Natural Hazard Assessment for the Township of Franz Josef, Westland District

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EXECUTIVE SUMMARY

GNS Science has undertaken a natural hazards review and semi-quantitative hazard assessment for the town of Franz Josef (Glacier) and its wider township area in Westland District. This work was commissioned by the West Coast Regional Council as a dual Medium Advice Envirolink project.

Franz Josef is sited at the foot of the rangefront of the Southern Alps, straddling the Alpine Fault and immediately adjacent to the Waiho River. The wider township area is at risk from a number of natural hazard perils including flood, fault rupture, seismic shaking, landslide, debris flow, damburst flood, alluvial fan inundation, liquefaction and lateral spreading. The effects of climate change, sea-level rise or tsunami inundation have not been considered as part of this study.

The community of Franz Josef in consultation with the West Coast Regional Council, Westland District Council and other providers need to develop plans to manage or mitigate the serious natural hazards that are likely to occur in the area of the town of Franz Josef in the coming years to decades. Such plans will provide the community with more certainty regarding future life safety, property, infrastructure and investment. The three most significant natural hazard events that we have highlighted are: flooding from the Waiho River, rupture of the Alpine Fault (fault movement plus shaking), and the combined landscape consequences (multi-hazard cascade) posed by an Alpine Fault earthquake event.

Flooding from the Waiho River remains an ever present threat to the town. The current flood-protection system (stopbanks) is capable of protecting the main part of the town from modelled 10-, 20-, 50-, and 100-yr flood scenarios. Future flooding scenarios that include further river bed aggradation need to be mitigated through management of the river. Because of the relatively low elevation of the town relative to the current river bed, it is imperative that flood-protection measures (e.g., stopbanks), particularly on the north bank of the Waiho River, are maintained. If the town is exposed to flood waters and debris through failure of the stopbank network, then the implications are similar to those observed for the Scenic Circle Hotel during the March 2016 flood event. Large alluvial fans like the mid Waiho River will seek to shift their course and fill in lower-lying areas, for example, the area of the current and suggested new town centre locations are susceptible to flooding if they are not protected. To mitigate the possibility of bed aggradation resulting in serious flooding, it might be useful for the community to consider a relaxation of the river's confinement on the south side of the Waiho River. Such an activity would need to be carefully managed in consultation with hydraulic engineers and other relevant experts, considering the location of State Highway 6, and its bridge abutments, relative to relaxation of the stopbank system.

A strategy needs to be developed for a managed retreat from the Alpine Fault 'Fault Avoidance Zone' areas in and around the town of Franz Josef. Due to the moderate to high probability of a large to great (Magnitude M_w > 7 to 8) earthquake occurring on the Alpine Fault in the next 50-100 years, we recommend that the town centre move toward the northeast toward (along) the extension of Cron Street, with a managed retreat away from the Alpine Fault FAZ at the south end of the town. Our analysis of seismic shaking indicates that there would be no significant change in shaking Intensity related to such a small move in the town's location, i.e., the town's location means that it is in a very high shaking zone with respect to rupture of the Alpine Fault.

The multi-hazard cascade initiated by rupture of, and shaking caused by the next Alpine Fault earthquake event has a likelihood of occurrence of >27% in the next 50 years. The councils and town should consider plans to make the town more resilient to individual and combined perils in the coming years firstly through mitigation but also through planning for civil defence actions designed to cope with a major disaster that could impact up to a few thousand tourists in the peak tourist season. Several other individual hazard perils (non-seismic driven landslides, alluvial fan aggradation, debris flood) are discussed in this report. Each in its own right is manageable if the location, extent, magnitude and severity of the hazard is understood and mitigated.

Because fault rupture can be avoided by a relatively small amount of town re-planning, flooding can be mitigated via flood-protection activities, but MM Intensities of >VIII cannot easily be avoided, we recommend that the council undertakes a Cost-Benefit Analysis in consideration of re-locating the town of Franz Josef versus mitigating against the hazards that are likely to seriously impact the town in its current configuration and through pre-planning response activities. Nonetheless, at the level of assessment we have undertaken here, the current town site is satisfactory, provided the river is kept from overtopping/scouring the north side stopbank.

1.0 INTRODUCTION

New Zealand straddles the boundary between the Australian and Pacific tectonic plates (Figure 1.1), and lies within the westerly mid-latitude wind belt in the southwest Pacific Ocean. As such, the country is prone to seismic, weather and climate related natural hazards, and its landscapes are sometimes impacted by the combined effects of these systems. This is particularly true for the West Coast region of the South Island where the Alpine Fault and the Southern Alps form imposing seismic and tectonic features which arguably are responsible for developing their own climatic cycles through the uplift of a mountain barrier against an oceanic climate (e.g., Koons, 1989; Norris & Cooper, 1997). Nowhere are these natural impacts of climate and tectonics (e.g., fault rupture, shaking, landslides, flooding, debris flows etc.) more obvious than in the town of Franz Josef Glacier[1] in Westland District, which is the subject of this report (Figure 1.2).

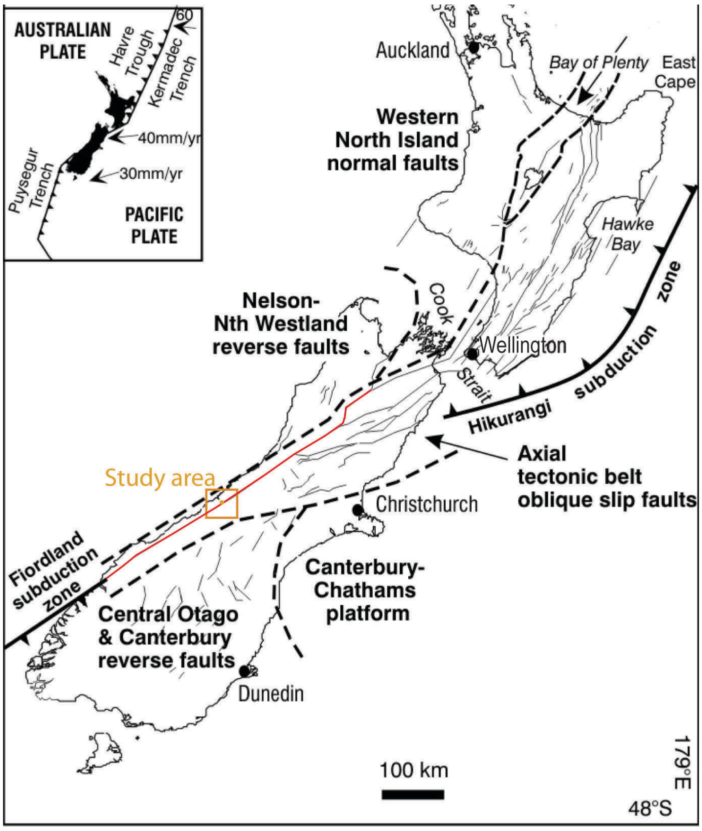

Figure 1.1 Active tectonic setting of New Zealand. The study area is centred on the town of Franz Josef in Westland District. The Alpine Fault is marked by the red line.

The Franz Josef working group, comprised of local government, crown agencies, Iwi, and local business owners, is examining future land use at Franz Josef to ensure that the most appropriate future development of the township is undertaken. One of the focal points of this exercise is obtaining a sound understanding of the exposure of its citizens, visitors, and businesses to natural hazards and the risks that these hazards pose. The West Coast Regional Council (WCRC) wishes to obtain an overarching review of natural hazard assessment for the Franz Josef area using the most up-to-date data in order to give some direction toward the future planning of the town and wider township.

[1] We abbreviate the town name to 'Franz Josef' throughout the remainder of the report.

This work has been funded through dual Medium Advice Envirolink Grants. GNS Science will examine individual hazards and discuss impacts and possible solutions to the multiplicative risk from local and regional earthquakes, displacement on the Alpine Fault, river floods, landslide and other hazards driven by either earthquake shaking or rainfall (or a combination of both). The probability of a large to great (M_w >7 to 8) Alpine Fault earthquake has recently been re-assessed by Biasi et al. (2015) and the Waiho River flood in March 2016 has reminded the community and Council of the ever-present Waiho River flood risk (e.g., LandRiverSea, 2014).

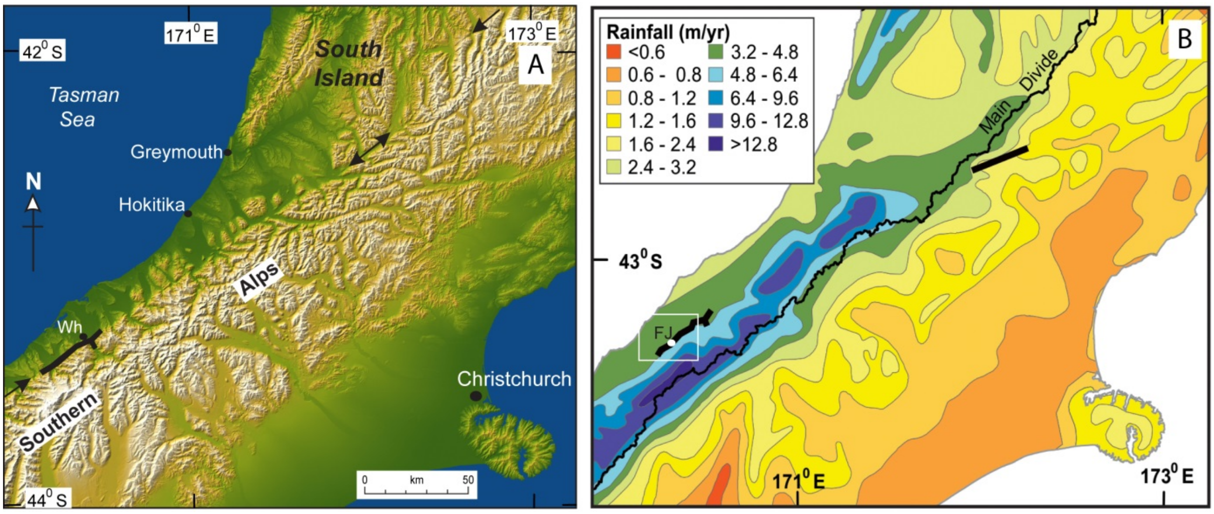

Figure 1.2 Digital elevation and rainfall gradient of the central South Island (modified after Langridge et al., 2014). A. An SRTM digital elevation model of the central South Island highlighting the Southern Alps and Alpine Fault (black arrows). The town of Whataroa (Wh) is shown at the NE end of the Franz-Whataroa LiDAR acquisition (black strip). B. Precipitation contour map (in metres/yr) of the central South Island. FJ refers to Franz Josef. White box shows the wider study area highlighted in Figure 2.1.

1.1 Scope of Work

GNS Science will undertake the following: 1) review the natural hazards that the wider Franz Josef community (i.e., considering the area from Docherty Creek in the southwest through to Potters Creek, including the township and farmland on the Lower Waiho Flat) are exposed to; 2) report a semi-quantitative multi-hazard assessment for the current town site where data permit, and 3) outline knowledge gaps in the hazard information for the wider Franz area, pin pointing the work that is required to further our understanding for potential areas for future development.

The project deliverables will provide WCRC and the Franz Josef working group a basis for best practice management including mitigation strategies for flood and earthquake hazard, and a basis for informing future land use across the Franz Josef township.

1.2 PROJECT DESIGN

This project consists of two main objectives that are closely aligned and dealt with in two stages.

Stage 1 Franz Josef Hazardscape – an integrated review of natural hazards

The most up-to-date information on natural hazards affecting the study area is reviewed and collated into a report that summarises the current knowledge on the natural hazards that Franz Josef is exposed to. This will include review of:

- Seismic-related hazards, including: fault rupture, ground shaking, liquefaction and lateral spreading;
- Water-related hazards, including: river flood and aggradation, alluvial fan and debris flood events;
- Slope-related hazards, including: landslides, giant landslides, landslide breakout events;
- The impact of short- to medium-term weather-related hazards (flood, landslide);
- The multi-hazard cascade generated by rupture of the Alpine Fault.

The information gathered in Stage 1 is presented in Chapter 3 which summarises the current knowledge on the natural hazards that Franz Josef is exposed to.

At various scales some of the water and slope-related hazards form a continuum in space or in time. For example, landslides resulting from rainstorm can give rise to dam-burst debris floods, and alluvial fan deposition. Strong ground shaking can also result in landslides and ground failures at free surfaces such as terrace edges (which is effectively a type of slope failure) and liquefaction.

Another of the challenges in presenting and comparing the suite of natural hazards from shaking to flooding to landslides is in understanding the scale (magnitude, size) of events and over what time period each of these hazards occurs or is relevant. We compiled a geologic map of the wider Franz Josef area using Barrell et al. (2011) to provide some insight into where and when hazard events, such as landslides and alluvial fan building, has occurred. In addition, a LiDAR swath (Figure 1.2) is used to assist geological mapping at a finer scale along the rangefront, including Franz Josef, to map the local distribution of geologic hazards and the age of local surfaces and landscapes. Up-to-date flood modelling and recent academic assessments of landslide hazard have been used to drive the analysis of these hazards. Aside from these datasets, this study is limited by a lack of other new data with which to quantitatively characterise hazard.

Stage 2 Franz Josef Hazard Analysis – considering the impacts and mitigation of natural hazards

Using the results of the hazards review conducted in Stage 1, the following tasks will be undertaken to provide a semi-quantitative hazard assessment for the study area:

- Present a series of GIS-derived maps to highlight the extent of individual hazards (e.g., landslide, ground shaking, fault rupture, alluvial fan, flood extent). The results are produced in a format that can be input later into risk or cost benefit models.
- Develop a hazard analysis for the current town location of Franz Josef.
- Consider the case of the 300-year return period event (i.e., Alpine Fault rupture and ensuing multi-hazard cascade) given its current conditional probability of occurrence.

The hazard analysis is presented as a series of hazard scenarios for the town at 10, 50, and 100 year time intervals. The report will include a discussion on the distribution of the combined hazards for the town and across the wider study area and some indication of where the areas of lowest aggregated risk are located.

2.0 SETTING

2.1 FRANZ JOSEF TOWNSHIP

The study area includes not only the tourist village of Franz Josef but the areas to the northeast as far as Potters Creek, and to the coast at Waiho Flat/Beach (Figure 2.1). The area was first visited by Europeans in the mid-19th century (1865-1867) and a settlement has existed for the purposes of showing the Franz Josef Glacier to tourists since the late-19th century. The village of Franz Josef is sited on the true right side of (and next to) the Waiho River downstream of its junction with the Callery River at the foot of the rangefront of the Southern Alps (Figure 2.1). The village grew up and around what was later recognised as the active fault scarp of the Alpine Fault (Wellman, 1953; McSaveney and Davies, 1998; Langridge and Ries, 2010). The wider community of Franz Josef is settled adjacent to several secondary catchments that emanate from the Southern Alps; namely Docherty Creek, Tartare Stream, Stony Creek and Potters Creek. All but Potters Creek flow into the Waiho River.

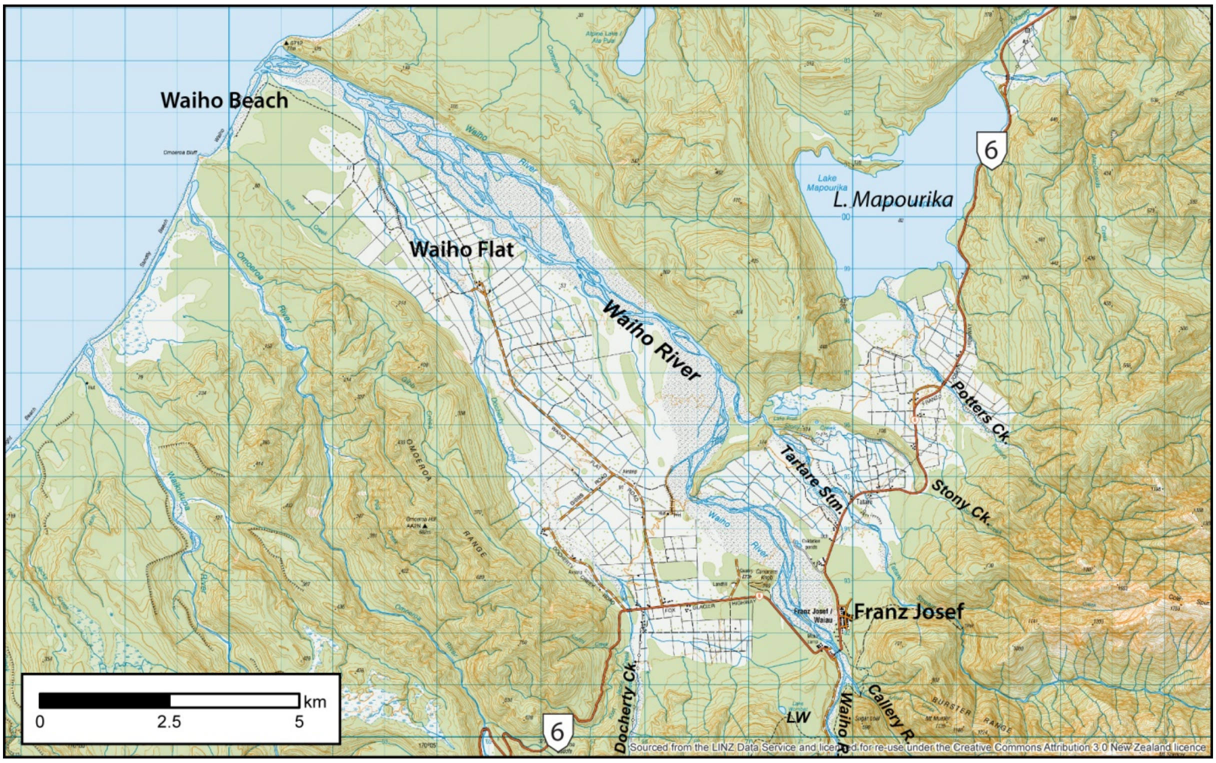

Figure 2.1 Location map of the wider Franz Josef area. The study area includes the area from Docherty Creek in the southwest to Potters Creek in the northeast, and to the coast. LW, refers to Lake Wombat.

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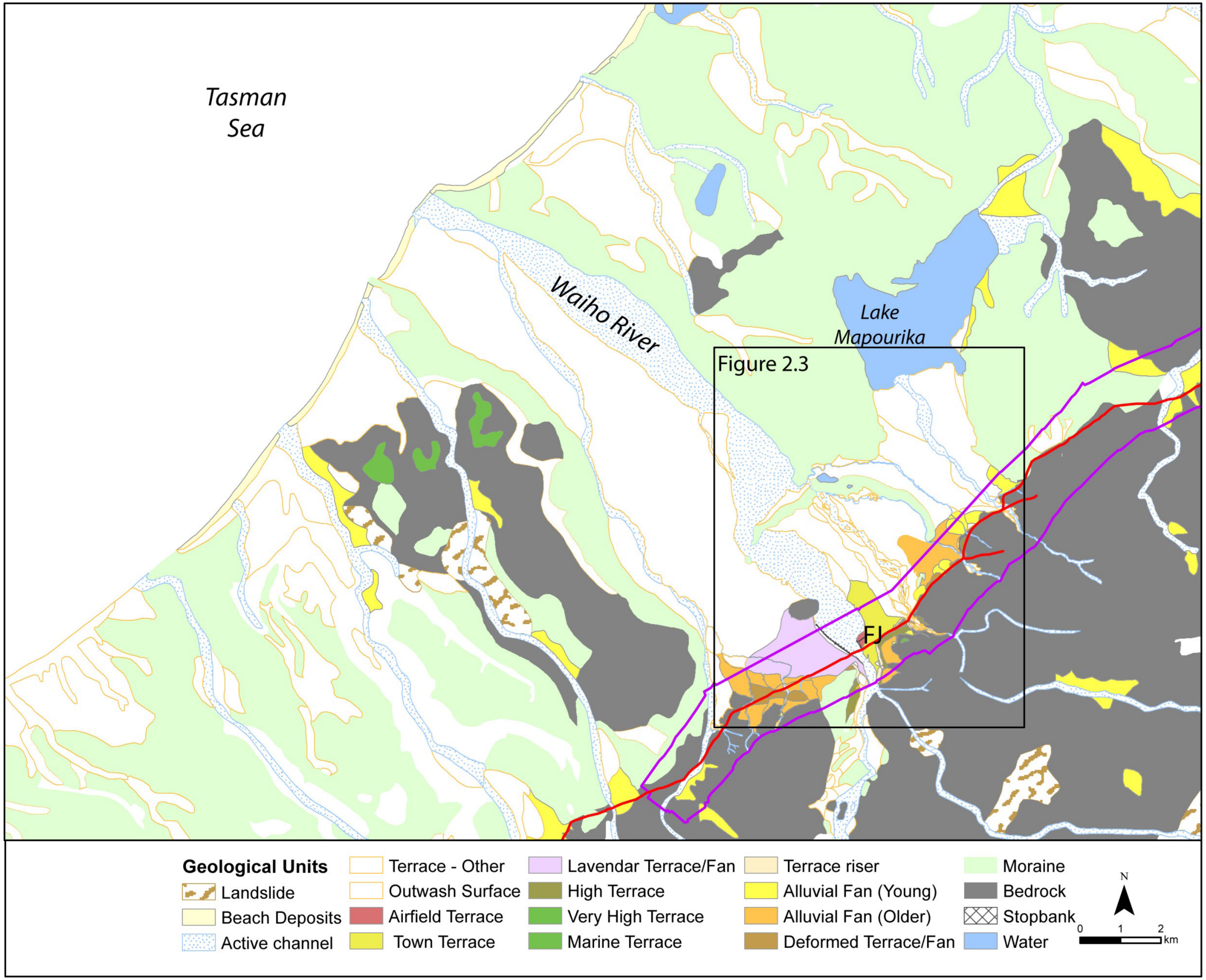

Figure 2.2 Simplified geological map at scale 1:100,000 (modified after Barrell et al., 2011). Geological units are broadly categorised into bedrock, moraines, terraces, landslide and floodplain deposits. The simplified trace of the Alpine Fault comes from the NZ Active Faults Database (Langridge et al., 2016). The purple outlined polygon shows the LiDAR swath from which detailed mapping is shown in Figure 2.3. FJ shows the general location of Franz Josef.

