AF8
ALPINE FAULT MAGNITUDE 8

Alpine Fault Magnitude 8 Hazard Scenario

Report prepared for the AF8 Steering Group

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October 2016

AF8 [Alpine Fault magnitude 8]

AF8 is an award-winning programme of scientific modelling, coordinated response planning and community engagement designed to build collective resilience to the next Alpine Fault earthquake, across the South Island.

It is a collaboration between science and the six South Island Civil Defence Emergency Management (CDEM) groups. It commenced in July 2016, and is led by Emergency Management Southland on behalf of the six South Island CDEM groups.

AF8 aims to share the Alpine Fault hazard and impact science and preparedness information widely, through communication and engagement activities, to increase awareness, enable conversation and build societal preparedness to natural hazard events in the South Island.

The Alpine Fault Hazard Scenario

The Alpine Fault Hazard Scenario outlined in this document is a key output of the programme's first year, 2016-17. In its first two years, the programme was known as 'Project AF8'. In year three, the name changed to AF8 [Alpine Fault magnitude 8] to reflect the transition from a response planning project to a wider programme of scientific modelling, coordinated response planning and community engagement. The Hazard Scenario (also known as the AF8 Scenario) remains central to this work, where science provides a robust foundation for response and recovery planning, risk communication and engagement.

AF8 would like to thank all the contributors listed for lending their expert knowledge and time in the development of this report and for their ongoing support of the AF8 programme.

This report was funding by the Ministry of Civil Defence Emergency Management Resilience Fund 2016-17.

For more information about AF8 visit: www.af8.org.nz @ALPINEFAULT8

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Executive Summary

AF8 is a Civil Defence Emergency Management (CDEM)-led response planning initiative for a future Alpine Fault earthquake in the South Island. This report presents a maximum credible event hazard scenario for a future Alpine Fault earthquake, informed by expertise from researchers representing six Universities, two Crown Research Institutes and two consulting firms. An initial Alpine Fault Scenario workshop was held in Christchurch (August 23-24th 2016) to bring together Alpine Fault researchers for the purpose of developing the scenario. The AF8 Steering Group is grateful for the generosity of the scientists who volunteered their time before, during and after the workshop to bring the project to this point in its development.

The Alpine Fault scenario presented here details the earthquake source and geomorphic components of the work, which we term a 'hazard scenario'. This describes a M_w 8.2 Alpine Fault event with a rupture length of more than 400 km, and c. 9m of dextral-reverse surface displacement. This event has been assessed to have a recurrence interval of c. 300 years. The last known major rupture of the Alpine Fault was in 1717. A range of co-seismic and cascading geomorphic hazards of the mainshock will lead to a wide and complex range of landscape responses spread across a large area and over a range of timescales.

The outputs of the hazard scenario will inform consideration of the impacts and consequences of a future Alpine Fault earthquake on the built and social environments. This next phase of work on societal consequences will be added to the scenario document once it is completed.

It is anticipated that this scenario report will stimulate discussion amongst scientists and practitioner communities, and as a 'living document' will continue to be developed as new information becomes available.

October 2016

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Introduction

Background

With the introduction of the Civil Defence Emergency Management (CDEM) Act in 2002, New Zealand adopted a risk management-based approach to disaster risk and emergency management. The generic 'all hazards' approach used by local, regional and local CDEM planning since 2002 has been useful in moving planning from smaller-scale emergencies to larger-scale and more complex disasters and their consequences.

Limitations of the all hazards approach became apparent as the enormity and complexity of the community, environmental, infrastructure and cultural needs were realised during the Canterbury earthquake sequence. The February 22nd 2011 earthquake resulted in 183 fatalities, over 7,000 injuries, displacement of tens of thousands of people, substantial economic impact, and infrastructure and residential damage at cost of approximately NZ$40 billion. The community and multi-agency response to the Christchurch earthquake was the largest in New Zealand's history, as well as New Zealand's first declared state of national emergency. It was the first time a National CDEM Controller was required to coordinate all response activities, staged from an ad-hoc Christchurch Response Centre. The subsequent review of the Civil Defence Response to the Christchurch earthquake found it was not as effective as it could have been, due in part to a lack of regional and local planning for an emergency of that scale.

A more focused approach to planning and resourcing for specific large-scale hazards was identified as a priority prior to the Canterbury earthquakes, exemplified in the 2010 Wellington Earthquake National Initial Response Plan (WENIRP). The WENIRP is a national-level plan, focused on a major Wellington Fault or other regional earthquake event in the Wellington region, intended to provide form and function to the initial few days of response.

The need for a scientific risk-informed, maximum credible scenario as the basis for CDEM planning and response in the South Island was proven in 2012 to 2013. At that time the six South Island CDEM groups worked with Canterbury University Hazard and Disaster Management programme staff and students to develop and deliver a South Island-wide Alpine Fault earthquake response exercise, Exercise "Te Ripahapa", in mid-2013.

The Alpine Fault is the active boundary between the Pacific and Australian tectonic plates. It runs for about 600 km along the west of the South Island's Southern Alps, and is thought to sustain a major rupture several times per millennium. As the largest known seismic hazard in South Island it has received considerable scientific attention recently, and because its effects will be felt island-wide it has been chosen by the South Island CDEM Groups as a suitable hazard source for planning and exercise purposes. It is expected that a large earthquake in the Southern Alps will lead to a "cascade" of hazards including aftershocks, landslides, landslide tsunami, landslide dams, landslide dambreak outburst floods, debris flows, river aggradation, river avulsion and exacerbated river flooding.

Since 2002 each CDEM Group has worked largely in isolation preparing plans and commissioning scientific work on a relatively ad-hoc basis. The scale of a future Alpine Fault event will necessitate a nationally coordinated response. The coordination required to respond to the relatively localized, smaller scale outcomes of the Canterbury earthquakes will be significantly different to the South Island-wide impacts and outcomes of an Alpine Fault event. One of the biggest challenges will be the need for coordination across all six South Island CDEM Groups, and with MCDEM in Wellington.

The success of Exercise Te Ripahapa and the seismic, geomorphological, infrastructure, and community impact data that underpinned it, led the South Island CDEM groups to initiate a scenario-based project to develop a comprehensive plan for the response to a future magnitude 8 Alpine Fault earthquake. MCDEM Resilience Funding was sought ($245,000 for year 1) and approved in June 2016. This project became known as "Project AF8" ("**A**lpine **F**ault magnitude **8**"). The MCDEM funding supports the development of a collective plan for a South Island-led multi-agency response to a future Alpine Fault earthquake. It brings emergency management planning and science together to identify the full consequences of a large Alpine Fault earthquake and to develop coordinated initial response actions for all CDEM groups, their member local authorities, partner agencies, businesses and communities.

The outcomes of Project AF8 will include:

- Improved understanding of the likely consequences of a large Alpine Fault earthquake across the South Island;
- Identification of initial response actions, interdependencies between CDEM Groups, partner agencies, and communities, and priorities for response;
- Identification of opportunities for improving emergency management arrangements at both the CDEM group and national levels;
- Planning for community resilience in areas likely to be heavily impacted.

Project AF8 Scope

Project AF8 focuses on two work streams:

1. RISK:

Hazard understanding, consequences modelling and risk communications

- Creating an inventory of existing research and knowledge of the hazard and associated risks, including likely cascading hazards and risks e.g. liquefaction and landslides.
- Developing scenario models in order to assess the likely consequences from maximum credible fault rupture events, in order to determine consequences and associated risks.
- The scenario will be divided into: Earthquake source; Geomorphic Hazards, and Impacts.
- Identifying and prioritising needs for response actions across all South Island CDEM groups for the first seven days after onset of an Alpine Fault earthquake and aftershock sequence.
- Identifying potential constraints, conditions and limits that the consequences of fault rupture and cascading hazards and risks (by type and scale) may pose for formulating and carrying out response priorities and actions.

2. RESPONSE:

Planning, control, direction, coordination, tasks, resources, communication, risks

- Overview assessment of existing capacity and capability within regions to respond, identifying key gaps, issues, overlaps and assumptions.
- Identifying and prioritising pre-planning for coordinated and integrated arrangements across regions and the national level.
- Gaining understanding and commitments required for an initial response plan, enabling ongoing development, implementation and maintenance.
- Carrying out phase-one implementation of the arrangements, either as further described in this plan, or agreed to as part of the project process – including planning for a South Island-wide exercise, public communications, and resource registers.
- Providing a basis for long-term, multi-stakeholder coordination of research, policy and operational arrangements to manage the risks from Alpine Fault rupture across the 4Rs.
- Establishing a common picture of strategic priorities for ongoing and/or new research on the hazard, that aligns with CDEM planning and operational needs, to inform research and development programmes at the national, regional and local levels.

