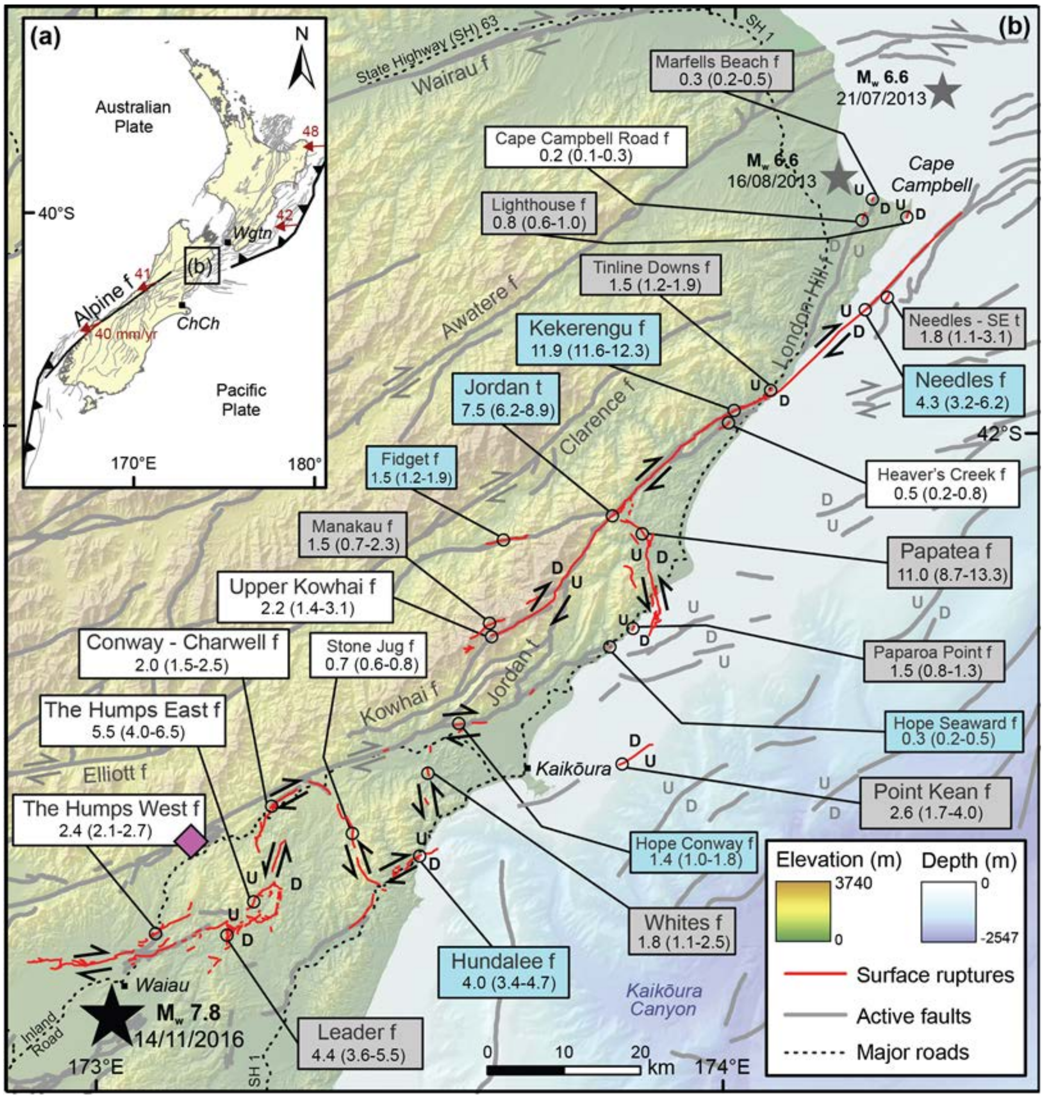

Figure 1.1 Fault ruptures that occurred during the 2016 Kaikōura earthquake (from Litchfield et al., in review). (a) Active tectonic setting of New Zealand including the main plate boundary fault structures. (b) 2016 fault ruptures (red lines) with named faults and their maximum slip value in metres. Grey lines indicate active faults that did not rupture during the 2016 earthquake. The purple diamond shows the location of Mt Lyford Village. Note also the epicentres of two M_w 6.6 earthquakes that occurred in 2013.

It was agreed that further geological reconnaissance studies would be required to understand what happened within the village during the earthquake (in terms of land damage and consequential damage to houses), and the ongoing safety of houses in the village. Bearing in mind the history of previous geotechnical investigations at Mt Lyford, HDC and ECan liaised with post-earthquake projects being managed through the Department of the Prime Minster and Cabinet (DPMC) and the Natural Hazards Research Platform (NHRP). The goal was to engage a multi-partisan team including geologists and geotechnical engineers. The team would be led by local experts from GNS Science and Golder Associates (NZ) Ltd.

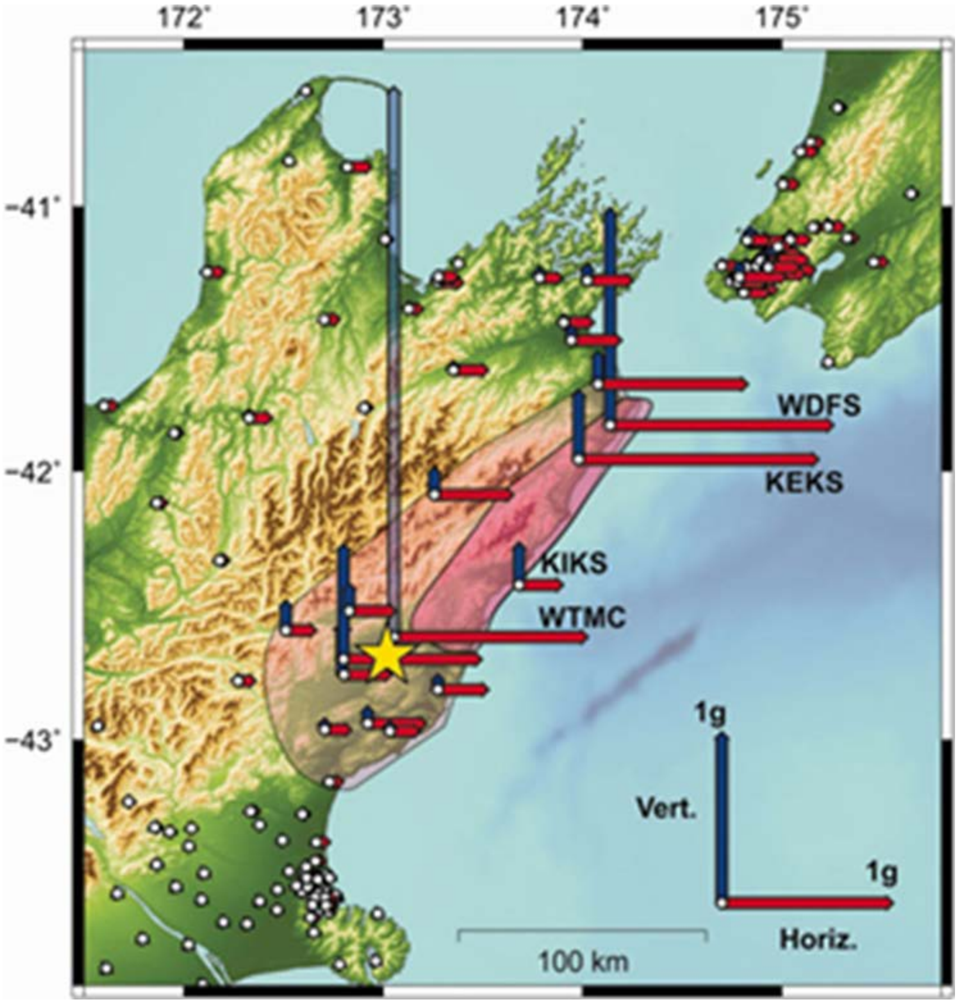

Figure 1.2 Peak ground accelerations in the horizontal (red) and vertical (blue) directions recorded at GeoNet strong-motion stations (from Kaiser et al., 2017). The epicentre of the Kaikōura earthquake is shown as a yellow star. Note that the vertical value of over 3g recorded at station WTMC (transparent blue bar = Waiau) has unusual characteristics, which are related to soil-structure interactions at the recording site. The approximate extent of mapped landslides is shown as pink shaded area, with the majority occurring in the darker shaded region.

This report has been constructed from a multi-institutional team whose task was to assess the co-seismic land damage that occurred during the earthquake and the ongoing hazard to built structures in the village itself.

The project team included, from:

- GNS Science – Dr. Rob Langridge (Earthquake Geologist), Dr. Dougal Townsend (Regional Geologist). Rob and Dougal were co-authors on the Hancox et al. (2006) report. Dougal was also involved in post-earthquake helicopter reconnaissance of the area.
- Golder Associates (NZ) Ltd – Tim McMorran (Principal Engineering Geologist), Clive Anderson (Principal Geotechnical Engineer)
- PTL (NZ) – Dr. Daniel Moroder (Log Cabin Structural Engineer)
- Hurunui District Council – Monique Eade, Rachel Elliott (Planners), Judith Bachelor
- Environment Canterbury – Marion Schoenfeld (Natural Hazards Coordinator)
- Natural Hazards Research Platform – Catherine Pinal (Director)
- DPMC (on behalf of) – Dr. Kelvin Berryman (External Relations Manager, GNS Science)

Following project approval by Hurunui District Council members, an initial town meeting took place on June 10th, 2017, after which the majority of Mt Lyford villagers agreed that a NHRP-funded project to investigate the land damage and offer recommendations for future action should be undertaken.

A reconnaissance field visit was undertaken during the week of 21st-25th August 2017 (see Section 2.6).

1.2 SCOPE OF THIS REPORT

In order to consider the possible outcomes for Mt Lyford Village we established several potential science goals that could draw on new and existing datasets, as follows:

1. to archive the data in previous reports in a GIS so that these could be compared with what happened in the 2016 earthquake, and considering the future of the village;
2. to undertake a field reconnaissance with the goal of comparing land damage in and around the village with those buildings that had greater structural damage
3. to construct a new geomorphic/geologic map of the village using post-earthquake airborne LiDAR data to assess the recent geological history of the village area, focusing especially on the scale and activity of landslide features;
4. to use post-earthquake LiDAR data to develop derivative products such as a slope map to enhance mapping and interpretation of slope erosion and landslide features, comparing the effects of co-seismic and post-seismic erosion with previous mapping;
5. to assess differential LiDAR (D-LiDAR) data and other remote sensing datasets to consider the broader regional deformation that occurred during the earthquake.
6. to provide advice to HDC with regards to managing the risk associated with slope instability;
7. to provide advice regarding the hazard of surface faulting within the village by mapping active faults in detail on post-earthquake LiDAR datasets in order to develop Fault Avoidance Zones, designed around mapping accuracy and fault recurrence interval;
8. to provide an update on the likelihood of a large earthquake occurring on the Hope Fault.

This project significantly benefitted from the post-earthquake acquisition of a regional-scale set of airborne LiDAR data. A comprehensive LiDAR survey was sought by the scientific community and acquired through the Ministry of Building, Innovation and Employment (MBIE) in order to have a complete digital topographic coverage of both co-seismic landslides and landslide-dammed areas, and also of the large number of active faults that ruptured during the earthquake. Due to the ambiguity concerning the role of the Hope Fault in the Kaikōura earthquake, the area along the eastern part of the fault, including the area of Mt Lyford Village was included as part of the survey. Airborne LiDAR surveying involves the collection of many millions of individual (laser) topographic points from tree and grass-covered landscapes, which can be resolved to produce 'bare-earth' digital models of the land surface (e.g. Langridge et al., 2014). Such digital models can be used to map in much more detail, develop secondary products such as slope maps, and in conjunction with pre-existing LiDAR data, can be used to assess the changes to topography between LiDAR surveys.

Chapter 2 of this report (Mt Lyford Village) includes a description of the village area including its location, geology and a history of previous investigations, followed by a description of

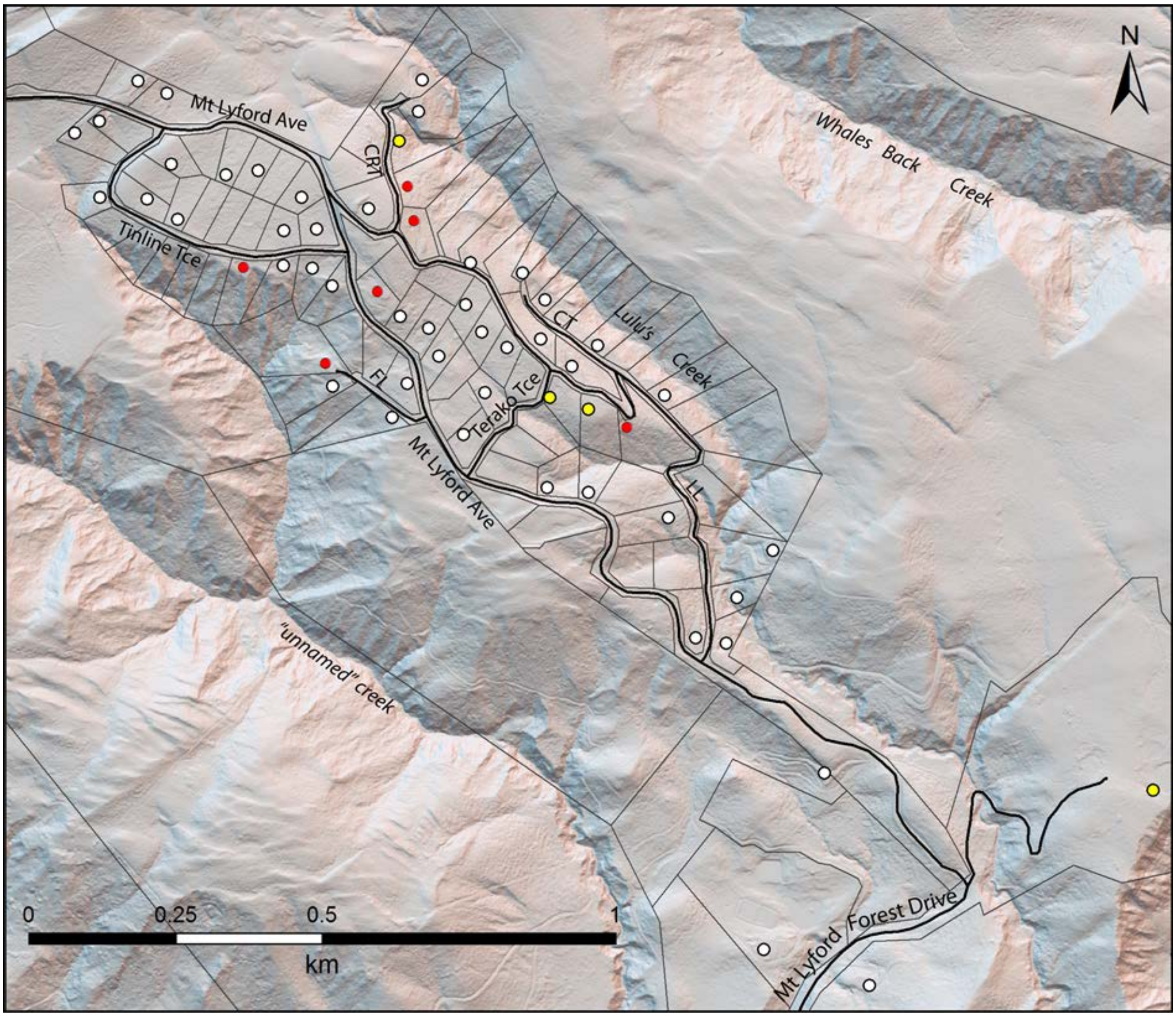

Figure 1.3 Airborne LiDAR-derived hillshade model of the Mt Lyford Village area highlighting street names, property boundaries, and post-earthquake rapid assessment placarding on houses. Dots are house sites, and the colours correspond to red, yellow and white 'placarding'. Abbreviations for street names are: FL, Foggy Lookout; LL, Lulus Lane; CT, Charwell Terrace; CRT, Cloudy Range Terrace.

post-earthquake placarding and our field reconnaissance in August 2017. Chapter 3 (Geological Data and Results) contains much of the scientific analysis concerning what happened at the village during the 2016 Kaikōura earthquake and why? This chapter comprises a description of bedrock and alluvial deposits, geomorphic surface mapping, field observations of land damage, GIS slope maps, active faulting, (including fault recurrence interval results), and relating the damage to co-seismic tectonic deformation that occurred in the wider area. Chapter 4 (Characterising Geological Hazards at Mt Lyford Village) discusses how we have characterised gully erosion, slope-related hazards, fault avoidance zones and future seismic hazard from the Hope Fault. The report is wrapped up with some Conclusions and preliminary Recommendations.

Appendix 1 to this report contain examples of field observations of land and building damage within Mt Lyford Village. Hurunui District Council worked closely with landowners in order for GNS to gain reasonable access to properties in the village for its post-earthquake reconnaissance. Appendix 2 contains building assessment criteria from which planning decisions can be made. Appendix 3 provides examples of planning decision tables from Kerr et al. (2003) for faults of Recurrence Interval Class I and II. Appendix 5 describes log cabin performance in the village.

2.0 MT LYFORD VILLAGE

2.1 LOCATION AND TOPOGRAPHY

Mt Lyford Village is located on a broad, gently sloping spur that is part of a deeply dissected range-front fan surface between the Wandle and Mason rivers on the southeast flank of the Amuri Range. It lies c. 20 km northeast of Waiau at an altitude of 500-730 m above sea level, and is accessed via the Inland Road (formerly State Highway 70) and Mt Lyford Forest Drive (Figure 2.1). The village area is bounded by deeply (50–100 m) incised streams which drain the highly dissected fan apron flanking the base of the Amuri Range – to the northeast by Lulus Creek, and southwest by an “unnamed” creek referred to in Hancox et al. (2006). The spur on which Mt Lyford Village is located and the spur northeast of Lulus Creek are broad-crested and slope gently (5–15°) to the southeast. These spurs are crossed by a number of ‘slope rents’ and active faults (Hancox et al., 2006). The hazard potential and planning recommendations relating to these features is a major focus of this report.