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2.2 LATE QUATERNARY GEOLOGY OF THE FRANZ JOSEF AREA

The late Quaternary geomorphology and geology sets the scene for the natural hazards that Franz Josef is exposed to. Franz Josef sits at the foot of the highest part of the Southern Alps with peaks of up 2800 m within 20 km of the town (elevation 160 m a.s.l.). The elevation gradient drives orographic rainfall (or snowfall at higher elevations).

Runoff from high elevations is transferred to the coast via rivers with short steep catchments. The Southern Alps relate to the oblique collision between the Pacific and Australian tectonic plates. They provide a barrier of significant relief and topography caused by tectonic activity related to the Alpine Fault, which occurs at the boundary between typically steep, elevated topography and the coastal plain (Cox & Barrell, 2007).

The late Quaternary geology of the region is dominated by alpine glacial and fluvial processes, slope processes and tectonic activity. Figure 2.2 shows the late Quaternary geology of the wider Franz Josef area at a scale of 1:100,000, modified from mapping by Barrell et al. (2011). A more detailed geomorphic map has been developed at a scale of c. 1:10,000, that is mainly focused up to c. 1 km from the trace of the Alpine Fault (Figure 2.3). The purpose of the finer-scale mapping is to highlight the geomorphology of landforms that can be seen using the LiDAR strip flown along the rangefront of the Alpine Fault and in the proximity of most of the urban development of the wider Franz Josef community.

2.2.1 1:100,000 Scale Geology

The late Quaternary geology (Figure 2.2) can be broadly divided into a southeast and a northwest sector. In the southeast the map is dominated by ice-free slopes composed of bedrock of Alpine Schist and Torlesse greywacke (Cox & Barrell, 2007). Large glaciers have carved out valleys such as the Waiho valley, with smaller valleys and tributaries, such as the Dochertys Creek or Callery River joining with the Waiho. Within these valleys, particularly the Waiho River valley, the remnants of smaller glaciers exist in the form of Holocene (<11,000 year old) moraines. Following the retreat of glaciers the valleys have been dominated by alluvial systems, whereby rivers have carried the debris from glaciers away to the coast leaving behind the coarse boulder deposits. Barrell et al. (2011) also map landslide deposits in the southeast sector. Examples of two such deposits are mapped in the Callery river valley. These deposits indicate a landslide-dammed lake probably existed at these localities and its eventual failure probably resulted in a dam outburst flood (Davies, 2002). Remnants of latest Pleistocene (c. 11-18,000 years) glaciation exist at the rangefront near Lake Wombat on the true left of the Waiho River. The rangefront is characterised by very steep hillslopes often exceeding 45°, minor alluvial fans and scarps relating to the fault zone of the Alpine Fault.

The geomorphology of the northwest sector of Figure 2.2 can be attributed to Pleistocene glaciation and Holocene (<11,000 year) alluviation Much of the high-standing (up to 400 m a.s.l.) topography on the northwest side of the Alpine Fault comprises terminal and lateral moraines deposited by large glaciers during the Otiran glacial period (c. 14,500-74,000 years BP) (Barrell et al., 2011), draped over bedrock. Based on geomorphology, elevation and age dating, sets of glacial landforms have been distinguished by Barrell et al. (2011) as latest late Otiran (c. 14,500-19,000 yr BP), late Otiran (21,500-28,000 yr BP), Otiran (c. 45,000 yr BP), or early Otiran or older (>45,000 yr BP) (Alloway et al., 2007). In places, remnants of marine terrace surfaces are preserved on pre-Otiran moraines near the coast (Figure 2.2).

Between the remnants of larger late Pleistocene (18-30,000 yr) glaciers are the Holocene river floodplains and lakes, i.e., the valleys that were once filled with ice have more recently been occupied by fluvial systems. The trough that held the 'Waiho glacier' is partially filled with Holocene alluvium and outwash deposits that form an alluvial plain. The current active bed of the Waiho River has the capacity to migrate laterally across it (Davies, 1997). In the case of smaller valleys, such as Potters Creek, sub-branches of the Waiho glacier did not extend to the coast and formed terminal moraines that now form the margins of Lake Mapourika (Figure 2.1). It has recently been confirmed from the Whataroa River valley and exposures at the Paringa River that such evacuated glacial troughs were initially filled by fiords and lakes that were eventually buried by the influx of gravel transported by rivers and streams (DFDP Stage 2 drilling results).

The youngest glacial features on the northwest side of the Alpine Fault form the Waiho Loop, which is related to a younger glacial advance dated to c. 12-14,000 years ago (Denton & Hendy, 1994; Alexander et al., 2014). The Waiho Loop formed an obstacle in the path of Tartare Stream and Stony Creek, have had to cut courses through the moraine loop to continue to the coast.

2.2.2 1:10,000 Scale Geology

LiDAR point data was used to create a digital elevation model (DEM) of 3-m pixel size (Langridge et al., 2014) along the swath that was acquired and centred on the Alpine Fault zone between Dochertys Creek and the Whataroa area (Figure 2.3). This coverage enables improved interpretation of geomorphology and hazard within the zone at a scale of 1:10,000 by extrapolation. This allowed for detailed mapping of the geomorphology across and beyond this 1.5 km wide swath (Langridge & Beban, 2011; Barth et al., 2012). Because the Barrell et al. (2011) mapping was undertaken at a scale of 1:100,000 it does not show some of the details, nor is as accurate, as can be seen in the LiDAR image along the rangefront.

Some of the specific differences between the 1:10,000 and 1:100,000 mapping are: the identification of mappable terraces, landslide source areas and alluvial fans along the rangefront and within valleys on the upthrown (southeast) side of the Alpine Fault; the improved mapping of the surface detail of the fault, a basis for profiling of land surfaces to understand their form, origin, and slope.

LiDAR enables a view through the dense vegetation covering much of the rangefront allowing for the fine-scale detail of geomorphic units to be mapped. From these a spatio-temporal hierarchy of geomorphic units was established. That is, a map facilitates understanding the relationships between, for example, older terraces and younger fans, or younger terraces and older fans (Figure 2.3). In this way, a relative chronology of units and deposits can be developed.

The LiDAR DEM showed individual terrace remnants within the gorges of the Waiho River and Tartare Stream, including the 'High terrace' (Langridge & Beban, 2011) and individual degradation terraces that have been raised on the hangingwall (uplifted side) of the Alpine Fault (Figure 2.3). We also mapped small rangefront alluvial fans that emerge out onto these terraces. Profiling with the LiDAR shows individual lobes of alluvial fans (at the scale of the Waiho River "fan", e.g., the Lavender lobe/ terrace, the Town terrace, the Airfield terrace, which may be a guide to the future activity of the Waiho River (see Section 3.2.1).

The LiDAR DEM reveals that a fresh, but complex zone of faulting along the trench of the Alpine Fault. In some places younger alluvium covers the fault trace, i.e., the fault cannot be located and must be mapped as uncertain, while in an adjacent location, fault scarps that offset older surfaces can be profiled and their height assessed.

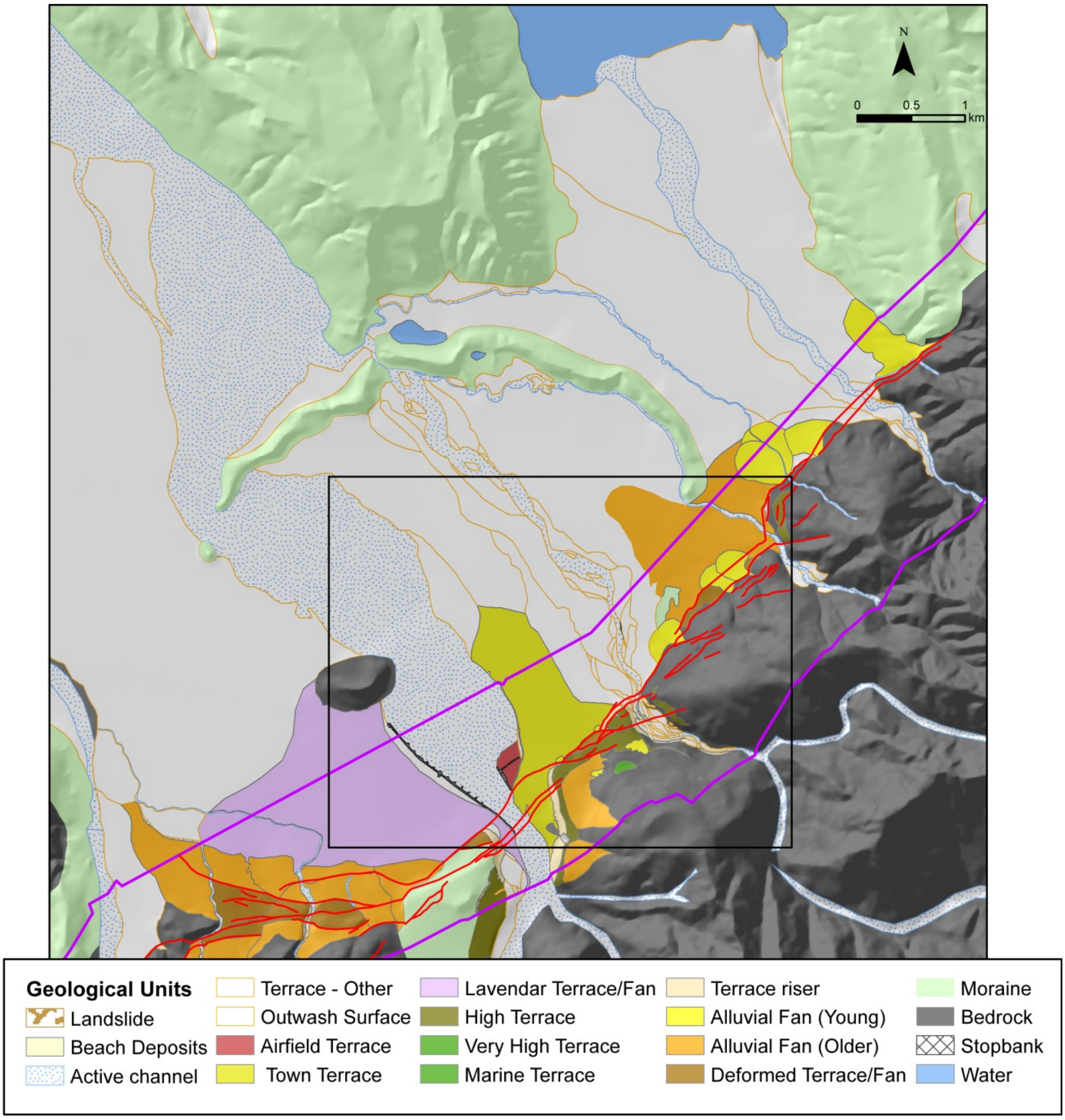

Figure 2.3 Geologic and geomorphic map produced at scale c. 1:12,000 developed using, and extending from, the underlying LiDAR DEM. Geological units are broadly categorised into bedrock, moraines, terraces, landslide and floodplain deposits. The detailed traces of the Alpine Fault are modified from Langridge and Beban (2011). A detailed portion of this figure is shown as Figure 3.10 (see box around town).

Thus, fault ruptures that have built fault scarps over many earthquake cycles have been preserved along the foot of the rangefront slope and generally not eroded or buried by slope deposits that would have the potential to collapse from higher up on the rangefront, across the fault zone. In this area much of the fault scarp is formed by the warping of the High terrace down to the edge of the Town terrace. This implies that slope processes have not overwhelmed the lower slopes of the rangefront or indeed the area of the town of Franz Josef for some considerable time, in at least the past several repeats of the rupture of the Alpine Fault and perhaps during the last 11-12,000 years.

2.2.3 Estimates of Surface Ages for the High and Town Terraces

Understanding the age of terrace surfaces provides a basis for estimating the age of other features in the landscape. For example, alluvial fans and landslides that can grade to, or cover alluvial terraces formed by rivers indicates a younger age of fan than terrace. On the upthrown side of the Alpine Fault upstream of Franz Josef a High terrace of probable 12-24,000 year age occurs (Figure 3.3) (Cox & Barrell 2007; Nathan et al., 2002). Terrace gravels at similar elevation in an equivalent position in the Whataroa valley have been dated at 11-12,000 years (T. Chinn, unpublished data; De Pascale, 2013), and we assume this age for the High terrace in the vicinity of Franz Josef.

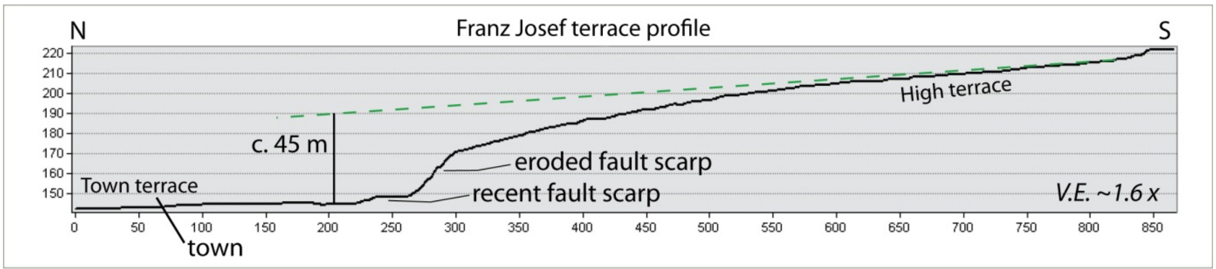

Figure 2.4 A south to north profile across the High terrace from upstream of Franz Josef, running into the town. The High terrace is not exposed (and presumably buried) in the town; rather the town is constructed on the Town terrace.

In the Waiho catchment, the High terrace has not been dated. However, if we assume that valley-wide aggradation occurred at the same time in the Waiho and Whataroa river catchments then this terrace (Q2a or High terrace) ought to be of a similar age. While the High terrace is not exposed on the northwest (downthrown) side of the fault due to burial (in combination with erosion or relative subsidence) it projects above the town from southeast to northwest. The High terrace is c. 40-45 m above the Town terrace in Franz Josef, noting that a significant proportion of this deformation is due to bending of the terrace surface toward the fault zone (Figure 2.2). This requires a vertical slip rate of at least 3-4 mm/yr (it is a minimum because we do not know the extent or depth of the High terrace on the downthrown side of the fault). Interestingly, the High terrace in the Whataroa valley is c. 60-80 m higher than the exposed terraces on the downthrown side of the fault there, implying that a higher rate of vertical motion occurs across the fault in the Whataroa area.

In Franz Josef the height of the fault scarp as expressed across the Town terrace is c. 8-10 m. By the ratio of the amount of vertical motion of the Town and High terraces, this suggests an age of c. 2000-3300 years for the Town terrace, i.e., late Holocene. In other words, we expect that to build a fault scarp of 8-10 m high across the Town terrace would take c. 2000-3300 years. Such an age and rates of vertical motion are consistent with other estimates of vertical motion along the central part of the Alpine Fault (Norris & Cooper, 2000). The High terrace represents a valley-filling aggradation surface that post-dates the retreat of the Waiho Glacier from the Waiho Loop We are comfortable that our age estimate for the High terrace in Franz Josef (c. 11,000-12,000 years) is reasonable because this terrace shows no evidence for the glacial advance that formed the Waiho Loop further down valley (12,000-14,000 years ago).

Because the High and Town terraces are planar markers with definable ages, they allow us to assess the relative ages of the deposits that sit on them, and what has happened around this area in the past few thousand years. Therefore it is possible to construct a hierarchy of surface and deposit ages along the rangefront of the Alpine Fault and beyond. Another strength in developing this kind of region-wide chronosequence lies with the fact that the fault zone can be buried by rangefront deposits or preserve small to large fault scarps (as described above). The most recent surface faulting event along the Alpine Fault occurred in about 1717 AD (Yetton et al., 1998; Wells et al., 1999; Howarth et al., 2012, 2014, 2016). Thus, if there were a small scarp of 1-2 m across a surface then the deposit underlying the terrace is probably slightly older than 300 years, and if a scarp has a height of 8-10 m, or >40 m height, then the surface that is faulted is likely to be a few thousand, or many thousands of years old, respectively. In addition, if the fault can be projected across or beneath a deposit that does not appear to be deformed, then the inference is that the material has been deposited since the last earthquake in 1717 AD.

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3.0 NATURAL HAZARDSCAPE

The town of Franz Josef could be affected by several types of natural hazards that could cause damage in the town. This chapter provides a summary of what is presently known about how these hazard types could affect the town. Specific natural hazards can be divided into fault (seismic) hazards (e.g., ground surface deformation, ground motions), river hazards (e.g., flooding, alluviation and dam-break floods), and mass movement hazards (e.g., rockfalls and landslides,), which recognises that the three greatest hazards are associated with seismicity, water and slopes. In the event and aftermath of a large to great Alpine Fault earthquake the likelihood is that more than one individual hazard will be activated. Therefore, one of the goals of this chapter is to outline each natural hazard event individually and then to consider the probability and consequences of a multi-hazard cascade of events, particularly in light of the elevated probability of an Alpine Fault earthquake.

3.1 DIRECT SEISMIC-RELATED FAULT HAZARDS

Seismic fault hazards include ground-surface deformation including fault rupture, strong ground shaking from rupture of the Alpine Fault, aftershocks following an Alpine Fault rupture, and strong shaking from any other regional fault source. Liquefaction and lateral spreading are included in this section as they occur as a response to strong ground motion.

3.1.1 Ground Surface Rupture Hazard

The Alpine Fault has long been known to occur in the vicinity of Franz Josef village, but until recently was not precisely mapped through the town. Following a regional-scale report on the location of the Alpine Fault throughout the West Coast region by Langridge and Ries (2010), it was recognised that more accurate fault location data was required for Franz Josef township. This was so that the hazard from ground surface rupture could be quantified and applied in a useful way via the Ministry for the Environment's Guidelines (MfE Guidelines) regarding building on, or adjacent to, active faults (Kerr et al., 2003; King et al., 2003).

The acquisition of airborne LiDAR along the central Alpine Fault has allowed for mapping at more detailed scales both through the town and bush-covered areas, than was previously possible (Barth et al., 2012). Langridge and Beban (2011) remapped the fault using a RTK-GPS ground survey and also using the 3-m LiDAR DEM created for the area (Langridge et al., 2014). The LiDAR DEM allowed for the recognition of individual fault traces and for profiles to be obtained from a GIS to consider bending and folding deformation related to fault scarps and fault-related features. An outcome of recommendations in the Langridge and Beban (2011) report was the adoption by Westland District Council of Fault Avoidance Zones for the area between south of Landfill Road and Potters Creek.

In the Langridge and Beban (2011) report, the Alpine Fault is mapped as a distributed zone of deformation with several sub-parallel or branching traces extending from a frontal fault trace into the hangingwall of the fault (i.e., to the southeast). The fault zone has a partitioned pattern of faulting comprising a frontal thrust or oblique-slip (strike-slip + dip-slip movement) fault.

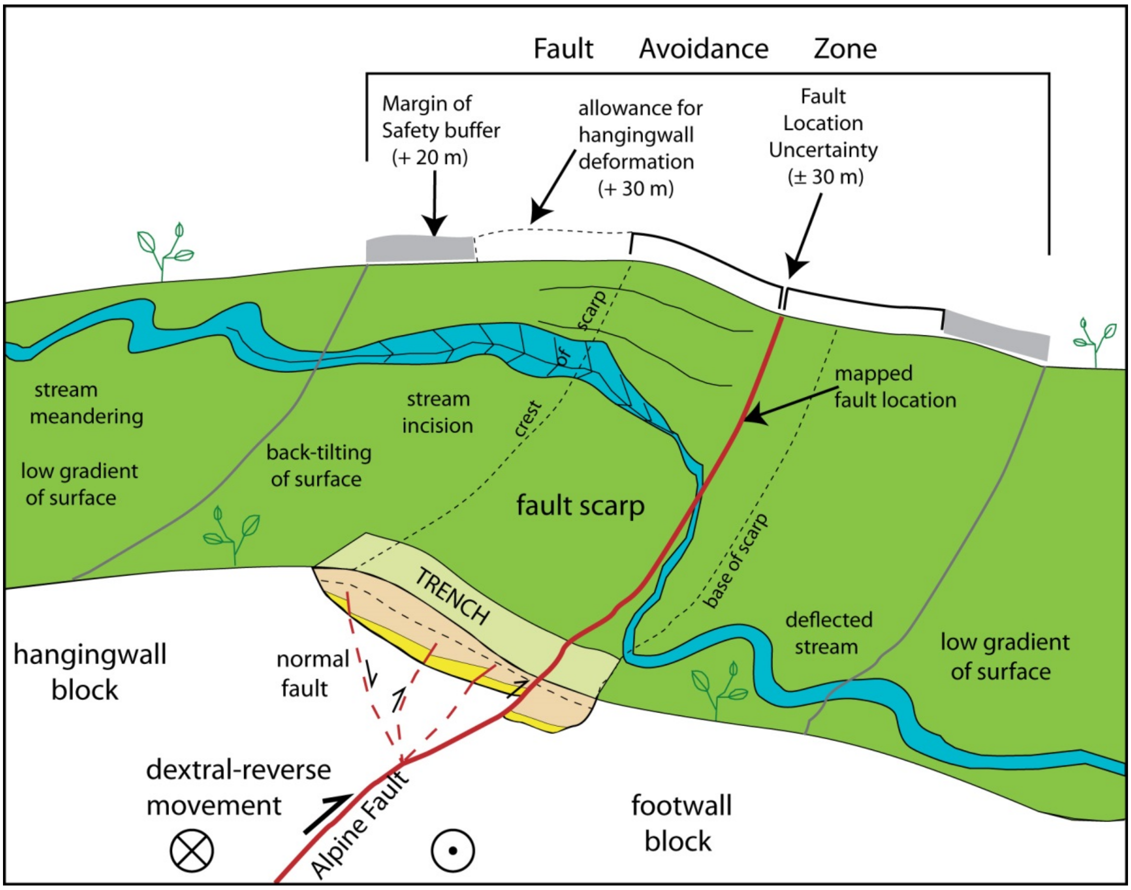

Figure 3.1 Schematic diagram of the dextral- reverse Alpine Fault and its Fault Avoidance Zone (FAZ). In this case the mapped fault trace (rupture surface; bold red line) is mapped near the base of the scarp. The scarp itself is mapped as '*Approximate'*, i.e., ±30 m definition on LiDAR, as it is through the town of Franz Josef. The growth of such scarps affects the long–term morphology of streams that cross the structure. The trench shows the expectation for documenting surface faulting events (e.g., faulted yellow layer). The Location Accuracy and Fault Avoidance Zone are shown by the different sized parentheses that make up the FAZ.