Limitations and "Out-of Scope" Considerations

The Project has some limitations due to time, resourcing and required deliverables. Therefore, the following will not be included in the scope of this Project:

Extended Research

- Undertaking new or extended research into the Alpine Fault or cascading hazards*. Any such research needs to be included in university, Crown Research Institute, Ministry of Business, Innovation and Employment, South Island CDEM groups or partner agencies, or other commissioning and funding processes.

New Modelling Capabilities

- Development of core modelling capabilities (e.g. RiskScape) that are ordinarily funded through other means.

Detailed Vulnerability or Consequence Assessment

- Detailed assessments of vulnerabilities and consequences of localities, or that relate to a specific organisation's needs that are not required for 'overview' modelling. This level of assessment remains the responsibility of relevant councils or organisations to undertake/commission from research providers (e.g. a lifeline utility company's specific risk assessment).

Detailed Remedial Recommendations

- Detailed reviewing and development of recommendations for remedial actions for further capability needs within specific organisations at the local, regional or national levels (though recognising that this is a potential outcome from the project that participating organisations may individually undertake or advocate).

Entirely Novel Response Arrangements

- Formalised and fully integrated response management and action planning to follow after an initial response to an event. This response management is based on pre-existing national and CDEM Groups' generic arrangements, that will be tailored to the actual consequences, needs and capabilities in play at that time.

Risk Reduction and Disaster Recovery Actions and Capabilities

- While the project is to fit within a 4Rs approach to managing this risk, reduction and recovery policy, planning and programmes are not within scope.

* 'Cascading hazards' refers to geomorphic hazards that take place immediately after and as a direct consequence of the mainshock, brought about by a range of climatic and landscape processes. E.g. heavy rainfall resulting in landslide dam formation, or landslide dam break occurring after a large aftershock.

Milestones and deliverables

Year 1

Year 1 of the project focuses mainly on reviewing current work, exercising current plans and knowledge, identifying gaps and opportunities in planning, and agreeing on key principles and content for the Project.

The following will be achieved in Year 1:

- Inventory report of current Alpine Fault hazard and risk research.
- Development of flexible scenarios that offer some 'if not this, then this' options. For example, a Milford Sound landslide-induced tsunami from the Alpine Fault main shock versus a heightened risk of such an event from an aftershock will, in turn, lead to different response issues to consider.
- A set of scenario models for an Alpine Fault rupture that covers, 1) north-to-south and south-to-north rupture scenarios*, and 2) an aftershock sequence and cascading hazards and risks likely to be encountered in the first week of an event that could influence emergency response management (longer-term consequences that may affect recovery, for example significant accummulation of gravels and other outwash material from rivers, are out of scope).
- AF8 website, promoting the project and its activities, earthquake knowledge, readiness advice, and community interaction with the project.
- Scenario-based, multi-organisation planning workshops in each CDEM Group area.
- Report of identified response needs in the first week after the event, and priorities within each Group area.
- Assessment report of existing capability and capacity for response management, and identifying the key gaps and issues to collectively address.

Year 2

Pending confirmation of the approval for Year 2 of Project AF8, the following will be completed in 2017-2018:

- Review all outputs from Year 1.
- Develop Alpine Fault Initial Response plan^, associated MOUs, and ancillary plans, based on identified South Island-wide CDEM Groups, partner agencies, community, and national priorities and needs.
- Plan for a large-scale 2018-2019 Alpine Fault earthquake response exercise.
- Maintain and update the science scenario to include the most up-to-date research to inform the response exercise.
- Develop a South Island-wide community earthquake resilience-building strategy.
- Develop a project exit strategy to guide ongoing activity in the management of the Alpine Fault earthquake risks.

* This refers to the direction of seismic energy as it moves away from the hypocentre. i.e. 'North-to-south' refers to southward-directed seismic wave propagation from an earthquake that has initiated on the northern segment of the Alpine Fault. Similarly, south-to-north indicates seismic waves moving northward from the southern part of the fault.

^ UPDATE: The SAFER (South Island Alpine Fault Response) Framework was published in 2018, see: https://af8.org.nz/safer-framework/

The Alpine Fault Scenario

Initial planning

While the MCDEM Resilience Fund Project AF8 application was still under consideration in early 2016, an initial meeting was convened in April with several geoscientists* and the CDEM Otago Group Manager to discuss the needs of an Alpine Fault scenario from a CDEM perspective. The group identified existing sources of data and expertise, and discussed how best to bring together the necessary researchers to develop the scenario within the short timeframe. There was consensus amongst the group that sufficient earthquake source and geomorphic knowledge already existed to generate a maximum credible event impact scenario, without the need to wait for 'more data'. The idea of a workshop was agreed as the best approach, with two teams of researchers being proposed to contribute their source and geomorphic response knowledge to building the scenario.

Subsequent discussion highlighted the need to include an engineering and social science perspective of the consequences of a future Alpine Fault event for the built and human environment. The involvement of QuakeCoRE and Resilience to Nature's Challenges (National Science Challenge) programme leaders in the planning for the AF8 Scenario workshop acknowledged the synergies across current Alpine Fault research programmes and projects, and added significant strength to the consideration of impacts in the scenario.

The timeframe for delivering this scenario was established as October 2016. Building the scenario is the first major output of the Project AF8 workplan.

Goals of the Science Scenario

The goals of the AF8 Scenario focused on delivering the best existing science on seismic source, geomorphic hazards, and potential impacts on the built and human environment for a 7-day response period after a future M_w8.2^ Alpine Fault earthquake. This included consideration of hazards and risks that will occur during the first week post-event, specifically:

- → Surface rupture
- → Ground motion
- → Aftershocks
- → Landslides
- → Liquefaction
- → Tsunami and seiching
- → Cascading hazards and consequences
- → Impacts of lifelines infrastructure and the built environment
- → Impacts on people, including communities, businesses and social systems

* Dr. Simon Cox (GNS Science), Prof. David Prior, Dr. Virginia Toy, Dr. Caroline Orchiston (University of Otago), Prof. Tim Davies (University of Canterbury) were present. Prof. Mark Stirling (University of Otago), Prof. John Townend (Victoria University) and Dr. Tom Wilson (University of Canterbury) were invited but were unable to attend.

^ AF8 refers to a future magnitude 8 Alpine Fault earthquake, however the most likely magnitude lies within a range of M_w8 +/- 0.2, with the median value in the National Seismic Hazard Model (NSHM) stated as M8.1.

Other long term consequences, including aggradation or changes in river systems, were out of scope for the workshop.

It should be noted that the rapid prototyping of the scenario by October will then be followed by future refinement and feedback during the latter part of Year 1 and through Year 2 of Project AF8, as improved modelling and geomorphic data become available. It is anticipated that the scenario remains a 'living document' throughout the term of Project AF8, leading into Tier 4 Alpine Fault Scenario Exercise at the end of the project to test the South Island Alpine Fault Response (SAFER) Framework.

AF8 Scenario process model

Figure 1 illustrates the AF8 Scenario process model by which the three science teams worked collaboratively to produce the each component of the scenario. The earthquake source, geomorphic response, and cascading hazards of an Alpine Fault event are considered earth science (the green box on the left hand end of the model in Figure 1). We refer to these as the hazard scenario. The social science and engineering components of the scenario are then developed using the hazard scenario, producing a maximum credible Alpine Fault impact scenario (blue box in Figure 1). The impact scenario is then used to inform the planning process for CDEM, involving six planning workshops at each of the South Island CDEM Groups. The ultimate goal of Project AF8 is the development of the SAFER (South Island Alpine Fault Response) Framework.