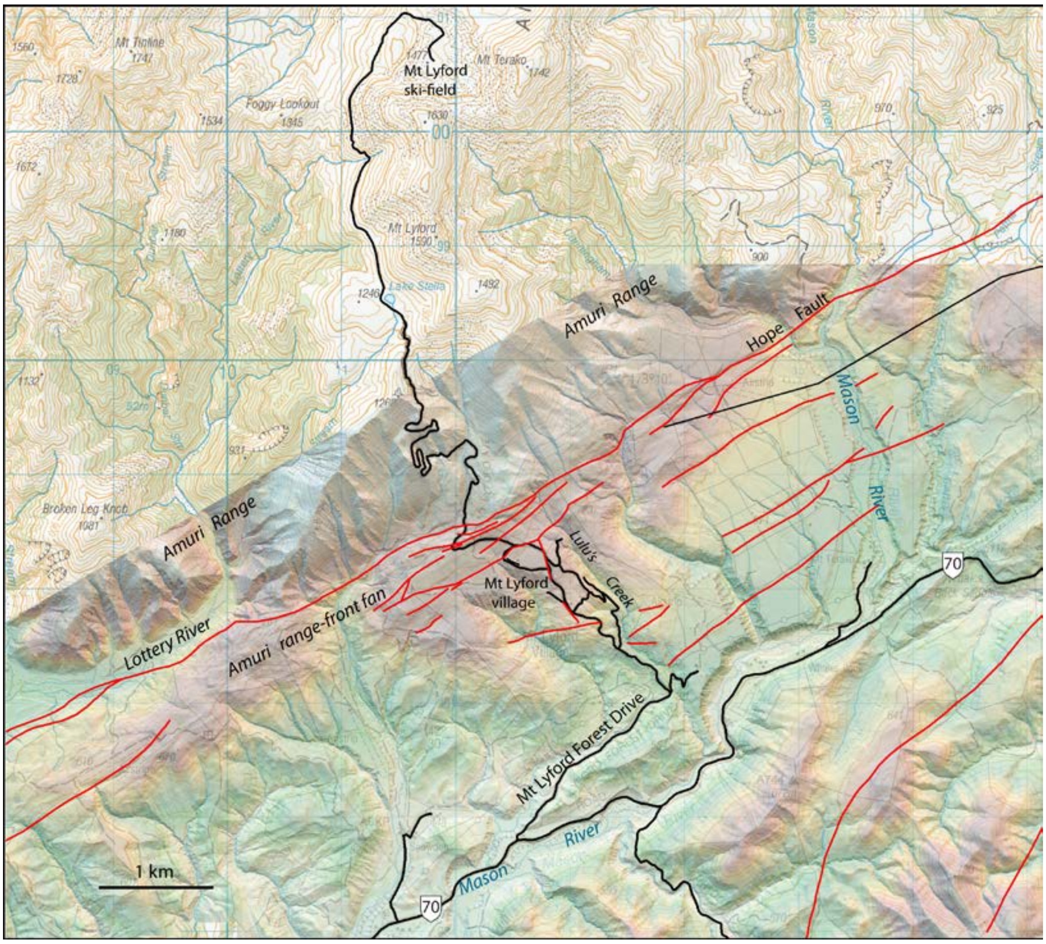

Figure 2.1 Topographic map of the Mt Lyford area from the Inland Road in the south to the ski field in the north, highlighting major roads and street for reference. Physiographically, the area is dominated by the Amuri Range in the northwest and the Amuri range-front fan which slopes toward the Mason River. Red lines represent the active faults shown in the HDC database at present.

The steeper (25–35°) valley sides of Lulus Creek, Whales Back Stream, and the unnamed creek west of the village show evidence of extensive slumping. Previous studies have identified several large, deep-seated landslides south and west of the Mt Lyford village area (Hancox et al., 2006; Rattenbury et al., 2006). The largest landslide in the area lies immediately southeast of Mt Lyford Village and is crossed by Mt Lyford Forest Drive. This is an inactive prehistoric feature, identified from the large area of hummocky debris. A large rock avalanche scar and deposit is present northwest of the village and is crossed by the road to the ski field. Part of this rock avalanche was reactivated as a slope failure during the Kaikōura earthquake, causing parts of the ski field access road to slip away.

2.2 GEOLOGY

The Mt Lyford Village area is underlain by weak siltstone and sandstone of the Waima and Greta formations (Motunau Group), which are of upper Tertiary (Neogene) age (~2–5 million years), and which overlie calcareous mudstone and conglomerate of mid Tertiary age (~24 to 5 million years) (Figure 2.2; Rattenbury et al., 2006). The high topography of the Amuri Range, northwest of the village, is formed in upper Jurassic to lower Cretaceous age Torlesse Terrane greywacke (strong sandstone and argillite). The active Hope Fault is a major crustal structure in this area, and it separates the much older greywacke rocks in the northwest from the younger Tertiary rocks to the southeast. The Tertiary sequence is folded into a syncline on the south-east side of the Hope Fault.

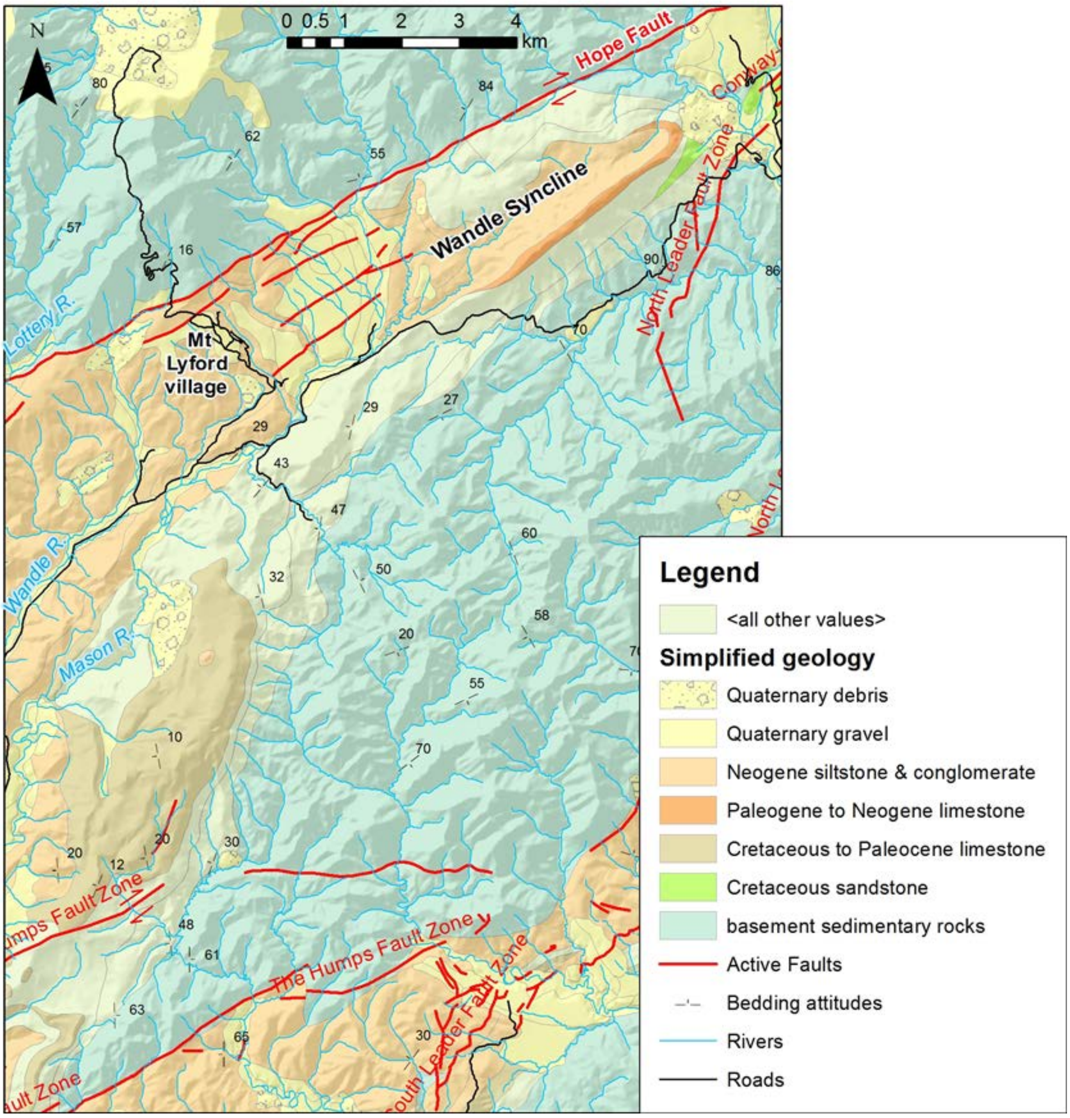

Figure 2.2 Simplified geological map of the Waiau-Mt Lyford area (after Rattenbury et al., 2006). Mt Lyford village is sited on the range-front fan of the Amuri Range (formed along the Hope Fault). Active faults from previous datasets are shown as red lines. The Leader and Humps fault zones ruptured during the 2016 Kaikōura earthquake.

The Hope Fault is a major northeast-striking, reverse dextral strike-slip fault. The fault zone is up to 2 km wide in the Mt Lyford Village area, and contains several active fault traces and secondary fault scarps. The main trace at the foot of the Amuri Range is relatively straight, and is defined by the bedrock contact between the Jurassic-Cretaceous rocks to the northwest and the Tertiary rocks to the southeast. Some rivers and streams crossing the fault are clearly displaced in a dextral (right-lateral) sense, with uplift on the northwest side1 (Figure 2.2). The last movement of the 'Conway' segment of the Hope Fault is thought to have occurred in about AD 1780 ± 60 yr and the average recurrence interval of this segment of the fault is estimated to be 180–390 years (Langridge et al., 2003). The role of the Hope Fault during the Kaikōura earthquake is equivocal. Some geodetic and geophysical models (e.g. Hamling et al., 2017) suggest that the Hope Fault ruptured (at depth), however there has been little evidence of surface rupture on this fault in 2016 (Litchfield et al., in review). Nevertheless, the Hope Fault is probably advanced in its earthquake cycle (i.e. the length of time between large earthquake ruptures).

2.3 HISTORY OF INVESTIGATIONS AT MT LYFORD VILLAGE

The history of geologic investigations at Mt Lyford Village is well summarised by an extensive report undertaken by GNS Science in 2006 (Hancox et al., 2006)[1]. Mt Lyford Village was developed as an alpine ski and lifestyle village from 1987 through to the early 1990s, when many of the houses were built. The original geological works to assess the subdivision of land on which the village sits were undertaken in the late 1980s (Bell, 1987; 1988).

Renewed interest in the geotechnical stability of the village area occurred from the mid-2000s in response to the introduction of Ministry for the Environment (MfE) Guidelines regarding active faults (i.e. the MfE Guidelines; Kerr et al., 2003) and an increased level of mapping undertaken to mitigate the hazard from slope movements (landslides). In 2005 ECan engaged Geotech Consulting Ltd. to map active faults in Hurunui District and slope features in the Mt Lyford Village area. These reports were reviewed by GNS Science (i.e. Hancox et al., 2006) and URS (specifically Tim McMorran and Don Macfarlane). Also, during this period, scientific studies were undertaken along the range front of the Hope Fault (Eusden et al., 2000; 2005; Langridge et al., 2003) and the 1:250,000 geological map was updated (Rattenbury et al., 2006; 'QMAP Kaikoura').

The Hancox et al. (2006) report, commissioned by HDC and specifically an extended review of work done by Geotech Consulting Ltd (i.e. ECan, 2005), is the most comprehensive study of slope instability and active fault features in the Mt Lyford Village area. The 2006 report was reviewed by Professor Jarg Pettinga (University of Canterbury). The conclusions of that report included recommendations on how to consider slope features and failures and how to treat active faults with respect to the MfE Guidelines (Kerr et al., 2003).

2.3.1 Digitising of Hancox et al (2006) data

Fault line and slope feature mapping by Hancox et al. (2006) formed the basis for planning decisions prior to the 2016 Kaikōura earthquake. Mapping undertaken for that project preceded the widespread use of Geographic Information Systems (GIS) mapping at GNS Science, and the acquisition of LiDAR data which now provide the tools and base data for undertaking high-resolution, detailed geological and geomorphological mapping. One part of

[1] Readers are referred to the comprehensive reference list on pages 45-46 of Hancox et al. (2006), which refers to specific reports and letters.

the current project has been to digitise the faults (line) and slope features (polygon) into a GIS for comparison with fault and slope feature data mapped following the 2016 Kaikōura Earthquake.

Post-earthquake placard designations and property boundary data also exists as GIS data and has been incorporated into this project. Hand-held GPS location data was collected during the field reconnaissance phase of this project. All GIS data in this report is presented using a New Zealand Transverse Mercator Projection and a metric grid.

2.4 POST-EARTHQUAKE PLACARDING

Rapid Building Assessment data was collected for 68 houses in the wider Mt Lyford Village area (Figure 1.3). Fifty-one of these assessments were on houses within the village above the junction between Lulus Lane and Mt Lyford Avenue, while a further eight properties were assessed between Lulus Lane and the Inland Road, along the Mt Lyford Forest Drive. Nine further properties were assessed along the Inland Road corridor southwest and northeast of the Mt Lyford Lodge. This project does not deal with the latter set of nine properties along the Inland Road corridor southwest and northeast of the Mt Lyford Lodge.

Simple definitions of placards are shown in Appendix 2 (Table A2.1). A comprehensive description of placarding can be found at:

https://www.building.govt.nz/assets/Uploads/managing-buildings/post-emergency-building-assessment/earthquake-field-guide-1-1.pdf.

Following the end of the Civil Defence Emergency Management transition period, HDC replaced placards with Section 124 notices on structural or geotechnical grounds on some properties. As part of Appendix 2, we have included information on sections 71 to 74 and section 124 of the Building Act along with a description of the criteria for Rapid Building Assessment placards.

2.5 FIELD RECONNAISSANCE

A field reconnaissance of the village and surrounding areas was undertaken 21-25 August 2017. The reconnaissance was led by Dr Langridge of GNS Science and the field team included Dr Dougal Townsend (GNS Science) and Mr Tim McMorran (Golder Associates). Mr Clive Anderson (Golder Associates) attended for a day (Tuesday 22nd August), as did Dr Daniel Moroder (PTL; Friday 25th August).

The main goals of the field reconnaissance were to assess areas of land damage and instability. In many cases it made sense to investigate house sites and properties where there was damage to the house, foundations or land around it. We used the MBIE Earthquake Rapid Assessment Form (Simple Residential Dwellings) to describe our geological observations in relation to land damage, See:

https://www.building.govt.nz/managing-buildings/post-emergency-building-assessment/field-guides-and-tools-for-building-assessment/earthquake-rapid-assessment-forms/

In our case, this did not describe building damage for life safety or property value concerns but acted as a guide for collecting consistent information about ground damage in relation to house sites and other buildings. Field photographs and notes, and Earthquake Rapid Assessment Form data are held at GNS Science and can be accessed with the permission of GNS and Hurunui District Council.

A summary of daily activities is listed below.

21st August – (half day) an introduction to the village from Doug Simpson. Visit to inspect damage at Doug's home. Initial visit to Ford's red-stickered property at 87 Tinline Terrace. Looked at 2-3 of the red-stickered properties including 62 Mt Lyford Avenue and the home opposite it at 84 Mt Lyford Avenue. Visited the red-stickered house on Foggy Lookout.

22nd August – visited the sites of trenches-1, -5 and -6 from Hancox et al. (2006) to consider rupture of secondary faults that traverse the village. Spent the rest of the day with McMorran and Anderson from Golder Associates looking at a variety of damage around the village. Finished up by looking at reactivated landslides on the north face of Lulus Creek, south face of Whales Back Stream, and at older geomorphology on the fan surface above Lulus Creek.

23rd August – met with Greg Ford at 87 Tinline Terrace for an update of recent ground movement. Looked at several properties along the south side of Tinline Terrace. Revisited damaged house sites on Foggy Lookout. Visited red stickered property at 17 Lulus Lane.

24th August – viewed several other properties along the south side of Tinline Terrace. Visited white placard properties along Mt Lyford Avenue (72-74). Re-visited red stickered property at 17 Lulus Lane. Spent the afternoon looking for evidence of rupture along the major strands of the Hope Fault north of the village and visited the Turnbull home (97 Mt Lyford Avenue). Re-visited the Mt Lyford ski area access road including looking at slips, road access and secondary faulting in outcrop along the Wandle River.

25th August – (half day) reconnaissance of several new and previously visited properties with Dr. Daniel Moroder. We gained many insights into the construction of log cabins and their performance in the Kaikōura earthquake.

3.0 GEOLOGICAL DATA AND RESULTS

3.1 BEDROCK AND DEPOSITS

Bedrock is exposed mainly at the range front and in steeper gullies beyond the edges of the piedmont surfaces where streams have cut down through the relatively thin terrace deposits (Figure 2.2). South of the Hope Fault, bedrock underlying the piedmont surfaces comprises Miocene to Pliocene Motunau Group (Rattenbury et al. 2006). Constituent formations in the group here include the Miocene Waima Formation (predominantly siltstone) and the Pliocene Greta Formation (predominantly mudstone, with siltstone, sandstone and minor conglomerate), and these are folded up against the Hope Fault.

The field reconnaissance identified Tertiary siltstone (probably the Miocene Waima Formation) in both Lulus and 'unnamed' creeks, and in various road cuttings around Mt Lyford Village. Because of the fine-grained nature of these rocks, bedding orientations that define regional geological structure are often difficult to determine. Bedding was unequivocally observed along Tinline Terrace, dipping steeply to the southeast (055/75° SE), and possibly in Lulus Creek (060/40° SE), although the features observed there could be related to jointing. The few sparse measurements, including those from previous work (e.g., Rattenbury et al. 2006), show that the siltstone dips moderately to the southeast.

At the Tinline Terrace exposure, the siltstone is truncated and overlain by weathered "rusty" gravels over a contact that has an attitude of 050/50° SE. These gravels are part of the much younger (less than 200,000 years old) deposit forming the main range-front fan surface that underlies the village. The orientation of this contact with respect to the dip of the underlying siltstone is consistent with folding of the Miocene Waima Formation and older units against the Hope Fault. Alternatively, the observed dip on the base of the gravel unit could be related to erosion of channels in the siltstone as the range-front fan was formed. This is important as it provides a context for slope instability issues that may be related to the contact between the Tertiary siltstone and overlying range-front fan deposits, and to the depth of their contact across the village area.

North of the Hope Fault, the bedrock is comprised of Jurassic to early Cretaceous sandstone and argillite (greywacke) of the Torlesse terrane (Figure 2.2; Rattenbury et al. 2006). Torlesse greywacke is relatively hard, but fractured and jointed. It forms the high topography of the Amuri Range, and the Seaward and Inland Kaikoura ranges. Near the Hope Fault, the greywacke is highly deformed and has been crushed to a fine-grained sandy clay a few metres wide by successive fault moments.

Gravel and breccia clasts ranging from pebble to boulder size within the range-front fan deposits are typically composed of greywacke. Mudstone clasts however, may weather over tens of thousands of years to form part of the matrix in these deposits.

3.2 GEOMORPHIC SURFACE MAPPING

3.2.1 Methodology

New geomorphological mapping has been undertaken for this project across the wider Mt Lyford Village area using a post-earthquake LiDAR digital terrain survey accompanied by high-resolution aerial imagery[2]. This LiDAR data has made possible the mapping of geomorphic features in much more detail than previously possible, i.e. at scales of 1:1000 to 1:10,000 (Figure 3.1). LiDAR surveying can produce vegetation-free digital terrain models (DTMs), which have not been used for mapping in this area before. The map prepared for this project supersedes those in Hancox et al. (2006). Geomorphic units mapped and described were based on the schemes of Townsend and Rosser (2012). Lines and polygons follow natural breaks in slope and were drawn using the LiDAR DTMs, oblique- and ortho-aerial photographs, slope maps (discussed below), and knowledge gained through fieldwork.

The new geomorphic map (Figure 3.1) provides fresh insight for understanding geologically recent landscape processes that have occurred over tens to many thousands of years, and is useful for interpreting the near-surface materials that make up the landscape (Table 3.1). The geomorphic map is also used to interpret the ages of both depositional and erosional processes and to assess the rates at which the landscape is building up or eroding down. The morphology allows delineation of the different processes that occur, for example, a steep, scallop-shaped landslide head scarp, or a conical shaped debris fan surface. Similarly, the linearity or curvature of risers (i.e. a slope-rise or step across a land surface) may differentiate between an alluvial cut riser, a fault scarp, or possibly a gravitational (non-tectonic) scarp.

