Evidence for coseismic rock avalanches and debris flows in fractured mylonites of the Alpine Fault, Paringa, New Zealand

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ABSTRACT: A 400m wide bowl-shaped depression with a volume of 3 million m^3 lies at the head of a valley below Ward Hill in the Southern Alps,and intersects a similar depression to the west. The features lie 1km from the active trace of the Alpine Fault (Australian-Pacific plate boundary) in fault cataclasite and fractured mylonites of an abandoned thrust nappe. They are inferred to be source area depressions of rock avalanches, probably triggered by earthquakes (Mw 8) on the fault. The Ward Hill feature has retrogressed by rockslide-debris flows, probably triggered by both earthquakes and rainfall events. Measurements of the largest specimens of trees on the debris fan have found none likely to be older than 300 years. This may be explained by debris flows associated with the last Alpine Fault earthquake in 1717. The high probability of a new Alpine Fault earthquake presents potential debris flow hazards to buildings and an important highway.

1 INTRODUCTION

The Alpine Fault of the South Island of New Zealand (AF) forms the boundary between the Australian and Pacific Plates (Figure 1). Major earthquakes with an average return period of 200-300 years have uplifted the Southern Alps to the east of the fault.

An associated zone of fractured and altered mylonites and cataclasites termed the Alpine Fault Zone (AFZ) is prone to slope instability (Korup, 2004). Landslides appear to be triggered by both strong shaking from Alpine Fault earthquakes and extreme rainfall events.

A small number of long run-out rock avalanches have been identified along the AFZ (Wright, 1998; Korup, 2004; Chevalier et al., 2009), but such features may be under-represented in the geological record due to the high rainfall and erosion rates of the region. Complex gully/slip systems are widely developed in the AFZ, and are activated by extreme rainfall events (Korup, 2004). Debris flows are common in these systems.

This paper is a preliminary study of two large bowl-shaped features at Ward Hill, Paringa, South Westland, considered to be rock avalanche source area depressions (Figures 1- 3). It is based on Google Earth imagery, data from previous geological mapping of the Alpine Fault at Paringa (Simpson, 1992; Simpson et al, 1994) and initial field surveys of the geology and vegetation of the debris fan.

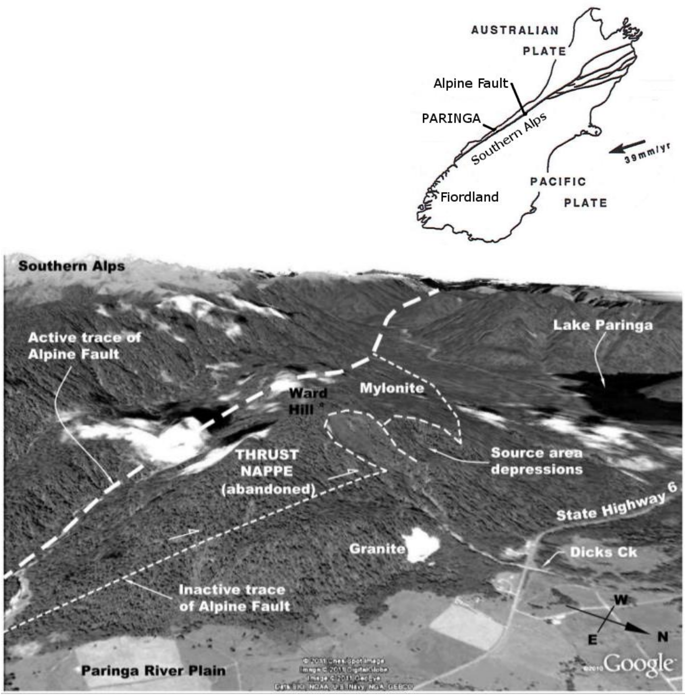


Figure 1. View of the Alpine Fault and the bowl-shaped source area depressions.