The existing Fault Avoidance Zone (FAZ) for the town of Franz Josef is 130 m wide. The FAZ included an uncertainty of ±30 m on the location of the most intense zone of deformation (is identified as an *Approximate* fault trace). This value is often called the *Fault Location Uncertainty* (Figure 3.1). The Alpine Fault has a significant reverse component of movement and an extra 30 m wide zone was added to the hangingwall (upthrown) side of the fault to account for the width of significant ground deformation and additional faulting on the southeast side of the fault. The MfE Guidelines suggest that a 'margin of safety' buffer of +20 m should be added to the area of mapping uncertainty. Thus the total width of the FAZ through the town is 130 m. This relatively narrow zone covers a length of c. 400 m through the town from the Waiho River to the Tartare Track at the end of Cowan Street.

As part of this study, the Langridge and Beban (2011) fault mapping methodology was adopted, reviewed and extended to some additional areas. For example in the southwest, the fault mapping was extended to Docherty Creek. In this area the Alpine Fault transitions from being a distributed zone of E-W striking strike-slip and reverse faulting, into a NE-striking zone of oblique-slip faulting toward Docherty Creek.

In addition, we reviewed the area either side of the Waiho River in more detail to see if there was further evidence of faulting or deformation within the hangingwall side of the fault not identified in Langridge and Beban (2011). We did this for three reasons: 1) the Waiho River occurs in the transition between the same distributed zone of E-W striking strike-slip and reverse faulting described above, and a NE-striking zone of oblique-slip faulting that persists through the town and northeastward beyond Potter Creek; 2) the earlier report had not considered the possibility of fault traces extending from the true left side bridge abutment on S.H. 6 (i.e., not visible due to erosion by the river); and 3) the earlier report had not considered the possibility of fault traces existing between the town and the Waiho River bridge (e.g., traces that were expressed only on older surfaces). Therefore, of relevance to the town is whether the original FAZ was extensive enough on the hangingwall at the southern end of the town and toward the river.

As part of this study we found previously unrecognised fault traces on the High (FJ-1) terrace above (south of) the town. Two NE-trending traces of c. 100 m length were mapped on the High terrace of Langridge and Beban (2011) with scarp heights of c. 1 m. These traces have been assigned an *approximate* location based on their expression on the LiDAR imagery. Between these traces and the left bridge abutment we have: 1) continued the traces from the High terrace to the southwest across the Town (FJ-0) terrace as *uncertain* fault traces; and 2) continued the two most obvious strike-slip faults from above the bridge abutment across the river in the vicinity of the S.H. 6 bridge (also as *uncertain* fault traces) to link in with the traces in 1.

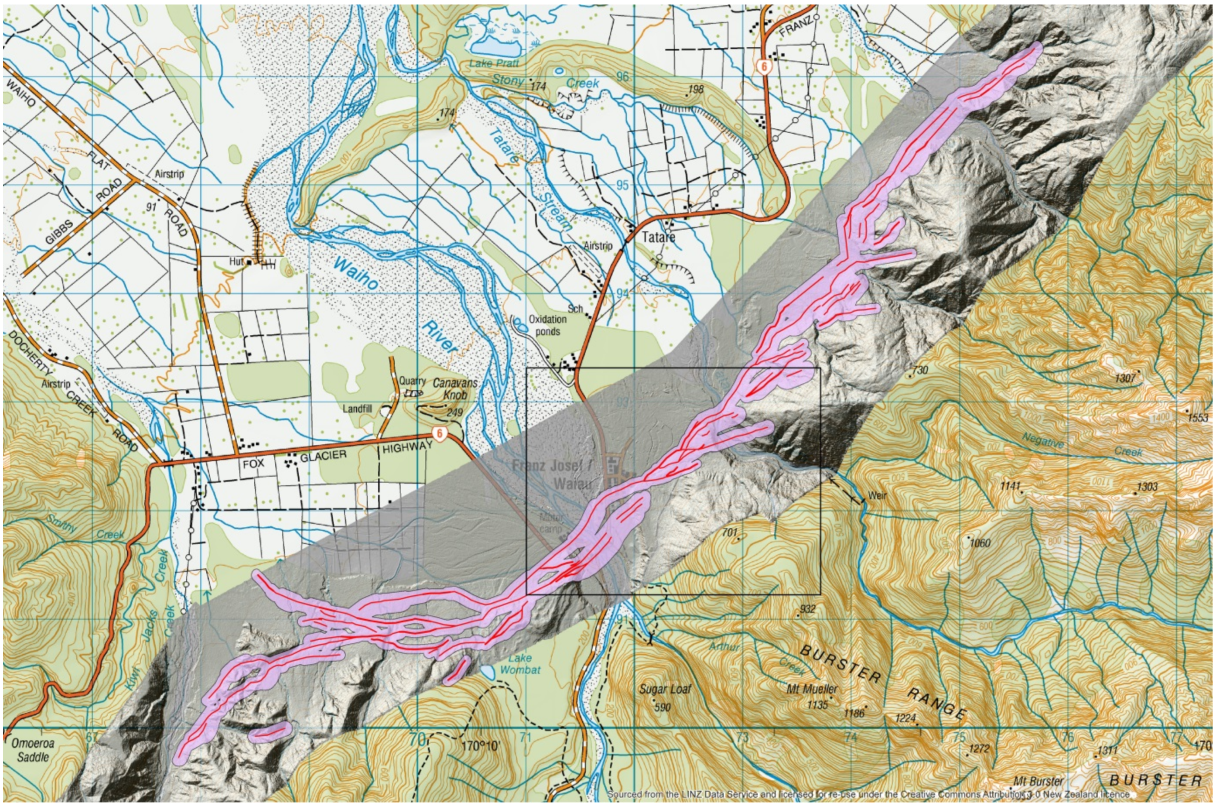

Figure 3.2 Updated Fault Avoidance Zones (purple polygonal shapes) for the area between Docherty Creek and Potters Creek. The Alpine Fault is characterised by a complex, distributed zone of faulting comprising NE-striking oblique-slip faults and east-west striking strike-slip faults (red lines). See Figure 4.1 for a detailed version for the town of Franz Josef area shown within the black box.

These revisions acknowledge that there are areas where faults probably exist but are not expressed on the LIDAR images due to burial or erosion. We also recognised that the previous FAZ mapping in Langridge and Beban (2011) was simplest through the town, whereas along the fault, the entire distributed fault zone between Dochertys and Potters creeks is characteristically >100-300 m in width. These results highlight that there are probably additional faults and a wider zone of deformation on the hangingwall side of the fault near the S.H. 6 bridge. The 130 m wide FAZ through the town of Franz Josef was not altered as part of revisions to the fault mapping and FAZ.

Some revision was made to the fault mapping coverage near Dochertys Creek and also in some areas along the rangefront of the fault between Franz Josef and Potters Creek. These changes update, but have no significant effect on the results presented by Langridge and Beban (2011).

In this study, we defined individual mapped fault traces as *accurate, approximate, or uncertain* in the GIS according to their *Fault Location Uncertainty*. *Accurate* traces mapped on LiDAR have a Fault Location Uncertainty of ±20 m, *approximate* traces ±30 m (such as the trace mapped through the town, and *uncertain* ±50 m. Using this scheme, the Fault Avoidance Zones are 100 m wide in total for *accurate*ly mapped fault traces (i.e., (20 x 2) + 20 + (20 x 2)), 130 m wide for *approximate* fault traces and 190 m wide for *uncertain* mapped fault traces.

3.1.2 Frequency and Expected Levels of Ground Surface Displacement

Langridge and Beban (2011) state that the expected horizontal, and vertical, movement in an Alpine Fault event is c. 8-9 m, and 1-2 m, respectively. Recent assessments of fault slip along the length of the Alpine Fault by De Pascale et al. (2014) suggest an average horizontal slip per event of c. 7.1 ± 2.1 m, which is consistent with previously published data (e.g., Berryman, 1975; Berryman et al., 2012a). In this study we adopt the new data for horizontal slip and maintain that 1-2 m vertical single-event displacement is expected. Based on the shape of deformation profiles run across the Town and High terraces on the upthrown side of the fault, the 1-2 m vertical movement may comprise roughly equal proportions of discrete co-seismic displacement (rupture) and bending or folding. Along NE-striking oblique-slip segments of the Alpine Fault, such as the one that runs through the town of Franz Josef, the majority of the fault deformation would be expected to occur along the frontal zone, i.e., the northwesternmost major fault trace. This is the fault trace and corresponding FAZ that was previously mapped and presented by Langridge and Beban (2011). Thus at the southern end of the town of Franz Josef c. 5-9 m of horizontal and 1-2 m of vertical movement should be expected in the next Alpine Fault movement.

The average recurrence of surface faulting on the Alpine Fault comes from paleoearthquake sites in Fiordland and recent data from lakes along the length of the Alpine Fault. At Hokuri Creek, the record of Alpine Fault events (combined with paleoseismic trenches in the Haast area) extends back 8000 years and yields an average recurrence interval of 329 ± 68 years (Berryman et al., 2012a; 2012b). Revision of those results following the addition of better records covering the last 1200 years indicates that the average recurrence interval is close to 300 years (Howarth et al., 2012, 2016; Cochran et al., in review). Biasi et al. (2015) use these revised datasets to define the conditional probability of failure of the Alpine Fault as c. 27% in the next 50 years. This analysis acknowledges that the Alpine Fault is currently late in its seismic cycle, i.e., the current interseismic interval is close to the average interval during the last 8000 years. Howarth et al. (2016) estimate an average recurrence interval for the central section of the Alpine Fault of 263 ± 68 years. The implication of this new result is that the elapsed time for the central section of the Alpine Fault may already be beyond the average repeat time.

3.1.3 Seismic Shaking

During an Alpine Fault rupture, Franz Josef will be subject to strong ground motions due to its immediate proximity to the Alpine Fault and in a broader sense due to its wider proximity to other possible 'regional' seismic shaking sources. The active fault component of the NSHM (Stirling et al., 2012) defines the Alpine Fault local to Franz Josef as the AlpineF2K fault source. The F2K (Fiordland to Kaniere) source has an input length of c. 411 km (± 10%) and slip rate of 27 ± 5 mm/yr. Within the NSHM the AlpineF2K source generates a M_w 8.1 ± 0.2 earthquake with a single-event (strike-slip + dip-slip) displacement of c. 9.2 m with a mean recurrence interval of 341 years. Differences in mean recurrence intervals between recent studies (Stirling et al., 2012; Berryman et al., 2012b; Howarth et al., 2016) illustrates that there remains significant uncertainty and that the information base is developing with more recent research.. Though many other seismic events are possible, Alpine Fault rupture is by far the largest and most likely earthquake scenario that will affect the town of Franz Josef.

The shaking estimates presented in this section of the report are based on an Alpine Fault scenario earthquake, the single fault that presents the most hazard to Franz Josef, and are thus *deterministic* in nature. The results are presented as measurements on the Modified Mercalli Index (MMI) scale which is a measure of shaking intensity and which links the shaking with the types of effects a person would expect to observe during an event. Previous work undertaken by GNS Science and others (Howarth et al., 2016; Robinson et al., 2016[2]) has estimated that Franz Josef might expect to experience MM 8 to 9 levels of shaking intensities in the featured Alpine Fault scenario. The generic description of effects that maybe expected from MM 9 shaking are (from Dowrick et al., 2008):

- Some masonry buildings completely destroyed, others may suffer partial collapse.
- Reinforced buildings with frames may suffer partial collapse, reinforcement frames maybe permanently distorted.
- Houses shifted off foundations.
- Widespread landsliding and rockfall, particularly on susceptible terrain.
- Landslide dams in narrow valleys.
- Widespread damage to infrastructure (roads, piped services).
- Liquefaction effects widespread with extensive lateral spread in susceptible areas.

Later sections of this report discuss some of these effects with particular reference to Franz Josef. Figure 3.2 shows a map of the MM intensities from an Alpine Fault scenario.

There are a number of things to point out whenever using a single scenario in this way. The forecast ground motions are of course a model, and the actual event is likely to have more variability and complexity than a simple model. This uncertainty needs to be kept in mind, but 'on average' we expect the MM 9 estimate to be a conservative basis for future planning purposes.

2 Shaking intensities calculated by GNS Science are derived using relationships from historical NZ earthquakes, while the Robinson et al. method uses a US derivation using ShakeMap

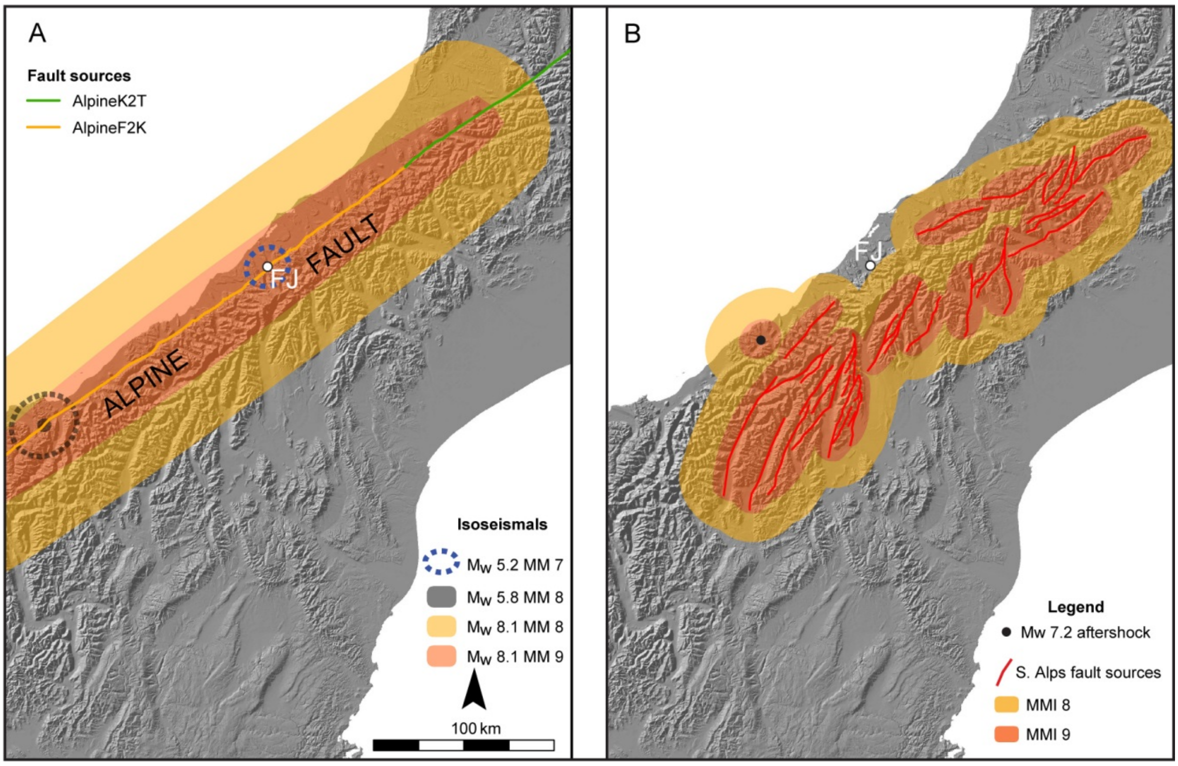

Figure 3.3 Modified Mercalli Intensity maps for the central South Island highlighting various earthquake sources (modified after Howarth et al., 2016). A. Shaking intensities for an Alpine F2K event, and for two other smaller scenario earthquakes: a shallow M_w 5.2 background' earthquake beneath Franz Josef and a M_w 5.6 earthquake near Lake Ellery. B. Earthquake scenarios from possible active fault sources within the Southern Alps and a M_w 7.2 aftershock that follows an Alpine Fault rupture. The latter can also be considered as the maximum cutoff magnitude earthquake for this region with the National Seismic Hazard Model. This M_w 7.2 event can occur directly beneath Franz Josef.

Another approach is to interrogate the NSHM to see what other sources may contribute to the shaking hazard at Franz Josef. Background earthquake sources that are not associated with mapped faults (or are too small to be) are important to consider (Stirling et al., 2012). A deaggregation plot for Franz Josef that combines earthquake fault sources and background seismicity sources is shown in Figure 3.4. For a probability of roughly 10% in 250 years (or 2500 years) the deaggregation plot indicates that the main contributor of seismic hazard is the M_w 8.1 AlpineF2K source (i.e., the Alpine Fault). The plot also indicates that the second largest hazard over 2500 years comes from small earthquakes (M_w 5-6) that occur < 10 km from the town.

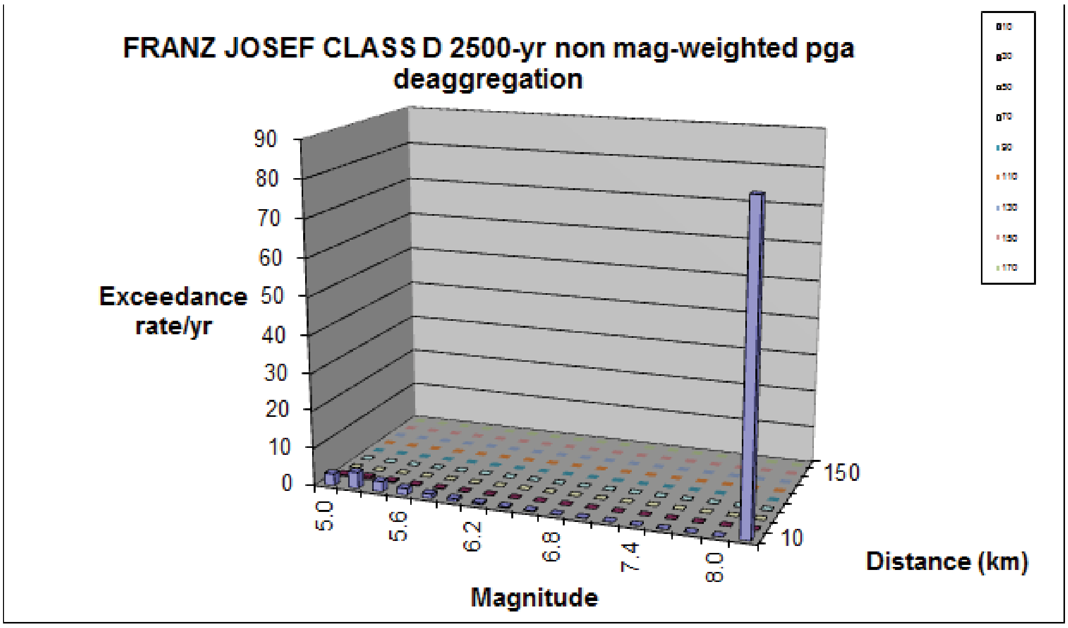

Figure 3.4 A 10% in 250 year (2500 year) deaggregation plot for the town of Franz Josef assuming Class D (deep) soils. The plot is dominated by the Alpine Fault (F2K) source, but includes a small component of hazard from small (M_w ~5 to 5.8) local earthquakes.

Figure 3.3 summarises the modelled effects of various earthquake sources in the central South Island in terms of Modified Mercalli Intensity (MMI) shaking (Howarth et al., 2016). These shaking models use the Smith (2002) methodology, modified for the town of Franz Josef. The Alpine F2K source produces ground motions of MM 9 along the fault and MM 8 at short distances from the fault over hundreds of kilometres. Figure 3.3 also displays a M_w 5.2 earthquake beneath Franz Josef as a possible background seismic source in Figure 3.2. The effects of such an earthquake are shaking intensities of MM 7 within 10 km of the town. This level of shaking is known to induce landsliding. Figure 3.2b displays a range of possible earthquake scenarios within the central Southern Alps in proximity to Franz Josef. 'Possibly active' faults of Cox et al. (2012) are identified as red lines and the shaking associated with each fault is shown by the brown and orange ellipsoids. Another possible seismic scenario is a maximum cutoff magnitude earthquake of M_w 7.2 that occurs along or close to the Alpine Fault. A M_w 7.2 background earthquake is considered to be the largest event that could occur on an unknown fault source anywhere within the central South Island (excluding known faults/sources). Such an event also replicates a large (but possible) aftershock that could occur following a great (M_w ~8.1) Alpine Fault earthquake. A M_w 7.2 earthquake or aftershock generates MMI 8-9 shaking over a localised area if it were centred on the town of Franz Josef.

Modelling by Robinson et al. (2013) estimates that several hundred potentially damaging aftershocks could result from an Alpine Fault earthquake. These could trigger further landsliding or could be the trigger for landslide dammed lakes to fail or be breached. Table 3.1 lists the modelling results.

Table 3.1 Alpine Fault aftershock modelling results.