3.2.2 Mt Lyford surfaces

Figure 3.1 shows constructional surfaces, formed by the accumulation of sediments, and erosional features that have modified the surfaces. In the Mt Lyford Village area, constructional surfaces have formed along the range front of the Amuri Range as a range-front fan (i.e. a surface that slopes away from a mountain front), where debris has been eroded from the Amuri Range, transported across the mountain front (defined by the Hope Fault) and deposited as a broad range-front fan. Range-front fan surfaces inspected in the field in the Mt Lyford Village area are underlain by boulders and gravel, often with a sandy to silty matrix. This reflects the depositional processes and grain size of debris being shed from the Amuri Range in an alluvial fan-apron environment. In many of the exposures that we observed the range-front fan units have a high proportion of fine-grained (silt to clay sized) matrix, with clasts of sub-rounded greywacke varying from cobble to boulder size. In some cases, remnant boulders and cobbles on the top of the surface reflect some erosion of the top of range-front fan surfaces. Loess (wind-transported silt) is also a common constituent on the terraces, and may form deposits several metres thick on older surfaces. The fine-grained matrix of the range-front fan deposits probably comes from eroded mudstone and loess and weathered greywacke incorporated into these poorly sorted deposits. Typically, the mapped range-front fan surfaces at Mt Lyford Village are no longer connected to large streams or alluvial fan systems that are the sources of the sediment from which they formed. This is probably because: (i) these surfaces formed during or following cold climate periods preceding the Holocene, (ii) the Hope Fault has translated these surfaces right-laterally (dextrally) away from their original catchment sources; and (iii) during the Holocene the secondary streams have cut down and through the older piedmont surfaces while themselves also being displaced along the Hope Fault.

We use this argument to develop an age model for the Amuri rangefront fan surfaces. Range front drainages, such as the Wandle and Lottery rivers and O'Malley Stream are right-

[2] LiDAR acquired by AAM, based locally in Napier, for the Ministry of Business, Innovation and Employment as a post-earthquake response tool

laterally deflected by c. 1.6 ± 0.1 km. If we assume a fault slip rate of 19-23 mm/yr, based on published values (McMorran, 1991; Langridge et al., 2003), this suggests that the incision of these rivers relative to the piedmont surfaces was achieved by 65,000-90,000 yr ago (median 76,000 yr). In terms of periods of Late Quaternary climate, this window of time overlaps with Marine Isotope Stage (MIS) 5 and 4[3]. Based on the current pattern of incision during MIS 1 (that we could infer for Whales Back Stream, Lulus and 'unnamed' creeks), it is likely that the Wandle River incised into its current course during the latter part of MIS 5 (c. 90-71,000 years ago; Rattenbury et al., 2006). By implication, this means that the range-front fan surfaces in the Mt Lyford area were formed in the early part of MIS Stage 5, or more likely, relate to the previous cold climate period (MIS 6; 186-128,000 yr BP), or earlier. This gives us some basis for understanding the antiquity of geomorphic surfaces and features, and erosional processes that have occurred along the range front of the Amuri Range during the last 100,000 years or so.

Table 3.1 Mapped geomorphic units and corresponding interpreted near-surface materials in the Mt Lyford Village area.

Mapped geomorphic unit	Description and interpreted near-surface materials
Hill country – high	Steep hill country, mostly underlain by greywacke, with thin scree and colluvium.
Hill country – low	Rolling hill country, mostly underlain by mudstone (minor sandstone, limestone and basalt) of the Motunau Group (Waima or Greta formations).
Terrace – high	Ancient piedmont and terrace surfaces, formed from sand, gravel and boulders, possibly dating back to MIS 6.
Terrace – mid	Mid-level river terraces, formed from sand, gravel and boulders, possibly dating to MIS 3-4.
Terrace – low	Lower-level river terraces, formed sand, gravel and boulders, possibly dating to MIS 2-3.
Valley floor	Floors of modern (Holocene/MIS 1) stream channels and low terraces, comprising sand, silt and gravel.
Hillslope – smooth	Smooth hill slopes and fans comprising colluvium and scree in higher areas. Mixtures of slope-remobilised debris.
Hillslope – hummocky	Hummocky ground typical of landslide debris. Mixtures of fine to coarse, blocky debris.
Swamp	Peat, sand, organic silt and water.
Water	Water in small ponds, mostly man-made.
Anthropogenic	Deposits of human origin. Boulders and gravel to clay.

[3] Odd numbered MIS stages correspond to warm climatic periods like the Holocene (MIS 1), while even numbered periods correspond to cold climate periods (ice ages), e.g. MIS 2 was the last glacial period.

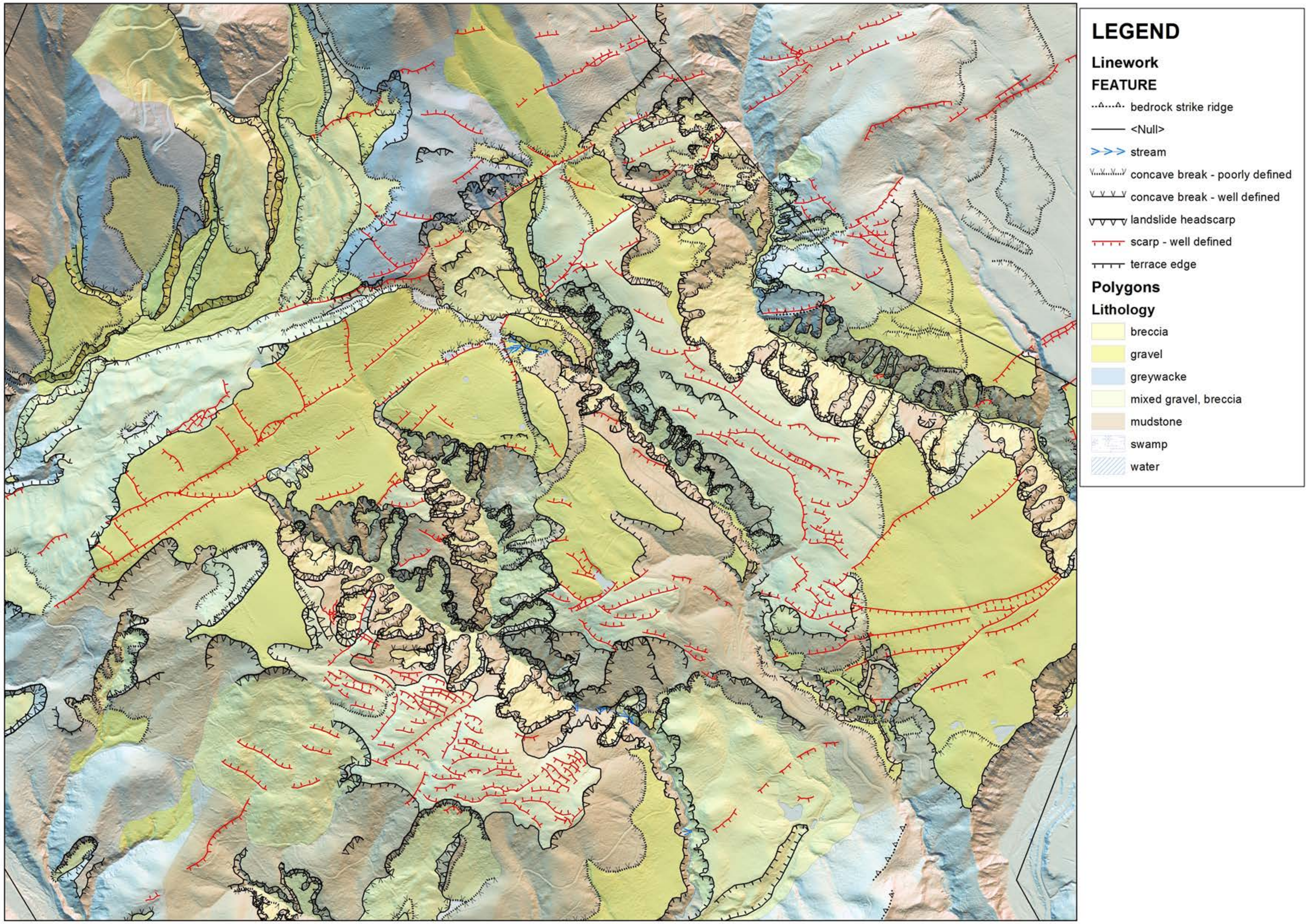

Figure 3.1 Geomorphic map of the Mt Lyford area. The map extends between the Wandle and Mason Rivers (top left to bottom right), and from the Hope Fault to the Inland Road. The geomorphic map identifies mainly: hill terrain – high (blue – mostly greywacke); hill terrain – low (orange – mostly mudstone); high terraces (dark yellow – constructional piedmont), mid-level terraces (yellow) and valley floor alluvium (pale yellow); hillslopes and hummocky ground (yellow with overprint – colluvium and landslide debris). Line work depicts erosional processes such as breaks in slope (black), and tectonic and gravitational scarps (red lines). The rangefront spur on which most of the village is built is at centre.

As an independent check of these interpretations, the alluvial terraces of Mason River seen on Mt Terako Station have the morphology of many other typical large trunk rivers that come out of mountains in the South Island. The Terako terrace surfaces (Beaupretre et al., 2012) are generally of lower gradient and are composed of greywacke cobbles with a matrix of greywacke sand. They form flatter surfaces that are connected to and grade roughly to the modern streams and rivers (MIS 1 terraces and channels; c. 12,000-0 yr BP). They are also less incised and eroded and have thus been designated as MIS 3 and 2 alluvial surfaces by Rattenbury et al. (2006). This is consistent with their position in the landscape relative to the range-front fan surfaces at Mt Lyford.

3.3 Field Observations of Land Damage

In general, land damage caused by strong seismic shaking can be divided into that related to slope instability, fault rupture and liquefaction. Of these, slope instability is by far the most relevant within the Mt Lyford Village caused by the 2016 Kaikōura earthquake, while there was no documented liquefaction (i.e. because we class any slope extension described below as slope instability-related rather than lateral spreading). There were no unequivocal documented fault ruptures in the village, although possible minor displacement occurred on a secondary fault near the Hope Fault.

3.3.1 Slope Instability

Slope instability, including most of the worst land damage, was observed at properties that lay adjacent to the steep to very steep slopes associated with ‘unnamed’ and Lulus streams. Typically, slope instability relates to extensional features whose ground tends to fail under gravity and allow unsupported material to be transported downhill. The following summarises those areas:

Tinline Terrace -

- oral account of superficial cracks observed in the packed dirt road following the earthquake. These appear to have been normal to the slope paralleling the ‘unnamed’ creek.
- shallow translational ground failure around the Spark (Telecom) repeater, with multiple cracks presenting displacements of up to 1 m and translation of land toward ‘unnamed’ creek (see Figure A1.7).
- several examples of slope-parallel, linear to arcuate cracks in the ground at #87, up-slope, underneath and downslope from the house. This resulted in significant damage to the house. Ongoing slope extension and widening of cracks resulting in downslope movement occurred up until August 2017; extension was also noted in October 2017 (Figure A1.1).
- superficial extension on cracks parallel to contours was observed on the bush-covered slope below #86, above ‘unnamed’ stream (Figure A1.5).
- cracks observed parallel to the contours in the property of #85; both around and below the house, above ‘unnamed’ stream (e.g. Figure A1.2).

Charwell Terrace –

- significant land failure at 17 Charwell Terrace characterised by large linear to arcuate tension cracks resulting in damage to the deck and foundations of the house. Cracks in ridgeline above the house and through the land under the house (Figure A1.9,Figure **A1.10**).
- minor slope failure above 34 Charwell Terrace. Shallow cracks and extension in fill of lawn area extending to the edge of cut slope (Figure A1.14).

General –

- significant, shallow rejuvenation of pre-existing arcuate landslide headscarps resulting in downslope movement of landslide debris between x and y metres, e.g. as observed on the NE face of Lulus Stream (see Figure A1.3).
- minor to moderate ground cracking and extension observed along the upslope edges of cut slopes, particularly where building pad locations have been excavated. e.g. 40 Cloudy Range Road (see Figure A1.11).
- superficial cracking and extension in areas of fill, such as along driveways, car parking pads and road edges, e.g. 41 Cloudy Range Road (see Figure A1.13).

In terms of slope instability, what happened at Mt Lyford Village can be summarised as:

1. Slumping occurred at the edge of terrace surfaces where unsupported slopes cracked and moved away (a few centimetres to tens of metres) from the flat ground.
2. Deeper-seated landsliding, where the slide plane is tens of metres deep, developed into large translational/rotational blocks separated by highly deformed areas.

Depending on the type of slide and runout length, different deposits will form. Less-travelled debris may form larger, intact blocks where longer runout debris becomes disaggregated to form a homogenous colluvium.

Most of the deformation styles described here form cracks at the ground surface that will allow ingress of surface runoff water that will later exacerbate slope instability issues. This could result in potential for on-going ground deformation related to severe rain events and poor drainage, not necessarily solely to future earthquakes.

3.3.2 Fault rupture

The field reconnaissance team also looked for evidence of surface fault rupture within the village area and along the Hope Fault, that could have been caused by the 2016 Kaikōura earthquake. Short sections of the Hope Fault adjacent to the ski-field road and along “Marg’s Track” were examined. No evidence of surface faulting was found at these sites.

The sites of trenches T-1, T-5 and T-6 from Hancox et al. (2006) were also revisited to look for evidence of surface faulting on these ‘secondary’ structures. No new surface cracking was observed at the T-1 and T-6 sites. In the case of trench T-5 along the NNW-striking Avenue fault a series of en echelon cracks with several cm of opening along the lower edge of the scarp were observed immediately north of the location of trench T-5. This cracking was over a length of only a few metres along the fault but it provides evidence of some surface faulting related to the 2016 earthquake in the village. The cracks dipped back into the scarp and not down-slope indicating a faulting origin rather than a slope instability origin.

3.4 SLOPE MAPS

Erosion will occur mainly on steeper slopes. Therefore, a slope map has been developed from the LiDAR DTM to map the steepest slopes, and to determine if there is a slope angle threshold that can be used to characterise the performance of land in the village during the earthquake, and in the likely performance in similar future events.

3.4.1 Methodology

Geomorphological mapping involves making interpretations about the ages and origins of landscape features (Figure 3.1). Hilly terrain is often underlain by bedrock geological units and may be rolling or steep, depending mainly on how erosion resistant the bedrock material is and on the rate of erosion. Terrace and fan (depositional) surfaces are flat to moderately sloping but may, over time, be eroded to become subdued or rolling with increased erosion.

A scarp is a linear step or sharp drop in the level of the land surface. Scarps can be formed due to erosion (e.g., landslides, cutting of alluvial channels) but additionally could have a tectonic origin (i.e., fault displacement). Erosional channel edges commonly have sharp, convex tops, especially where they cut older alluvial terraces (a ‘terrace riser’). They usually bear an obvious, often parallel, relationship to the alluvial channels or streams which formed them. Landslide head scarps are similarly marked by a sharp, convex break in slope, but are usually arcuate to scallop-shaped in map view. Landslide deposits are typically hummocky and usually have a lower gradient than the head scarp areas (vacated source material) above them. Tectonic features (faults) may also cut the landscape and appear similar to terrace risers, but they commonly cut across drainage lines, terraces and hill terrain alike, with no relationship to erosional streams or rivers (although sometimes drainages will be diverted to flow along a fault scarp). Other morphological features mapped on Figure 3.1 include bedrock strike ridges, which are linear, commonly asymmetrical ridge lines relating to some erosion-resistant planar body such as limestone or sandstone bed.

3.4.2 Slope maps

The slope map presented in Figure 3.2 is a derivative from the LiDAR DTM, and is developed by converting a pixel’s elevation data, as stored in the DTM, into a slope angle in degrees based on neighbouring pixels. We have classified the continuous slope angle data into discrete bins and coloured those ranges, in order to easily view ranges of specific slope angle.

The slope angle ranges defined by Hancox et al. (2006) were gentle to moderate (<15º), gentle to moderately steep (10-20º) and steep (15-25º). In this study, we consider the upper margin of what Hancox et al. (2006) defined as ‘steep slopes’ to be an important slope angle break. Thus, we define slope angles of >25º as being ‘very steep slopes’ (Figure 3.2). In adopting the term ‘very steep slopes’, we acknowledge the slope designations of Hancox et al. (2006), which are all coloured grey in Figure 3.4. Most of the subdivided area of Mt Lyford Village is sited on slopes designated by Hancox et al. (2006) as gentle to moderately steep (0-20º).

Figure 3.3 shows a profile drawn down the axis of the piedmont surface through the village. Very steep slopes occur mainly in the streams, creeks and gullies and along their adjacent hillslopes.

From Figure 3.2 we define three types of area with very steep slopes: (i) areas of very steep slopes consistently greater than 25°, limited to the steeply eroded gullies and streams (Whales Back Stream, Lulus and unnamed creeks); (ii) very steep slopes defined by alluvial and fault scarp risers; and (iii) terraced, patchy or 'marbled' areas of moderate to very steep slopes with a mixture of slope angles greater than and less than 25°, but often with up to 50% of the area greater than 25° slope. Figure 3.4 highlights the important slope cut-off value of very steep slopes greater than 25º.

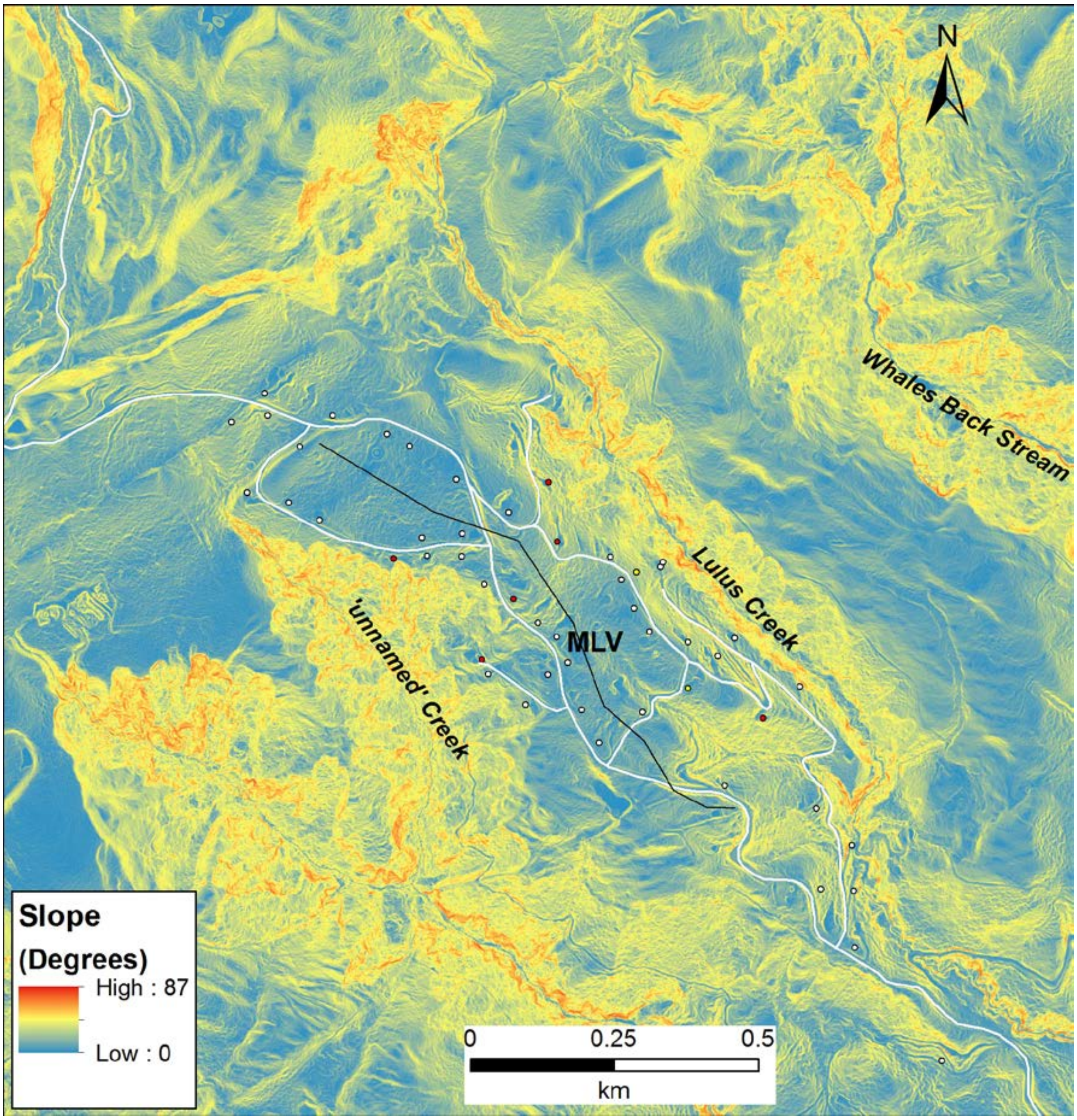

Figure 3.2 A digital Slope map of the wider Mt Lyford village (MLV) area. Slopes in bluish colours are between c. 0-20º, while slopes in yellow and orange are c. >25º). Village road network is shown in white and post-earthquake response placards are shown as dots. The black line is the profile shown on **Figure 3.3**

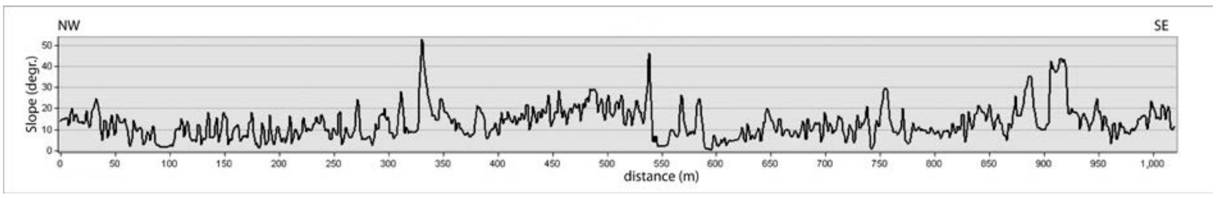

Figure 3.3 A Slope profile graph running NW to SE from the top of Mt Lyford Village toward the bottom, indicating that most slopes are between 5-20º. See **Figure 3.2** for the profile location.