2 GEOLOGICAL SETTING

The Alpine Fault is a major transpressional plate-boundary fault associated with an oblique plate collision (Figure 1). The Southern Alps have been thrust up on the south-eastern side of the fault, with the highest peaks rising over 3000m above sea level.

The plane of the Alpine Fault is inferred to dip about 45^o to the SE. However, near the surface the fault is segmented, with nappe-like over-thrusts alternating with more steeply dipping strike-slip sections (Norris and Cooper, 1995).

Basement rocks in the Southern Alps to the south east of the fault are garnet-zone Haast Schist (Permian-Mesozoic), with a cataclasite/mylonite zone <1km thick adjacent to the fault plane. Granite and Paleozoic sediments lies to the west. The region was glaciated in the Pleistocene and deposits of till and outwash gravels are widespread.

Evidence from dendrochronology and fault trenching studies indicates that the AF underwent movements in 1717, 1620, ca.1450 and ca.1100 (Sutherland et al, 2007), indicating an average return period of 200-300 years. Fault movements can result in up to 8m horizontal and 3m vertical displacements, and earthquakes inferred to be about Mw 8.

3 TOPOGRAPHY GEOLOGY AND CLIMATE

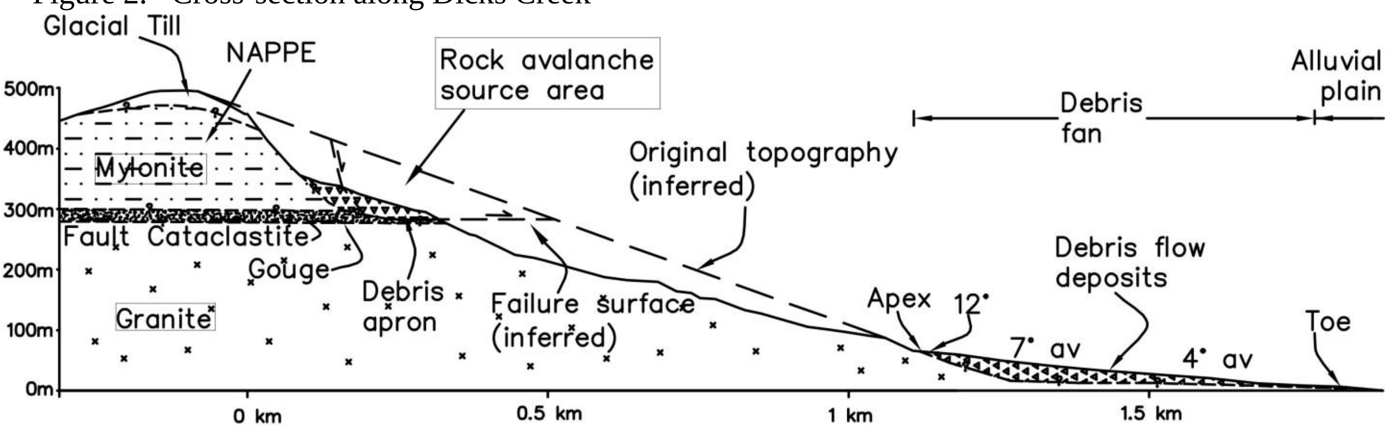
A large bowl-shaped depression lies at the head of Dicks Creek below Ward Hill (544m above sea-level), and is termed the Ward Hill source area (Figures 1- 3). It shows clear evidence of current rockslide activity. A deeply incised gully leads to a large debris fan crossed by State Highway 6, an important transport route. The fan grades onto the flood plain of the Paringa River.

An inactive, similar sized bowl-shaped depression, termed the western source area, lies immediately adjacent. It is intersected by the Ward Hill feature, that extends further back towards the head of the catchment.

The climate is temperate, with annual rainfall estimated to be in excess of 5000mm, and is characterized by intense rainstorms. The mountain slopes and debris fan are covered in rain-forest, with the adjacent flood plain cleared for farming.