Magnitude	0–90 days	0–365 days	365–730 days
M5+	380	428	23
M6+	35	40	2
M7+	3	4	0.2

In summary we have provided an overview of the estimated seismic hazard at Franz Josef concentrating on the nearby Alpine Fault as a scenario. The most likely and most severe earthquake scenario in the NSHM in proximity to Franz Josef is rupture of the AlpineF2K source in a M_w ~8.1 earthquake. MMI 9 shaking is likely for the Alpine Fault rupture event which has an estimated conditional probability of 27% in the next 50 years. Shaking intensities in the MMI 7-8 range as aftershocks or from other local sources will be more frequent (Figure 3.2).

3.1.4 Liquefaction and Lateral Spreading

Liquefaction is the process that leads to a soil suddenly losing strength, most commonly as a result of ground shaking during a large earthquake. Not all soils however, can liquefy in an earthquake. The following are particular features of soils that potentially can liquefy:

- Loose sands and silts. Such soils do not stick together the way clay soils do.
- Saturated, below the water table, so all the space between the grains of sand and silt is filled with water. Dry soils above the water table will not liquefy.

During strong shaking such soils may lose strength and liquefy. Soil that was once solid can behave like a fluid.

Lateral spreading is the lateral movement of gently to steeply sloping, saturated soil caused by earthquake-induced liquefaction (Kramer, 2016). The movement of soil undergoing lateral spreading can range from a few centimetres to a few meters, and can cause significant damage to buildings, bridges, pipelines, and other elements of infrastructure. Lateral spreading often occurs along riverbanks, shorelines and man-made structures where loose, saturated sandy soils are commonly encountered at shallow depths (Cubrinovski et al., 2012). Structures supported on shallow foundations, pavements, and buried pipelines are particularly susceptible to damage from lateral spreading. Lateral spreading occurs as the generation of porewater pressure in the soil during earthquake shaking reduces the stiffness and strength of the soil.

Liquefied soil cannot support the weight of whatever is lying above it – be it the surface layers of dry soil, or the concrete floors (or piles) of buildings. The liquefied soil under that weight is forced into any cracks and crevasses it can find, including those in the dry soil above, or the cracks between concrete slabs. It may flow out onto the surface as boils, sand volcanoes and rivers of silt. In some cases, the liquefied soil flowing up a crack can erode and widen the crack to a size big enough to accommodate a car. Some other consequences of the soil liquefying are:

- Differential settlement of the ground surface due to the loss of soil from underground;
- Loss of support to building foundations;
- Floating of manholes, buried tanks and pipes in the liquefied soil – but only if the tanks and pipes are mostly empty;
- Near streams and rivers, the dry surface soil layers can slide sideways on the liquefied soil towards the streams. This is called lateral spreading and can severely damage a building and buried infrastructure such as buried water and wastewater pipes. It typically results in long tears and rips in the ground surface; and
- Lateral spreading adjacent to smaller streams may reduce their water-flow capacity leading to increased flood frequency.

Not all of a building's foundations, buried pipe networks, road networks or flood protection stop-banks might be affected by liquefaction. The affected part may subside (settle) or be pulled sideways by lateral spreading, which can severely damage the building. Buried services such as sewer and potable water pipes can be damaged as they are warped by lateral spreading, ground settlement or floatation.

Not all soils are susceptible to liquefaction. Generally, for liquefaction to occur there needs to be three soil preconditions (Tinsley et al., 1985; Youd et al., 1975; Ziony, 1985):

- Geologically young (less than 10,000 years old), loose sediments, that are
- Fine-grained and non-cohesive (coarse silts and fine sands), and
- Saturated (below the water table).

If all three of these preconditions are met, then an assessment of the liquefaction hazard is required. Assessment of liquefaction hazard can be on a regional or district scale or it can be site specific using, for example, cone penetrometer tests. Note that the 'saturated' condition need not be permanent, but may be seasonal or ephemeral, i.e., the potential for saturation must be assessed. When any one of these preconditions is not met, the soil is not susceptible to liquefaction. If soils are not susceptible to liquefaction then liquefaction would not need to be assessed in an urban or rural planning context.

Once it has been ascertained that soils are susceptible to liquefaction, it needs to be determined if the seismic hazard is sufficient to warrant consideration of liquefaction as a hazard. This is done by considering if earthquakes are strong enough and frequent enough to warrant concern. Whether earthquake shaking is strong enough or frequent enough will in part depend on the type of the facility or infrastructure being considered (e.g., for domestic dwellings the seismic hazard that can be expected to occur more frequently than once every 500 years should be considered, but for a critical facility liquefaction should not impact on continued functionality of the facility in a 1 in 2500 year event).

If the seismic hazard is sufficient to warrant consideration for the infrastructure or facility under consideration then an assessment of the consequences of liquefaction on that land use needs be undertaken. The primary impacts of liquefaction are to the built environment (e.g., buildings); infrastructure (i.e., underground pipes and services, roads); and to socio-economic resilience if people are not able to live in their homes and/or access places of education or employment.

If the impacts of liquefaction are insignificant, then it may be appropriate that no planning actions are required. If, however, the potential consequences are more than insignificant, and a cost-benefit assessment indicates possible future losses can be mitigated, either by avoidance or by engineering solutions; then liquefaction should be a criteria assessed during land use planning. Saunders and Beban (2012) provide an explanation for how the consequences of liquefaction can be assessed in a risk-based planning context.

3.1.5 Liquefaction Hazard – Franz Josef Area

We have not specifically mapped areas of liquefiable deposits in the GIS, nor have we undertaken any specific field studies or tests of materials as part of this desktop study. Therefore, the following section draws on observations from previous visits to the area and from what is now known from the 2010-2011 Canterbury earthquake sequence (Cubrinovski et al., 2012; Van Ballegooy et al., 2015).

The wider Franz Josef area is subject to high ground motions due to its proximity to the Alpine Fault and from more distant earthquake sources at longer time intervals (Stirling et al., 2012). In terms of liquefaction it is worth considering whether the three necessary soil pre-conditions described above (i.e., covering young fine-grained non-cohesive sediments and high water table) are met locally.

The Waiho river plain is characterised by typically coarse-grained alluvial sediments that are mostly younger than 10,000 years in age Figure 2.2). Alluvial sediments of the outwash plains are dominated by sandy gravels derived from the Alpine Schist (schist, gneiss and mylonite; Cox and Barrell, 2007). Undoubtedly, there will be medium to coarse sand interbeds in the floodplain sequence that relate to flood-filled channels and migrating facies across the floodplain. Non-cohesive fine sands and silts may accumulate in specific sedimentary environments where the energy of these alluvial systems has dropped away considerably, i.e., slackwater environments. Some examples of such areas where fine sands and silts could accumulate are: (i) in coastal environments, including estuaries and lagoons, e.g., Okarito lagoon; (ii) in lake and marginal lacustrine environments, e.g., Lake Mapourika; (iii) in alluvial backwaters such as those in and around the Waiho Loop; and (iv) in low-lying alluvial areas found between the major catchments, e.g., the recently developed NE part of Franz Josef town that occurs between the Waiho and Tartare catchments.

In some of these areas the groundwater table is likely to be high, e.g., marginal marine and lacustrine environments and also in the recently developed part of Franz Josef where drainage ditches have evidently been excavated (Figure 3.5). Liquefaction potential of these areas and across the wider Franz Josef area is possible but is likely to be restricted in extent in the gravel-dominated alluvial terraces and fans. We surmise that to a large extent in gravel terrace dominated environments, such as exist across the alluvial floodplains, that the conditions for liquefaction would not often exist, or at least would not exist to the extent that has been witnessed during the 2010-11 Canterbury earthquake sequence (Cubrinovski et al., 2012; Van Ballegooy et al., 2015). However, liquefaction (as sandblows) is possible and has been observed in paleoseismic trenches across the Alpine Fault at Haast (Berryman et al., 2012a).

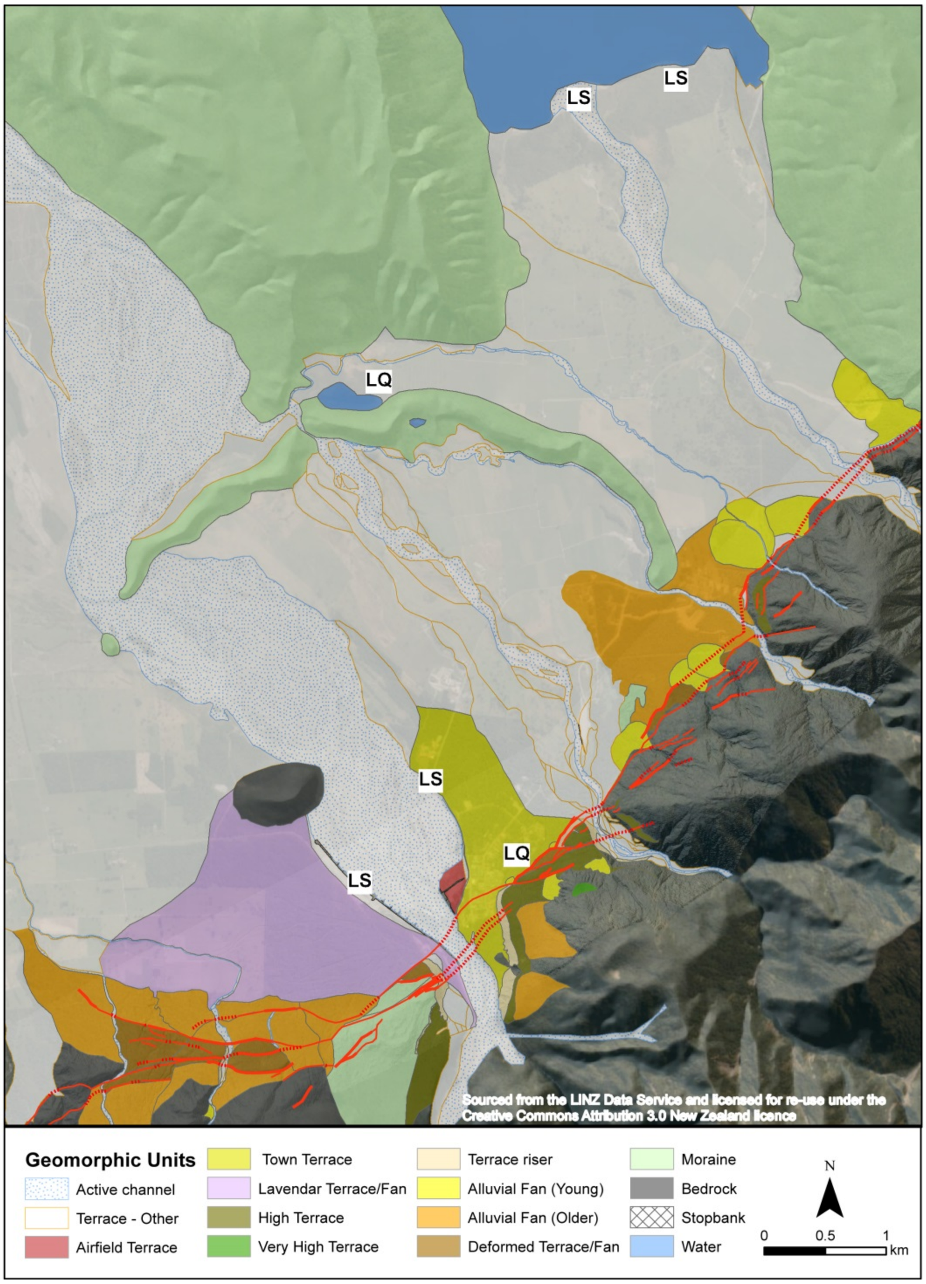

Figure 3.5 Areas that may be susceptible to liquefaction (LQ) and/or lateral spreading (LS) in the wider Franz Josef area. Liquefaction typically requires fine sediments and a high water table. Lateral spreading is possible where topographic edges are exposed laterally to a free surface, e.g., lake shore, deltas, terrace risers and stopbanks).

3.1.6 Lateral Spreading Hazard – Franz Josef Area

As part of this study we have not specifically mapped areas that could be prone to lateral spreading. By definition, lateral spreading is the finite, lateral movement of gently to steeply sloping, saturated soil deposits caused by earthquake-induced liquefaction (Kramer, 2016). As stated, lateral spreading often occurs along riverbanks, shorelines and man-made structures where loose, saturated sandy soils are commonly encountered at shallow depths. Lateral spreading is promoted in areas where there is space into which material can spread, i.e., from a solid into water or air. Some examples of environments in the wider Franz Josef area where lateral spreading could occur are therefore: (i) in coastal environments, including estuaries and lagoons, e.g., Okarito lagoon; (ii) in lake and marginal lacustrine environments, e.g., Lake Mapourika; and (iii) along river banks of any incised river or stream like the Waiho River; and (iv) in association with man-made structures, including stopbanks and embankments that are close to the water table (Figure 3.5).

Howarth et al. (2014) documents the effects of mass wasting in Lake Mapourika caused by strong shaking. Potters Creek reaches Lake Mapourika and forms a subaerial delta and subaqueous fan delta. Lateral spreading of the shoreline areas and particularly the deltaic area is likely during strong shaking. Within the subaqueous fan delta, lateral spreading is synonymous with mass wasting of the delta (i.e., landsliding or slumping, and generation of turbidity currents).

Few planned developments would be sited close to alluvial terrace edges, however of river-bank erosion may bring structures into proximity with active river edges to the point where they are in a hazardous environment. Similarly, seismic shaking may cause lateral spreading within the flood protection stopbanks built along the Waiho River and other rivers. Failure of part of the stopbank system due to shaking and lateral spreading may make them vulnerable to erosion and/or flood damage, particularly if that follows after the shaking and other ‘downstream’ hazards posed by an Alpine Fault rupture event (McSaveney & Davies, 1998). Failure of part of the Waimakariri and Kaiapoi river flood protection stopbanks occurred during the 2010 Darfield earthquake (Duncan 2011; Van Ballegooy et al., 2015), highlighting the need to consider stopbank failure as a hazard that could impact on Franz Josef.

3.2 WATER-DRIVEN NATURAL HAZARDS

In this study, river and water-related hazards include flooding, alluviation, alluvial fans, and debris floods and flows. Most of the available data on these hazards relates to the Waiho River, the Callery River tributary and along the rangefront where LiDAR was used to map the geology in detail.

3.2.1 Waiho River Flooding

The Waiho River is a major flooding hazard to the town of Franz Josef; a fact that has been made more obvious as a result of the March 2016 flooding event which severely impacted the Scenic Circle Hotel complex, north of the main town centre. River flooding will continue to be a serious issue as pointed out by McSaveney and Davies (1998), in part due to the river management regime put in place to control the width and position of the Waiho River.

Geologic mapping at scales of 1:100,000 or 1:10,000 (on LiDAR) highlight that the Waiho River – like others along the West Coast with a short catchment on the coastal plain – acts rather like an alluvial fan. That is, once the river has emerged from its steeply walled valley on the upthrown side of the Alpine Fault, it spreads out quickly across a broader floodplain. In addition, like an alluvial fan such a floodplain will tend to be lobate in shape and will build, erode and re-build itself by fanning of the main channel across the valley with time. Profiling across the entire floodplain using the LiDAR DEM highlights the lobate shape of the wider floodplain and issues regarding the height of the current managed channel in the vicinity of the town, and the height of the town itself (Figure 3.6).

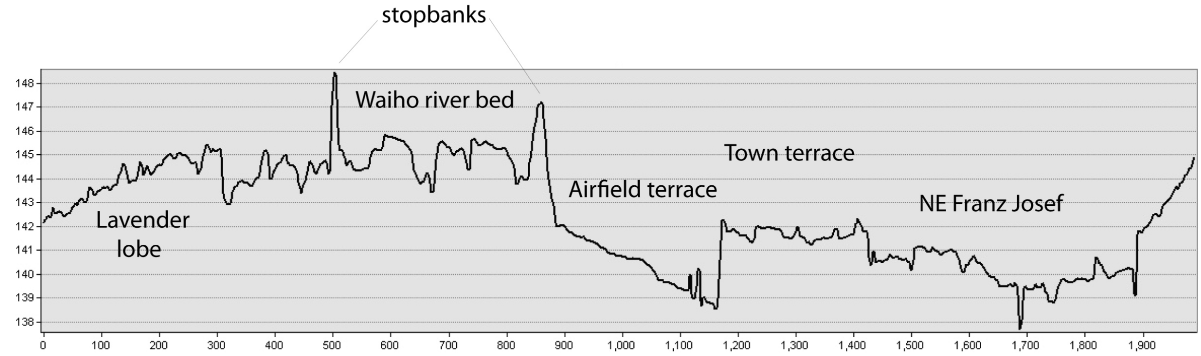

Figure 3.6 A topographic profile drawn across the Waiho fan from the 'Lavender' lobe in the SW to the edge of the Tartare fan, NE of Franz Josef town using LiDAR data. The Waiho River currently occupies the area between the two highest stopbanks and is considerably higher than either the Airfield terrace or the Town terrace.

The profile in Figure 3.6 shows that: (i) the southwestern (Lavender) lobe of the Waiho River fan is higher than the Town terrace on which Franz Josef is constructed; (ii) the bed of the river in its current position adjacent to the town is higher than all of the land around it (barring the stopbanks); (iii) the Airfield terrace is lower than the Town terrace and would be prone to flooding before the town; and (iv) the Town terrace slopes away (gets lower) to the NE toward the Tartare River.

In 2014 a hydrologic flow modelling study was undertaken by Land River Sea (LRS) Consulting Ltd. We use this hydrologic modelling to assess flood levels in the town and their likely extent downstream. LRS supplied hydrologic models for a 10-yr return period Waiho River flood, as well as a 20-yr, 50-yr and 100-yr Waiho River flood. In addition, LRS undertook an analysis for a scenario where the entire bed of the river built up through sediment deposition, to 4 m higher than its present level. This scenario was driven by the observation that bed levels have been increasing since the 1940's at a rate of 0.16-0.2 m per year at a point below the S.H. 6 river bridge.

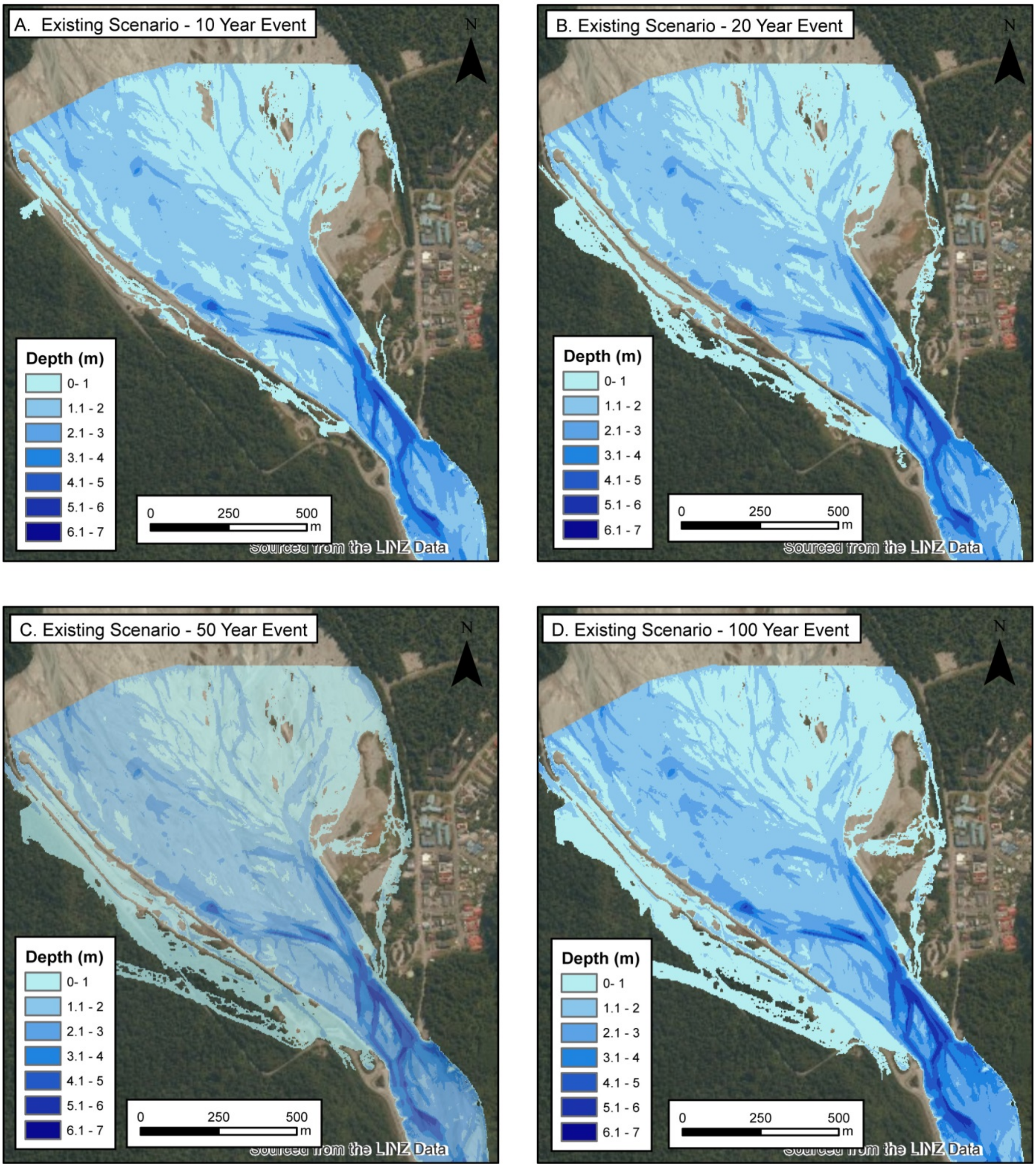

Figure 3.7 Flooding scenarios for the Waiho River for four time periods based on modelling undertaken by Land River Sea Ltd. (2014). The existing scenarios presume that the current bed level of the river is maintained, however a feature of the Waiho River behaviour is that current bed levels have not been maintained.