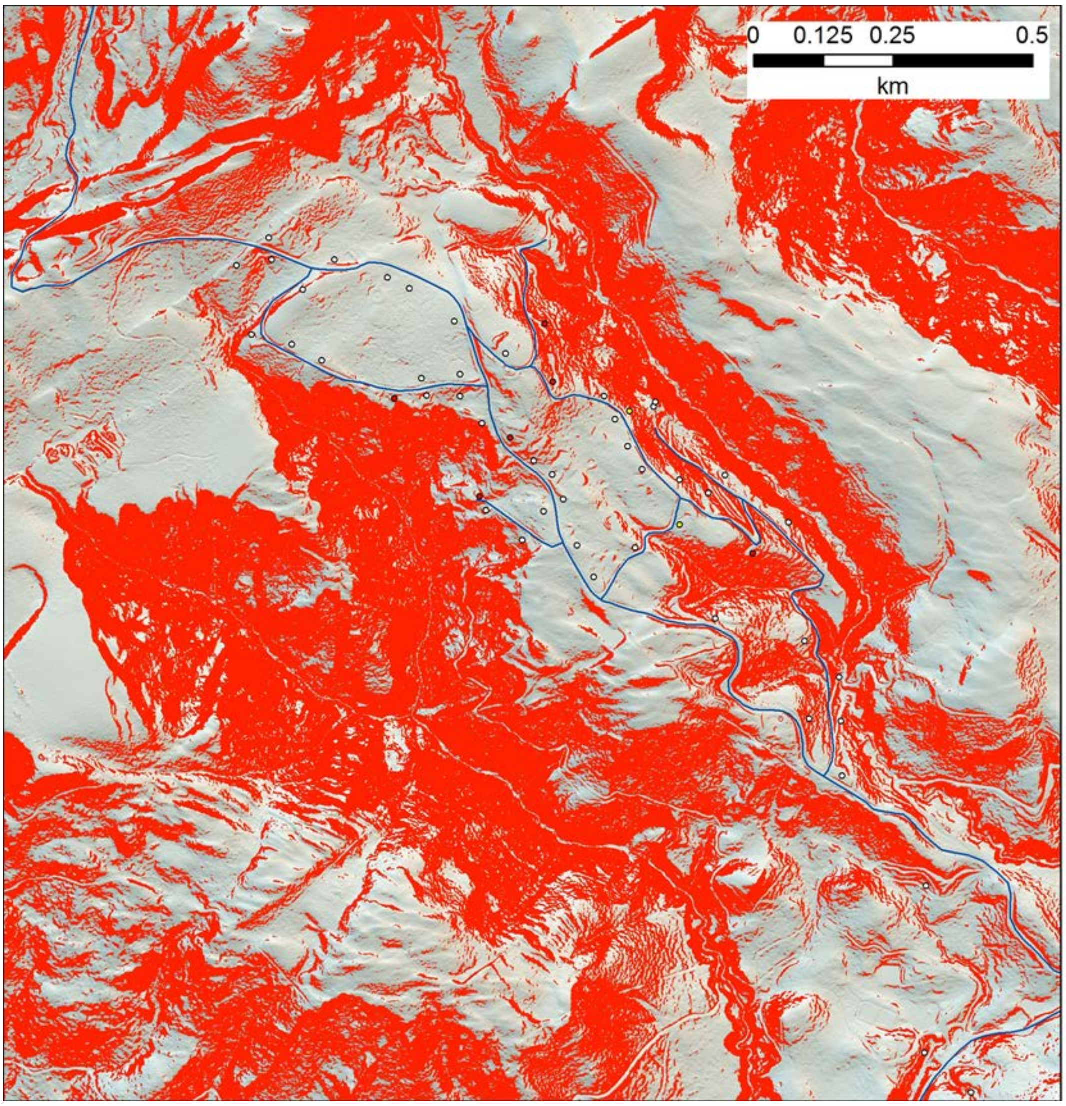

Figure 3.4 Digital Slope Map of Mt Lyford Village. Slopes ≥25º are coloured red and are termed 'very steep slopes'. Areas with slope <25° are transparent, revealing the underlying hill-shaded DTM.

3.4.3 Measuring rates of landscape change at Mt Lyford

In Section 3.2 we suggested that the main range-front fan surfaces at Mt Lyford Village were most likely constructed during MIS 6 (186-128,000 yr BP) and were abandoned by their source catchments (e.g. Wandle River) late in MIS 5, or during MIS 4 (c. 71-59,000 yr BP). Although these surfaces were abandoned, they have a history of erosion, deposition and deformation since MIS 5 that is reflected in the geomorphology of the Mt Lyford Village area as it exists today.

This is also discussed by Hancox et al. (2006) with regards to active faults and trench sites where specific surfaces are faulted by the subsidiary active faults that transect the village area. Individual geomorphic surfaces of MIS 3 or 4 age are difficult to differentiate with any certainty. Fill terraces corresponding to MIS 2 (referred to as Q2a alluvial terraces and related deposits in Rattenbury et al. 2006) have been identified in Whales Back Stream where Holocene erosion has been less vigorous.

Evidence for erosion in the form of gullying and landsliding can be mapped accurately using modern digital mapping methods (LiDAR DTMs, hill shade models and slope maps) and can be characterised as being due to geomorphic process of local- to regional-scale. We believe that most of the erosion and gullying observed in today's landscape, especially that observed in relation to Whales Back Stream, Lulus and 'unnamed' creeks occurred during the Holocene (MIS 1) and has resulted in the above-mentioned areas of very steep slopes. This includes incision into MIS 2 surfaces, and where these are not present it is evident that they have been eroded, along with the slopes above and below them.

3.5 ACTIVE FAULTING

3.5.1 Active Fault Mapping

Mapping active faults is important because they have the potential to rupture in a moderate to large earthquake, causing both ground motions (strong shaking) and ground surface deformation and surface faulting, both of which can damage structures or result in permanent ground deformation.

The acquisition of post-earthquake LiDAR data allows for a re-assessment of the location of active faults in the vicinity of the village, for the purposes of developing 'Fault Avoidance Zones' (FAZs)[4]. The Hope Fault, which traverses the base of the Amuri Range to the northwest of Mt Lyford Village, is one of New Zealand's most active on-land faults, and therefore has a significant body of mapping and scientific study related to it (e.g. Lensen, 1962; Freund, 1971; Kieckhefer, 1979; McMorran, 1991; Langridge et al., 2003; 2013). With the advent of more detailed base maps and finer scales of mapping, potentially active secondary faults to the southeast of the main Hope Fault zone were recognised in the Mt Lyford area (Eusden et al., 2000).

As a result of the development of MfE Guidelines regarding building on or near active faults (Kerr et al., 2003), studies by Geotech Consulting Ltd. and GNS Science recognised a need to better characterise the location and accuracy of active faults in Mt Lyford Village (ECan, 2005; Hancox et al., 2006). GNS Science was commissioned by ECan to map all active faults within Hurunui District and these new datasets were taken up as geological hazards in the HDC District Plan (Barrell and Townsend, 2012). Subsequent to these studies, GNS Science produced a version of its Active Faults Database at a national scale of 1: 250,000, and this is the version now available on the website (Langridge et al., 2016; https://data.gns.cri.nz/af/). Fault mapping at that scale is not as detailed as that presented by Barrell and Townsend (2012), and thus has a lesser number and density of mapped active fault traces.

For this project, we have used the LiDAR data to map active fault and possible active fault traces from the Hope Fault zone to the Inland Road between the Wandle and Mason rivers. Fault traces are common within the strike-slip Hope Fault zone and across the wider piedmont and alluvial surfaces of Mt Lyford Village and Mt Terako Station (e.g. Figure 3.5). For the purposes of distinguishing separate zones of fault traces within the wider Hope Fault zone, we have applied a few local names to traces mapped in this study, for example: Hedgerows fault, Avenue fault, Airstrip fault and Terako Station fault. The term 'Tinline fault' was introduced in Hancox et al. (2006) for trenches excavated into this fault.

The LiDAR data allows us to recognise and map features with a higher precision than before, including faults that cut the ground surface. The predominant structural grain (orientation of

[4] In Canterbury the term Fault Avoidance Zone (FAZ) has been used consistently to define fault hazard, as opposed to Fault Avoidance Zone (FAZ).

faults) is of NE-striking fault traces cutting the piedmont and alluvial surfaces. In the Hope Fault zone, we see evidence for these faults having slightly sinuous traces across the landscape, with branching and stepping patterns of faulting also apparent. Secondary faults are also typically NE-striking but also typically have straighter traces. This pattern of faulting is particularly clear across the alluvial terraces on Mt Terako Station (Figure 3.5).

In addition to faults striking NE, other fault strike populations exist. For example, northwest of the Tinline Terrace loop we observe a pattern of faulting where there are short NNW- to NW-striking traces set in between the main NE-striking fault traces of the Hope Fault (Figure 3.5), e.g. the Avenue fault. While these features could be interpreted as alluvial or gravitational in origin, we prefer to consider them as active faults at this time (though we know little about their activity). In other cases, we observe fault traces that bend away from NE-strikes toward having NW-strikes. For example, there is an area of faulting between T-1 and T-2 (Figure 3.5) that takes this form, with curved fault traces bending from the Terako Station fault toward the northwest.

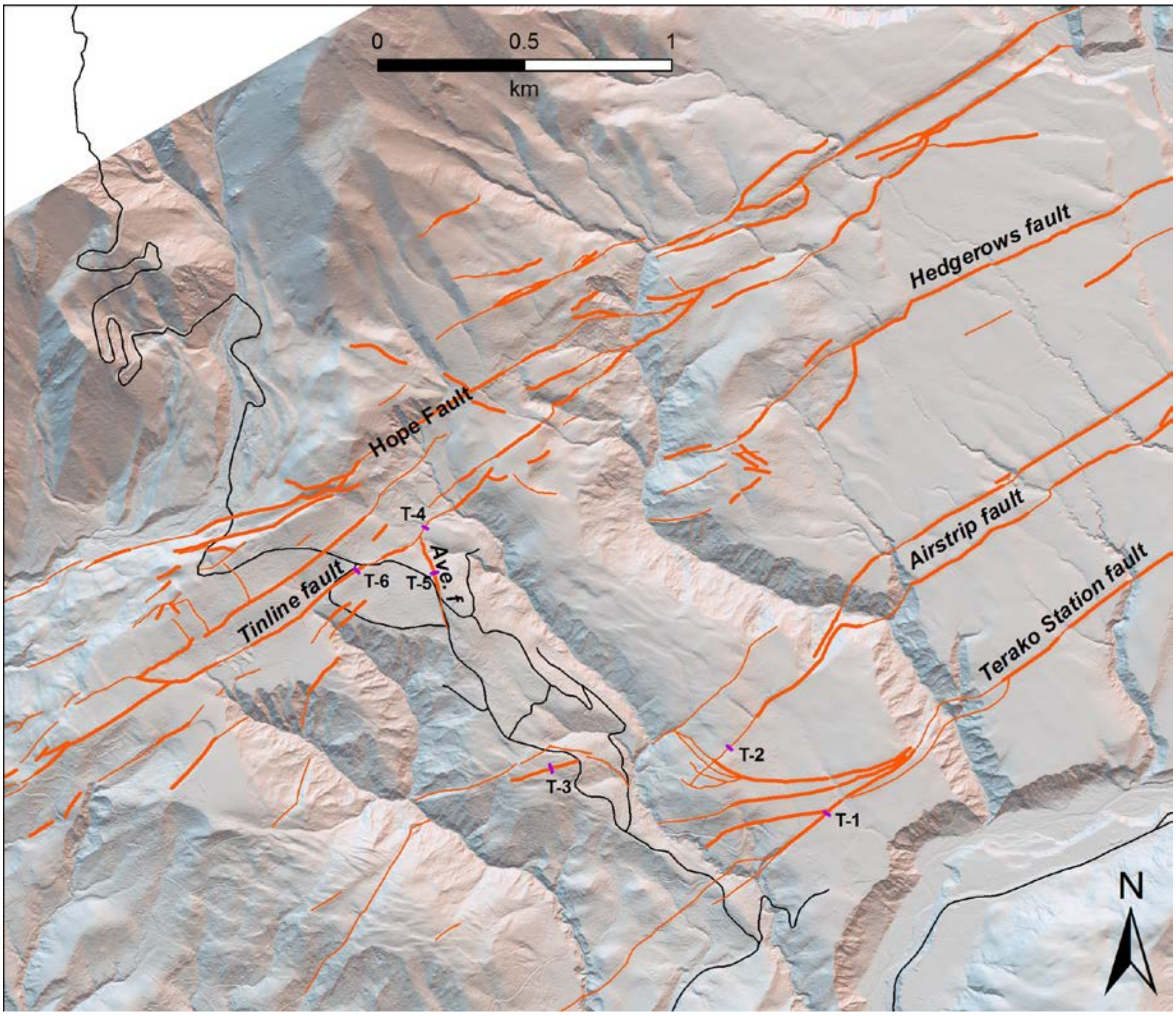

Figure 3.5 Updated active fault map for the Mt Lyford Village area. The Hope fault is a distributed fault zone of up to 0.5 km width, and could include informally named faults (those in italics) such as the Tinline Fault. The accuracy of fault location is shown by the thickness of lines (accurate = thickest). The trenches excavated in 2006 are shown by purple dashes across faults and labels T-1, T-2 etc.

Finally, many short, linear scarps were recognised on both ECan (2005) and Hancox et al. (2006) along the ridge between Lulus Creek and Whales Back Stream, and many of the other ridges. The origin of these linear scarp features was unclear; that is, whether these features were tectonic or gravitational (related to slope movement) in origin remained contentious. ECan (2005) defines 5-15 individual definite or inferred Slope Rent features on each of the ridgelines. Their map indicates that these features are potentially active Class 1 (Holocene) fault features. Hancox et al. (2006) mapped 7-12 such features across the ridgelines between 'unnamed' and Lulus creeks and Whales Back Stream. However, they suggest that these features are 'not active'. They also mapped a series of drainage channels on these ridges, inferring a fluvial origin for the features.

The village is sited on the ridge between Lulus and the unnamed creeks. Inspection of this ridge, and the next one to the southwest, suggest that a similar pattern and density of sinuous, NW-trending, short linear traces exists across them. Re-inspection of old black and white aerial photos, in conjunction with the LiDAR models, indicates that these NW-trending linear features could be slope rents as originally mapped by ECan (2005). With the aid of LiDAR, we have remapped several of the same features shown in ECan (2005) and several new traces (Fig. 3.1). The possible nature and activity of these features is discussed in Section 4.1.

3.5.2 Development of Fault Avoidance Zones (FAZs)

Active fault traces and other linear features that could be fault traces have been mapped in a GIS using post-earthquake LiDAR data. The strategy we took with mapping these features was toward using the linework to develop FAZs for faults in the village. Our methodology was to map fault traces and assign them with a locational precision of either 'accurate', 'approximate', or 'uncertain'. In practical terms, if we can map a definite line on LiDAR and are confident that this represents a fault (given the cross-cutting relationships that it might have with other topographic features – see above), then it is attributed as 'Accurate'. An 'Approximate' trace is a mapped trace that is not as clearly observed or there is an ambiguous relationship regarding its expression. An 'Uncertain' fault can be mapped where we believe one should or may exist, that is, where a fault is projected across an area where it could be concealed or eroded away, e.g. beneath a younger river deposit or across a landslide, or where it is unclear whether the feature is indeed of tectonic origin. The spatial resolution assigned to the mapped feature's accuracy is shown in Table 3.1.

Table 3.2 Parameters for Fault Location Accuracy used to define the Fault Avoidance Zones (FAZs).

Mapping Accuracy	Location Uncertainty (m)	Margin of safety buffer (m)*	FAZ width (m)
Accurate (Well-defined#)	± 10	+ 20	60
Approximate			
(Distributed#)	± 20	+ 20	80
Uncertain#	± 50	+ 20	140

#Accuracy terms equate to Well-defined, Distributed and Uncertain in Kerr et al. (2003). *The buffer added to the Location Uncertainty, in accordance with Kerr et al. (2003).

Even when a fault trace is accurately located, we still expect there to be some uncertainty in the mapped position of the fault, or exactly where the fault will rupture in future. We typically map the fault as a line between the middle and the base of a scarp feature; therefore, there is some uncertainty in where a line is placed relative to the intersection of the fault plane with the ground surface. This can be exacerbated by erosion and rounding of the scarp. Uncertainty may be increased depending on the type and spatial resolution of base data being used to map the features, e.g. faults mapped from aerial photographs scanned into a GIS have greater uncertainty than georeferenced digital elevation models.