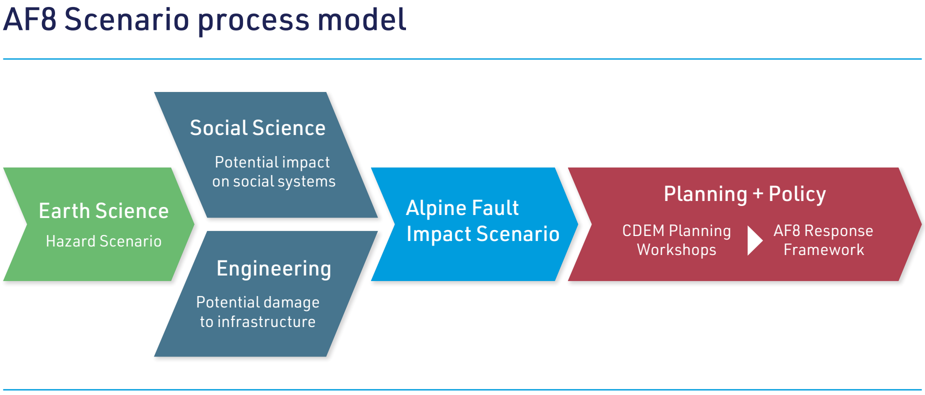


Figure 1: The AF8 Scenario process model, illustrating the development of the scenario in three teams (earth science, engineering and social science), resulting in a maximum credible event Alpine Fault Impact Scenario. This scenario is then used to inform CDEM Planning workshops, and subsequently the SAFER (South Island Alpine Fault Response) Framework.

Approach to building the scenario

On August 23-24th 2016, the AF8 Scenario workshop was held in Christchurch. A total of 35 researchers attended (29 academic, 6 postgraduate students), representing six New Zealand universities, two Crown Research Institutes and two consulting firms. Also in attendance were Civil Defence and Emergency Management Group managers representing four of the six South Island CDEM groups, and the AF8 programme leader (Angus McKay) and programme manager (Jon Mitchell).

The researchers were provided with background information before the workshop, in order to frame the context of Project AF8, and expedite discussions at the workshop. Three teams were formed before the workshop, to address the following components of the scenario:

1. Earthquake Source
2. Geomorphic Hazards
3. Infrastructural and societal impacts

The next section presents the Hazard Scenario, comprising the earthquake source and geomorphic hazards.

Earthquake Source

Introduction

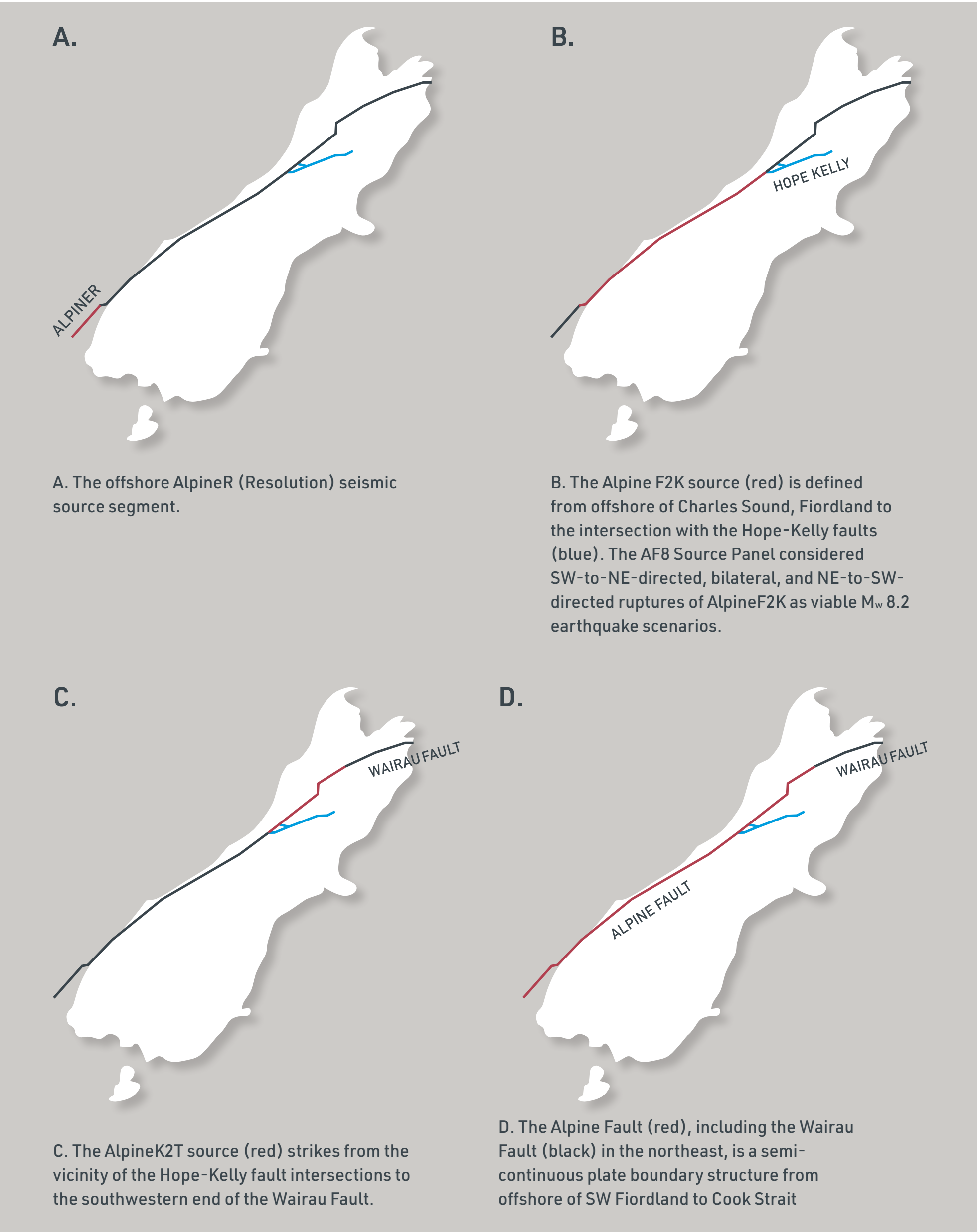
The northeast-striking Alpine Fault is a major active fault that traverses the length of the South Island (Berryman et al., 1992; Langridge et al., 2014). It is the largest slipping fault in the South Island, and is recognised as a major source of seismic hazard for the region. The Alpine Fault is 600 km in length and forms the onshore Australian-Pacific plate boundary (Cox and Sutherland, 2013). The fault extends from offshore of the southwestern tip of Fiordland to the Nelson Lakes area (Lebrun et al., 2000; Berryman et al., 1992). Further north, the northern reaches of the fault continues as the Wairau Fault beyond Nelson Lakes to within Cook Strait (Pondard and Barnes, 2010; Zachariasen et al., 2006) (Figure 2d).

In the National Seismic Hazard Model (NSHM) the Alpine Fault is divided into several distinct segments, each of which defines a potential large (M_w >7) to great (M_w >8) earthquake source (Stirling et al., 2012; Litchfield et al., 2014). These segments of the Alpine Fault were defined by changes in slip rate, strike, throw (uplift), and kinematics (Berryman et al., 1992; Barnes et al., 2005; Langridge et al., 2010).

Within and adjacent to the central and southern parts of the South Island the long-term slip rates on the fault are consistently high at c. 27 ± 5 mm/yr (Norris and Cooper, 2000; Barnes, 2009). The Alpine Fault strikes offshore at Milford Sound (Turnbull et al., 2010). A change in fault structure occurs near the Cascade River (between Lake McKerrow and Jackson Bay) which has been suggested as a segment boundary (Howarth et al., 2016; Barth et al., 2013). South of the Cascade River, uplift occurs on the west side of the fault. However, to the north of Fiordland plate motion drives rapid uplift of the Southern Alps on the southeast side of the fault (Cox and Sutherland, 2007). Near Hokitika the Alpine Fault intersects the southwestern end of the Marlborough Fault System (MFS), defined by the ESE-striking Kelly Fault (Berryman et al., 1992). About half of the slip rate on the Alpine Fault is transferred to the Hope and Kelly faults in this area (Langridge et al., 2004). Slip rates on the Alpine Fault measured to the northeast of its junction with the Hope Fault are c. 14 ± 2 mm/yr and decrease to c. 10 ± 2 mm/yr farther northeast at Springs Junction (Langridge et al., 2010; 2017). Slip rates on the Wairau Fault are lower at 3-4 mm/yr (Litchfield et al., 2014; Zachariasen et al., 2006). These characteristics define the Alpine Fault earthquake sources inferred in the National Seismic Hazard Model (NSHM) (Stirling et al., 2012).