Initial field work has been confined to the debris fan and highway. However, the geology can be inferred with some confidence from existing mapping data and the fan composition.

Figure 2. Cross-section along Dicks Creek



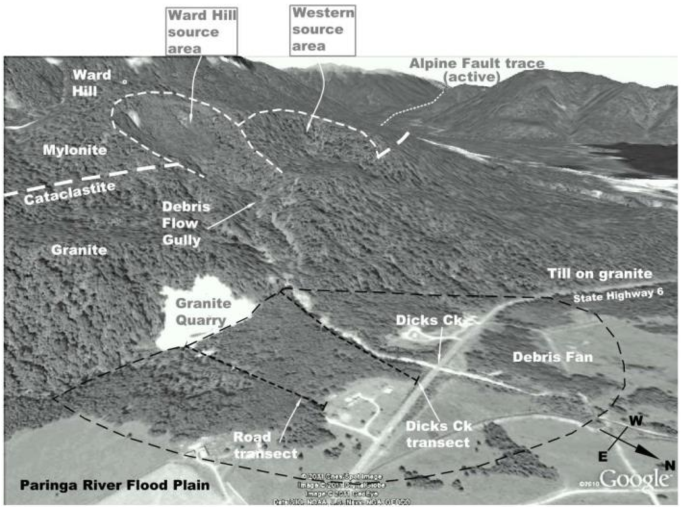


Figure 3. View of the Ward Hill source area, gully and debris fan at Dicks Creek, and the adjacent western source area.

The geology of the area is shown on Figures 1 & 3 and the cross-section, Figure 2. The upper part of Ward Hill is an abandoned thrust nappe of the Alpine Fault, that was active during the last glaciation (Simpson et al, 1994). Following de-glaciation, the nappe was isolated from the basement fault by fault-parallel fluvial erosion to the south-east, and the active trace relocated about 1km towards the Southern Alps (Figure 1).

The cataclasite zone of the thrust nappe is exposed 2km to the south-west of the site, and is inferred to extend around the side of Ward Hill as shown on Figures 1- 3 (based on Simpson, 1992 & Simpson et al., 1994).

The Alpine Fault typically exhibits a low shear strength gouge up to about 0.5m thick along the fault plane. Above the gouge is the weak cataclasite zone up to about 30m thick, composed of angular fragments of quartz and mylonite in a silty matrix (Figure 4). A similar sequence would be expected at Ward Hill.

The overlying schist derived mylonites are commonly closely sheared, shattered and altered (Figure 5), and prone to slope instability. Defects comprise foliation shears/ fractures, joint sets orthogonal to

Figure 4. Cataclasite composed of cm diameter fragments of quartz and mylonite in a silty matrix, overlain by shattered mylonite (Photo V. Toy)

Figure 5. Sheared and shattered mylonite in the AFZ. (Photo V. Toy)

foliation, and gouge filled shear zones.

Granite and Paleozoic meta-sedimentary rocks occur beneath the AF plane, with granite exposed in a hillside quarry below Ward Hill.

During the last glacial maximum, Ward Hill was over-topped by ice, and till forms a widespread mantle on bedrock. With ice retreat the Paringa valley was initially occupied by a fiord, now represented by Lake Paringa to the west of the site (Figure 1).

4 SOURCE AREAS

The distinctive bowl- shaped Ward Hill source area is about 400m in diameter, and lies at the head of Dicks Creek. The volume is estimated to be about 3 million m^3. It has a headscarp 100m high with an average slope of up to 50^o (Figures 2, 3 & 6). The debris apron at the base has an average slope of about 15°, and contains a slightly elevated central ridge flanked by shallow depressions containing small streams. Below the bowl, the valley slopes more steeply down to the head of a gully that runs 600m out to the debris fan.

The bowl is developed in mylonite, with a hill-capping veneer of glacial till. The fault cataclasite is inferred to lie at the level of the lower lip of the bowl, with granite forming the steeper face beneath and extending downslope.