Using the current river bed heights, the 10-year flood event is modelled as an event with a water level c. 5.7 m above mean channel flow. Figure 3.8a shows water depths and inundation for the 10-year flood event. Such a flow would essentially fill the area (bank-to-bank) between the high stopbanks. On the true right side of the river, flooding across the Airfield terrace would be up to c. 1 m water depth and slightly higher in channelled areas. Downstream of the limits of the main flood protection stopbanks the 10-year flood could be expected to overtop the Town terrace and flow across it. On the true left bank, flows of up to 1 m water depth could be expected if water breaches the main stopbank in the area of the abandoned motor camp. Using the current river bed heights, the 20-year flood event is modelled as an event with a water level c. 5.9 m above mean flow. Figure 3.8b shows water depths and inundation for the 20-year flood event. Such a flow would have similar effects and impacts to the 10-year flood, though with 20 cm more water depth.

Using the current river bed heights, the 50-yr flood event is modelled as an event with a water level c. 6.0 m above mean channel flow. Figure 3.8c shows water depths and inundation for the 50-year flood event. Such a flow would produce similar effects and impacts to the 10-yr flood, though with 30 cm more water depth. The added impacts of this event on the true left bank would include outflow of water in channels across the Lavender lobe/ terrace.

Finally, using the current river bed heights, the 100-yr flood event is modelled as an event with a water level c. 6.1 m above mean channel flow. Figure 3.8d shows water depths and inundation for the 100-year flood event. Such a flow would produce similar effects and impacts to the 50-yr flood, though with 30 cm more water depth. Flood waters would not enter the main part of the town under this scenario.

The estimated peak flows for a series of flood return periods for the Waiho River at the S.H. 6 bridge are displayed in Table 3.2. LRS Consulting used this data to create conservative peak flow values for the 100, 200 and 400 year flood situations.

Table 3.2 Estimated peak flows for a range of return period events on the Waiho River at SH6 Bridge (data from LRS, 2014).

Return period (years)	Peak flow range (m^3/s)	Adopted Peak flow* (m^3/s)
20	1857-1953	-
50	2128-2238	-
100	2330-2451	2500
200	2553-2664	2700
400	2735-2876	2900
500	2800-2945	-

*The final value adopted by LRS Consulting (2014) in their flood hazard study.

3.2.2 Alluviation in Rivers

Alluviation refers to the deposition of sediment by water – in this case by rivers. Debris comprising gravel, sand and silt formed by the collapse and erosion of rocky slopes released in the upper parts of the Waiho-Callery catchment is being delivered as sediment to the Waiho fan (Davies, 1997). Figure 2.1 highlights the broadly mapped Holocene units that make up the Waiho fan between the rangefront and the coast. It has long been known that the Waiho River is aggrading downstream of the S.H. 6 bridge. The Land River Sea (2014) report suggests that the rate of aggradation since the 1940's is c. 0.16-0.2 m per year. The Waiho River acts as a very large alluvial fan (see next section) and builds lobes of alluvium across one sector of the fan until such time as it migrates to another sector of the fan. This occurs so that deposition is spread rather evenly across the fan over the medium to long term. This is an inherent property of alluvial fans, i.e., a tendency to abandon an entrenched channel and avulse so as to occupy and fill lower-lying parts of the fan complex.

The LRS (2014) report also presents the 100-year flood condition of the Waiho River and models it with an additional 4 metres of aggraded sediment within the flood control river channel (Figure 3.8). The effect of the raised river bed means that the 100-year flood event is able to overtop the Town Terrace at the south end of the town, and flow into the town. Franz Josef town would be flooded under this scenario with up to 1 m of water in parts of the town.

Based on the current rate of bed aggradation the bed of the Waiho River could be raised by 4 m within 20 years. Alternatively, a single 100-yr flood could raise the bed of the river by that amount. In such an occurrence the town could be threatened by the 100-yr flood at any given time following bed aggradation.

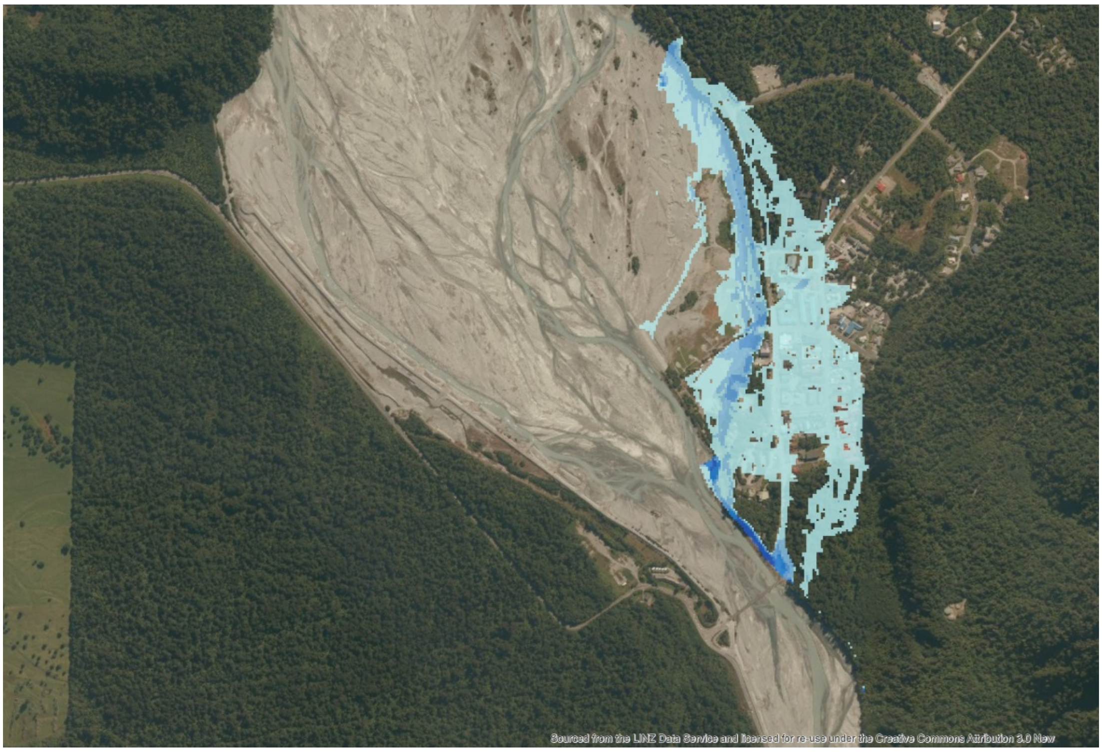

Figure 3.8 A 100-year flood scenario for the Waiho River following aggradation of the river bed by 4 metres at a rate of up to 0.2 m per year (based on modelling undertaken by Land River Sea Ltd. 2014).To visualise the effects of 4 metres of extra flood water in the main part of the river flow, consider Figure 3.7d with an extra 4 m of water.

3.2.3 Alluvial Fans

Alluvial fans are one of the downslope products of landsliding and in this section we categorise them as a water-related phenomenon or hazard, as they form by the deposition of debris by water. The source of that debris is from landslides in the catchments upstream. Here, we treat alluvial fans as mappable fan or cone-shaped deposits that eventually grade into alluvial terraces having lower gradients. We typically mapped alluvial fans as being limited to within 1.5 km of the rangefront of the Southern Alps on, and extended to the NW of, the LiDAR DEM at a scale of 1:10,000 along the rangefront and extending out to the Waiho Loop (Figure 2.3). One exception to this is the Potters Creek floodplain, which can be considered as an alluvial fan from the rangefront entirely to Lake Mapourika. Alluvial fans that have been constructed across other surfaces (fans or terraces) are younger than those that they bury.

We interpret fans that extend across the fault zone of the Alpine Fault without disturbance (i.e., lacking faulting recognised by a scarp) to have been active since the most recent earthquake, i.e., active since about 1717 AD, in the same way that terrace ages were assigned in Section 2.2.3. Fans that are faulted (or have been correlated across the frontal fault zone) can be assigned relative ages based on the height of the fault scarp or from terrace levels that they grade to. For example, a 1-2 m high frontal fault scarp across a fan may be the result of only 1-2 faulting events, therefore that fan must pre-date 1717 AD (be somewhat more than c. 300 years in age). Whereas a fan surface has been matched across a 4-8 m high scarp implies that at least 4 surface faulting events have affected the fan. The timings of the last four surface faulting events on the Alpine Fault are c. 1717, 1388-1407, 1008-1213 and 915-967 AD (Howarth et al., 2016). Thus, we can infer that a fan with 4-8 m of displacement across it is likely to have been active 1000-2000 years ago.

These basic interpretations come from simply mapping the geomorphology along the rangefront and fault zone. The following paragraphs describe the possible ages and extents of alluvial fans from: (i) west of the Waiho River; (ii) between the Waiho and Tartare; (iii) between the Tartare and Stony; and (iv) between Stony and Potters creeks. These observations assess the size, activity and relative age of rangefront fans and the likelihood that they could be rejuvenated and how far they could extend out from the rangefront.

West of the Waiho: West of the Waiho River a set of higher alluvial fans are mapped to the south of the Lavender lobe/terrace. Individual fans have areas of c. 0.2 km^2, i.e., they do not extend far from the rangefront. These fans have been trimmed by the fluvial activity that preceded formation of the Lavender lobe, at which time the 'higher' fan activity there was abandoned. Creeks are incised into these fans and these creeks yield small alluvial fans (area c. 0.1 km^2) that grade to or can be mapped on the Lavender lobe/terrace. The higher, older fan surfaces are cut by several traces of the Alpine Fault in this area. The fault has formed scarps of several metres high across these fans. In addition, the creeks incised into the older fans are deflected to the right along the fault, implying measureable right-lateral offset of stream courses, i.e., they also give an indication that the surfaces have experienced several earthquakes. Under the current climatic and tectonic regime we might expect that the smaller alluvial fans could be rejuvenated by the release of sediment caused by major storms or strong shaking, and extend more than 0.3 km distance from the rangefront.

Waiho to Tartare: In proximity to the town of Franz Josef between the Waiho and Tartare Stream the recent geology is dominated by the Town and High terraces. Alluvial fans have been mapped as emanating from the rangefront slopes and extending onto the High terrace (estimated age 11-12,000 years). Only two small alluvial fans (area c. 4000 m^2 =0.004 km^2) have been mapped at the back edge of the Town terrace. These emanate from the two small creeks that have flowed across and off the High terrace, and across the fault zone.

Based on these observations we believe that the current town site extending to the NW to Tartare Stream has not been subject to extensive alluvial fan sedimentation since the formation of the Town terrace and possibly for much longer. While the fans formed on the High terrace may have been rejuvenated several times over the past millennia and even post-1717 AD, they have never extended across and over the faulted edge of the High terrace. In this way, the High terrace armours the rangefront and provides some protection to the town from the active growth of alluvial fans.

Tartare to Stony Creek: The distance along the rangefront between the Tartare and Stony Creek is c. 1.8 km. Based on interpretation of the LiDAR DEM there are several well-developed minor catchments that have formed as a result of landsliding within the rangefront.

Three fan lobes of area c. 0.07 km^2 extend out c. 300 m from this part of the rangefront. These smaller fans appear to be unfaulted and overlie older, more extensive fan surfaces that are faulted. The smaller fans are therefore considered to be young and have probably been rejuvenated following the most recent surface rupturing earthquake on the Alpine Fault (i.e., post-1717 AD).

The identification of a 5-8 m high fault scarp and incision by Tartare Stream indicates that the older fan here may be >1000 years in age. Incision of Tartare Stream corresponds to abandonment of the older fan, which once abandoned was able to accumulate fault deformation (i.e., build a scarp). The older fan is the surface upon which the Stony Creek subdivision has been developed.

Under the current climatic and tectonic regime we might expect that the smaller alluvial fans will extend and be rejuvenated as a result of large rainfall or strong shaking events that release sediment from small erodible catchments above them. In contrast, the older, broader alluvial fans are abandoned.

Stony Creek to Potters Creek: A similar pattern occurs along this 1.3 km stretch of the rangefront. The scale of the smaller, younger alluvial fans as mapped on Figure 2.3 is larger (are c. 0.1-0.2 km^2) along this stretch of rangefront compared to the previous two sections described above. The smaller fans extend up to 0.55 km from the rangefront. The greater extent of these fans correlates with the more ‘evacuated’ or eroded appearance of the rangefront suggesting more material has been delivered from small landslides, across the rangefront to the fans. The smaller fans host incised creeks and once again are deposited across older abandoned fan remnants derived from Stony and Potters creeks. No young alluvial fans have extended across or buried this surface. As stated above, under the current climatic and tectonic regime we might expect that the smaller, younger fans to have the potential to be rejuvenated as a result of large rainfall or as a consequence of strong shaking events.

Based on the observation of their past activity and because this part of the rangefront is quite steeply dissected we might expect that rejuvenation of these Stony to Potter Creek rangefront fans would be of larger magnitude in future (compared to those fans SW toward Franz Josef town).

Potters Creek: Potters Creek itself is unique because it is considered to comprise an alluvial fan floodplain for c. 3.8 km from the rangefront to Lake Mapourika. The catchment area of Potters Creek is highly dissected and the volume of eroded material is proportional to the volume of material that forms the Potters Creek fan to the shores of Lake Mapourika. Although the current channel of Potters Creek is incised, it is likely that the Potters Creek fan could be rejuvenated following strong shaking and landsliding.

In summary, the hazard from rangefront alluvial fans appears to be greater where the rangefront is already dissected, allowing for a greater release of material in future rainfall or shaking events. There is an increase in the area and volume of rangefront fans from SW to NE from Franz Josef to Potters Creek. This does not preclude the development of new or larger alluvial fans at Franz Josef, especially if new landslides occur at or east of the rangefront, although it appears this has not occurred through multiple large earthquake cycles on the Alpine Fault. In the vicinity of the town of Franz Josef, the rangefront is armoured by the High terrace, which acts to stop smaller fans and landslides from impacting the Town terrace.

3.3 GRAVITY-DRIVEN NATURAL HAZARDS

Mass movement hazards include those hazards that are dominated by gravitational processes but have a low component of water as a driver, i.e., they are not alluvial in nature. In this section we describe non-seismic and seismically-induced landsliding, rock avalanche, landslide dams and their subsequent outburst floods.

3.3.1 Landslides

Landslides represent a major hazard to the built environment and a life safety risk to the inhabitants of range front towns in the Southern Alps, such as Franz Josef. The landslide susceptibility of hillslopes is mediated by a complex interplay between hillslope gradient, the strength of the bedrock and dynamic stress changes operating within slopes governed by rainfall and seismic shaking. The range front hillslopes to the east of Franz Josef are characterised by steep range front topography and weak fault-crushed rock mass that when combined with high rates of rainfall and seismicity equate to high landslide susceptibility (Korup, 2004). To review and semi-quantify the hazard posed by landsliding to the Franz Josef township and surrounding area we distinguish between landslides triggered by non-seismic processes and seismically-triggered landsliding.

3.3.2 Non-Seismic Landsliding

To evaluate the hazard posed to Franz Josef by non-seismic landsliding, including rainfall induced landsliding, spontaneous slope failure and reactivation of existing landslides, requires information on the rate of landsliding driven by these processes. Further, for a landslide to pose a threat to the township it must have sufficient runout (the downslope distance that landslide debris travels after failure) to reach the town. Consequently, the non-seismic landslide hazard is governed by the rate of landslides with sufficient runout to reach the town. We estimate the hazard using empirical relationships between the rate and size of non-seismic landslides in the Southern Alps combined with the relationship between landslide size and runout distance. The empirical calculations are supported by the 1:10,000 scale mapping of geomorphology in the township area.

The spatio-temporal distribution of non-seismic landsliding in the Southern Alps has been quantified by mapping landslide occurrence over the last 60 years in multiple sets of aerial photography (Stark & Hovius, 2001). The dataset is complete for landslides in the size range of 10^{-2} km^2 to 10^{-1} km^2 and follows a power law relationship between landslide size and frequency (Eqn.1) (Hovius et al., 1997; Stark & Hovius, 2001).

$$n_r(A \geq A_r) = 5.4x10^{-5} A_r^{-1.16} \qquad \textbf{Eqn.1}$$

Where $n_r(A \geq A_r)$ is the annual number of landslides per km^2 of landslide area A greater than reference area A_r. This magnitude frequency distribution allows the annual rate and return period of landslides of a given size (area) to be determined.

The relationship between landslide area and runout distance has been determined by mapping the detachment area and runout distances of 151 landslides in the Southern Alps (Korup, 2005). From this mapping a power law relationship between landslide area and runout length was derived (Eqn. 2). This power law has a R^2 of 0.75 demonstrating a reasonable correlation between runout and area but there is still a factor of two variation in runout for a given landslide area (Korup, 2005).

$$R = 1558A^{0.39} \qquad \textbf{Eqn.2}$$

Where R is runout distance in metres and A is landslide area in km^2. By combining the two power law relationships it is possible to develop a model for the frequency of landslides with sufficient runouts to impact Franz Josef. Before outlining the results it is important to review the assumptions and limitations of this simplistic model. Applying the spatio-temporal distribution of non-seismic landsliding derived for the Southern Alps does not take into account any local conditions such as hillslope gradient, rock-mass strength or ground water conditions that could change the probability of failure at a specific site. Landslide runout is also governed by a complex set of phenomena and the empirical relationship used here provides only an average of the potential runout distances (Korup, 2005). Nevertheless, our calculations may provide an order of magnitude estimate of the hazard to the town (Davies & Scott, 1997; Korup, 2005).

The distance from the base of the rangefront hillslope behind Franz Josef to the edge of the town is approximately 400 m. Based on the scaling between landslide area and runout for the Southern Alps this requires a landslide with an area of approximately >0.03 km^2 to generate sufficient runout to reach the town. In the approximately 1 km^2 area of hillslope immediately east of the town (Figure 3.9) the annual probability of a landslide impacting the town is 0.003. This equates to a return period of ~300 years, which is probably an underestimate given that there is no evidence of landslide deposits on the c. 11-12,000 year old High terrace that buffers Franz Josef township from the range front hillslopes (Figure 3.9).

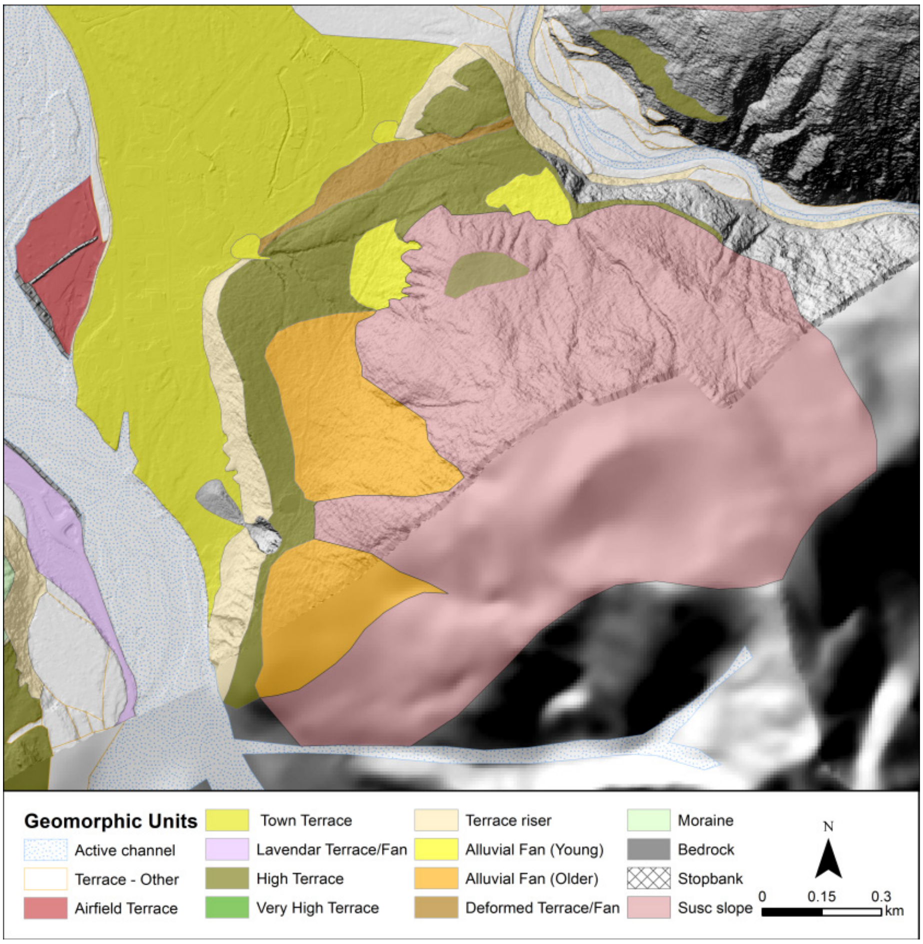

Figure 3.9 Geomorphic map of Franz Josef town. The map shows the area of range front hillslope (coral coloured) that is susceptible to non-seismic and co-seismic landsliding. The High terrace (olive green) buffers the town from landslide runouts off the slope. The absence of substantial landslide deposits on this c. 11,000 year old terrace may indicate that landslides with sufficient runout to reach the town are rare.