Mainshock source

The NSHM defines four main seismic sources for the Alpine Fault: Alpine (offshore), or "AlpineR"; Alpine (Fiordland to Kaniere), or "AlpineF2K"; Alpine (Kaniere to Tophouse), or "AlpineK2T", and; the Wairau Fault (Figure 2). For the purposes of the AF8 Scenario, the most favoured earthquake source is a NE-directed rupture of the AlpineF2K source (Figure 2b). This scenario is described in more detail below. AlpineF2K, with a length of c. 411 km, occurs from offshore Fiordland at Charles Sound to the vicinity of Lake Kaniere (hence F2K). At Charles Sound there is a step in the surface trace to the right across a width of 3-6 km (Barnes et al., 2005). This step-over is interpreted as an area where a rupture on the AlpineF2K source could potentially terminate. The northeastern end of AlpineF2K source is near the junction with the Kelly Fault. However, this does not exclude the possibility of individual Alpine Fault ruptures extending beyond this boundary and northeast (Yetton and Wells, 1998).



A. The offshore AlpineR (Resolution) seismic source segment.

B. The Alpine F2K source (red) is defined from offshore of Charles Sound, Fiordland to the intersection with the Hope-Kelly faults (blue). The AF8 Source Panel considered SW-to-NE-directed, bilateral, and NE-to-SW-directed ruptures of AlpineF2K as viable M_w 8.2 earthquake scenarios.

C. The AlpineK2T source (red) strikes from the vicinity of the Hope-Kelly fault intersections to the southwestern end of the Wairau Fault.

D. The Alpine Fault (red), including the Wairau Fault (black) in the northeast, is a semi-continuous plate boundary structure from offshore of SW Fiordland to Cook Strait

Figure 2. The Alpine Fault in the South Island of New Zealand, highlighting earthquake source segments in the NZ National Seismic Hazard model of Stirling et al. (2012).

AlpineF2K includes what have been referred to as the 'southern' and 'central' sections of the Alpine Fault in other literature, with the section boundary in the Cascade or 'Theta tarn' area (Barth et al., 2013; Berryman et al., 1992). For the AF8 Scenario, there is rupture continuity between the southern and central sections.

The NSHM constructs simulated earthquakes from parameters of fault length, dip and dip direction, and fault depth to derive an earthquake magnitude. Uncertainties are applied to length, depth and dip angle resulting in a range of magnitude uncertainty. Based on global empirical relationships that relate fault dimensions to earthquake size, the AlpineF2K represents an earthquake of M_w 8.1 with an uncertainty ranging between M_w 7.9-8.3 (De Pascale and Langridge, 2012; Stirling et al., 2012). For the purposes of the AF8 Scenario, we use a magnitude $M_w = 8.2$ (a great earthquake), but note that some analyses have used magnitudes ranging from $M_w = 8.0$-8.2.

Field observations of surface displacements from a past Alpine Fault earthquake in 1717 indicates that the fault slips c. 7-9m right-laterally (horizontally) and c. 1-2m vertically in great earthquakes (De Pascale et al., 2014; Berryman et al., 2012a). The source characterisation method for the NSHM compares field observations to magnitude scaling relations to provide an internal consistency between observations and model parameters. Recurrence interval is also treated similarly. The results for the AlpineF2K source are a mean recurrence interval for an M_w 8.1 earthquake of 344 years (range 199-607 years; Stirling et al., 2012). Fault slip in such an event is c. 9.2m (range 6.4-13.3m). These values are consistent with paleo-earthquake data from trenches and near-fault sedimentary sites such as at Hokuri Creek in Fiordland (Berryman et al., 2012a; 2012b; Clark et al., 2013).

In summary, for the AF8 Scenario, an M_w 8.2 rupture of AlpineF2K involves a fault rupture length of more than 400 km with c. 9m of dextral-reverse surface displacement. This event has a likely recurrence interval of c. 300 years. The last such rupture is believed to have occurred in 1717. New and developing science indicates that recurrence intervals may be slightly shorter (c. 270-290 yr; Biasi et al., 2015; Cochran et al., 2013) for the AlpineF2K source, highlighting the urgent need to consider planning for a major natural disaster related to the Alpine Fault seismic event (AF8).

Hypocentre, directivity and shaking

The hypocentre* of such a 'great' earthquake cannot be known with any certainty. Three possible locations chosen by the AF8 Workshop Source team are near the southwestern and northeastern ends of AlpineF2K, i.e. near Charles Sound or the Kelly Fault, and the midpoint (near Haast). Placing the epicentre in each of these locations implies that the earthquake would rupture mainly toward the opposite ends of the AlpineF2K source, or in the case of the Haast midpoint, bi-laterally toward the southwest and northeast ends of the source. Each of these sub-scenarios would imply significant differences in duration and strength of shaking, i.e. the pattern and intensity of shaking. The northeast-directed rupture scenario could potentially have wider geographic impact, as it would mean stronger shaking in the more populated areas of Canterbury and Westland due to forward directivity (the enhanced ground motions at sites in the direction of rupture propagation). and this sub-scenario is favoured by the panel as discussed below (Figure 3). The implications for seismic shaking of a northeast-directed rupture are discussed in the ground motions section.

* The hypocentre lies directly beneath the epicentre, and is the point where the earthquake initiates at depth.

A northeast-directed AlpineF2K rupture is favoured from a rupture mechanics-perspective for the following reasons:

1. The plate boundary changes from relatively simple in the southwest to more complex once the Alpine Fault encounters the Marlborough Fault System;
2. There have been several large-magnitude thrust to reverse-slip earthquakes in the Fiordland region during the last two decades (Reyners and Webb 2000; Fry et al., 2014; Barnes et al., 2013). These earthquakes may have had an effect on the state of stress on the southern end of the Alpine Fault, or may do so in future;
3. Some clusters of large earthquakes during the modern period of New Zealand history (post-1840) have seemingly progressed SW to NE through New Zealand (McGinty et al., 2005; Dowrick and Rhoadesk, 2011).

A NE-directed AlpineF2K rupture is also favoured from the perspective of the resulting earthquake ground motions. This is because the predominant forward directivity occurs to the north-east which results in stronger ground motions in north Westland, Nelson Tasman, and Canterbury, than for the other two hypocentre location scenarios. As a result, the stronger shaking to the immediate north of the northern-most point of the fault indicates that strong ground motions will be experienced in the vicinity of Lewis Pass (it needs to be kept in mind that the northern termination of the rupture scenario is one of many possible rupture scenarios, and a rupture further north would also lead to stronger shaking in this region).

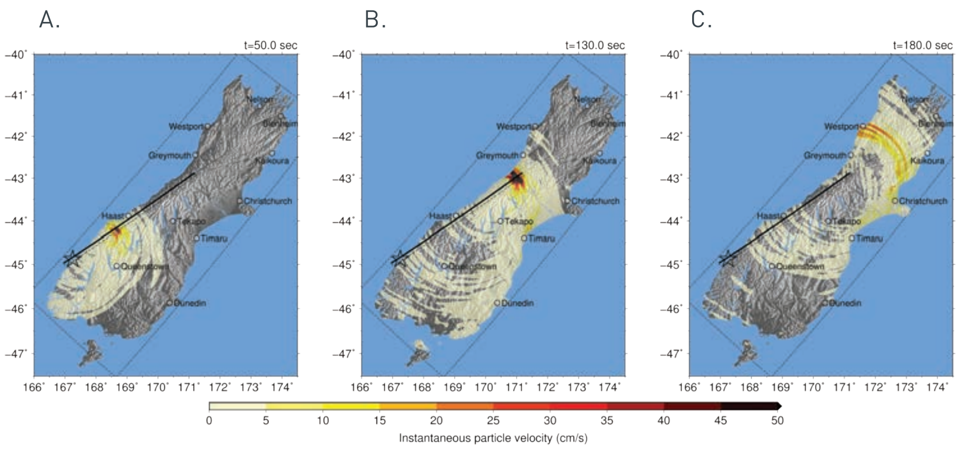


Figure 3. Illustration of the particle velocity (vector maximum in the horizontal plane) at three time instants during ground motion simulation of the Southern Hypocentre AlpineF2K rupture scenario:

(a) t = 50s, illustrating significant rupture directivity in the wavefield;

(b) t = 130s, directivity-basin coupling as the wavefield enters the the Canterbury basin;

(c) t = 180s, directivity leading to relatively large amplitudes North of the rupture and critical reflections resulting in a long duration of significant ground motion in the Canterbury sedimentary basin.

A simple South Island distribution of peak horizontal acceleration (PGA; Holden et al., 2013) indicates that ground shaking is controlled by three key parameters: the fault geometry, the presence of asperities and soil amplification. The following are important relevant observations and conclusions made in the Holden and Kaiser study:

→ the largest shaking intensity is concentrated along the fault trace and decreases rapidly away from the fault trace, very much controlled by the unique fault geometry of the Alpine Fault. PGA values are greater than 1g near the fault trace. Regions on the east coast of the South Island experience very little acceleration (less than 0.1g).