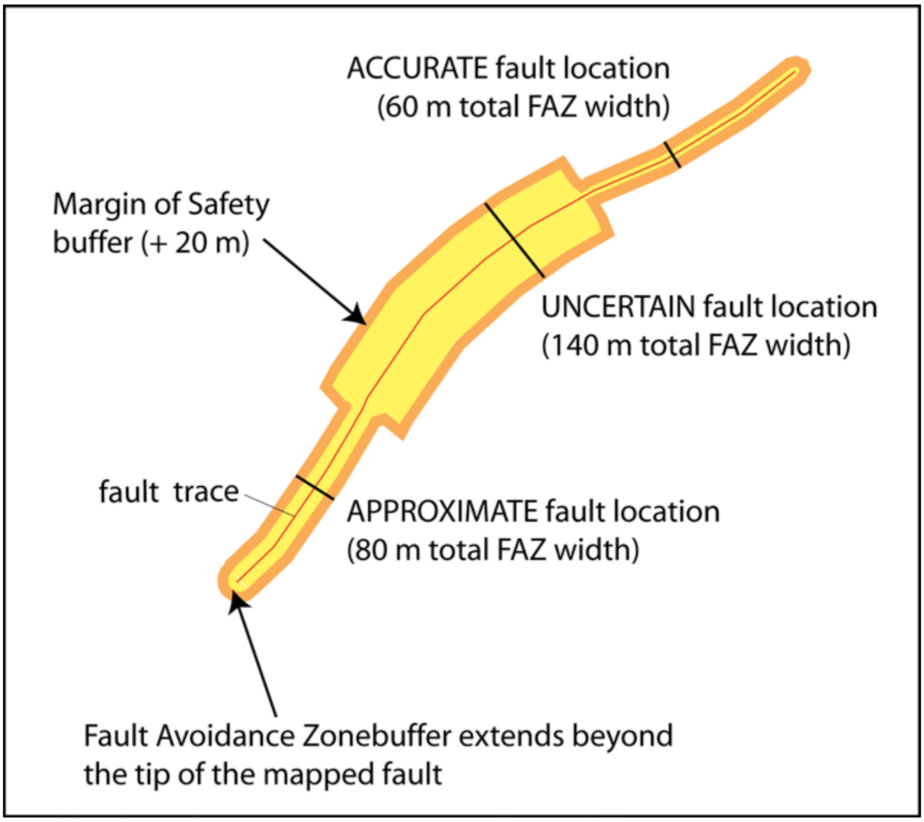

Figure 3.6 Cartoon showing the development of FAZ buffers used for active faults in the Mt Lyford Village area (not to scale). The FAZs include the full area encompassed by and within the outer orange buffer.

The MfE Guidelines recommend that a ‘Margin of Safety’ buffer of an additional 20 m be applied to either side of the fault trace (Kerr et al., 2003). Thus, an ‘accurately’ mapped trace will have a Fault Avoidance Zone of 60 m FAZ centred on the mapped fault location. Similarly, the FAZ widths for faults attributed ‘approximate’ and ‘uncertain’, are 80 and 140 m, respectively (Table 3.1).

Changes in fault location accuracy (from ‘accurate’ to ‘approximate’ or ‘uncertain’) along strike reflect differences in the ability to map these features. When FAZs are developed from the merging of individual buffers of varying widths, the FAZ will appear like a distorted string of sausages (Figure 3.6, Figure **3.7**).

The MfE Guidelines give provision such that a FAZ can be investigated to test and refine the location of any fault deformation within it (see Figure 6.1 in Kerr et al., 2003).

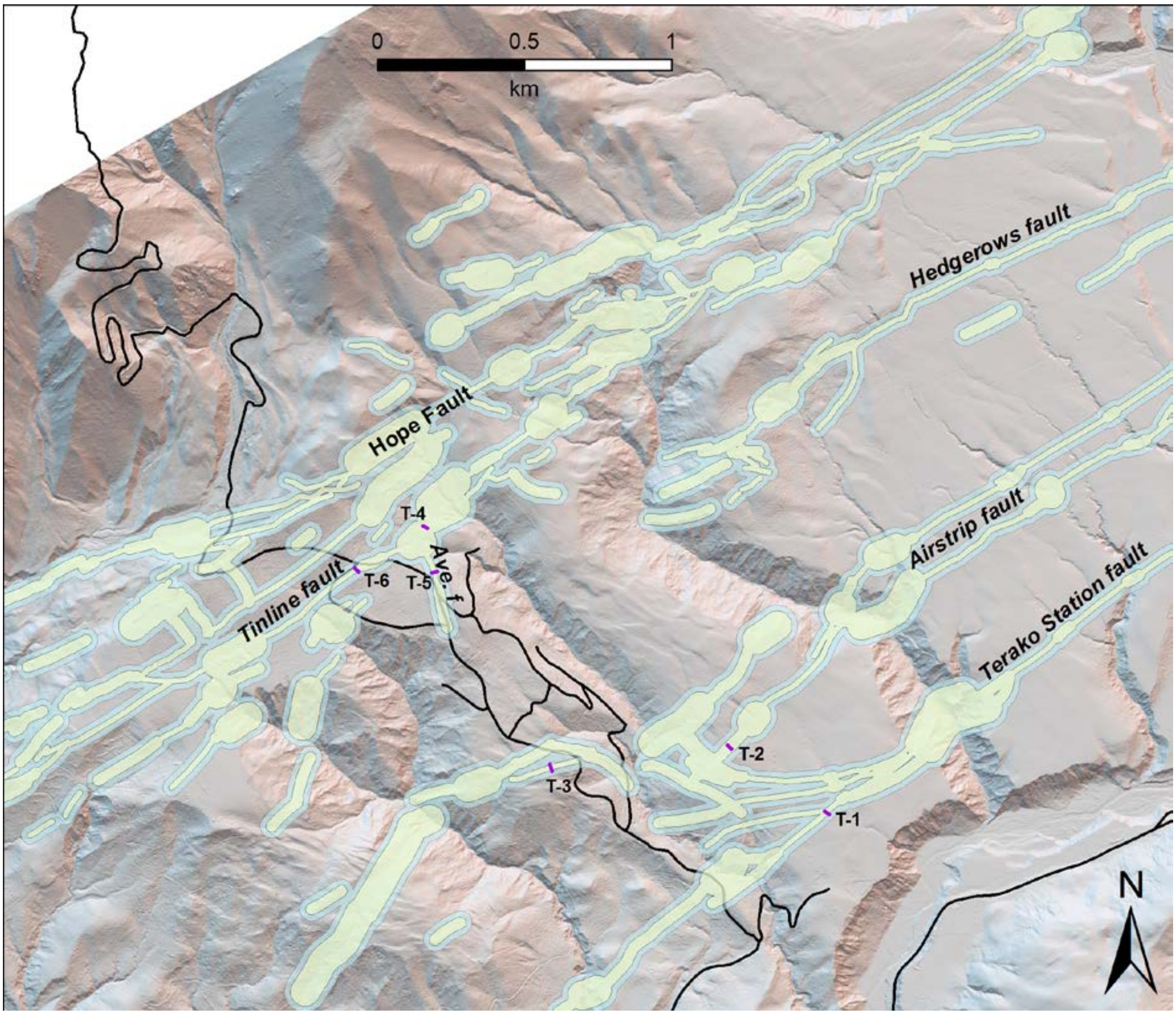

Figure 3.7 Fault Avoidance Zone (FAZ) map of the Mt Lyford Village area. The light green regions represent the width of the Fault Location certainty (expressed as ‘accurate, approximate, or uncertain’). The light blue edges are a 20-m wide margin of safety buffer. The FAZ is the sum of both coloured areas. Purple lines represent the locations of paleoseismic trenches excavated for Hancox et al. (2006).

3.6 FAULT RECURRENCE INTERVAL DATA

According to the MfE Guidelines, the most relevant parameters in assessing whether it is permissible to build structures adjacent to active faults are Fault Location and Accuracy, Building Importance Class, and Recurrence Interval Class (Kerr et al., 2003). The MfE Guidelines define six classes of active faults[5] (I-VI), within ranges of fault rupture recurrence interval (RI), e.g. RI Class III refers to a range of >3500 to ≤5000 years. The presence of a RI Class III fault will have differing planning implications than for other classes and, in addition, there will be differing planning implications for an ‘Already developed or subdivided’ site versus a ‘Greenfield’ site due to land ownership provisions from the Resource Management Act.

Six paleoseismic trenches were excavated across scarps within the wider Mt Lyford Village area as part of the Hancox et al. (2006) report see Figure 3.5 for locations). At the time of the dissemination of that report, there was no direct geochronologic dating from within these trenches, therefore, the recurrence intervals defined in that report were based on estimates

[5] In New Zealand, an active fault is defined as a fault that has ruptured the ground surface within the last 125,000 years (Langridge et al., 2016). RI Class I (RI <2000 years) refers to the most active faults in New Zealand.

of landscape ages. Two radiocarbon dates, one each from Terako trenches -5 and -6, provide some constraint on the age of the deposits in the trenches and therefore the surfaces in the Mt Lyford Village area (Figure 3.8).

Terako trench-5 (Figure 3.8a) was excavated into a NNW-trending scarp (Figure 3.7) of a fault we informally call the Avenue fault due to its proximity to Mt Lyford Avenue (Table 3.2). The trench shows evidence for a complex zone of steeply-dipping (to the west) faulting associated with the scarp. Siltstone bedrock was observed in the footwall of the fault, interpreted as belonging to either the Waima or Greta formations. The calibrated radiocarbon date Ter 5-1 (4440-4813 cal. years BP) comes from a pod of gravelly silt that is arguably overlain by a scarp-derived colluvial wedge (upper white unit on Figure 3.8a), i.e. a silty gravel deposit that reflects a surface faulting event. This deposit itself is faulted at its base and the lateral continuity of the white (silty gravel) unit is broken by a triangular zone of friable yellow-brown silt, which may be filling a small wedge derived by faulting. From this description, we argue for two (or more) surface faulting events since the deposition of charcoal sample Ter 5-1, i.e., since 4440-4813 cal. years B.P. (Table 3.2).

As described above, we visited the site of trench-5 along the Avenue fault to look for evidence of recent surface faulting, noting a series of *en echelon* cracks with several cm of opening along the lower edge of the scarp, immediately north of the location of trench T-5. While this cracking was over a length of only a few metres along this fault, we infer that it provides evidence of possible surface faulting related to the 2016 Kaikōura earthquake. In terms of the recurrence of faulting along the Avenue fault, the events in the trench and, arguably in 2016, suggest at least 3 occasions of surface faulting or deformation during the last c. 4800 years. Even if we discount the evidence for recent faulting, there has been at least 2 events during the last 4440-4813 years. Given also that there has been no other known surface faulting during the New Zealand historical period at this site, we conclude that the Recurrence Interval for the Avenue fault is <2000 years and it should therefore be assigned to RI Class I.

Terako trench-6 was excavated into a NE-trending scarp related to a fault informally named as the Tinline fault (Hancox et al., 2006). This trench (Fig. 3.8b) shows evidence for a zone of steeply NW-dipping faulting. Tertiary siltstone (Waima or Greta formations) was mapped in the hanging wall of the fault, which was used as evidence to suggest that there was a strike-slip (horizontal) component of motion on this fault, in addition to the vertical component of motion as indicated by local geomorphology. The calibrated radiocarbon date Ter 6-2 (4258-4520 cal. years BP) comes from a pale yellow stony clay. We interpret this deposit (olive coloured unit in Figure 3.8b) as a scarp-derived colluvial wedge, i.e. a silty gravel deposit that reflects a surface faulting event. The base of this colluvial unit is faulted, which provides some evidence that there has been more than one faulting event recorded in the upper part of this trench. If this is the case, then there are two (or more) faulting episodes that have occurred since the deposition of charcoal sample Ter 6-2, which has a calendar calibrated age range of 4258-4520 cal. years BP (Table 3.2). We did not see any evidence for recent surface faulting along the Tinline fault. Despite this, and considering the lack of faulting events since AD 1840, it is again reasonable to concur that the Tinline fault has a Recurrence Interval which is very close to 2000 years. Based on its proximity to the Hope Fault (and Avenue fault) it is reasonable to also place the Tinline fault in RI Class I (Table 3.2).

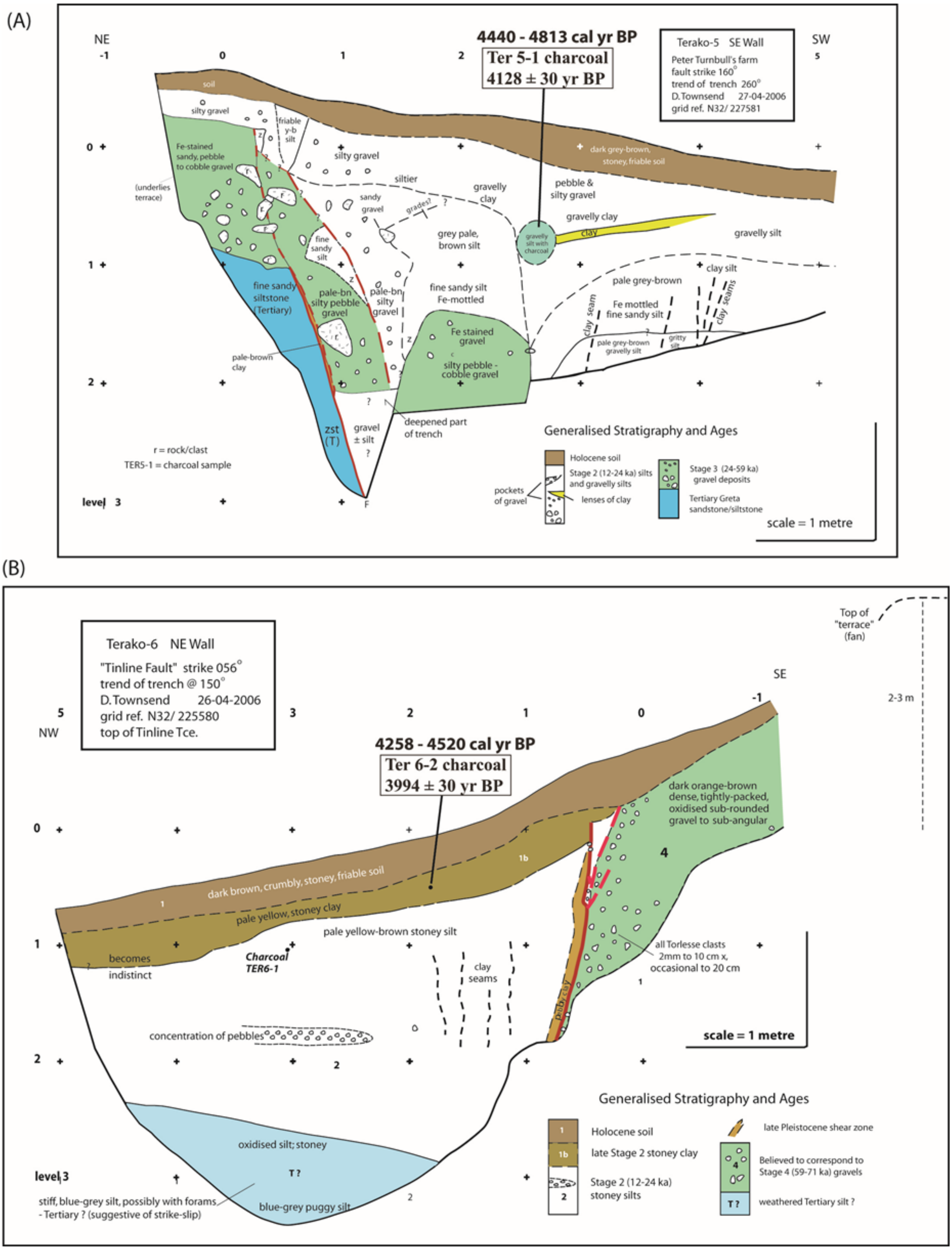

Figure 3.8 Logs for paleoseismic trenches Terako-5 (A) and Terako-6 (B) after Hancox et al. (2006), with radiocarbon dates and calibrated ages added. Stratigraphic columns and interpretations have not been changed from the 2006 report.

Table 3.3 Revised slip rate and recurrence interval data for faults in the My Lyford area.

Trench	Informal Fault name	former Slip Rate (mm/yr)*	former RI (yr)*	Radiocarbon data (yr BP) [calibrated age]	New Slip Rate (mm/yr)#	New RI (yr) [RI Class]
T-1	Terako Station fault	0.03-0.08	>8000	-	0.05-0.19	2000-3500 [II]
T-2	Airstrip S fault	<0.05-0.1	≥12,000	-		
T-3	Airstrip N fault	0.07-0.17	c. >6000	-	0.1-0.29	2000-3500 [II]
-	Hedgerows fault	-	-	-	0.1-0.3	[I]
T-4	Tinline fault	?	≥12,000	-	-	2000-2200 [I]&
T-5	Avenue fault	>0.09-0.11	c. 10,000	4128 ± 30 *[4440-4813]*	-	1480-2318 [I]&
T-6	Tinline fault	0.03-0.08	>2500-13,300?	3994 ± 30 *[4258-4520]*	-	2000-2200 [I]&
-	Hope Fault	<23 ± 4			19-23	180-310 [I]

Notes: *Values defined in Hancox et al. (2006). &Placed in RI Class I due to its proximity to this age range band. #Slip rate reflects data from other sites. Inferred from slip rate and proximity to other faults of RI Class I.

The other new dataset from which we can address recurrence interval is the LiDAR data. From the LiDAR models, we have mapped the faults in greater detail than before. We can also use this digital data to profile the height of fault scarps across geomorphic surfaces of different ages. More detailed digital topography has allowed us to recognise the along-strike continuity of faults that are mapped and trenched near the village. Many of these faults continue to the northeast onto the set of alluvial terraces formed by the Mason River and preserved at Mt Terako Station. These terraces have been mapped within a regional stratigraphic framework and correlated to MIS 1-3 (Rattenbury et al., 2006). Scarps with measurable heights cross these terraces of known or inferred age, allowing us to develop vertical slip rates for several of them (informally named in Table 3.2).

A fault's slip rate – in many of these cases its vertical slip rate - provides us with some basis for assessing its recurrence interval. The vertical slip rate can be derived by dividing the amount of vertical displacement, measured from a profile by the expected single-event displacement. Alternatively, we can derive the recurrence interval if we have slip rate and single-event displacement data.

3.7 2016 Kaikōura Earthquake Uplift and Deformation

LiDAR acquisition and trig station surveying undertaken by Land Information NZ (LINZ) after the 2016 Kaikōura earthquake has enabled us to consider the relative co-seismic vertical and horizontal deformation that occurred in the Mt Lyford Village area. As part of a regional post-seismic survey of trig monuments, LINZ have reoccupied several of the trigs in the area (Figure 3.9). The surveying shows that there has been a measurable co-seismic vertical and horizontal movement of the Earth's surface, i.e. a crustal movement, relative to before the Kaikōura earthquake. In the village, the land has moved on the order of c. 1.7-1.8 m vertically, and about one metre horizontally, with motion directed upwards and toward the NNE, respectively. Two other trig monuments (one near Mt Lyford Lodge, the other near Mt Terako Station; Figure 3.9) suggest even larger vertical motions (2.5-2.7 m upwards) and about the same horizontally 0.7-1.1 m). These larger movements can perhaps be explained by their closer proximity to The Humps Fault, and Conway-Charwell Fault, respectively (Figure 1.1; Nicol et al., 2018).