3.3.3 Seismic-Induced Landsliding

Strong ground motion produced by large earthquakes (M_w>7) has been observed in historic events to result in tens of thousands of landslides in mountainous regions (Hancox et al., 2002; Parker et al., 2011). The hazard associated with coseismic landsliding can exceed that posed by the activating earthquake shaking. The landsliding can trigger a cascade of geomorphic hazards that persists for decades following an earthquake and include increased frequency of post-earthquake landsliding, debris flow, fan and flood plain aggradation, and river avulsion. Rates of coseismic hazards and the cascade of geomorphic hazards that follow an earthquake are highest in the area of topography immediate above or adjacent to the ruptured fault (Hovius et al., 2011; Parker et al., 2011; Wang et al., 2015). A large earthquake on the Alpine Fault dominates the shaking hazard for Franz Josef, therefore, we focus the review on this scenario acknowledging that similar geomorphic impacts are also possible under the less likely scenario of a lower magnitude earthquake on an unknown regional fault.

Robinson et al. (2016) provided a first-order estimate of the co-seismic landslide susceptibility of Westland for an M_w8 Alpine Fault earthquake scenario. They used a GIS-based fuzzy logic approach (c.f. Kritikos et al., 2015) to estimate the susceptibility of hillslopes in the Southern Alps to co-seismic landsliding given expected shaking intensities for the Alpine Fault earthquake scenario. Modelled landslide likelihoods for the Franz Josef area are shown in Figure 3.10. The susceptibility map shows that areas of high coseismic landslide hazard include the rangefront hillslopes and catchments on the western flank of the Southern Alps, including the Waiho/Callery, Tartare and Potters creeks, and the Waiho loop and Lake Mapourika moraines. In the areas of most intense co-seismic landslide hazard, such as those mentioned above the rate of landsliding is estimated to be between 0.6 and 12.0 landslides per km^2 (Robinson et al., 2016). Consequently, it is highly likely that the rangefront hillslopes above the town and Tartare subdivision would experience landslides during the next Alpine Fault earthquake.

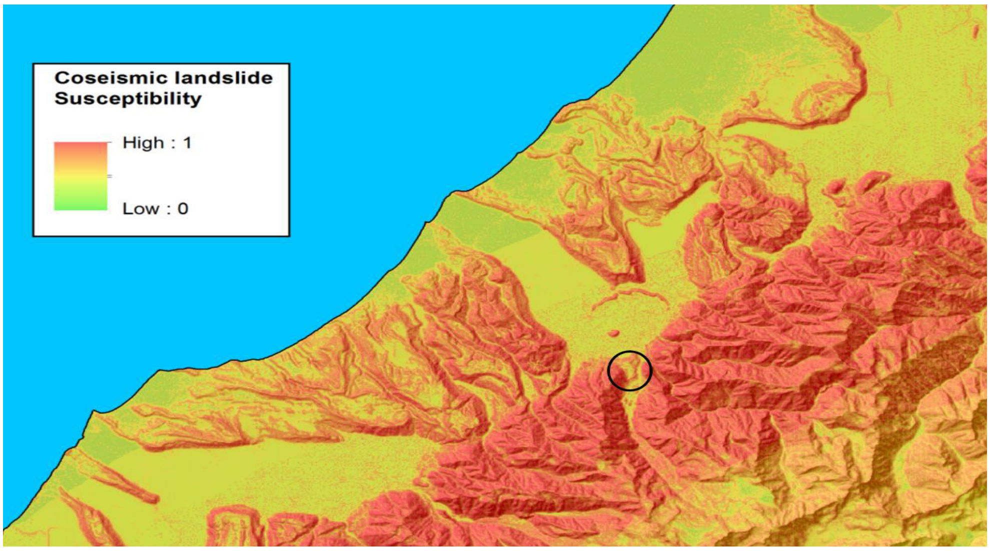

Figure 3.10 Co-seismic landslide susceptibility map for an M_w 8 Alpine Fault earthquake scenario Warm colours represent high susceptibility. Black circle is centred on the Waiho River gorge. From Robinson et al. (2016), based on England (2010).

The annual probability of co-seismic landslide occurrence can be determined using the conditional probability of M_w>7 rupture of the Alpine Fault assuming that this scenario dominates the seismic hazard as indicated in Section 3.1.3. The conditional probability for rupture of the Alpine Fault is c. 27% in 50 years (Biasi et al., 2015) but recent unpublished data suggests it may be as high as 50% in 50 years (Howarth et al., 2015). This equates to an annual probability of between 0.006 and 0.01. However, whether this hazard presents a significant risk to the town depends on whether the landslides could have sufficient runout to impact infrastructure in the town and surrounding areas. We have no site-specific information on the magnitude frequency distribution for coseismic landslides driven by an Alpine Fault earthquake it is difficult to estimate the probability that landslides could impact the built environment. The absence of significant landslide deposits on the 11,000 year old terrace bordering the township (Figure 3.10) provides some indication that landslides with sufficient runout to impact the town are rare or at least have not occurred at this specific locality in the past 11,000-12,000 years. We would expect that the deposits of these landslides should be visible in the 3 m LIDAR-derived digital elevation model of the terrace surface which has seen more than 30 Alpine fault earthquakes since the abandonment of the High terrace.

Given the direct relationship between the process of landsliding and the generation of alluvial fans it is likely that the remnants of landslide deposits underlie the more readily mappable alluvial fan deposits along the rangefront. Nevertheless, even if this were the case, the extent of such landslide deposits does not persist to the edge (or beyond) the High terrace above the town.

To summarise, the hazard associated with co-seismic landsliding in areas of steep topography such as the rangefront hillslopes to the east of Franz Josef, catchments on the western flank of the Southern Alps, and moraines is considerable. If Alpine Fault earthquakes dominate the seismic hazard as suggested by our analysis then the annual probability of such landsliding is between 0.006-0.01 and is probably accurate to an order of magnitude. Determining the risk to the Franz Josef township from coseismic landsliding will require a more detailed local study of landslide susceptibility similar to that conducted for the Port Hills following the Christchurch earthquake sequence (Massey et al., 2013).

3.3.4 Rock Avalanche

Tectonic damage of the rockmass in close proximity to active faults increases the potential for catastrophic, deep seated large rock avalanches (Korup, 2004; Brideau et al., 2009). There are several examples of prehistoric rock avalanches that have nucleated in the hanging wall of the Alpine Fault, the largest of these being the John O' Groats, Round Top and Cascade rock avalanches (Barth, 2013; Dufresne et al., 2009; Yetton et al., 1998). These rock avalanches were >10^6 m^3, had debris runouts >4 km and deposits that cover areas >5 km^2.

There are commonalities in precursor hillslope morphology and failure mechanisms of the Cascade and Round Top rock avalanches that have important implications for Franz Josef rock avalanche hazard. Barth (2013) highlighted the importance of asymmetric hillslope/valley morphology (where the elevation of the valley on one side of the ridge is lower than the other) and the development of asymmetric sachungen (ridgeline tension cracks) as precursors to catastrophic rock avalanches (Figure 3.12). By comparing the Cascade and Round Top rock avalanches Barth (2013) identified five key characteristics for identifying slopes susceptible to catastrophic failure. These include (1) the length of sackungen and degree of segmentation (as greater length and less segmentation imply a more continuous failure surface at depth), (2) the amount of throw on a sackung (as more throw may indicate a better developed and frictionally weaker failure surface), (3) presence of tectonically damaged bedrock at the base of the slope, (4) presence of bulging or over-steepened slopes below sackungen, and (5) degree of asymmetry of sackungen distributions.

The rangefront hillslope immediately to the east of Franz Josef meets most of these criteria and hence has the potential to fail in a catastrophic large rock avalanche (Barth, 2013; Davies, 2015). In the event of catastrophic failure, the potential for long runout and large surficial area of the debris could result in a considerable portion, if not the entire town, being overrun. Quantifying the risk associated with this scenario is complicated based on current data because it is not possible to determine the recurrence time of such events. Both the Round Top and Cascade rock avalanches are inferred to have been triggered by ground accelerations from Alpine Fault earthquakes (Barth, 2013; Dufresne et al., 2009), suggesting that a similar failure at Franz Josef may be more likely when the next great earthquake on the Alpine Fault occurs. The preservation of the 11,000 year old terrace at the base of the hillslope suggests that tens of Alpine Fault earthquakes have not caused catastrophic failure of the slope but does not preclude failure in the next earthquake. Further, historic large rock avalanches have also occurred spontaneously without notable triggers, for example the 1999 Mt Adams and 1991 Mt Cook rock avalanches (McSaveney, 2002; Hancox et al., 2005), demonstrating that these systems can gradually evolve towards failure.

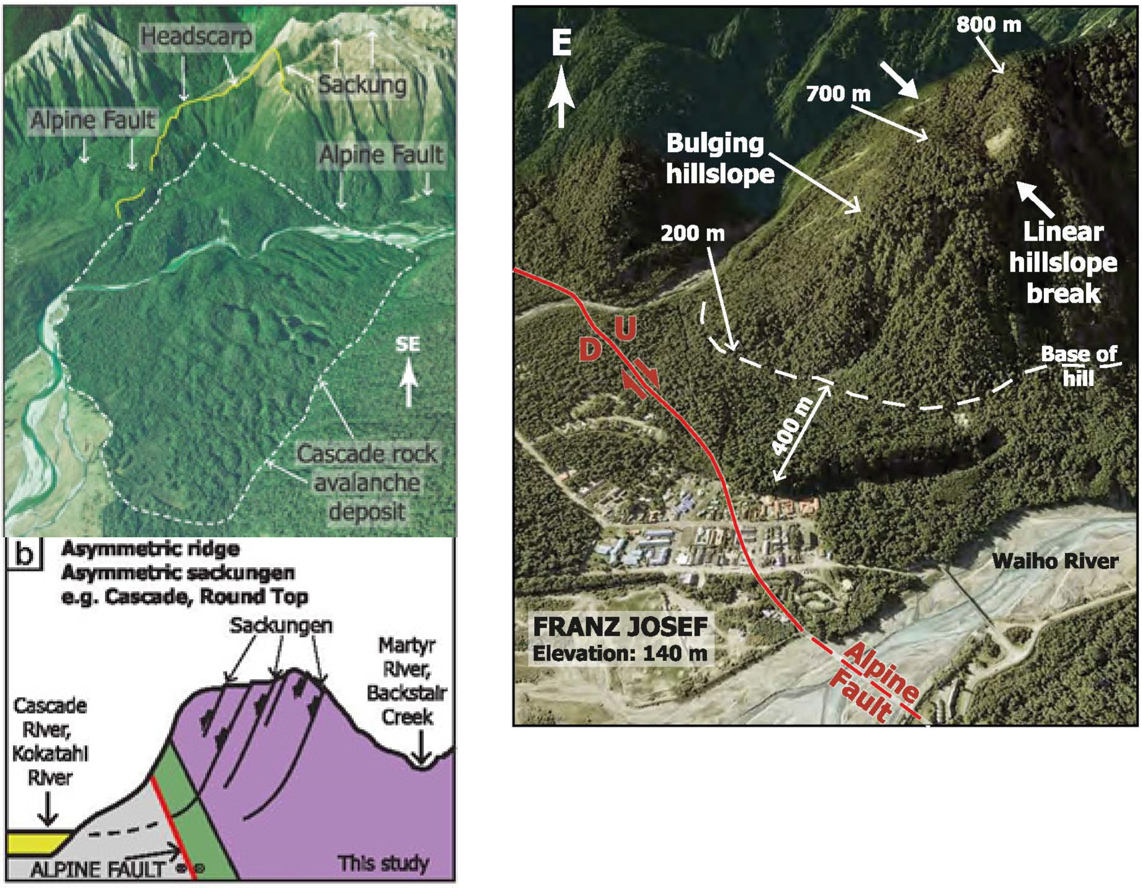

Figure 3.11 Large to giant landslides or rock avalanches along the Alpine Fault Zone (modified from Barth 2013).A. the Cascade rock avalanche northern Fiordland; B. the mechanism behind failure; and C. the potential hazard to Franz Josef from failure of the rockmass above the town).

Further work is required to better determine the probability of large rock avalanches occurring. Monitoring of the sackungen (tension cracks) at the top of the hillslope to determine whether they are actively slipping would provide some indication as to the stability of the hillslope. A PhD study is currently underway under the supervision of Prof. Davies at University of Canterbury aimed at assessing the stability of the slope.

3.3.5 Landslide Dams and Outburst Floods

A landslide dam can generate a series of geomorphic hazards that may reach significant distances up and down stream of the original dam site. The impacts include inundation from dam filling, a catastrophic outburst floods that usually occur within days to weeks of the dam forming (Costa & Schuster, 1988), and longer term effects on river dynamics, such as aggradation and avulsions caused by overloading from landslide derived sediments. A recent example of the hazard posed by a landslide dam leading to an outburst flood and aggradation is the 1999 Mt Adams landslide in the Poerua River valley (Hancox et al., 1999). A ~10^7 m^3 landslide formed a 100-m high dam in the Poerua River 5 km upstream from the range front of the Southern Alps. The dam impounded 5-7 x10^6 m^3 of water and failed rapidly a week later, producing a flood with a peak flow rate of about 3000 m^3s^{-1} at the range front (Davies, 2002). The flood overtopped the banks of the active channel in the upper 2-3 km of the valley depositing silt over much of the valley width and damaging native forest. Substantial aggradation of the fan followed the outburst flood.

A similar scenario to the Poerua River example is possible for the several catchments in the study area including the Callery River, Tartare River and Potters Creek. The magnitude and frequency of a landslide dam and outburst flood in the Callery River and the potential impacts on Franz Josef township are investigated by several studies (Davies, 2002; Davies & Scott, 1997; Korup, 2005; Ollett 2000). Ollett (2000) uses numerical modelling to identify five potential landslide scenarios capable of generating landslide dams in the Callery gorge and models the outburst flood hydrographs expected as a result of dam failure. The modelling is then used to estimate flood warning times for Franz Josef township. Warning times range from 1 to 14 hr if dam formation occurred during a 1 in 5 year flood flow, a likely possibility given the relationship between landsliding and extreme rainfall. The scenarios involving the shortest warning times were for landslides in the order of 1.0x10^6 m^3 and had peak flows of ~3000 m^3s^{-1}.

Davies (2002) used this landslide size, the spatio-temporal distribution of non-seismic landsliding in the Southern Alps, the 5-year flood exceedance probability and historical occurrence of landslide dams in the Callery River valley to estimate the annual probability of a landslide dam causing a damburst flood with little warning time as 0.01-0.02. Further, the annual dam break flood probability estimated for the Callery as a consequence of Alpine Fault rupture was estimated to be ~0.006 (Davies & Scott, 1997), so the total annual probability could be as high as 0.016-0.026 (40-60 year return period; Davies, 2002). During the 100 years of historical record one landslide damburst flood has been seen for the Callery River (Davies & Scott, 1997).

The similarities in peak flow, geomorphological and hydrological characteristics, and the generalised down-stream topography of the Poerua and Callery/Waiho catchments led Davies (2002) to argue the damage from a Callery damburst flood could be equivalent. A damburst flood originating in the Callery could significantly impact infrastructure down-stream as far as Canavan's Knob (Figure 2.3). Severely impacted infrastructure would include the S.H. 6 bridge and accommodation units in the vicinity of the bridge, while breaching of the stop bank and damage to the roads, heliport and lower part of the township would also be likely.

The annual probabilities of landslide damming and outburst flooding for the Tartare Stream and Potters Creek catchments have not been calculated. However, similarities in the morphology of these catchments with the Callery catchment would suggest that the annual probability could be similar to that estimated for the Callery River. A more in-depth study of the damburst flood hazard posed by the Tartare is advisable given the development occurring on the terraces immediately downstream of where the Tartare emerges from the rangefront.

To summarise, damburst floods from rapid failure of landslide dams in the Callery gorge have an annual probability of between 0.016 and 0.026, which equates to a return period of 40-60 years. The impacts from such an event could be significant. Further work is required to estimate the hazard and risk associated with damburst floods from the Tartare River.

3.4 MULTI-HAZARD SCENARIO – THE ALPINE FAULT EARTHQUAKE

The most recent rupture of the Alpine Fault occurred in about 1717 AD and ruptured the fault over a length of at least 290 km between Fiordland and Hokitika (Yetton & Wells, 2010; Howarth et al., 2014). The next rupture of the Alpine Fault (AlpineF2K source) is expected to be of an equivalent magnitude, i.e., M_w 8.1 ± 0.2 (De Pascale & Langridge, 2012). Current revisions of recurrence interval data from Fiordland (Hokuri Creek and John O'Groats) are set to reduce the average recurrence interval from 329 ± 68 years to closer to 300 years (Berryman et al., 2012b; Cochran et al., 2016). Furthermore, recurrence interval data from lakes proximal to the central section of the fault indicate average recurrence intervals of c. 270 years. Because the fault is therefore late in its seismic cycle, i.e., closer to the next rather than the last failure, then the conditional probability of failure (at least c. 27% in the next 50 years) is moderately high (Biasi et al., 2015).

In terms of natural hazards it is clear that though the frequency of smaller to medium-sized hazard events can be expected to occur through random or weather/climatic effects, larger events could well be linked with the occurrence of Alpine Fault earthquakes. Table 3.3 was developed using Eqn. 3 in order to compare the probabilities of water- or gravity-driven hazards that have assigned annual probabilities of exceedance, with the current probabilities of Alpine Fault rupture.

$$P = (1 - e^{-rt}) \quad \textbf{Eqn.3}$$

where P is the probability of exceedance, r is the rate term and t is the time interval of interest over which the rate is being assessed. This represents a Poissonian approach to the estimation of hazard.

Table 3.3 The probabilities (%) of exceedance for natural hazard events occurring over given time periods

Hazard event	10 yr	20 yr	50 yr	100 yr	300 yr	500 yr	2500 yr
10-yr flood*	**63**	86	99	99.9	-	-	-
20-yr flood	39	**63**	92	99	99.9	-	-
50-yr flood	18	33	**63**	86	99.9	-	-
100-yr flood	10	18	39	**63**	95	99	99.9
300-yr flood	3	6	15	28	**63**	80	99.9
Alpine Fault rupture	**5.4**	**11**	**27†**	**50**	**~99.9**	-	-

*flood can be replaced by landslide, debris flood etc. †Conditional probability value from Biasi et al. (2015). 100-yr flood and Alpine Fault probabilities are highlighted.

For example, Table 3.3 shows that any time-factored hazard event has a 63% probability of exceedance in the time over which it is considered. Put simply a 100-year flood has a 63% probability of exceedance in 100 years. Thus, the 100-year flood which is a benchmark for flood hazard levels has an approximately equivalent probability of exceedance/occurrence in the next 100 years, to an Alpine Fault rupture[3]. Similarly, the benchmark for seismic hazard is the 50 year interval, across which time the 100-yr flood and Alpine Fault event have a similar probability of exceedance/occurrence.

So, flooding (at the 100-yr level) and Alpine Fault rupture are roughly equally as likely to occur in the next 50-100 years, and an Alpine Fault rupture is more likely than the 300-yr flood level. Also, when the Alpine Fault rupture does occur, there is likely to be a hazard cascade that involves many of the natural hazards discussed above (Figure 3.12), including landslides, alluvial fan and terrace formation, and landslide dam failures and consequent flood events.

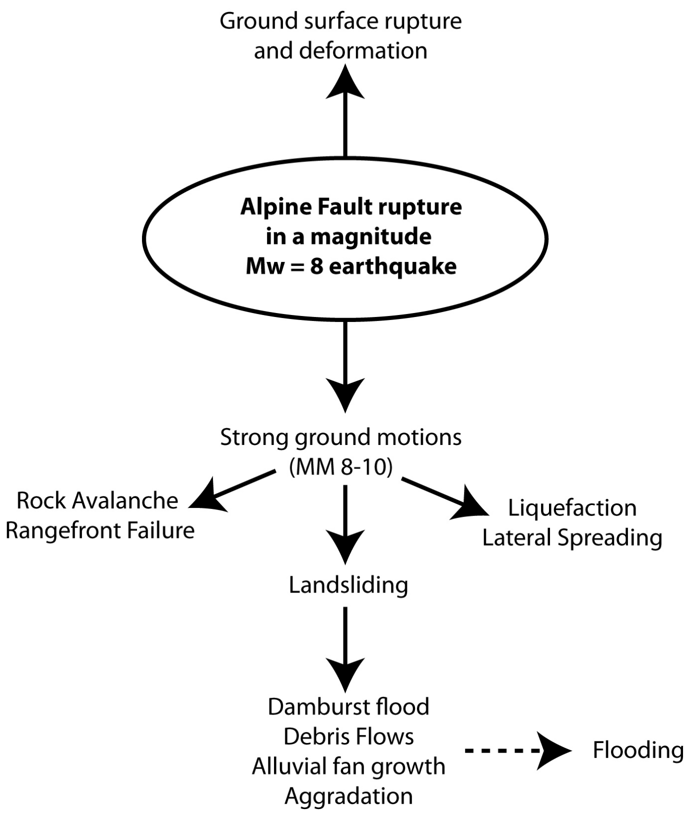

Figure 3.12 Flow chart for a multi-hazard event that follows rupture of the alpine Fault in a M_w 8 earthquake.

When the Alpine Fault ruptures the strong ground motions will generate landslides, including rock avalanches, and potentially liquefaction and lateral spreading. Rangefront collapse as discussed by Barth (2014) is a significant hazard, but we consider it has a low probability of occurrence immediately above Franz Josef due to the stability of the rangefront shown over at least the last 11,000 years, as evidenced by the presence of the High terrace. Landsliding will likely bring with it a raft of secondary hazards including damburst failure and breakout floods, debris flows, alluvial fan growth and aggradation (Davies and Scott, 1997; McSaveney and Davies, 1998). Avulsion of active channels as a product of the increase sediment loads and floodplain/fan aggradation (i.e., extreme flooding events) is a likely cascading result of the Alpine Fault ground motions. Evidence from lake sediment records

[3] The comparisons between flood probabilities and seismic conditional probabilities are not exactly the same, because Eqn 3 reflects a Poissonian process, while conditional probability is a time-dependent calculation.

proximal to the fault indicates that following past Alpine Fault earthquake shaking generated turbidites and that post-seismic sedimentation occurred in the lakes for several decades after as the system responded to the increased sediment load and moves back toward an equilibrium state (Howarth et al., 2012, 2014).