→ The map shows a strong correlation between the location of largest slip displacement (asperities) and very high shaking levels.

→ The shaking intensity is enhanced by amplification due to soft superficial soil layers and basin effects.

→ Shaking duration will be significant over the whole island (over 3 minutes).

Ground surface faulting and deformation

Rupture of the Alpine Fault (AlpineF2K source) causes surface displacements along its length, both offshore and onshore. Observations of past fault movements from geomorphic features indicate that there would be 7-8m of right-lateral displacement in Fiordland, c. 9m of right-lateral displacement near Haast and 7-8m of slip elsewhere along the fault (Berryman et al., 2012a, Clark et al., 2013; De Pascale et al., 2014). The vertical displacement would also vary along strike. Indications from fault scarps and long-term uplift rates indicate that there would be c. 1m of vertical displacement in Fiordland (up-to-the-west), <1m near Haast and 1-2m of vertical displacement elsewhere along the fault (Berryman et al., 2012a; Norris and Cooper, 2000; Langridge and Beban, 2011).

Surface displacement affects human-built structures and utilities on, across or immediately adjacent to the fault. Surface displacement will be particularly critical where the fault crosses State Highway 6 (Figure 2a) at the Haast, Paringa, Karangarua, Cook and Fox rivers, through the Fox Hills highway, the town of Franz Josef (Langridge and Beban, 2011), and the Whataroa and Wanganui rivers. Roads also cross the fault at the Martyr and Toaroha river areas. In the AF8 Scenario surface displacement would terminate near the Toaroha or Kokatahi rivers, and not extend further north to the Taipo River, Inchbonnie, or Arthur's Pass Highway (SH 73).

Other utilities affected by rupture of the Alpine Fault include road bridges, electricity transmission lines, river stopbanks, and embankments. Due to the geometry of the West Coast highway (SH 6) many of the locations listed for surface deformation also have a highway bridge nearby, which is close to or within the wider zone of Alpine Fault deformation. These include Paringa, Karangarua, Cook and Fox rivers, the Waiho River at Franz Josef, and the Whataroa and Wanganui rivers (Figure 4b).

Figure 4c highlights towns, electricity transmission-fault crossings and railway-fault crossings. Franz Josef is the largest and most important village sited within the fault zone of the Alpine Fault. The effects of surface faulting through the town are described by Langridge and Beban (2011). As the West Coast railway ends at Hokitika, there are no rail crossings across the AlpineF2K source. If the Alpine Fault ruptures farther to the north, then the TransAlpine rail route could suffer surface deformation between Inchbonnie and Lake Poerua. We have a poor coverage of the electricity powerline network. However, there are areas where the local electricity networks could be severed due to ground surface rupture and deformation in the Fox Glacier area.

Figure 4d highlights the major rivers of the West Coast and sites along these where ground surface deformation could impact flood protection stopbanks. Right-lateral faulting and vertical deformation could potentially weaken the stopbank system, allowing for subsequent floods to attack and breach them. The most obvious example of this causing a secondary hazard following the earthquake are at Franz Josef on the Waiho River (Robinson and Davies, 2013). Other localities where stopbanks and road embankments could be deformed by surface faulting include at the Paringa, Whataroa and Wanganui rivers.

Collectively, SH 7, comprising roading, bridges, stopbanks and embankments, would be seriously impacted by ground surface faulting and deformation, particularly at the gorge mouths of the major rivers. This effectively breaks the West Coast into lengths of 10-30 km where road access is not possible immediately following the earthquake. This section describes only fault rupture; other impacts on highways caused by landslides and liquefaction are dealt with in the Geomorphic Hazards section.

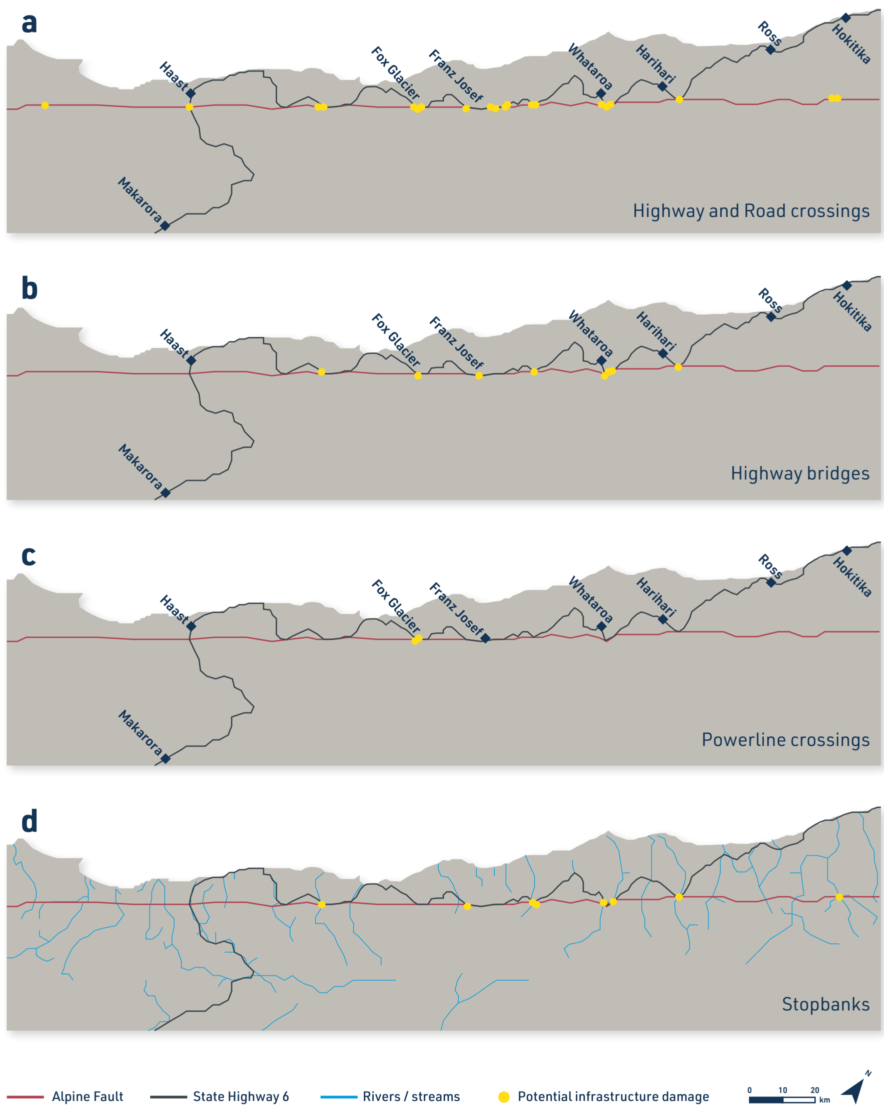


Figure 4: Sites of potential infrastructure damage caused by ground surface rupture of the Alpine Fault, between the Cascade and Kokatahi rivers.

Aftershocks

Table 1 presents the average number of aftershocks for the first seven days after the mainshock, Alpine F2K M_w8.2 earthquake.

Magnitude	0-7 days
5.0-5.9	215
6.0-6.9	20
7+	2

Figure 5 presents one scenario of an aftershock sequence that could occur in the first week following a M_w 8.2 on the AlpineF2K Fault. The black lines represent all of the faults that rupture in an aftershock in this scenario. Only aftershocks of M_w >= 5.0 are shown. The length of the black line is proportional to the magnitude of the aftershock, with longer lines representing larger magnitude aftershocks. The colour scaling represents the maximum Peak Ground Acceleration (PGA) experienced in any 0.05 degree X 0.05 degree cell during the aftershock sequence; it does not include the shaking from the M_w 8.2. This scenario is one of thousands of possible aftershock scenarios and represents an average sequence. In other scenarios both the numbers of aftershocks and where they are located in space can be noticeably different.