The hillsides surrounding the bowl and also the lateral margins are typically covered in mature forest (Figure 6). However, the vegetation of the head-scarp and floor is dominated by small regenerating trees, indicating forest destruction by relatively recent landslide activity.

Fresh rockslide scars are visible on the steep mylonite slopes on the eastern and western sides of the source area. Below the western scar lies a 30m wide x 150m long strip of small trees that appear to be regenerating in a rockslide run-out zone.

The intersected western source area has roughly similar dimensions, and a cover of mature forest (Figures 3 & 6). The head slopes at about 35^o, and the floor is a planar bench, probably underlain by debris over granite. It shows no evidence of current landslide activity.

No obvious run-out paths or hummocky rock avalanche deposits have been detected to date in the valley below the source areas, either on Google Earth images or during field work on the fan surface and along SH6.

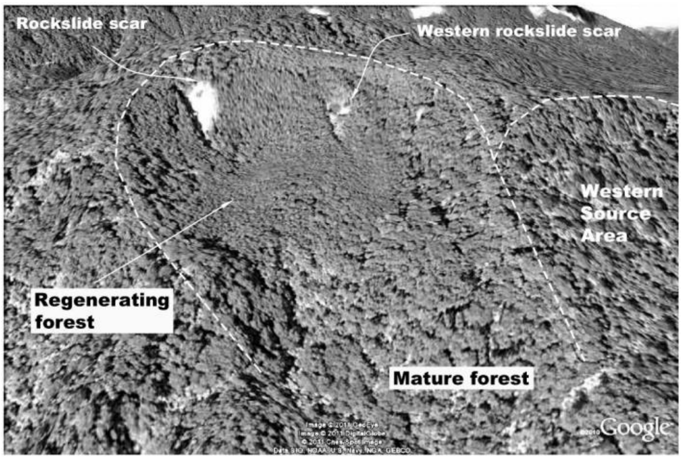


Figure 6. The Ward Hill source area showing fresh rockslide scars on the headscarp and young regenerating vegetation

5 DEBRIS FAN

5.1 *Topography and Geology*

The debris fan of Dicks Creek is about 700m wide and extends down-slope about 600m (Figures 2 & 3). The average slope of the upper fan is about 7^o, rising to 12° at the apex. Bouldery levees and associated channels indicating debris flow deposition are widespread, and boulders up to 2.5m diameter lie on the fan surface. The slope decreases to about 4° in the toe.

The stream is entrenched into the head of the fan for about 200m below the apex, and further downslope is confined by debris flow levees along the channel sides.

The dominant clast lithology in the debris is mylonite, with schist probably derived from till, and minor granite.

5.2 *Vegetation*

The fan is covered in native forest, apart from a section at the toe converted to pasture (Figure 3). Tree species of the genus Nothofagus constitute a major part of the forest canopy in the area (Wardle, 1980). The dominant tree species on the fan is *Nothofagus menziesi* (silver beech) with *Dacrydium cupressinum* (rimu), *Podocarpus totara* (totara) and *Weinmannia racemosa* (kamahi) also present.

An area approximately 200m x 200m consisting of an apparently even-aged cohort of trees was identified, that was considered to represent the oldest forest on the fan. Diameters at Breast Height (DBH) of trees were measured along two transects of 200m length and 20m width, 200m apart. One transect runs along the road to the quarry end (road transect) and the other along Dicks Creek from the fan apex (Dicks Creek transect) (Figure 2).

Along each transect, the DBHs of the two largest trees within a distance of up to about 5m were measured, at approximately 20m intervals. Twenty-two trees were measured along the road transect, 18 along the Dicks Creek transect. In addition, two trees encountered in the area between the transects were measured. Where a sampling spot was not accessible due to thick vegetation, tree DBH was measured at the next accessible spot along the transect.