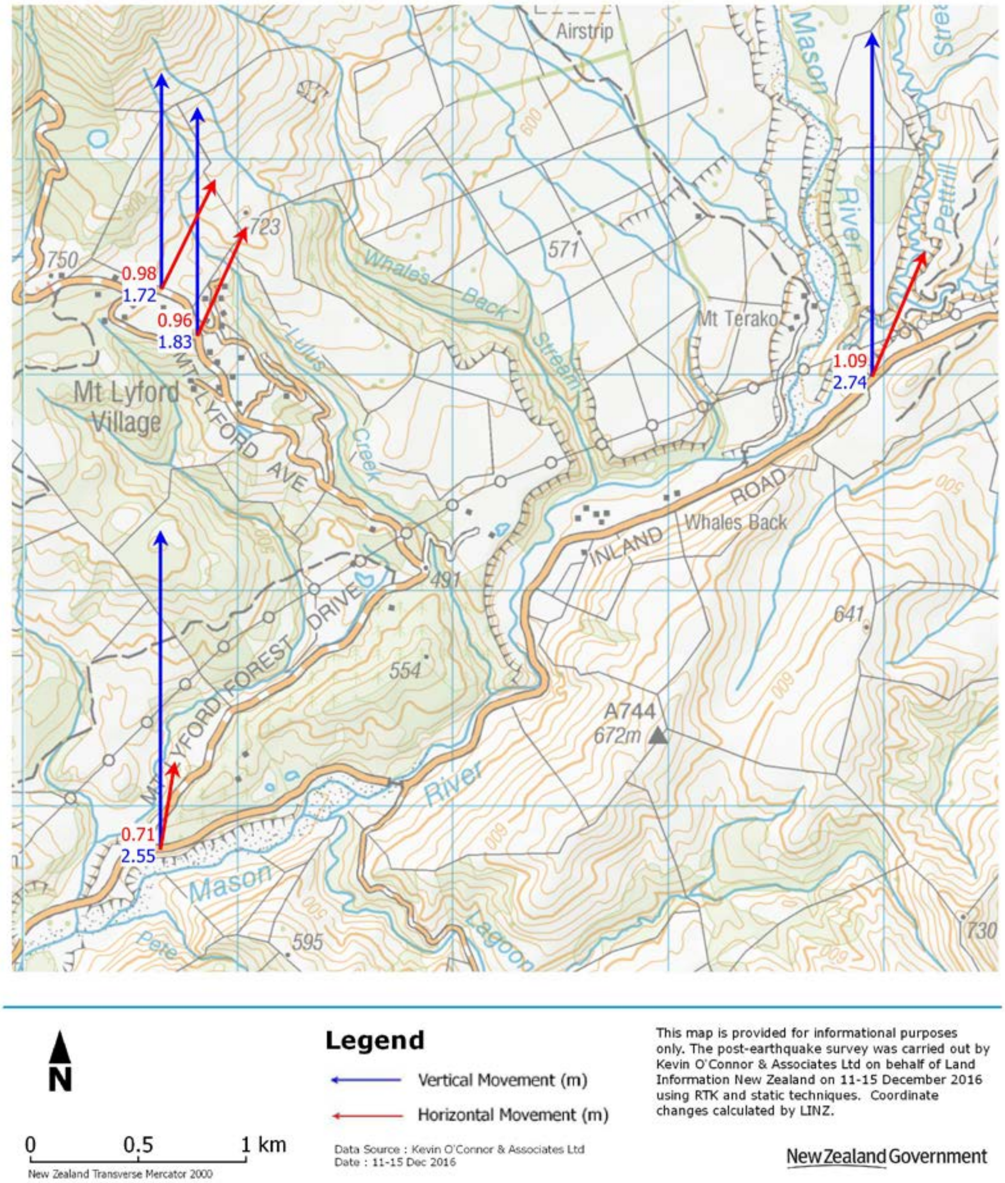

Figure 3.9 Co-seismic movement of the land during the 2016 Kaikōura earthquake, measured at the available LINZ trig monuments (data supplied by LINZ). Movement has vertical (upwards/blue) and horizontal (to the NNE/red) components.

With LiDAR surveys of the area taken both before and after the Kaikōura earthquake, we can quantify co-seismic deformation via a simple subtraction of these digital datasets in a GIS. This differential LiDAR (or 'D-LiDAR') is a tool that can be used for any region where there are pre-event and post-event LiDAR (or other digital) surveys (e.g. Clark et al., 2017). Rather than single point observations, such as from LINZ trig monuments, D-LiDAR offers the opportunity to observe deformation of continuous surfaces (but only gives the vertical component of motion).

A LiDAR survey was undertaken in 2012 along the Hope Fault for scientific purposes. This survey was an approximately 1.5 km wide strip (750 m either side of the fault), which covered the upper part of Mt Lyford Village. Differencing (subtraction) of the more extensive post-

Kaikōura earthquake LiDAR acquisition with the 2012 survey provides an image of how much permanent land deformation has occurred in the overlap area (Figure 3.10). The LINZ trig survey data was acquired as a cross-check, because it was not clear that the pre- and post-earthquake LiDAR datasets were registered in the same way, meaning that the resultant D-LiDAR signal could have been misleading. The height changes for the two trig monuments in the upper part of the Mt Lyford Village measured by LINZ are within c. 10-12 cm of the D-LiDAR results at the same locations, thereby corroborating the validity of the D-LIDAR signal. The post-earthquake data was acquired soon after the event, in mid-December 2016; therefore, the differences observed in the D-LiDAR data mainly reflect changes between 2012 to 2016. While we consider that most of the change is due to the 2016 Kaikōura earthquake, some differences may be the result of changes that occurred after 2012 but before the earthquake (e.g. landslides occurring due to storm events).

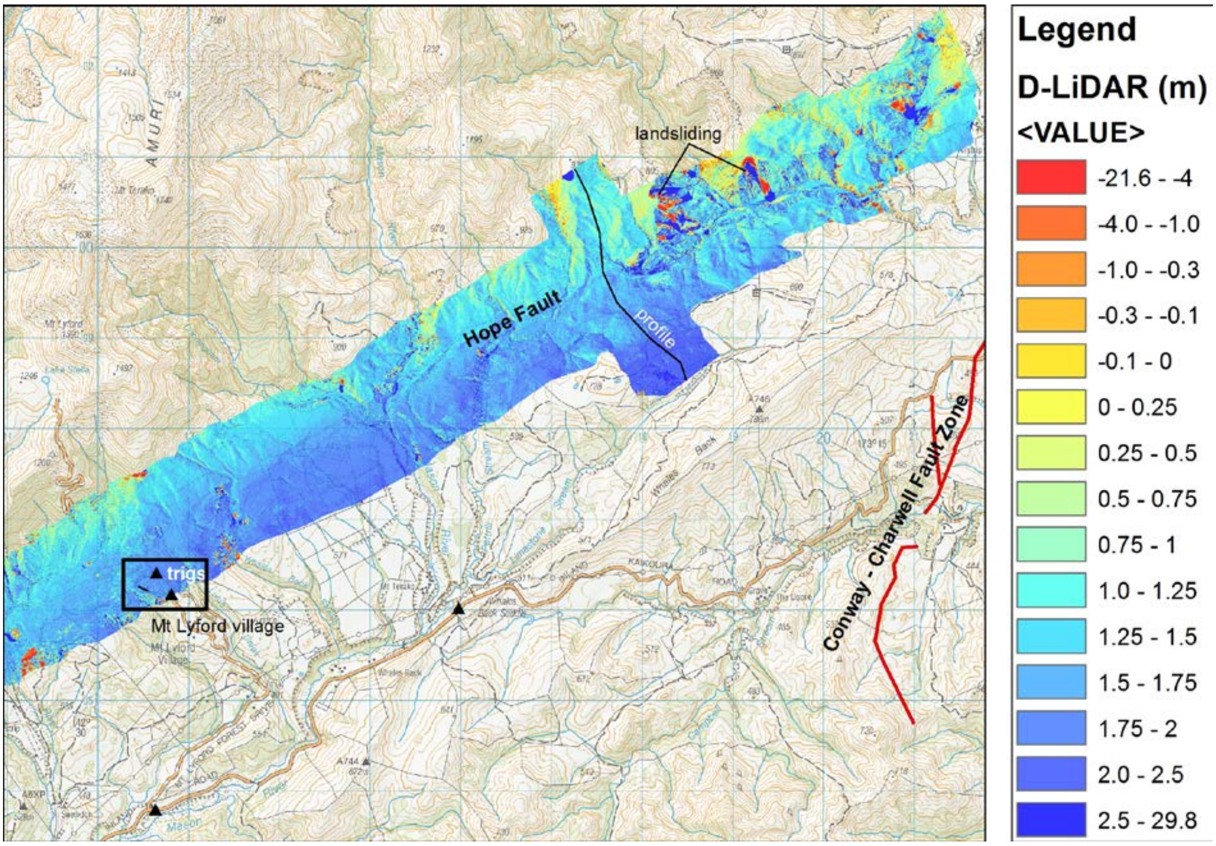

Figure 3.10 Available D-LiDAR coverage includes a strip along the Hope Fault between the Wandle River and Cloudy Range Station. Colour gradient reflects vertical change pre- versus post-Kaikōura earthquake. Black triangles are positions of LINZ re-survey monuments (Figure 3.9) and black line indicates the location of a topographic profile shown in Figure 3.11. Box shows area of detail shown in Figure 3.12.

A profile across the widest part of the D-LiDAR strip in the Towy River area gives a good indication of the vertical deformation from NW to SE (Figure 3.11). Uplift of the Amuri Range to the north of the Hope Fault is c. 1-1.5 m. Uplift on the south side of the Hope Fault is c. 1.5-2 m and increases to 2-2.5 m towards the Conway–Charwell Fault Zone, which ruptured during the 2016 Kaikōura earthquake.

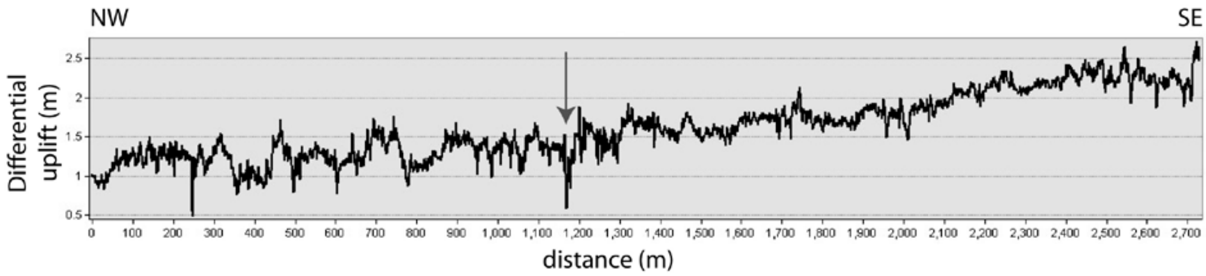

Figure 3.11 D-LiDAR profile showing differential uplift (in m) from the Towy River headwaters north of the Hope Fault (marked by arrow) to Limestone Creek in the southeast. Arrow marks the location of the Hope Fault. Uplift to the NW of the Hope Fault is lower than to the SE of it. The profile location is shown in Figure 3.10.

The main signals observed from D-LiDAR analysis (Figure 3.10) are:

(a) Region-wide uplift of the whole area, both northwest and southeast of the Hope Fault (which is spanned by the D-LiDAR strip);

(b) Higher uplift southeast of the Hope Fault;

(c) Higher uplift across the strip toward the southeast, i.e. toward the Conway-Charwell Fault Zone, observed along a profile perpendicular to the strike of the Hope Fault (Figure 3.11), and progressively higher uplift along the strip to the northeast compared with the southwest;

(d) Landsliding, indicated by coupled areas of intense red and blue colours in Figure 3.10, indicates significant elevation losses (red; landslide source areas) and gains (bright blue; in landslide accumulation areas).

The amount and styles of deformation are consistent with the observations shown by the 4 LINZ trig monuments (Figure 3.9). For example, the two trig monuments along the Inland Road suggest uplift of >2.5 m, which is borne out from the wider D-LiDAR coverage.

Figure 3.12 displays the D-LiDAR coverage within Mt Lyford Village in detail. Some of the most intense differences (bright red to bright blue) relate to landslides indicating a consistent red-at-top (headscarp/elevation loss) to blue-at-bottom (deposit/elevation gain) signal. A good example of this is a fresh and active landslip on the face northeast of Lulus Creek (visited during the field reconnaissance) (Figure A1.3). This provides some control between field observation and the digital model. However, at this scale there are effects in the D-LiDAR image that are artificial and not related to real land movement or deformation, e.g. the finely speckled bright red/blue pattern observed in the steep gullies of Whales Back Stream, Wandle River, and Lulus, ‘unnamed’ and other creeks. This may be an artefact of significant differences in the 2012 vs. 2016 LiDAR acquisitions (or processing) that are exacerbated in the gullies and streams, particularly where penetration through the vegetation cover. Above all, Figure 3.12 highlights that the upper part of the village has been consistently uplifted by c. 2 m, and the hazard potential posed by slope movements in the steep gully walls of the drainages around Mt Lyford Village.

A third type of co-seismic deformation that warranted consideration is surface fault deformation. We undertook field reconnaissance to look at the Hope Fault in the vicinity of the village and several of those faults that were trenched in 2006 (Hancox et al., 2006), including the Tinline fault, Avenue fault and Terako Station fault (see Section 3.3.2).

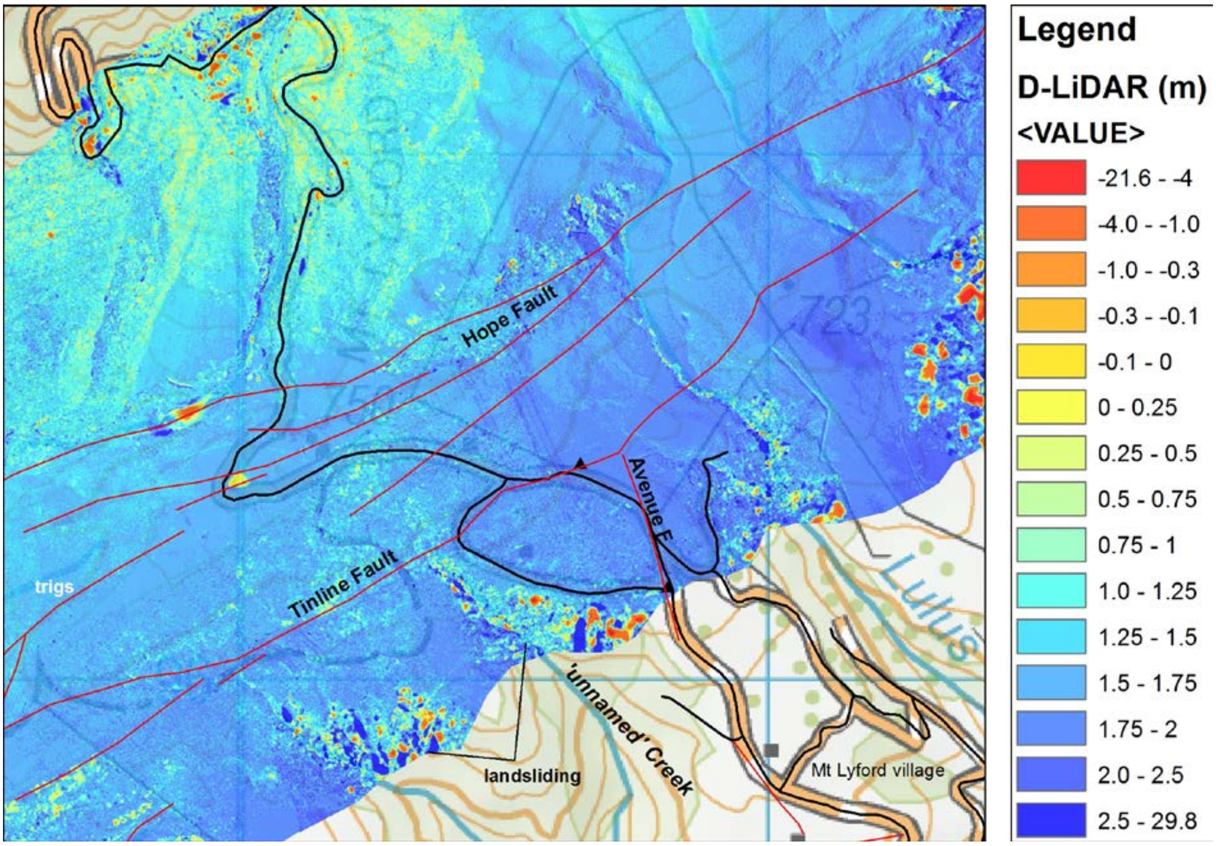

Figure 3.12 D-LiDAR coverage centred on the upper part of Mt Lyford Village. Caveats related to the interpretation of this data are discussed in the text.

Reconnaissance of the Hope Fault near the upper part of Mt Lyford Avenue did not reveal any evidence for surface rupture. Similarly, there was no evidence for surface rupture or deformation observed along the Tinline or Terako Station faults. In contrast, reconnaissance at the northern end of the NNW-striking Avenue Fault within Mt Terako Station allowed for the recognition of dcm-length, open cracks of 3-4 cm width in the lower part of the scarp that was trenched nearby in 2006. These cracks had arguably been preserved in an open state from November 2016 to August 2017. Interrogation of the D-LiDAR suggests that there had been c. 10 cm of vertical motion across the Avenue Fault. This amount of deformation would usually not be visible or measured in typical reconnaissance. However, these data imply that the Avenue Fault responded to stress during the Kaikōura earthquake and ruptured with minor displacement. This is not without precedent as several other NNW to NNE striking faults, including the Papatea, Stone Jug, and Leader faults also ruptured during the Kaikōura earthquake (Langridge et al., in review; Nicol et al., in press). While there is evidence for minor rupture of the Hope Fault in places along the range front near Kaikōura, these results (i.e., little rupture of the NE-striking Hope fault and its subsidiaries, but rupture of N-striking faults) are consistent with the overall pattern of faulting observed during the Kaikōura earthquake (Litchfield et al., in review).

4.0 CHARACTERISING GEOLOGICAL HAZARDS AT MT LYFORD VILLAGE

Geological data and interpretations from Section 3 are used below to consider the hazards in Mt Lyford Village from slope instability (landslides) and active faulting (ground surface rupture). The discussion presented in Section 4 is restricted to the types of natural hazard that the village is susceptible to, and which were the main causes of land damage during the 2016 Kaikōura Earthquake. This report does not specifically deal with the causes of structural damage to the integrity of buildings, particularly log cabin style houses, or to the effects of earthquake ground motions (shaking).

4.1 CHARACTERISING GULLY EROSION AND SLOPE RELAXATION

In Section 3.1 of this report we describe the Late Quaternary geological history of the Mt Lyford area, by describing the development of sediments and surfaces built by geomorphic processes and the impact of erosion and tectonics on the Amuri Range and range-front fan surfaces.

The geological history for the last 200,000 years (MIS 6 to MIS 1) at Mt Lyford Village indicates that much of the observed incision of creeks like Lulus, 'unnamed' and Whales Back Stream occurred during the warm MIS 1 (Holocene) period. Whales Back Stream shows a distinct right deflection (of c. 150 ± 10 m) that is likely to be related to continued right lateral motion on the Hope fault. If we use the slip rate range (19-23 mm/yr) for the Hope Fault from Table 3.2, then the current deflection of the incised Whales Back Stream could have occurred in 6100-8400 years (median value 7100 yr). These streams existed prior to the Holocene (i.e. are older than 11,700 years) because MIS 2 age alluvial surfaces are preserved in some places. However, much of the stream incision through these surfaces and associated slope instability related to this incision must have occurred during the Holocene.