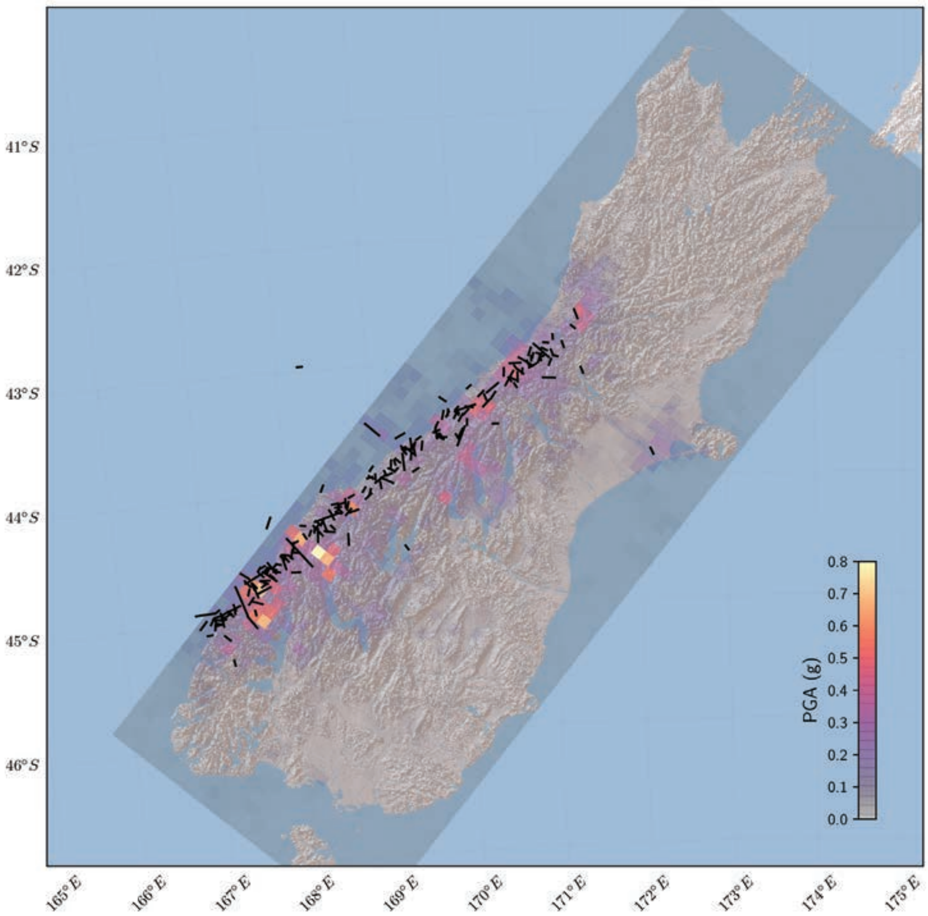


Figure 5: A scenario forecast of one potential aftershock sequence for the first seven days following a M_w 8.2 on the AlpineF2K fault. Shown are individual aftershock ruptures (black lines) and the maximum PGA experienced during the sequence at each location (shown in colour shading). (Aftershock model: M Gerstenberger, GNS Science)

Geomorphic Hazards

Scope and data sources

This section describes the likely geomorphic hazards of an Alpine Fault earthquake and aftershock sequence in the Southern Alps and environs, for the purposes of helping to plan for such an event. The first part of the section describes the full range of geomorphic and associated hydrological hazards that could eventuate as a result of a major earthquake sequence, providing estimates of the nature, magnitude and relative likelihood of expected phenomena. The second part presents an estimate on the likely timing, magnitude, and location of phenomena resulting from a M_w 8.2 Alpine Fault (AlpineF2K source) earthquake sequence (including the main shock and aftershocks) up to 7-days following the main shock, to help guide the planning of response during this initial 7-day period.

The hazards described here are based on the geological records of past events, experiences from other New Zealand and overseas earthquakes, modelling, expert judgement, and draws on existing literature, principally Robinson and Davies (2013) and Robinson et al., (2016).

The range of geomorphic hazards

A major earthquake in a mountainous landscape will initiate a wide and complex range of landscape responses with repercussions that spread across a large area and over a range of timescales. The potential geomorphic and hydrologic hazards can be sorted according to their sequence within a cascade of events likely to occur following a major earthquake (Figure 6).

These phenomena will occur at different points in time, and their effects will range in duration. Some of the phenomena will be triggered directly by shaking in a mainshock or subsequent aftershocks (referred to herein as coseismic), while others will develop subsequent to, and partly as a result of, those initial co-seismic events. While many are short-lived (such as rock fall), others may continue to pose a threat for months to years (such as landslide dammed-lakes and river aggradation).

Predicting the magnitude, location, and timing of coseismic events is difficult, and considerably more difficult for the cascading hazards. The cascading phenomena are dependent on not only the events triggered by the main shock, but also the dynamics of the aftershock sequence, and external variables such as the weather and river flow at the time, and over the proceeding days to years. Nonetheless, we consider all of the coseismic and cascading events as credible in the context of a great Alpine Fault earthquake, given the mountainous nature of the landscape.

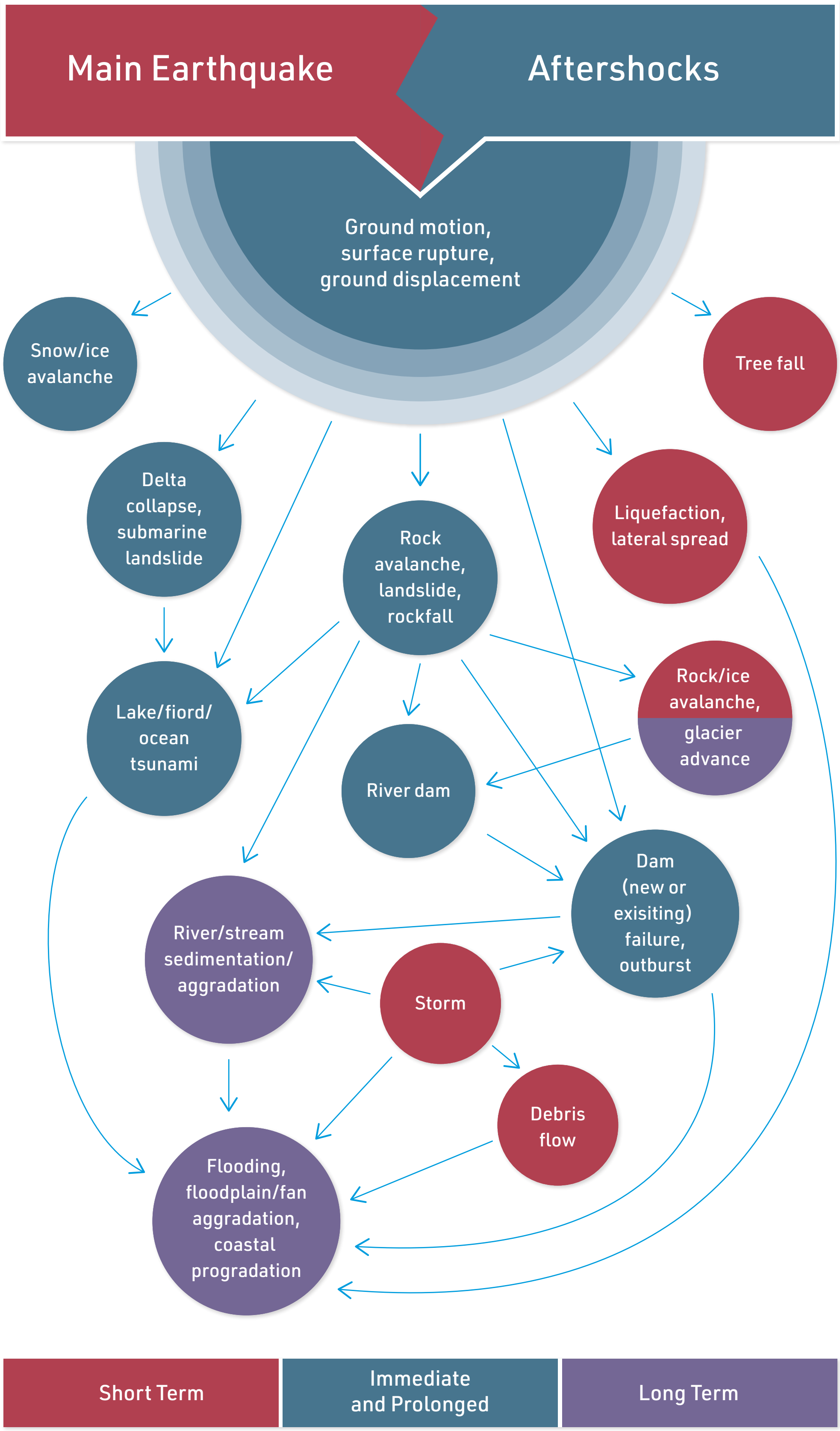


Figure 6: The range of geomorphic phenomena triggered by a major earthquake sequence, and their relationship cascade. The earthquake sequence and subsequent storms provide the drivers, and are shown in the boxes with thick black outline. The longevity of each resulting phenomenon is indicated by colour.