Along the road transect, 13 *N. menziesii* trees, three *D. cupressinum* trees, four *W. racemosa* trees and two *P. totara* trees were measured. Along the Dicks Creek transect, 17 *N. menziesii* trees and one *D. cupressinum* tree were measured, whilst only two *N. menziesii* were measured from the area between the transects.

Nothofagus menziesii DBH along the road transect ranged from 47cm to 120cm with an average of 59.6cm. *D. cupressinum* DBH along the same transect ranged from 38cm to 50cm with an average of 44.7cm. *W. racemosa* DBH ranged from 40cm to 50cm with an average of 46cm. *P. totara* DBH ranged from 51cm to 68cm with an average of 59.5cm.

Nothofagus menziesii DBH along Dicks Creek transect ranged from 43cm to 106cm with an average of 76cm. The DBH of the single *D. cupressinum* measured was 56cm. In the area between the two transects the two *N. menziesii* measured were of 54 and 106 cm DBH.

The results revealed the average *D. cupressinum* DBH on the road transect to be 44.7cm, which indicates an age of about 300 years based on studies elsewhere in South Westland by Stewart et al. (1998). Similarly, the *N. menziesii* are also not likely to be more than 300 years. Few trees of any Nothofagus species live longer than 400 years (Wardle, 1984). These results imply the synchronous regeneration of a new cohort of trees in the area at a time roughly corresponding with the last earthquake on the Alpine Fault in 1717.

6 DISCUSSION

The presence of a mantle of till on the summit of Ward Hill indicates that it lay beneath glacial ice at the peak of the last glaciation. With glacial retreat, the slopes were exposed to fluvial erosion and potential slope instability.

The geomorphic form of the two bowl-shaped features on the hillside is strongly suggestive of rock avalanche source area depressions, albeit modified by slope processes. Similar depressions (with associated hummocky debris deposits and hence clearly of rock avalanche origin), have been documented at several other sites in the AFZ e.g. Wright, 1998.

There are no obvious hummocky debris deposits on the Paringa flood plain,or run-out paths visible on satellite images of the hillside. Occasional exposures along SH6 beneath the western source area show till and granite, with no evidence of mylonite- derived rock avalanche debris. Possible explanations for the lack of debris deposits include fluvial erosion, burial beneath the debris fan, run-out into a proto- Lake Paringa or fiord with subsequent fluvial infilling, or run-out onto glacial ice.

The geology of the slope suggests the failure mechanism is likely to be basal sliding along the low strength, sub-horizontal gouge/cataclasite horizon, with back release through the fractured mylonite, as shown in Figure 2. Elevated pore pressures above the low permeability gouge/cataclasite horizon may have facilitated failure. This inferred failure geometry is consistent with the form of the less modified western bowl, which exhibits a planar base.

Triggering by strong seismic shaking from the Alpine Fault appears likely, but an aseismic origin cannot be precluded. AF earthquakes have also been suggested as the likely trigger for other rock avalanches in the AFZ (Wright, 1998; Chevalier et al, 2009).

A typical Alpine Fault earthquake of about Mw 8 would be expected to generate prolonged shaking at Paringa, with intensities of up to MM X (Smith, 2002) and peak ground accelerations possibly in excess of 1g. Local site amplification effects would be expected due to the ridge topography of Ward Hill, and the highly fractured cataclasite/mylonite above the fault plane.

It is thought that progressive failure may have occurred through the fractured mylonites at the head under intense, prolonged seismic shaking, allowing basal slide release through the gouge/cataclasite. Bozzano et al., (2011) have shown the potential for such progressive failure in similar closely fractured rocks, by dynamic numerical modelling of the 1783 Scilla coseismic rock avalanche in Italy. Modelling indicated the development of tension cracking and plastic zones in a suite of fault cataclasites and closely fractured metamorphics, leading ultimately to slope failure.

The debris fan down-slope of the Ward Hill bowl indicates it has been enlarged by subsequent erosion. Dicks Creek is believed to have cut headwards into the lip of the source area depression, eventually breaching the bowl and providing an outlet channel for debris flows from the upper catchment (Figure 2). Debris flows probably originated as rockslides in the fractured mylonites forming the headscarp of the bowl (Figure 6).