The timing of this cycle of incision is relevant because, at Mt Lyford Village, it is driven by landsliding and other slope movement processes. These streams have incised relatively recently and rapidly. This is probably exacerbated by the underlying Tertiary bedrock, which is relatively soft and easily eroded. Lulus and 'unnamed' creeks and Whales Back Stream have all incised deeply and removed a significant volume of material from the edges of the range-front fan surfaces. Where it is possible to measure the incision from the presence of MIS 2 terraces in the stream, incision during the Holocene is at least 7-20 m, which equates to a minimum rate of downcutting of c. 1-2 mm/year over the last 10,000 years.

This rate is partly climatically driven (rainstorm events) and partly tectonically driven (regional uplift and stream base level changes). The Kaikōura earthquake uplifted the landscape in the area of the village by c. 1.7-1.8 m (Figure 4.1). The local streams will begin to respond to this tectonic change in level by incising further. This incision will have the effect of steepening and destabilising the valley side walls as the streams erode, which will likely have a detrimental impact on the stability of the land above.

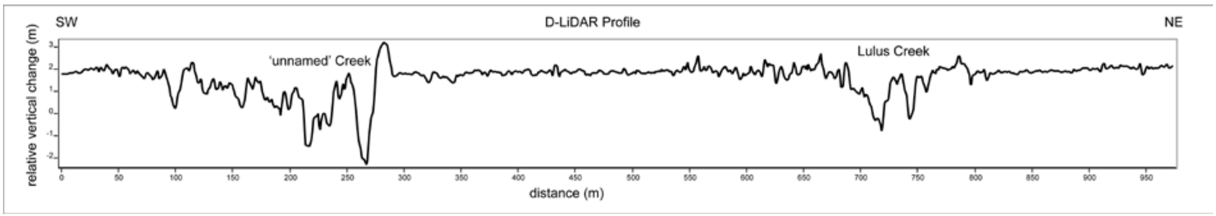

Figure 4.1 Profile along the SE edge of the D-LiDAR dataset in Mt Lyford Village. The profile indicates that there was broadly 2.0 m of co-seismic uplift in the central part of the village.

A secondary effect of gully erosion that has been previously noted is gravitational extension (collapse) of the range-front fan spurs. ECan (2005) and Hancox et al. (2006) both note and map a series of NW-SE trending sinuous linear features individually less than about 400 m in length, on both the Terako Station range-front spur (i.e. the spur between Whales Back Stream and Lulus Creek, and the Mt Lyford range-front spur (i.e. the spur on which the village has been developed). Using LiDAR to map the geomorphology, these features have been confirmed on these two spurs and, also on the next spur to the southwest of the village (Figure 3.1). The origin of these features remains uncertain. They could be tectonic in origin or slope-related, particularly as the streams adjacent to them have been incising at rapidly throughout the Holocene, as implied above. The hazard presented by these structures, which could be related to slope relaxation, is not well understood. In any case, they appear to be structures on which deformation of the older terraces surfaces and broad spurs is occurring, so they need to be acknowledged.

4.2 CHARACTERISING SLOPE-RELATED HAZARD

In this study, we have considered the upper limit of what are defined as 'steep slopes' (i.e. 15-25º) by Hancox et al. (2006) as an important slope angle break. Thus, we define slope angles of ≥25º as being 'very steep slopes' (Figure 3.3). We consider that building in such areas of very steep slope should be managed and avoided if possible. Based on our observation and analysis, we also suggest that a setback distance of 20 m from the upper edges of areas of very steep slopes is warranted. Figure 4.2 shows an example of the suggested set-back zoning for the upper part of Mt Lyford Village. Set-back limits skirt around the upper catchment of 'unnamed' Creek and other creeks with very steep slope edges. Landslide run-out has not been considered in this study and so building below very steep slopes is not considered in this analysis.

The set-back distance is supported by the observations of land (and building) damage in some of the very steep areas at Mt Lyford. For example, the southwestern side of Tinline Terrace sits partly within the 20-m setback buffer. Co-seismic land damage in this area within the setback buffer was extensive with two buildings structurally damaged to the point they were declared dangerous buildings (red-placard/Section 124 in effect). Oral accounts regarding Tinline Terrace suggest that slope movement was ongoing after the earthquake with post-seismic cracking and extension of the slopes above the very steep slopes continuing until at least October 2017.

This continued movement above these very steep slopes may be due to the continual infiltration of rainfall and other water run-off into ground cracks. Rainfall was greater than normal through the autumn, winter and early spring of 2017[6].

[6] Rainfall data can be obtained from the Environment Canterbury website https://www.ecan.govt.nz/data/rainfall-data/sitedetails/234201 (this link is for the Cloudy Range rainfall station).

Cracking and land damage was also observed along the southwestern loop of Tinline Terrace. An oral account suggests that, following the Kaikōura earthquake, there were tensional cracks in this packed dirt road. Part of the road would be included in our 20-m setback exclusion zone (Figure 4.2). In addition, there was significant land damage (cracking and downslope movement) around the telecommunications repeater on Tinline Road (Figure A1.7).

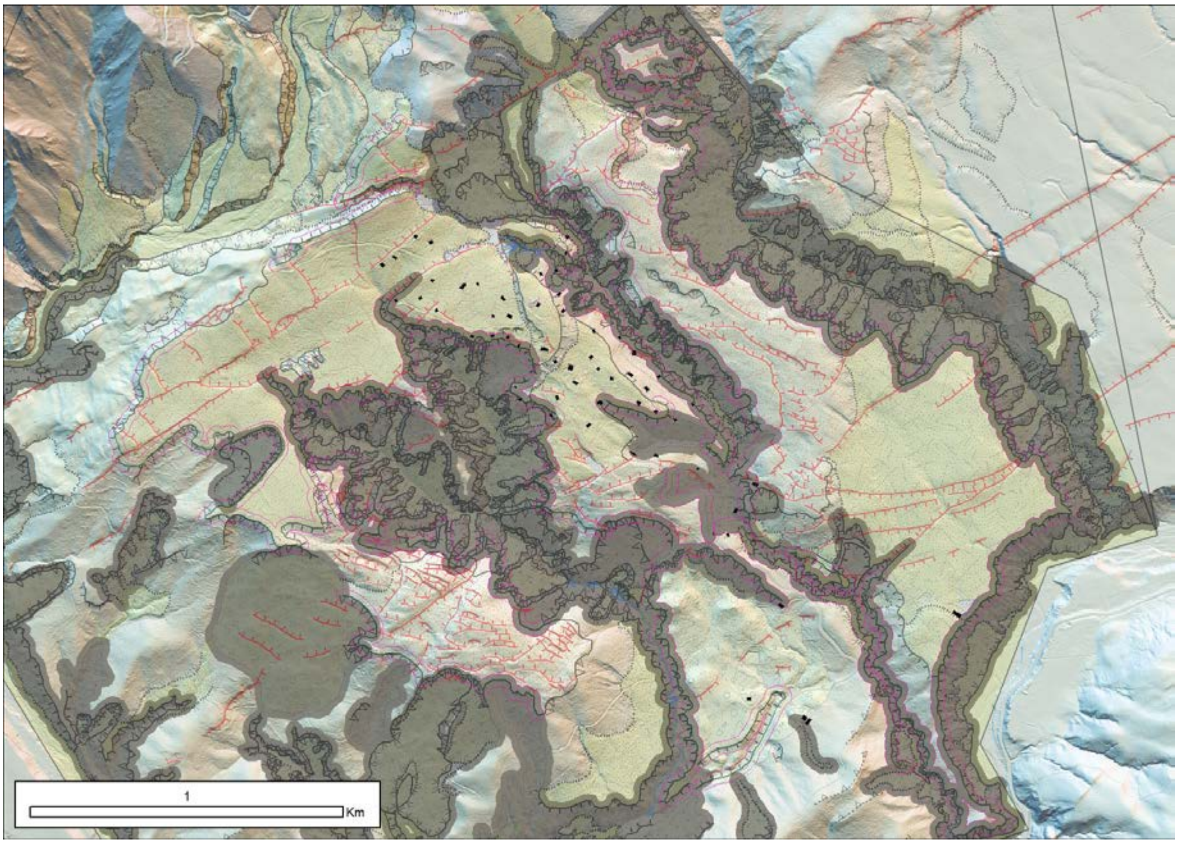

Figure 4.2 A geomorphic map of Mt Lyford Village with a 20m wide buffer added above the slope break between very steep slopes and less steep slopes. Current house footprints are shown as black polygons. Slopes of less than 25º are depicted as light green and light orange areas, (there is some variation in colour due to the underlying grey hill shade model). Slopes of 25º or steeper (including a 20m set-back buffer) are shown in grey. Thus, the grey areas represent very steep and/or vulnerable slopes. The darker brown-grey areas represent areas the highest slope stability hazard in the Mt Lyford area.

In this area, the land slumped away by at least 0.5-1.0 m downslope across a zone of land extension toward the head of 'unnamed' Creek.

Land damage was also observed at two properties downhill from 87 Tinline Terrace. These areas were characterised by open, extensional cracks amongst the native scrub and regenerating beech forest near the house locations, and further open extensional cracks in the slope beneath 85 Tinline Terrace. This was also within the proposed 20 m setback buffer.

Another red-placarded house at the edge of very steep slopes is 17 Charwell Terrace. The property of #17 was severely impacted by land damage, characterised by extensional cracking and failure of the slope at the back of, and underneath, the house. Decking foundations on the front of the house were unseated by extension and slumping downslope. Again, the damage to this property was within the 20m setback buffer.

4.3 FAULT AVOIDANCE ZONES AND PLANNING

Active faults such as those mapped in the Mt Lyford Village area can cause ground surface deformation including surface faulting and folding. The purpose of the MfE Guidelines is to recognise the hazard from active faults, with respect to a range of criteria, and to provide guidance to planners on how to mitigate the risk for different types of buildings and building use.

Figure 3.7 and Figure **4.3** show fault avoidance zone maps for the Mt Lyford Village area. These show the areas where restrictions on building activity might apply in relation to active faults. The width of fault avoidance zones is defined by how accurately the fault can be located, termed the fault complexity in the MfE Guidelines (Kerr et al., 2003). The structure of planning decisions developed in the MfE Guidelines use fault recurrence interval, fault complexity, building importance class, and current land use type to determine the appropriate resource consent category for a building type/use at a site.

In this study, we have defined the active faults that cut across the land in the Mt Lyford Village as having a recurrence interval (RI) class of I or II. The Hope, Tinline and Avenue faults are defined as RI Class I (RI <2000 years), while the Airstrip1, Airstrip2, and Terako Station faults are defined as RI Class II (≥2000-<3500 years). Based on estimates of vertical slip rate from offset terraces on Terako Station and its proximity to other RI Class I faults, the Hedgerows fault has been placed in Recurrence Interval Class I.

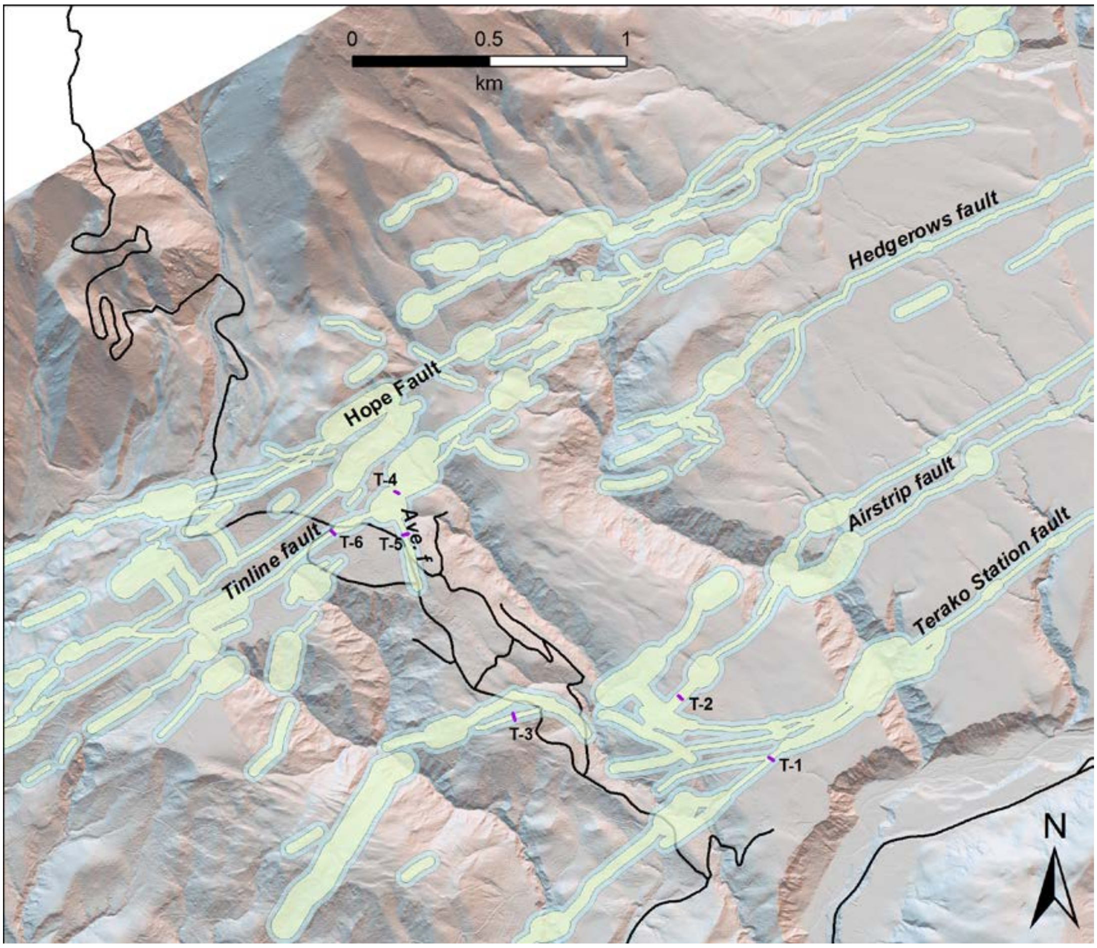

Figure 4.3 Fault Avoidance Zone (FAZ) map for Mt Lyford Village. FAZ 'sausages' are shown with their associated active faults as labelled. See text and **Figure 3.7** for details of how this is constructed. Fault line data is intentionally left off this map to focus on the avoidance zones.

In terms of building importance category (BIC), all of the structures currently located in the village, or that are likely to be built in future under the village covenant, will be BIC 1, 2a and 2b structures. BIC 1 are ‘Simple’ structures and often do not require specific planning consent. BIC 2a refers to standard New Zealand residential timber-framed single-storey house construction. BIC 2b refers to large (>300 m2) or wooden-framed houses with more than one storey (and also larger ‘Normal’ and unclassified structures; see Table 9.1 in Kerr et al., 2003). Most of the occupied buildings at Mt Lyford Village are therefore of category BIC 2a or 2b.

For more information, readers are referred to Tables 11.1 and 11.2 in Kerr et al. (2003). Variations on these tables specific to active faults at Mt Lyford Village are presented in Appendix 3 (Table A3.1 andTable **A3.2**). These tables define the resource consent activity status for building on, or adjacent to, RI Class I and II active faults. Table A3.1 applies to Greenfield sites, while Table A3.2 applies to sites that are ‘developed or already subdivided’.

For Greenfield sites, the recommended resource consent activity status ranges (because of variations in fault complexity) between Non-Complying and Discretionary for BIC 2a/2b structures in RI Class I and II fault avoidance zones.

For developed or already subdivided sites the recommended resource consent activity status ranges (because of variations in fault complexity) between Non-Complying and Discretionary for BIC 2a/2b structures in RI Class I fault avoidance zones, and ranges between Discretionary and Permitted for BIC 2a/2b structures in RI Class II fault avoidance zones.

4.4 THE HOPE FAULT AND GROUND MOTIONS

As part of the post-Kaikōura earthquake response and rebuild, GNS Science was contracted to re-examine the National Seismic Hazard Model (NSHM; Stirling et al., 2012), focused on the Kaikōura area and more widely across the northern South Island, encompassing the State Highway network (Goded et al., 2017). One component of this work was to estimate the conditional probability of rupture of the Hope Fault. In the NSHM, the Hope-Conway seismic source extends from the Hanmer basin to the Kaikōura coast over a distance of 81 ± 8 km (Litchfield et al., 2014; Stirling et al., 2012).

The Conway segment of the Hope Fault was not recognised as having had significant (>1.5 m of displacement) surface rupture during the 2016 Kaikōura earthquake (Litchfield et al., in review). As a result, there has been a perception that this fault is ready or ‘overdue’ for rupture. By calculating the conditional probability (CP), it is possible to assess whether such claims are well founded. Goded et al. (2017) calculate a conditional probability for rupture of the Conway segment of the Hope fault of 28% in the next 50 years. This means that the fault has a moderate probability of rupture in the next 50 years. Similarly, the calculated conditional probability for the Conway segment of the Hope fault until the end of 2018 is c. 1.3%. Fifty-year conditional probabilities were also calculated for the Awatere (eastern) and Kekerengu faults (Goded et al., 2017). These produced CPs of 5.7% and 2.9%, respectively, in the next 50 years. The eastern Awatere and Kekerengu faults ruptured in 1848 and 2016, respectively. Therefore, it is assumed that these faults are in the early part of their earthquake cycle, having ruptured relatively recently.

The conditional probability for the Conway segment of the Hope Fault is understandably higher than for the eastern Awatere and Kekerengu faults. The Hope Fault may be well advanced in its earthquake cycle because the most recent rupture event has been dated at c. AD 1780 ± 60 and the fault has an average recurrence interval of 180-310 years

(Langridge et al., 2003). Nonetheless, the conditional probability value of 28% in 50 years is instructive as it does not imply that a large earthquake (~Mw 7.4) on this fault segment is overdue, but has a moderate probability of occurring during the next 50 years.

The question of whether the Hope Fault is more or less likely to rupture as a consequence of the Kaikōura earthquake is a topic of ongoing science. Litchfield et al. (in review) suggest that the Hope Fault may not have ruptured due to unfavourable stress conditions following rupture of the nearby Humps Fault, and also by the rupture of faults to the northeast of the Humps Fault, as the Kaikōura rupture sequence progressed (toward the NE). In addition, the horizontal block motion of c. 1 m to the NNE measured from surveys (e.g. LINZ re-surveys) suggests a relative de-stressing of the Hope Fault by effectively applying a left-lateral shear to it.

5.0 CONCLUSIONS

The purpose of this report has been to consider land damage caused by the 2016 Kaikōura earthquake and ongoing hazard from slope instability, active faulting and strong ground shaking. One of the outcomes is the characterisation of different classes of land hazard at Mt Lyford Village related to slope instability and active faulting.

Shaking and deformation related to the 2016 Mw 7.8 Kaikōura earthquake caused considerable damage in Mt Lyford Village. Some of the damage including some of the worst cases of structural failure (resulting in red placards and/or section 124 notices) can be directly attributed to land damage. Land damage is mostly attributed to slope instability observed as cracking, extension and slumping at the top edge of very steep hillslopes and ridgelines. This is corroborated by the discussion of building performance in Appendix 4.

Results from this study should be used by Hurunui District Council toward considering current and future land use practice at Mt Lyford Village. This report differentiates five classes of ground within the village based on observations from fieldwork and interpretation of geomorphology, including landslide/gully erosion features and fault surface rupture traces. These are:

1. Areas with gentle, moderate and steep slopes (all <25°); these are common throughout the village and provide good land for building and potential for future development. These areas may be limited by the presence of FAZs or other features that require investigation (such as ridge-parallel extensional features, formerly described by Hancox et al. 2006). For these reasons, a geotechnical study is suggested for future development of these areas.
2. Areas with consistently very steep slopes (>25°) are not recommended to be used for further development.
3. Areas that are within 20 m of very steep slopes. We recommend that a buffer of 20 m is applied to the upper edge of very steep slopes (2 above). A geotechnical report would be required in order for such areas to be developed in future to consider the issue of slope instability.
4. Areas that have a mixed or terraced slope (i.e. having very steep slopes mixed with slopes <25°). For future development, a geotechnical report is recommended because of the potential for slope instability issues.
5. For areas that fall within FAZs we recommend that any plans for future development of these areas apply the MfE guidelines (see Kerr et al. 2003) for building on or near active faults, as prescribed in this report.