Co-seismic hazards

Landslides

Tens of thousands of landslides (i.e. mass movements, including falls, slides, topples, avalanches) will be triggered by the shaking during the main shock and major aftershocks. The number and extent of landslides and their direct and indirect threats makes them the most significant geomorphic impact.

The number of landslides produced during an earthquake and their distribution is partly related to the strength and duration of shaking. A range of empirical relationships between earthquake magnitude and landsliding (e.g. Keefer, 1984; Keefer and Wilson, 1989; Malamud et al., 2004) have allowed Robinson and Davies (2013) to estimate that for a M_w 8 Alpine Fault earthquake, there is likely to be somewhere between 17,000 and 148,000 landslides produced, spread around an area of approximately 12,000 to 102,000 km^2, and with a total volume of between 0.4 to 4.2 km^3 (Robinson and Davies 2013). Using an alternative method, that applies historical coseismic landslide data to a relative landslide susceptibility map, Robinson et al., (2016) estimated the number of landslides to be between 30,000-70,000, which could be considered to be a more likely range for a M_w 8 Alpine Fault earthquake because it explicitly takes into account the landslide susceptibility of the South Island. More precise estimates are precluded by the uncertainty of the specific earthquake shaking characteristics and stability conditions at the time, but these provide a realistic range for an Alpine Fault earthquake, and have been used as the basis for the 7-day M_w 8.2 scenario.

Landslides pose two main direct threats; from disturbance of the ground that fails, and impact or inundation by the landslide debris produced by the failure. The debris produced by landslides can also lead to several types of indirect or secondary hazard discussed below (under **cascading hazards**), which include blocking of rivers, accretion in river channels and floodplains, and providing source material for subsequent landslide events (namely debris flows).

Landslides will occur more densely where the shaking is strongest (i.e. near the fault and where ground conditions amplify shaking), and especially densely where this strong shaking coincides with unstable slopes (i.e. those slopes that are steep and the materials are relatively weak). Some slopes, however, will fail in areas of only moderate shaking intensities, if the slopes are very unstable prior to the earthquake. Fortunately though, most of the landslides will occur in the steeper topography of the Southern Alps which tends to be more unstable but also directly threatens only a minor proportion of the population. However, some of these remote landslides may generate significant secondary cascading hazards.

Some of landslides will cause direct impacts from localised failure of the ground beneath communities or infrastructure on sloping ground. These impacts may result from cracking, subsidence, or small differential movements (twisting, rotating, or shearing of foundations) in situations where there is partial slope failure, or may result in very destructive wholesale disruption and movement of the ground in the case of a complete failure of a slope. This type of impact is very likely to affect linear infrastructure (including lifeline utilities such as transport, energy, telecommunication services) across wide areas, due to the extensive exposure of these infrastructures.

Most direct landslide impacts are likely to arise from the landslide debris falling, sliding or flowing on to inhabited areas situated below or downstream of sloping topography, and these impacts could include substantial loss of life and property. Some of the larger landslides and rock avalanches have the potential to travel many kilometres at very high velocities (up to hundreds of kilometres per hour), and thus may be able to reach populated areas located kilometres from the landslide source areas. Several such landslides with long travel distances, are thought to have been triggered in previous Alpine Fault earthquakes (Bull, 1996, Yetton et al., 1998; Wright, 1998). Many thousands of smaller landslides, such as rockfalls ranging from individual rocks and boulders up to perhaps hundreds of cubic metres in volume, will also occur, and can still have very severe impacts. This is the case where any road or building sits beneath cliffs of any size. Massey et al., (2014) found that a peak ground acceleration of 0.3-0.4g was sufficient to trigger rockfalls, which corresponds to a shaking intensity of about MMI 8 and peak ground velocity of 0.3 ms^{-1}. In addition to the shaking close to the fault, locations at large distances (e.g. Nevis Bluff, Central Otago) are expected to be active during the Alpine Fault scenario earthquake. Landslide debris will block or partially block roads and rail throughout the Southern Alps, with road and rail cuttings being particularly susceptible to failure.

Landslides are likely to also occur on artificial slopes (i.e. within materials that have been produced by earthworks, such as road fill, canal or river embankments, and earth dams). Some of these failures would cause considerable disruption and danger, but a full risk assessment is beyond the scope of the geomorphic impacts planning.

For all of the direct landslide hazards, there will be very little warning time to make evacuation and avoidance feasible once strong shaking begins. However, there will be many places where only partial failure of a slope occurs (e.g. cracking, displacement and subsidence of sloping ground) during the main shock; these locations should be considered as being unstable and highly likely to fail during subsequent aftershocks or heavy rainfall.

Liquefaction

Liquefaction, the temporary transformation of a soil into a liquid state, is likely to be triggered by shaking during the main shock and some major aftershocks (>M_w 5; e.g. Quigley et al., 2013), in locations with susceptible soils. Local mapping has identified a number of areas throughout the South Island susceptible to coseismic liquefaction, and Christchurch, Westport, Murchison, Greymouth, Invercargill and Te Anau are known to be vulnerable (McCahon et al., 2005; McCahon et al., 2006a,b). Particular concern has been expressed for the Taieri Plains (location of Dunedin airport) in this regard. The occurrence of liquefaction in Tokyo during the 2011 Tohoku earthquake (450 km from the closest point on the rupture) shows that low-frequency, long-duration shaking can cause liquefaction far from the earthquake source. Liquefaction effects during the earthquake are unlikely to be directly life-threatening, but they may make some locations uninhabitable, cause surface flooding, render roads unusable, and damage lifelines.

Tsunamis

Tsunamis may be triggered by fault rupture during the mainshock or major aftershocks, from either the off-shore section of the Alpine Fault, or from faults that transect lakes.

Downes et al., (2006) have suggested that a M_w 7.8 earthquake affecting the offshore (submarine) segment of the Alpine fault can generate significant tsunami in the nearby fiords. A more significant regional tsunami is unlikely due to the small vertical component of displacement expected for the off-shore section of the Alpine Fault.

Rupture of the onshore section of the Alpine Fault, or surface rupture of other faults during major aftershocks, may generate localised tsunami where faults cross lake beds. Within the Southern Alps, several major lakes have known active faults crossing them, and therefore have the potential to trigger tsunami: The Alpine Fault crosses Lake McKerrow in Fiordland, and a tsunami would possibly affect trampers on the Hollyford Great Walk track or huts adjacent to Lake McKerrow. There is the potential for an Alpine Fault earthquake to trigger earthquakes on other faults in the region, which could lead to tsunami on local lakes, however this is considered outside the scope of the current hazard scenario*.

Potential tsunami sources could generate waves of several metres high that could produce run up heights of approximately double the wave height, causing water to inundate coastal or lake-shore areas within minutes of the initiating earthquake. However, while tsunamis from rupture of the off-shore (fiords) and onshore (Lake McKerrow) sections of the Alpine Fault are quite likely, the other tsunami sources are much less likely. They will occur only if the aftershock sequence produces a sufficiently strong, ground-rupturing, displacement under a lake. However, for the 7-day scenario, fault-rupture tsunamis are considered for the southern section of the Alpine Fault, and the Te Anau fault. In general, coseismic, fault-rupture tsunami is a credible threat, but probably less of a concern compared with landslide-triggered tsunami sources (considered below under **cascading hazards**).

Fault-rupture hazards

The surface rupture of the Alpine Fault and other surface-rupturing aftershocks, will cause displacement of the ground, causing infrastructure damage in places where these intersect.

Cascading hazards

Landslide-triggered tsunamis

Coseismic landslides are a very probable source of tsunamis in a major earthquake. Sources could include submarine and lake floor landslides, and landslide debris falling into water bodies (i.e. lakes or fiords).

There is some geological evidence of tsunamis having occurred along the West Coast, likely associated with Alpine Fault earthquakes (Nichol et al., 2007; Nobes et al., 2016). Submarine landslides could occur on the steep margin of the continental shelf, which, at the southern end of the Alpine Fault, is very close (< 10 km) to shore. The deposits from past submarine landslides have been identified offshore from the southern end of the Alpine Fault, and may have been earthquake-triggered (Barnes et al., 2013). The shelf margin extends farther offshore towards the north, making shelf margin source areas less likely, but landslides could occur within the offshore canyon systems that funnel sediment into the offshore basins in the more northern areas, such as the Hokitika Canyon. Tsunamis are also likely to be triggered in coastal areas of Fiordland, by landslides falling into the fiords. Milford Sound has been recognised as being susceptible to landslide-triggered tsunami, based on evidence of submarine landslide deposits within the fiord, many of which are likely to have been triggered by previous Alpine Fault earthquakes (Dykstra, 2012).