Such a multi-hazard cascade logically has a recurrence interval matched to the Alpine Fault (i.e., c. 300 years). Therefore, the effects of the Alpine Fault earthquake in this environment must be equivalent to the 300-year landslide event, debris flow or flooding event, for example. Thus while, the effects of a 100-yr flood have been modelled, the 300-yr flood, which may be caused by a damburst failure or debris flood following an Alpine Fault event are likely to be larger, and because of the likelihood of an Alpine Fault rupture, they are roughly as likely to occur as a 100-yr weather-related flood or other event.

Validation of this hypothesis would require extensive mapping and dating of Holocene deposits along the rangefront to understand the magnitude-frequency-age relations of landslides or runout deposits. It is reasonable to assume that the magnitude of secondary and tertiary natural hazards following an Alpine Fault earthquake event could be greater than anything observed within the historic period.

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4.0 ASSESSMENT OF NATURAL HAZARDS

We have approached the issue of the hazard profile to the town of Franz Josef by assessing the natural hazard literature, and through modelling and mapping of the geologic environments in the vicinity of the town. GIS-based mapping has led to an appreciation of the ages and locations of natural hazard 'deposits', e.g., alluvial fans, landslides. A major caveat of any hazard or risk assessment is that it would not be justified to unreasonably extend it beyond the limitations of the available scientific data. For this reason we have chosen to synthesise the hazards that the current town of Franz Josef is exposed to, and suggest a path forward for future efforts that may help to design a more resilient wider Franz Josef community.

The robust datasets that we have with which to base an assessment on are:

- Surface fault mapping using the LiDAR DEM, extending the coverage presented by Langridge and Beban (2011);
- Probabilistic and deterministic seismic ground motion predictions from the National Seismic Hazard model (Stirling et al., 2012);
- Flood behaviour for the area that was modelled by Land River Sea (2014) and perhaps beyond to consider the current path of floods between Franz Josef and the Waiho Loop;
- Detailed geologic mapping of river terraces, alluvial fans, landslides, and debris floods along the rangefront of the Alpine Fault/Southern Alps using the LiDAR DEM, and extending beyond that within c. 1 km. This analysis draws on a relative geomorphic age model which is limited by a lack of field work and geologic dating;
- The published literature regarding the extent and frequency of landslides, dam-break flood events and other water- and gravity-driven hazards.

In the next sections we assess the impacts of known natural hazards on the current Franz Josef town site. We chose the time intervals of 10, 50 and 100 years to reflect the frequency and potential impacts of various hazards, including the multi-hazard cascade (Section 3.4). These time periods reflect in each case, the timespan over which: (i) the town might look to re-locate, the council governance might change, or over which time storms such as the March 2016 can occur (10-yr); (ii) a large storm is possible, a house might be designed for under the Building Code, or over which time an Alpine Fault earthquake is now fairly likely (50-yr); and (iii) the time over which a very large storm, flood or Alpine Fault earthquake is very likely. These assessments are not applicable to other areas without a more detailed analysis.

4.1 DIRECT CO-SEISMIC HAZARDS

4.1.1 Surface Faulting and Deformation

Surface faulting from the next Alpine Fault rupture will occur in proximity to the mapped traces of the Alpine Fault and ground-surface deformation (faulting, folding) is likely to occur within the Fault Avoidance Zones (FAZ) as mapped by Langridge and Beban (2011). Revisions have been made to the fault mapping between the S.H. 6 bridge and the High terrace above the town that extend the scope of the FAZs to the south end of the current town location. That is, although fault traces cannot be seen across the active Waiho River, we expect that a wider zone of fault deformation is more consistent with that which has been mapped to the NE and SW of the town.

The probability of surface faulting during the next 10-, 50- and 100-years is based on the values from Table 3.3 and is as follows. Fault rupture and deformation within the distributed FAZs are both of low probability over the next 10 year period (c. 5.4%). For the 50-yr period the probability of fault rupture and deformation within the distributed FAZs within the next 50 year window is moderate (27%). For the 100-yr period the probability of fault rupture and deformation within the distributed FAZs within the next 100 year window is high (50%).

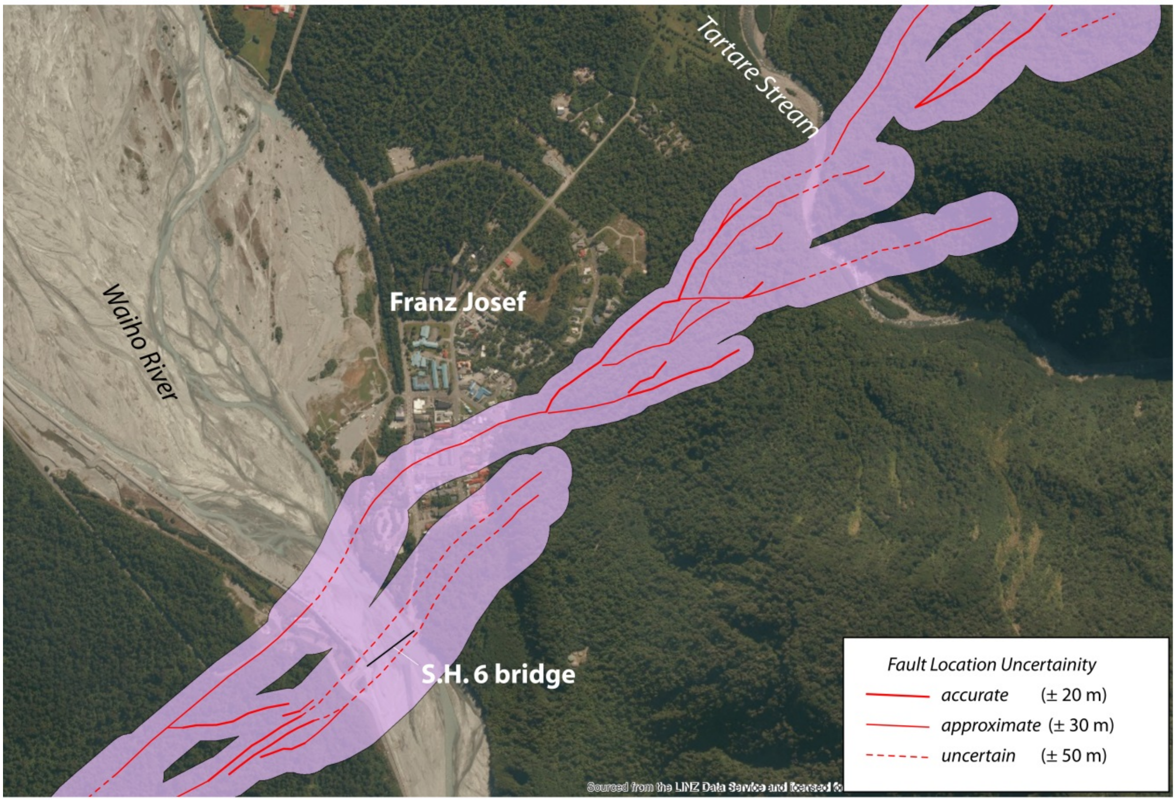

Figure 4.1 Updated Fault Avoidance Zones for the area between the S.H. 6 bridge (black line) and Tartare Stream and encompassing the town of Franz Josef. FAZs have been extended between the south end of town and the S.H. 6 bridge, acknowledging the possibility of distributed deformation through this area.

4.1.2 Strong Ground Motions

The frequency and strength of shaking that the wider Franz Josef township might be subject to is provided through the National Seismic Hazard Model (NSHM; Stirling et al., 2012) and through deterministic (source) approaches (see Section 3.1.3). Here we describe the potential peak ground accelerations (PGA's), as opposed to an MM Intensity (Figure 3.2). The PGA for the town and wider area at a probability of 10% in 2500 years are shown in Figure 4.2. This equates roughly to the shaking expected in a 250 yr window, which is similar to the return period for an Alpine Fault earthquake. The orange band represents a PGA value of >0.75 g and spans a width of c. 9 km centred about the trace of the Alpine Fault. The NSHM predicts PGA's of c. 0.85 g along the trace of the Alpine Fault in this event. Because the conditional probability of the next Alpine Fault earthquake occurring is moderately high (>27% for the next 50 years), then the coloured bands shown in Figure 4.2 are representative of the expected accelerations from an Alpine fault event in this time window.

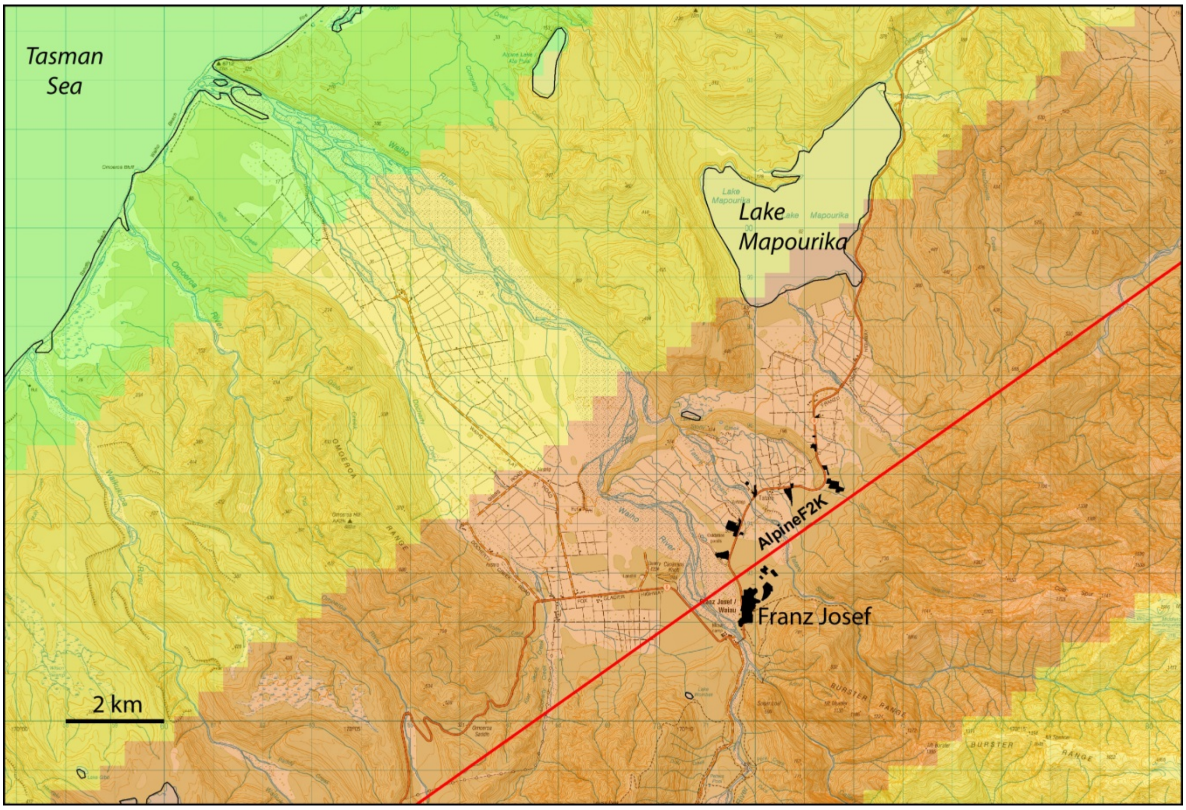

Figure 4.2 A gridded 10% in 2500 yr probabilistic shaking map for the wider Franz Josef area from the coast (top left) to near the main divide of the Southern Alps (bottom right). AlpineF2K is the central Alpine Fault seismic source within the NZ National Seismic Hazard Model. The coloured bands represent PGA's of >0.75 g (orange), 0.65-0.75 g (yellow) and 0.55-0.65 g (green). Black areas are built up or developed areas across the wider Franz Josef township.

The orange band highlights that peak ground acceleration will not differ greatly across the already-developed areas in and near Franz Josef township for the next 100 year time period. In essence, there would be very little difference in the expected ground shaking (PGA accelerations in Figure 4.2) if the town were in its current location or whether it was moved to a site within 5 km in any direction from its current location, i.e., it would still be within a zone of >0.75 g for an Alpine Fault earthquake expected to occur during the next century.

4.1.3 Liquefaction and Lateral Spreading

We have not undertaken a specific analysis of liquefaction or lateral spreading. Instead we have presented the properties that are required to induce liquefaction and lateral spreading and considered whether there are environments where these phenomena could occur. Figure 4.3 indicates potential 'example' sites of liquefaction or lateral spreading near the current town site. We recognise that non-seismic lateral spreading of river banks (effectively erosion) is possible due to migration or avulsion of the active channels of the Waiho River channel. Co-seismic failure and lateral spreading of river banks, terrace risers and flood protection stopbanks due to Alpine Fault shaking is also possible, in particular where the substrate beneath the stopbank is liquefiable. In Figure 4.3 we also indicate that the area where the new town has been developing, particularly in the area of the Kamahi Crescent-Paganini Road cul-de-sacs may be susceptible to liquefaction. There, the sedimentary environment is of lower energy than toward the Waiho River or Tartare Stream, so that finer sediments may be able to accumulate there. In addition, the landscape is very low (Figure 3.6) and indeed drainage ditches were installed to drain this subdivision. In addition, we note that fine and liquefied sediments have been exposed in paleoseismic trenches in proximity to the Alpine Fault at Haast and at Whataroa (Berryman et al., 2012a; Langridge unpublished data). However, it should be stressed that these observations only suggest that liquefaction is possible in this environment. The presence of conditions conducive to liquefaction would have to be tested.

As liquefaction is directly linked to earthquake shaking then the probabilities of liquefaction occurring over 10-, 50- or 100 years must be tied to the probabilities of ground motions over those times. Thus, even if the three conditions required for liquefaction are met (geologically young, fine-grained non-cohesive sediments existing under a high water table) then the probabilities of it occurring at 10, 50, or 100 years must be considered as low, moderate, and high, respectively.

4.2 WATER-DRIVEN HAZARDS

4.2.1 Waiho River Flooding

In the short to medium-term, flooding caused by the Waiho River remains the greatest individual hazard to the wider Franz Josef community, as evidenced by the March 2016 flood event that seriously impacted the Scenic Circle Hotel complex. Section 3.2.1 of this report described hydrologic analyses of 10-, 20-, 50- and 100-year flood scenarios for the town of Franz Josef.

The results of these models indicate that the town itself will be little impacted by floods of these (10-, 20-, 50-, and 100-yr) magnitudes. The two significant caveats to this statement are that: (i) the river bed remains in its current state, i.e., that the river bed does not aggrade toward a state where flood waters can overtop the south end of Franz Josef; and (ii) that the stopbank system is not compromised by erosion. Historical observation shows that the Waiho River bed has in fact aggraded substantially over the last century.

Figure 4.3 shows a composite topographic profile of the Waiho River (fan) floodplain between Lavender terrace/ lobe in the southwest and Tartare Stream. Ultimately, these profiles show that the Lavender terrace/ lobe generally falls away in elevation from the southern river stopbank towards Canavans Knob and Dochertys Creek. The Lavender terrace/ lobe is roughly at or lower in elevation compared to the Town terrace in Franz Josef.

As a possible way forward to mitigate against future flood impacts into the town, it has been suggested that the river could be managed toward flowing northwestward rather than to the north. The current stopbank system provides for southern and northern stopbanks of roughly similar height (c. 149 m a.s.l. near the town). However, the southern stopbank is considerably longer, extending almost to Canavans Knob (Figure 4.4). Conversely, the northern stopbanks provide much less protection to the lower part of Franz Josef beyond the end of the Airfield terrace area (helicopter port). One consequence of this stopbank design has been the diversion of some active channels of the Waiho River toward the northern bank beyond the Airfield terrace. Ultimately, this has probably in part been a contributor to the flooding of the Scenic Circles Hotel complex in March 2016 (Figure 4.4). Flood mitigation for the town of Franz Josef could be approached by strengthening and/or lengthening of the northern stopbank system combined with a relaxation of the southern stopbank system allowing for the river to flow and aggrade along the northern edge of the Lavender terrace/ lobe. Such a policy would require the removal of the current stopbank system, a shift in the S.H. 6 alignment and a re-building of the southern stopbank farther west of its current location. One consequence of relaxing the southern stopbank and allowing the river to migrate toward the northwest is the loss of forest and farm land and services (roads, landfill) near Canavans Knob and toward Waiho Flat. This also needs to be considered in terms of future land use.

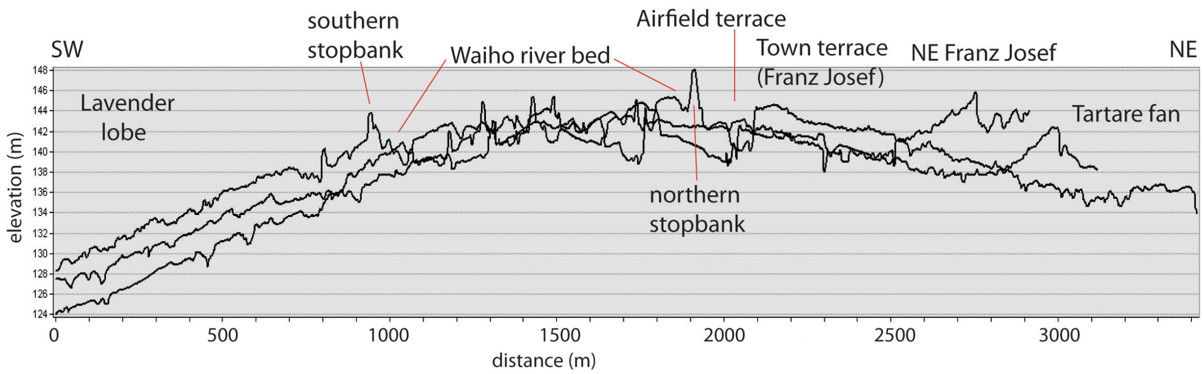

Figure 4.3 Combination of three digital LiDAR profiles drawn across (normal to) the Waiho River (fan) from SW to NE. The Waiho river channel is at centre, flanked by stopbanks. Franz Josef town is right of centre built on the Town terrace. The Lavender lobe south of the town is an area that could accommodate expansion of the Waiho fan.

4.2.2 Alluviation

Continued bed aggradation in the Waiho River will create lower freeboard for the S.H. 6 bridge and a lower freeboard for the town during a larger floods such as the 100-yr flood event (Figure 3.8). The Land River Sea (2014) report suggests that if the river were to aggrade by 4 m it would be possible for a 100-yr flood event to enter the town via the main highway and into the town (Figure 4.4), i.e., by overtopping the scarp of the Alpine Fault (which effectively forms a flood protection barrier on the south side of the town). Bed aggradation therefore has impacts for both the councils who manage the town and the New Zealand Transport Authority (NZTA) who manage the highway.

Relaxation of the southern stopbank and a migration of the river toward the northwest rather than to the north may alleviate the current trend of bed aggradation in the Waiho River and perhaps lead to incision and removal of part of the river-bed gravels adjacent to the town. Further research by hydrologists and hydraulic engineers needs to be undertaken on what benefits and impacts could arise from taking such action. Modelling of the future evolution of the floodplain is essential in the case that the stopbanks were to be re-located.

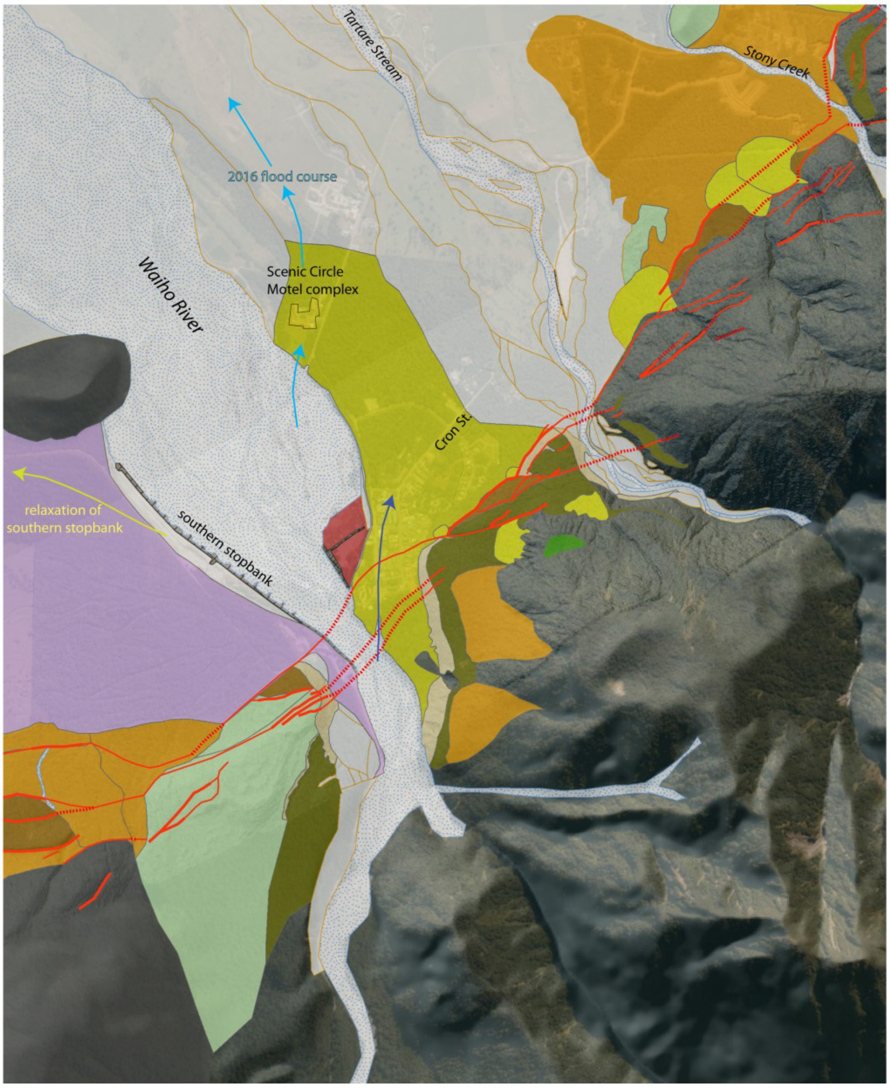

Figure 4.4 Considering the mitigation and impacts of flooding on Franz Josef. The course of flood waters in March 2016 are shown by light blue arrows. The river rose out of its bed near the transition from the Town terrace (fan lobe; yellow) and the lower gradient alluvial floodplain (as mapped here). Future 100-yr flood levels could overtop the broad scarp of the Alpine Fault (purple arrow) and enter the town. Alluviation and flooding may be alleviated by relaxing the stopbank system on the south side of the Waiho River (yellow arrow).