These classes of ground build upon earlier studies and provide an improved update to the Land Stability Classes of Hancox et al (2006) report. Fault Avoidance Zones range between 60 and 140 m wide depending on the fault's mapped accuracy. The width of the FAZ may be reduced with ground investigation work (e.g., trenching) to better define the fault's location and/or slip rate and recurrence interval. Planning restrictions are dependent on a combination of fault mapping accuracy, recurrence interval class (RI), Building Importance Class (BIC), and current land use status.

In general, the areas classified and buffered due to very steep slopes have axes parallel to the drainage network (typically NW) while FAZs have axes parallel to the fault network (typically NE-SW). This means that, given our recommendations, there is effectively a grid or mesh of higher hazard versus lower hazard land. The usable land corresponds well with the ridgeline on the main part of the Mt Lyford Village where the building and land damage during the 2016 Kaikōura earthquake was less severe.

The data presented here is a summary of the scientific (quantifiable) methodology of assessing areas that may have high slope instability and/or fault surface rupture hazard. We define areas within the Mt Lyford Village and wider area based on the above criteria.

In terms of life safety risk for occupation of built structures and for possible future development of Greenfield sites in the village area, a plan or policy is needed to take into account the above recommendations. This policy should come from HDC/ECan, with guidance from GNS.

Preliminary recommendations will be drafted to go alongside these conclusions and presented in a separate GNS Science report. These recommendations should be disseminated between all parties for consultation and discussion, before final recommendations are drafted. Based on the above set of criteria of very steep slopes, set-back distances and Fault Avoidance Zones, some properties may inevitably be deemed as “unsafe” to be maintained or developed. It is up to HDC and ECan to consider how these properties should be treated.

6.0 ACKNOWLEDGMENTS

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APPENDICES

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A1.0 APPENDIX 1: FIELD DATA

A1.1 RECONNAISSANCE PHOTOGRAPHS – LAND DAMAGE

Figure A1.1 Typical foundation settling adjacent to a split-level log house at Mt Lyford Village. Note the subsidence of the ground and ground cracking extending away from the house (concrete pad).

Figure A1.2 Typical ground extension observed at the downhill-facing edge of a house at Mt Lyford Village.

Figure A1.3 Reactivated headscarp area of an arcuate landslide on the NE face of Lulus Creek.

Figure A1.4 Linear ground cracking related to slope extension projecting beneath a house.

Figure A1.5 Arcuate ground cracking related to slope extension within scrub above 'unnamed' stream.

Figure A1.6 Ground cracking and downslope failure (projecting to back of photo beyond yellow notebook) of c. 20 cm, exposed in a car parking bay cutting.

Figure A1.7 Down-slope ground failure related to slope instability at the Spark repeater, Tinline Terrace. The scarp in the centre is c. 0.6 m high.

Figure A1.8 Typical slope extension and ground failure above a cut slope where structure has been erected. Site is above the SW edge of 'unnamed' stream.

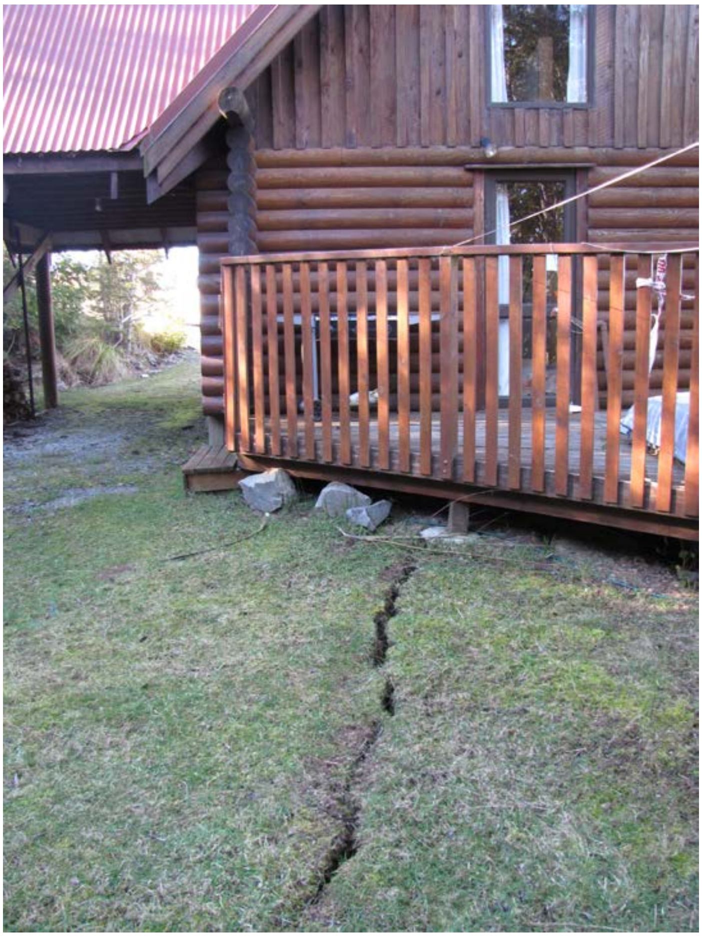

Figure A1.9 Extension crack extending beneath a property on Charwell Terrace. Flat surface is a cut surface developed for the house foundation.

Figure A1.10 Arcuate slope cracking (facing away from view angle) and ground failure (in foreground) above a cut slope at a property on Charwell Terrace.

Figure A1.11 Arcuate slope cracking and extension at the edge of a steep cut slope at property on Terako Terrace.

Figure A1.12 Arcuate cracking and extension in fill forming an off-street parking pad supported by a retaining wall adjacent to a property on Cloudy Range Road.

Figure A1.13 Cracking and extension in fill at the edge of a driveway approach above a steep slope adjacent to a property on Mt Lyford Drive.

Figure A1.14 Ground cracking and extension causing subsidence in a yard at a property on Lulus Lane, adjacent to a steep cut bank edge.

A2.0 APPENDIX 2: BUILDING ASSESSMENT CRITERIA

This appendix supplies statutory information regarding rapid assessment placarding and building in areas of natural hazard.

Table A2.1 Definitions of Rapid Assessment placards (Source: https://www.building.govt.nz).

Rapid Assessment placards		
Observed damage	**Rapid Assessment outcome**	**Placard**
Light or no damage (Low risk)	**W** CAN BE USED No ***immediate*** further evaluation required	**CAN BE USED** (WHITE)
Moderate damage (Medium risk)	**Y1** RESTRICTED ACCESS TO PART(S) OF THE BUILDING ONLY No entry to parts of building with significant damage	**RESTRICTED ACCESS** (YELLOW)
	Y2 RESTRICTED ACCESS – SHORT TERM ENTRY ONLY with or without supervision Entry restricted to removal of contents and securing work	
Heavy damage (High risk)	**R1** ENTRY PROHIBITED At risk from external factors such as adjacent buildings or from ground failure	**ENTRY PROHIBITED** (RED)
	R2 ENTRY PROHIBITED Significant damage	

Limitations and restrictions on building consents: Construction of building on land subject to natural hazards

Section 71 - Building on land subject to natural hazards

(1) A building consent authority must refuse to grant a building consent for construction of a building, or major alterations to a building, if—

(a) the land on which the building work is to be carried out is subject or is likely to be subject to 1 or more natural hazards; or

(b) the building work is likely to accelerate, worsen, or result in a natural hazard on that land or any other property.

(2) Subsection (1) does not apply if the building consent authority is satisfied that adequate provision has been or will be made to—

(a) protect the land, building work, or other property referred to in that subsection from the natural hazard or hazards; or

(b) restore any damage to that land or other property as a result of the building work.

(3) In this section and Sections 72 to 74, natural hazard means any of the following:

(a) erosion (including coastal erosion, bank erosion, and sheet erosion):

(b) falling debris (including soil, rock, snow, and ice):

(c) subsidence:

(d) inundation (including flooding, overland flow, storm surge, tidal effects, and ponding):

(e) slippage.

Compare: 1991 No 150 s 36(1)

Section 72 - Building consent for building on land subject to natural hazards must be granted in certain cases

Despite Section 71, a building consent authority that is a territorial authority must grant a building consent if the building consent authority considers that—

(a) the building work to which an application for a building consent relates will not accelerate, worsen, or result in a natural hazard on the land on which the building work is to be carried out or any other property; and

(b) the land is subject or is likely to be subject to 1 or more natural hazards; and

(c) it is reasonable to grant a waiver or modification of the building code in respect of the natural hazard concerned.

Compare: 1991 No 150 s 36(2)

Section 72: amended, on 15 March 2008, by Section 13 of the Building Amendment Act 2008 (2008 No 4).

Section 73 - Conditions on building consents granted under section 72

(1) A building consent authority that is a territorial authority that grants a building consent under Section 72 must include, as a condition of the consent, that the building consent authority will, on issuing the consent, notify the consent to,—

(a) in the case of an application made by, or on behalf of, the Crown, the appropriate Minister and the Surveyor-General; and

(b) in the case of an application made by, or on behalf of, the owners of Māori land, the Registrar of the Maori Land Court; and

(c) in any other case, the Registrar-General of Land.

(2) The notification under subsection (1) (a) or (b) must be accompanied by a copy of any project information memorandum that has been issued and that relates to the building consent in question.

(3) The notification under subsection (1) (c) must identify the natural hazard concerned.

Compare: 1991 No 150 s 36(2), (3)

Section 73(1): amended, on 15 March 2008, by section 14 of the Building Amendment Act 2008 (2008 No 4).

Section 73(2): amended, on 1 February 2010, by section 20 of the Building Amendment Act 2009 (2009 No 25).

Section 74 - Steps after notification

(1) On receiving a notification under Section 73,—

(a) the Surveyor-General or the Registrar of the Maori Land Court, as the case may be, must enter in his or her records the particulars of the notification together with a copy of any project information memorandum that accompanied the notification:

(b) the Registrar-General of Land must record, as an entry on the certificate of title to the land on which the building work is carried out,—

(c) that a building consent has been granted under section 72; and

(d) particulars that identify the natural hazard concerned.

(e) If an entry has been recorded on a duplicate of the certificate of title referred to in subsection (1)(b) under section 641Aof the Local Government Act 1974 or section 36 of the former Act, the Registrar-General of Land does not need to record another entry on the duplicate.

(f) Subsection (4) applies if a building consent authority determines that any of the following entries is no longer required:

(g) an entry referred to in subsection (1)(b):

(h) an entry under section 641A of the Local Government Act 1974:

(i) an entry under section 36 of the former Act.

The building consent authority must notify the Surveyor-General, the Registrar of the Maori Land Court, or the Registrar-General of Land, as the case may be, who must amend his or her records or remove the entry from the certificate of title.

Compare: 1991 No 150 s 36(5), (6), (7)

Section 74(1)(a): amended, on 1 February 2010, by section 21 of the Building Amendment Act 2009 (2009 No 25).

Subpart 6—Special provisions for dangerous, affected, and insanitary buildings

Subpart 6 heading: amended, on 1 July 2017, by section 12 of the Building (Earthquake-prone Buildings) Amendment Act 2016 (2016 No 22).

Interpretation and application

Heading: replaced, on 1 July 2017, by section 13 of the Building (Earthquake-prone Buildings) Amendment Act 2016 (2016 No 2).

Section 124 - Dangerous, affected, or insanitary buildings: powers of territorial authority

(1) This section applies if a territorial authority is satisfied that a building in its district is a dangerous, affected, or insanitary building.

(2) In a case to which this section applies, the territorial authority may do any or all of the following:

(a) put up a hoarding or fence to prevent people from approaching the building nearer than is safe:

(b) attach in a prominent place on, or adjacent to, the building a notice that warns people not to approach the building:

(c) except in the case of an affected building, issue a notice that complies with section 125(1) requiring work to be carried out on the building to—

(i) reduce or remove the danger; or

(ii) prevent the building from remaining insanitary:

(d) issue a notice that complies with section 125(1A) restricting entry to the building for particular purposes or restricting entry to particular persons or groups of persons.

(3) [Repealed]

Section 124: replaced, on 28 November 2013, by section 30 of the Building Amendment Act 2013 (2013 No 100).

Section 124 heading: amended, on 1 July 2017, by section 17(1) of the Building (Earthquake-prone Buildings) Amendment Act 2016 (2016 No 22).

Section 124(1): amended, on 1 July 2017, by section 17(2) of the Building (Earthquake-prone Buildings) Amendment Act 2016 (2016 No 22).

Section 124(3): repealed, on 1 July 2017, by section 17(3) of the Building (Earthquake-prone Buildings) Amendment Act 2016 (2016 No 22).

Source: http://www.legislation.govt.nz/act/public/2004/0072/latest/whole.html#DLM306818

A3.0 APPENDIX 3 – PLANNING DECISION TABLES FOR RI CLASS I & II FAULTS

Table A3.1 Example of relationships between resource consent category, building importance category, fault recurrence interval class, and fault complexity for greenfield sites, based on the Mfe active fault guidelines (for more detail see Kerr et al. 2003).

Greenfield Sites					
Fault Recurrence Interval Class I					**(Average Ri ≤2000 Years)**
Bic	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well Defined	Permitted	*Non-Complying*	*Non-Complying*	*Non-Complying*	Prohibited
Distributed	Permitted	*Discretionary*	*Non-Complying*	*Non-Complying*	Non-Complying
Uncertain	Permitted	*Discretionary*	*Non-Complying*	*Non-Complying*	Non-Complying
Fault Recurrence Interval Class Ii					**(Average Ri >2000 Years To ≤3500 Years)**
Bic	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well Defined	Permitted	*Non-Complying*	*Non-Complying*	*Non-Complying*	*Non-Complying*
Distributed	Permitted	*Discretionary*	*Discretionary*	*Non-Complying*	*Non-Complying*
Uncertain	Permitted	*Discretionary*	*Discretionary*	*Non-Complying*	*Non-Complying*

Notes:

* - Indicates that the resource consent category is permitted, but could be controlled or discretionary given that the fault location is well defined.

§ - this recurrence interval class is applicable to all of the faults in this study.

Italics: the use of italics indicates that the resource consent category of these categories is more flexible. for example, where *discretionary* is indicated, *controlled* may be considered more suitable by council, or vice versa.

Table A3.2 Example of relationships between resource consent category, building importance category, fault recurrence interval class, and fault complexity for developed and/or already subdivided sites, based on the Mfe active fault guidelines (for detail see Kerr et al 2003).

Developed And/Or Already Subdivided Sites					
Fault Recurrence Interval Class I					**(Average Ri ≤2000 Years)**
Bic	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well Defined	Permitted	Non-Complying	*Non-Complying*	*Non-Complying*	Non-Complying
Distributed	Permitted	*Discretionary*	*Non-Complying*	*Non-Complying*	Non-Complying
Uncertain	Permitted	*Discretionary*	*Non-Complying*	*Non-Complying*	Non-Complying
Fault Recurrence Interval Class Ii					**(Average Ri >2000 Years To ≤3500 Years)**
Bic	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well Defined	Permitted	Permitted*	*Non-Complying*	*Non-Complying*	Non-Complying
Distributed	Permitted	Permitted	*Discretionary*	*Non-Complying*	Non-Complying
Uncertain	Permitted	Permitted	*Discretionary*	*Non-Complying*	Non-Complying

Notes:

* - Indicates that the resource consent category is permitted, but could be controlled or discretionary given that the fault location is well defined.

§ - This recurrence interval class is applicable to all of the faults in this study.

Italics: The use of italics indicates that the resource consent category of these categories is more flexible. for example, where *discretionary* is indicated, *controlled* may be considered more suitable by council, or vice versa.

A4.0 APPENDIX 4: LOG HOUSE PERFORMANCE IN THE 2016 KAIKŌURA EARTHQUAKE

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For more in-depth detail regarding structural observations of log homes in the 2016 Kaikoura Earthquake refer to: Buchanan, A. Moroder D., 2017, Log House Performance in the 2016 Kaikōura Earthquake, Bulletin of the New Zealand Society for Earthquake Engineering, Vol. 50, No. 2

The comments below relate only to observations made during site visits performed.

Typical log houses at Mt Lyford were built using 200 mm diameter machined logs. A smaller number of log houses were built with much larger hand-hewn logs of less regular shapes, in a more traditional log house style. Most houses were constructed on a concrete slab incorporating the foundations. All inspected houses were built with machined or hand hewn round logs, so no information can be provided on the behaviour of 'blockhaus' style houses such as Lockwood or Fraemohs. A small number observed, especially those on steep sites, had timber poles supporting a timber ground floor platform.

Design of log houses for vertical gravity loads is not complex. All loads from the roof or from upper floors are supported on internal and external log walls, where the horizontal logs are stacked on top of each other. As in most domestic construction, earthquake loads in log houses are resisted by internal and external bracing walls (all made of horizontal logs). In general, the more walls, the better the resistance to lateral loads, as expected.

Log walls generally resist internal shear forces by friction or glue between logs, with an additional contribution from the notches at the intersecting corners. A further contribution is sometimes provided by the dowel action of vertical steel rods, tie-down anchors or timber dowels. Overturning moments are resisted by the self-weight of the walls and by vertical steel rods used as tie-down anchors at the ends of the walls. If the hold-down action becomes ineffective and logs uplift, the friction between the logs will be reduced. It is therefore important that the tie rods are re-tightened regularly during the drying out phase of the logs.

Several of the log houses observed suffered some lateral movement and subsequent damage while performing well within the intended limit state of the New Zealand Building Code. Very few of the houses were damaged beyond repair, and the overall structural performance was excellent considering the nature of the earthquake. Many of the houses inspected had geotechnical damage to the surrounding ground, which affected amenity and access, but not the main structure. A few houses lost support due to slope stability.

In a few houses with poor anchorage, the whole house slid horizontally on the foundations, by up to 100 mm. In a few exceptional cases, objects were trapped under the bottom log, showing that there had been considerable upward movement of the whole wall for a few moments during the earthquake. Most houses suffered damage through horizontal sliding between logs, to varying degrees. Sometimes this sliding was concentrated at one or two locations however more often the sliding was distributed between many logs. In either case the sliding resulted in non-structural damage and some permanent distortion. A large number of inspected houses showed some damage to vertical tie-down rods. This was most often visible at the bottom end connection, especially when the tie-downs were anchored in pockets in the foundation slab. Most foundations performed very well, provided that the land remained stable.

Most of the two-storey houses have log walls at the bottom floor and light timber framing with plasterboard lined walls at the second floor. In these cases, there was usually much less lateral movement in the upper storey, and therefore little damage to the second storey walls and the roof.

For the majority of houses which suffered minor damage, simple repair strategies are available. If the small permanent horizontal movement is acceptable, repair can consist of tightening tie-downs and repairing non-structural damage. Houses with larger horizontal movement may be able to be pulled back into line with turfers or jacks after releasing any highly stressed tie-down rods. Fractured rods can generally be replaced, depending on access. There are a large number of anchorages with minor damage, most of which can be repaired easily. Repairs to damaged linings and other non-structural damage will be required in some of the buildings and for a very small number of houses, demolition and rebuilding will be required, mainly due to foundation failure or loss of support.