Lake floor (subaqueous) landslides or landslides falling into lakes (subaerial) in response to AlpineF2K earthquakes could generate tsunami in a large number of lakes around the South Island. Lake floor landslides are most likely to occur from the

* Other potential faults that could be triggered by an Alpine Fault earthquake, and potentially result in lake tsunami include: the Te Anau Fault under the length of Lake Te Anau, and a tsunami would likely impact Te Anau township; the Hunter Valley Fault under Lake Hawea, and a tsunami there would likely impact Lake Hawea township and possibly the hydro control dam; the Moonlight Fault crosses Lake Wakatipu, which could induce a small tsunami at Queenstown, Glenorchy and Kingston; the Irishman Creek fault potentially crosses Lake Tekapo, and a tsunami there could affect some parts of Lake Tekapo township and the hydro control dam. Further north, the Kakapo Fault crosses Lake Sumner (though with little threat due to the remoteness of the lake) and the Wairau Fault (northern extension of the Alpine fault) crosses Lake Rotoiti, with a small threat to people near the shore of the lake. These examples only include lakes (or submarine locations) where active (or potentially) faults have been mapped; there may be many other lakes or areas of sea floor with active faults that have not yet been identified.

collapse of deltaic sediments (i.e. wedges of sediment built up at the margins of lakes where rivers deliver sediment), especially those entering deep glacial lakes, such as the Dart River delta at Lake Wakatipu, or the Tasman River delta at the head of Lake Pukaki. Landslides could also fall down into any of the lakes in the Southern Alps where they are surrounded by steep topography, though most of the smaller lakes of the Southern Alps are in remote, uninhabited areas. There is a high likelihood of landslide-triggered tsunamis in one or more of the large former-glacial lakes (such as lakes Te Anua, Wakatipu, Hawea, Wānaka, Ohau, Tekapo, Pukaki, Coleridge, and Rotoiti), all of which have populations or infrastructure at their margins. NIWA have recently identified numerous landslide deposits on the floor of Lake Tekapo, which indicates the potential for future events in lakes like this. However, only large (> 1000 cubic metre) landslides are likely to generate hazardous tsunamis. As with tsunamis generated by fault rupture, there will be very little warning time.

Landslide dams and breakout floods

Large coseismic landslides are likely to dam rivers in a major earthquake, all causing upstream flooding, and some generating a flood of water and sediment downstream in the event of failure of the landslide dam. Hundreds of previous landslide dams have been identified in the Southern Alps (Adams, 1981; Nash, 2003; Korup et al., 2004; Korup, 2005), many of which are likely to have been triggered by strong earthquake shaking (Adams, 1981; Costa and Schuster, 1988; Korup, 2005). A large number of catchments in the South Island have characteristics suitable for landslide dam formation (McCahon et al., 2006a; Robinson and Davies, 2013), and Robinson and Davies (2013) suggest that some tens of landslide dams could result from an Alpine Fault earthquake (perhaps similar to what happened in the 2008 Wenchuan Earthquake in China; Xu et al., 2009. While a landslide dam could form in any sufficiently narrow and steep-sided valley, blockages that have the potential to generate very large lakes (usually requiring blockage by a large, e.g. > 1M m^3, landslide), that are of most concern.

Flooding upstream of the landslide dams will begin immediately, but the rate that the dams fill with water will depend on the rate of inflow (which in turn depends on the upstream catchment area and runoff) and the topography of the blocked valley. The time until the dam crest overtops may range from days to months, with the river flow and weather conditions following the earthquake having a direct influence on this time. Failure of a dam is most likely to happen sometime after the dam has been overtopped, so the time to filling is an important consideration; though earthquake shaking in an aftershock, landslide-triggered tsunami into the lake, or internal erosion of the dam could also initiate a breach and failure of the dam prior to filling.

There may be some locations where upstream flooding causes a problem (i.e. affecting land and property or flooding of transport routes or other lifelines), but landslide-dams are most likely to occur where there is little habitation upstream, and there will be little immediate life-threat unless filling proceeds rapidly. The greater hazard is in the case of a breakout flood, which could affect communities many kilometres downstream, causing a large flash flood in the immediate term and a build up (aggradation) of sediment in the river channels and across floodplains over the immediate to long-term (i.e. days to decades); the consequences of the latter are outlined below. Breakout floods from pre-existing natural dams could also occur as a direct or indirect consequence of earthquake shaking. For instance, the Young River landslide dam (Bryant, 2010), has remained stable since its emplacement in 2007, despite overtopping (Massey et al., 2013), but could fail during strong shaking, or the dam could be breached by tsunami caused by a coseismic landslide falling into the lake.

River aggradation

Huge quantities of the debris produced by landslides in a major earthquake will make their way through the river systems, with a lot of this sediment being temporarily stored on the alluvial fans and floodplains, causing aggradation which could be in the order of several metres for many parts of the South Island (Robinson and Davies, 2013; Sheridan, 2014; Robinson et al., 2016). The aggradation could cause burial of land and infrastructure, and also reduce the flood capacity of the rivers, elevating flood hazard in these valleys. For the most part, these effects will be long-term (i.e. years to decades), but in the case of breakout floods, aggradation may occur much more rapidly, and the landslide debris and material stored within river channels also elevates the risk of debris flow hazards even in the short-term (i.e. days to weeks).

Debris flows

Widespread intense shaking will result in landslides of all sizes in catchments in the Southern Alps. Thus, unusually large volumes of sediment will be made available for rivers throughout the Alps. In particular, stream channels in small catchments along the western rangefront will receive substantial sediment volumes that, in rainstorms over the next few years, will result in debris flows in all these drainages. In a storm not preceded by an earthquake (e.g. January 1994) only a few catchments with enough accumulated sediment will generate debris flows*; by contrast, following an earthquake virtually all catchments smaller than about 10 km^2 will generate debris flows.

In normal circumstances about 200 small catchments (up to a few km^2 in area) between Arthur's Pass and Haast are known to be capable of generating debris flows at intervals of decades to centuries. Following a major earthquake, this number will increase significantly and the frequency of debris flows will increase by at least an order of magnitude. This increase in debris flow hazard will, as indicated by the aftermath of the 1999 Chi-Chi and 2008 Wenchuan earthquakes, continue for several years (e.g. Yu et al., 2014).

Fault-rupture hazards

The surface rupture or surface deformation produced by faults has the potential to cause surface flooding where the fault scarp or ground deformation impedes drainage, particularly along natural drainage lines such as streams and rivers. As with flooding in general, this will become a greater problem following rainfall. However, this particular hazard is not deemed to be easy to predict or significant in comparison to other hazards. Indeed, the surface rupture on the Alpine Fault, is expected to cause the western (and therefore generally the upstream) side of the fault to rise relative to the eastern (generally downvalley) for most of the major West Coast catchments, and therefore unlikely to impede drainage in most locations.

Glacier advance or dislocation

Where large landslides fall onto glaciers and blanket the glacier with thick debris, they can reduce glacier surface melting (e.g. Reznichenko et al., 2011). This can result in a glacier to advance (i.e. grow in length), which can in some circumstances could cause hazards where a glacier forefield is developed (e.g. the advancing Belvedere Glacier in Italy threatened tourist facilities; Haeberli et al., 2002). In the M_w 8.2 AlpineF2K scenario, a 3m^3 landslide is predicted to fall onto the Fox Glacier, which could initiate an advance, which will likely cause the Fox River floodplain to aggrade more rapidly, increasing flood hazards. However, this type of glacier response happens over timescales of years to decades, and therefore it can be ignored for the 7-day scenario. A more instantaneous

* See: https://www.youtube.com/watch?v=c_Zsjsgx1t8

and devastating, but rare, scenario is a dislocation of a glacier caused by a landslide. This involves a landslide falling on to a glacier and causing the whole glacier to surface forward instantaneously, potentially becoming incorporated into the original landslide and developing into a rapid rock-ice avalanche that can travel great distances. Such an event occurred at the Kolka Glacier in North Ossetia in 2002, and devastated villages located more than 15 km downstream of the glacier (Evans et al., 2009). While this particular event was not triggered by an earthquake, there is no reason why a similar event couldn't be triggered by a coseismic landslide.

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