4.3 GRAVITY-DRIVEN HAZARDS

Landslides, rock avalanches and similar slope-failures are dangers to the wider township of Franz Josef and need to be taken into consideration for the future safety of the town of Franz Josef. Landslides can be divided into non-seismic and seismically-induced landslides.

4.3.1 Non-Seismic Landslide Hazard

Non-seismic landslides are those that are caused by weather-related or occasionally spontaneous collapse unrelated to an earthquake trigger. Large landslides can be generated along the rangefront of the Southern Alps or within the major catchments and these could have different effects, impacts and outcomes to the town and other occupied areas. Mapping along the rangefront above the town of Franz Josef suggest that no significant landslides (or their alluvial fans) have extended beyond the mapped High terrace (assigned an age of c. 11,000-12,000 years) and into the town. The town is effectively armoured by the presence of the High terrace. Small alluvial fans mapped at the rangefront extends only c. 60 m from it and have not impacted the town since the formation of the Town terrace during the last 2000-

3300 years. Based on these geomorphic observations, we conclude that the threat from small to medium-scale landsliding along the rangefront at the town of Franz Josef is low. Our geomorphic mapping, based on the size and extent of alluvial fans, indicates that the level of landsliding appears to be greater between the Tartare Stream and Stony Creek, and still greater between Stony and Potters Creeks.

Landslides also occur within the major catchment sides within the western part of the Southern Alps, southeast of Franz Josef. The impacts of landslides in these catchments (Waiho, Tartare, Stony, Potters) result in the delivery of sediment from each catchment (and flow) and potentially to the development of landslide dams within catchments. Small landslide dams are ultimately destined to fail and generate debris floods. The impacts of landslides and debris floods within each catchment will depend on the current state of valley fill or incision and the capacity for each catchment to accept and deliver sediment.

4.3.2 Earthquake-Induced Landslide Hazard

The scale, effects and impacts of seismically-induced landsliding must be similar though more extreme than weather-induced events. The latter may be catchment-specific while the seismically-induced landsliding can be widespread across many catchments and occur both along the rangefront and deep within catchment areas where ground motions are weakening slopes to the point of failure. In addition, the severity of seismically-induced landsliding during an Alpine Fault earthquake could be on a much greater scale.

The landslides that have been mapped in Barrell et al. (2011) are large enough that they may represent the scars or deposits related to past Alpine Fault events. A significant proportion of the damage or landscape change that is visible in the shape of catchment walls may be attributed to seismically-induced landsliding and in particular, Alpine Fault earthquakes, that occur with a frequency of c. 300 years.

Given that the Alpine fault currently has a conditional probability of > c. 27% in the next 50 years and therefore a similar likelihood to the 100-year flood (or landslide) event then it should be considered moderately likely that extensive catchment-wide landsliding is possible during the next 50 years. The effects of such landsliding are discussed in the previous section.

4.3.3 Rock Avalanche

Barth (2013) and Davies (2015) hypothesise the potential for rapid failure of a significant rock-mass from above the town of Franz Josef within the short (1-km long) section of rangefront adjacent to the town. We acknowledge that the failure of a large mass of rock and debris from there could be disastrous to the town with the possibility that debris (including the hillslope and the High terrace) could collapse toward and/or across the town site. However, our mapping shows that the High terrace has existed along this rangefront and within the fault zone of the Alpine Fault there for c. 11,000-12,000 years. Indeed, the mappable geomorphology of the fault zone (Barth et al., 2012; Langridge and Beban, 2012) exists there because the High Terrace has been deforming within the fault zone since it was abandoned, and has not been inundated or buried by other slope debris from above. We assert that while collapse of the hillslope and rangefront is possible, that it is unlikely, because it has not happened through the previous 30 or so Alpine Fault ruptures since the formation of the High terrace along the Franz Josef rangefront (i.e., a rupture event every 300 years for more than 10,000 years). Although it is likely to occur in an Alpine Fault earthquake, it is no more likely than in any of the next 30 or so earthquakes. Nevertheless, the foreseeable extremely disastrous event could be avoided by relocating the town.

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5.0 SUMMARY

Franz Josef is sited at the foot of the rangefront of the Southern Alps, straddling the Alpine Fault and immediately adjacent to the Waiho River. The wider township area is at risk from a number of natural hazard perils including flood, fault rupture, seismic ground shaking, landslide, damburst flood, river avulsion, alluvial fan inundation, liquefaction and lateral spreading. Other hazards that have not been considered are wind, snow, fire and debris flows. The effects of climate change, sea-level rise or tsunami inundation have also not been considered as part of this study.

For various hazards we have used literature review of published modelling and analysis to understand the magnitude, frequency and aerial extent of each hazard. We have also used geomorphological mapping in order to assist in defining the age, extent and frequency of individual natural hazards, which we divide into seismic-, water-, and gravity-driven processes.

The zone of distributed faulting and deformation along the Alpine Fault has been reviewed to construct revised Fault Avoidance Zones (FAZs). Between the south end of the town of Franz Josef, and the S.H. 6 bridge, a wider zone of distributed faulting has been considered and a FAZ has been applied to potential fault traces mapped in this area. The previously documented FAZ through the town of Franz Josef is unchanged. According to the MfE Guidelines related to active faulting, active ground surface rupture and deformation are hazards that can be avoided. Future town planning should include consideration of retreat from the Alpine Fault FAZ through Franz Josef and avoidance of other areas that are within the wider FAZ.

The levels of seismic ground motion have been considered based on the National Seismic Hazard Model (NSHM). The biggest and most frequent seismic shaking threat comes from rupture of the central Alpine Fault segment. This source can generate an earthquake of magnitude c. M_w 8.1 every 300 years or so. The most recent Alpine Fault rupture occurred in about 1717 AD. The Modified Mercalli shaking intensities from smaller or less frequent large earthquakes are also modelled. While ground motions will be high to very high during an Alpine Fault earthquake (PGA of >0.75 g; MMI 8-9) buildings within the town should be designed to a specification that is consistent with the New Zealand Building Code (for this location). Potential sites where liquefaction or lateral spreading could be triggered by Alpine Fault shaking are suggested, however, liquefaction and lateral spreading are not expected to be the major issue that was observed during the Canterbury earthquake sequence of 2010-2012.

A map at 1:100,000 scale was used to interpret geological processes active in the area. Geomorphic mapping at 1:10,000 scale using a LiDAR DEM was used to define the extent of alluvial fans, river terraces, landslide catchments and other landforms. A geomorphic age model of terrace and fan surfaces has been developed using the LiDAR DEM, based on geomorphic relationships and available age determinations. The relative vertical deformation across faulted surfaces was also used to estimate the age of terrace and fan surfaces. A prominent ‘High’ terrace (preserved only on the upthrown side of the Alpine Fault and within its fault zone) is assigned an age of 11-12,000 years based on regional correlation to the Waiho Loop and the Whataroa River terraces. The ‘Town’ terrace directly below and above the High terrace in Franz Josef is assigned an age of 2000-3300 years, based on its elevations relative to the High terrace. These ages provide a basis for understanding the rate of geomorphic process in the landscape.

Modelling of flood hazard for the 10-, 20-, 50-, and 100-yr periods for the Waiho River was supplied by Land River Sea (LRS) Ltd. for an area within about 1 km of Franz Josef. With the current flood-protection scheme in place and assuming no further aggradation of the river bed, none of these four flood states is predicted to significantly impact the current town site. However, aggradation of the Waiho River bed has averaged c. 0.2 m per year since about 1940, so modelling assuming 4 metres of bed aggradation (20 years at current rates) was also modelled by LRS. The net result of continued aggradation (4 m) is that the 100-yr flood could flood the town from the direction of the S.H. 6 bridge and highway. Topographic profiling indicates that the bed of the Waiho River that is presently confined by stopbanks is higher in elevation than both the town and northeast extension of the town toward Tartare Stream.

Rangefront alluvial fans can be classified as: (i) smaller, younger fans that post-date 1717 AD and/or have built out during the last few Alpine Fault cycles, and (ii) larger, older fans that are now abandoned and are probably relict features in such an active landscape. At Franz Josef, the smaller fans are insignificant, while the older fans that emanate from the rangefront do not extend beyond the broad High terrace into the town. Along the pieces of the rangefront from Tartare Stream to Stony and Potters Creeks the size and extent of the smaller and larger alluvial fans increases to the NE, compared to near Franz Josef town. This means that the hazard from landsliding and fan activity is likely to be greater to the northeast of Franz Josef along the rangefront.

The size and extent of alluvial fans provides a measure of their source areas, i.e., the alluvium is derived from landsliding in the rangefront above the fans. Rangefront landsliding is believed to be less of a threat in the southwest (at Franz Josef) compared to from the rangefront northeast of Franz Josef. Debris floods could emanate from the Waiho River valley, but especially from the secondary level catchments (Callery, Tartare, Stony, Potters). In addition, despite the capacity of schist to quite easily fragment into smaller pieces, bouldery debris flows could emanate from rangefront slopes and threaten the town.

The landslide hazard in the area derives mostly from the Southern Alps but there are localised areas west of the rangefront where landslides are an issue – notably the steep eroded margins of glacial moraines. The hazard associated with both non-seismically and co-seismic triggered landsliding is highest on the range front hillslopes to the east of Franz Josef, within catchments on the western flank of the Southern Alps, and on glacial moraines. To directly impact Franz Josef landslides must have sufficient runout to cross the High terrace. There is no evidence for landslides deposits on the outer edge of this terrace suggesting that both non- and co-seismic landslides rarely have sufficient runout to impact the town. The morphology of the rangefront hillslope to the southeast of Franz Josef suggests that it could be susceptible to catastrophic failure as a rock avalanche during strong shaking.

Landslide-dam outburst floods are a significant potential hazard that has received considerable attention, albeit without much observed information on which to base the modelling. Historically, the Callery River has been the source of an outburst flood that impacted on the Waiho River. Damburst floods from rapid failure of landslide dams in the Callery River valley have an annual probability of between 0.016 and 0.026 (return period of 40 and 60 years). The potential impacts from an event could include damage to the S.H. 6 bridge and accommodation units in the vicinity of the bridge and the possibility of it entering the town if the bed is sufficiently filled in. If the northern stopbank was breached, the roads, heliport and lower part of the township would also be impacted. The Tartare and Potters Creek catchments also have potential to produce outburst floods. Further work is required to determine the hazard posed by floods originating from these catchments.

Major failure of the rangefront hillslope above the town of Franz Josef is recognised as a hazard. However, this potentially disastrous event for the town is considered to be unlikely due to the fact that the hillslope has not collapsed during at least the last 11,000 years or so. An earthquake trigger, most probably on the Alpine Fault, means that the scenario of rangefront collapse adjacent to Franz Josef is a component of a very serious compound hazard event.

These described hazards above mostly represent individual perils that could impact at any given time at a given scale (e.g., a 10-yr flood has a 63% chance of occurring in 10 years). What also needs to be considered for Franz Josef is a multi-hazard cascade that is likely to follow a M_w 8 Alpine Fault earthquake. In addition to fault rupture, MMI seismic shaking of intensity VIII-X would initiate landslides, possibly including a major failure from the rangefront, driving debris flows, floods, river aggradation and alluvial fan growth. The increased debris delivered to rivers and streams will have major impacts on the wider township. This may be most severe for the Waiho River (and the town), possibly raising the bed level enough that subsequent floods could enter the town.

To place each hazard in context, we compare flood versus seismic versus landslide hazard considering the probability of events of a given size (or impact) over three time windows (10-, 50-, and 100-years) that correspond to measureable political, planning and likely hazard return periods. For example, the conditional probability of the next Alpine Fault rupture is c. 27% in the next 50 years. In comparison, the probability of the 100-yr flood being exceeded in the next 50 years is 39%. Thus, the Alpine Fault event and a century-scale flood have roughly the same likelihood of occurrence (c. 0.01 per year). If these events are coupled or we consider the multi-event cascade scenario then the impacts go beyond a single peril scenario.

Figure 5.1 summarises the major natural hazards to the town of Franz Josef, including the 100-year flood of the Waiho River, rupture of the Alpine Fault, and the combined hazard of rupture of the Alpine Fault and its ‘downstream’ multi-hazard cascade. The figure outlines the hazards, their possible impacts and suggested mitigation against the hazard and its impacts. In a short-term outlook flooding from the Waiho River can be considered as the most likely serious hazard, although it is obvious that the magnitude M_w 8 Alpine Fault rupture event must eventually replace it at some time in the next 50 years, i.e., the Alpine Fault event will eclipse Waiho River flooding in seriousness of its likely consequences to the town.

Within the scope of this project we have been limited to a crudely quantitative assessment of the hazards to the current town of Franz Josef with scant consideration of other potential sites in the wider township area (between Dochertys and Potters creeks, the rangefront and the coast). The biggest threats to the town of Franz Josef and its broader community are from flooding from the Waiho River and from Alpine Fault movement and associated shaking, with its consequent multi-hazard cascade scenario. Non-seismic, weather-driven events appear to have a lower probability of impacting the town so long as the Waiho River remains within its confined course.

The resilience of the town to natural hazards depends to a large extent on managing the Waiho River and its sediment load and addressing likely impacts of Alpine Fault rupture. Based on this review, some hazards appear to be limited in their extent and possible severity (e.g., rangefront alluvial fan building, debris flood and landslide) while others will

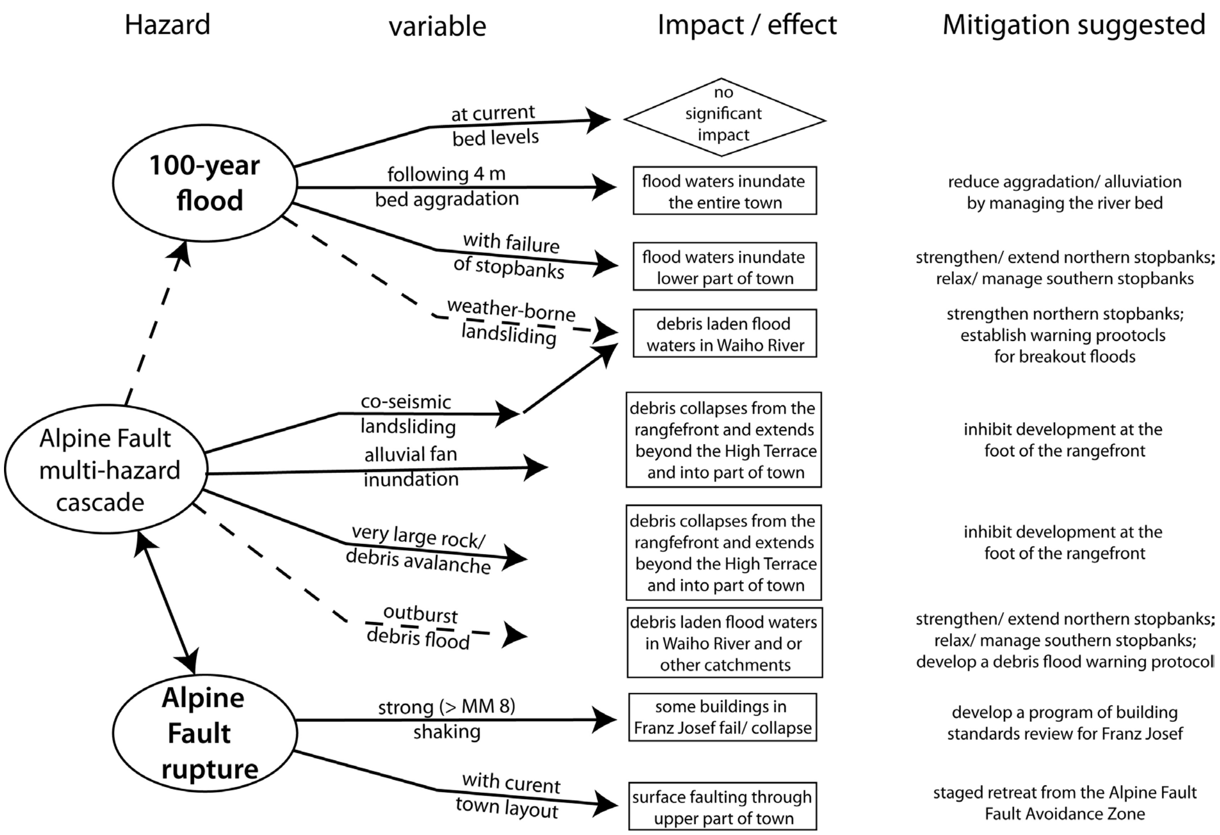

Figure 5.1 A flow chart considering the natural hazards, possible impacts and potential mitigation scheme with respect to the major natural hazard perils at Franz Josef.

directly impact the town (fault rupture, ground shaking) and others have a high probability of occurring as a secondary consequence of earthquake shaking (e.g., landslides in the Callery gorge that lead to damburst floods or debris flows), and tertiary impacts such as flooding and debris floods from an aggraded Waiho riverbed. Strong ground motions may also impact on the stopbank system, through lateral spreading, which would exacerbate secondary and tertiary Alpine Fault effects.

Comparative natural hazard risks at possible alternative town sites could be undertaken on a similar but more uncertain basis because most of the quantitative information exists only for the current town location. There would need to be a high level of confidence that a future town site would be in a significantly less risky location than the current town site to warrant consideration. It is clear that the majority of the hazards pose higher risk in closer proximity to the rangefront and the fault line, and that the risk generally diminishes with distance from there. Surface faulting and proximal rangefront processes can be avoided by moving out from the rangefront, but depending on the ability to control the course and bed level of the Waiho River and to a lesser extent other rivers and streams there can be a flood risk and sediment deposition a considerable distance westward of the rangefront. Catchments with flattish floodplain surfaces such as Potters Creek (which is a fan surface) could be wholly re-activated following an Alpine Fault earthquake. A safe town site suggested in a draft report by Davies (2015) in the Lake Wombat area is in part straddling the distributed fault zone of the Alpine Fault as shown by FAZs and within Westland National Park. Land ownership (DoC vs. private) and future service access realistically could also place constraints on future development.

6.0 DISCUSSION AND RECOMMENDATIONS

The community of Franz Josef in consultation with the West Coast Regional Council and Westland District Council need to manage or mitigate the serious natural hazards that are likely to occur in the area of the town of Franz Josef in the coming years to decades. Such action will provide the community with more certainty regarding future life safety, property, infrastructure and investment. The three most significant natural hazard events that we have highlighted are: flooding from the Waiho River, rupture of the Alpine Fault (fault movement plus shaking), and the combined landscape consequences (multi-hazard cascade) posed by an Alpine Fault earthquake event.

As was seen in the March 2016 flood, the Waiho River is an ever present threat to the town. The flood threat needs to be mitigated through management of the river. Because of the now relatively low elevation of the town relative to the river bed, it is imperative that flood-protection measures (e.g., stopbanks), on the north bank of the Waiho River are maintained. If the town is exposed to floods and debris through failure of the stopbank system, then the implications are similar to those observed for the Scenic Circle Hotel in March 2016. Large alluvial fans (like the Waiho River in a broader sense) will tend to avulse (shift their course) and fill in lower-lying areas. For example, the area of the current and developing new town centre location on Cron Street. To mitigate the possibility of bed aggradation resulting in serious flooding, it might be useful for the community to consider a relaxation of the river's confinement on the south bank of the Waiho River. Such an activity would need to be carefully managed and consider the location of State Highway 6, relative to relaxation of the stopbank system.

A strategy needs to be developed for retreat from the Fault Avoidance Zone areas, related to the Alpine Fault, in and around the town of Franz Josef. Due to the moderate to high probability of a large to great earthquake occurring on the Alpine Fault in the next 50-100 years, we recommend that the town centre move toward the northeast toward (along) the extension of Cron Street, away from the Alpine Fault FAZ. Our analysis of seismic shaking indicates that there would be no significant change in peak ground acceleration (pga) related to such a small move in the town's location. In order for the town to significantly reduce the ground shaking intensity related to an Alpine Fault event, it would need to be re-located to at least 5-10 km northwest of the Alpine Fault.

The multi-hazard cascade initiated by shaking in the next Alpine Fault earthquake event has a likelihood of occurrence of >27% in the next 50 years. The councils and town should plan to make the town more resilient to the above-described individual and combined perils in the coming years firstly through mitigation but also through planning civil defence actions designed to cope with the major disaster that could impact up to thousands of tourists in the peak tourist season. Several other individual hazard perils (non-seismic driven landslides, alluvial-fan aggradation, debris flood) have been discussed in this report. Each in its own right is manageable if the location, extent, magnitude and severity of the hazard is understood and mitigated.

Because fault rupture can be avoided by a relatively small amount of town re-planning, flooding can be mitigated via flood-protection activities, but MM Intensities of >VIII cannot easily be avoided, we recommend that the council undertakes a Cost-Benefit Analysis in consideration of re-locating the town of Franz Josef versus mitigating against hazards and planning for serious natural hazard events.

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