A number of studies have shown that rapid rockslides may transition to debris flows when they override and incorporate saturated substrate materials, a process attributed to liquefaction by rapid undrained loading (Sassa, 1988; Hungr & Evans, 2004). At Dicks Creek, rapid rockslides from the headscarp area are believed to transition to debris flows as they over-ride the apron of older slide debris at the toe. Such debris is likely to be a loose mixture of gravel, sand and silt, derived from the disaggregation of fractured mylonite. Saturated conditions would be expected, due to the high annual rainfall (>5000mm). The resulting debris flows would transport material from the bowl to the debris fan, scouring the channel floor and entraining additional regolith and vegetation.

In contrast, the western depression shows no fresh rockslide activity, has not been breached by stream erosion, and appears relatively unmodified in form.

Rockslides on the Ward Hill headscarp could be triggered by both seismic events and extreme rainfalls common in the area. Because of the quiescence of the AF since 1717, there are no historic records of coseismic rockslide-debris flows associated with the AFZ. However, a major coseismic rockslide-debris flow has recently been reported following an earthquake in the Fiordland region to the south, in similar steep, high rainfall, forested terrain (Hancox et al, 2003).

Preliminary field evidence from the Dicks Creek debris fan supports the hypothesis of major coseismic debris flows from the bowl. Botanical studies of the forest growing on debris flow deposits north of the creek indicate no trees likely to be older than about 300 years. This implies a significant phase of forest destruction by debris flows about 300 years ago, roughly co-incident with the 1717 AF earthquake.

Coseismic rockslide-debris flows from future AF earthquakes (and associated aftershocks) are likely to be followed by post-seismic rainfall induced landsliding. Such events are widely reported when heavy rainfall follows major quakes in mountainous areas (Dadson et al., 2004). Seismically weakened rock slopes may undergo sliding failure with increased pore-water pressures, (and loose debris re-mobilise), generating new debris flows. Elevated levels of landslide activity may continue for some years, until the catchment eventually stabilizes.

Young regenerating vegetation covers the headscarp and floor of the source area bowl. It appears to be the result of relatively recent forest destruction by small scale rockslide – debris flows or debris avalanches, likely triggered by extreme rainfalls. Debris flows from such events are likely to have deposited the fan levees along the sides of Dicks Creek.

A new AF earthquake has an estimated probability of up to 40% in next 50 years (Rhodes & Van Dissen, 2003). Resulting coseismic and post-seismic (rainfall induced) rockslide-debris flows would likely present a hazard to State Highway 6, the Dicks Creek bridge and buildings on the fan. Post-seismic events could continue for a period of some years, until revegetation eventually stabilizes the catchment.

Similar seismic induced landslide hazards would be expected in steep catchments throughout the adjacent Westland region in the event of a new AF earthquake, and may pose risks to communities and infrastructure.

7 CONCLUSIONS

Two large bowl-shaped features on a hillside at Paringa are inferred to be source area depressions of ancient rock avalanches. They lie in fractured mylonites and cataclasites of an abandoned thrust nappe of the Alpine Fault, 1km from the current active trace. The failures were probably triggered by major earthquakes (Mw 8) on the Alpine Fault, following glacial ice withdrawal.

The Ward Hill feature has been subsequently enlarged by rockslide-debris flows down Dicks Creek, that have built a large debris fan on the valley floor. They are believed to be triggered by both Alpine Fault earthquakes and extreme rainfalls. Evidence from initial botanical studies of the forest on the fan indicates a major debris flow event roughly coincident with the last Alpine Fault earthquake in 1717.

There is a high probability of a further Alpine Fault earthquake in the next 50 years. Coseismic, and rainfall induced post-seismic rockslide-debris flows are considered likely to result, presenting a hazard to SH6 and buildings on the fan.

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