

## Evidence of a post-glacial rock avalanche impact on Lake Wanaka, New Zealand

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**ABSTRACT:** The Lake Wanaka Rock Avalanche is a large translational rockslide (est. volume  $5\text{--}10 \times 10^6$  m) near the head of Lake Wanaka in the Southern Alps. Failure occurred in the early post-glacial era, on steep schist slopes weakened by toppling. The rock avalanche impacted the lake and a large tsunami is inferred. The trigger was likely a seismic event or extreme rainfall. There is a high probability of an Mw 8 earthquake on the nearby Alpine Fault (Australian-Pacific plate boundary) in the next 50 years. The quake is likely to trigger rapid “first-time” rockslides around the steep lakeshore, and the lakeside town of Wanaka is potentially at risk from any earthquake generated tsunami. The public needs to be informed of the risk, and advised to immediately move from shoreline areas to higher ground after a strong earthquake.

### 1 INTRODUCTION

The resort town of Wanaka (pop. 10,000) is located on the shoreline of an alpine lake, and is potentially at risk from tsunami generated by rockslides, delta collapse, fault displacements and seiche. During the peak holiday season the population in the region rises to about 40,000, with many people engaged in activities along the shoreline, and camping nearby.

The risk is elevated by the current high probability of a major earthquake on the nearby Alpine Fault that forms the Australian-Pacific plate boundary (Fig. 1). This would subject the Wanaka region to strong, prolonged ground shaking.

A preliminary examination of the shoreline of Lake Wanaka has identified a number of past rockslides, and areas susceptible to rockslides (Fig. 1). This paper concerns the Lake Wanaka Rock Avalanche, a large early post-glacial landslide near the head of the lake.

### 2 GEOLOGICAL SETTING

The rock avalanche is located in the Southern Alps 45 km from the Alpine fault, the Australian-Pacific Plate boundary (Fig. 1). Oblique plate collision results in earthquakes of up to Mw 8, with an average return period of about 300 years, the last in 1717 (Berryman et al., 2012). There is an estimated 30% probability of an Alpine Fault earthquake in the next 50 years. This would likely cause MM7-MM8 intensity shaking in the Lake Wanaka region

(Opus, 2005), with topographic amplification probably generating higher intensities on steep alpine ridges.

Bedrock is foliated mica schist, typically fissile along schistosity. Strong quartz rich rock units alternate with weak, mica rich horizons. The rock is tectonically deformed, dipping to the east at  $50\text{--}70^\circ$ . Foliation shears are common, and there are joint sets orthogonal to foliation.

The Southern Alps were heavily glaciated during the Pleistocene, leaving deep U-shaped valleys on ice retreat about 18,000 years ago. Lake Wanaka formed behind a terminal moraine at Wanaka, and was initially at about 300 m altitude, 20 m above current level.

With deglaciation, slow, deep seated toppling developed to depths exceeding 50 m, on inward dipping steep slopes on the eastern side of the lake, including the rock avalanche site (Halliday, 2010). This weak toppled rock is vulnerable to rapid rockslides, and slowly creeping debris landslides. Steep shoreline areas with outward dipping schistosity are also landslide prone.

There are rockslide susceptible slopes up to 700 m high on the Wanaka peninsula close to the town (Fig. 1). Similar slopes extend north along much of the eastern shoreline of the lake.

The vulnerability of the region to rapid rock slope failure was illustrated in 2007, when the North Young rockslide ( $11 \times 10^6$  m<sup>3</sup>), 15 km north of Lake Wanaka, formed a 70 m high landslide dam that threatened a dam-breach flood (Bryant, 2010; Massey et al., 2011).

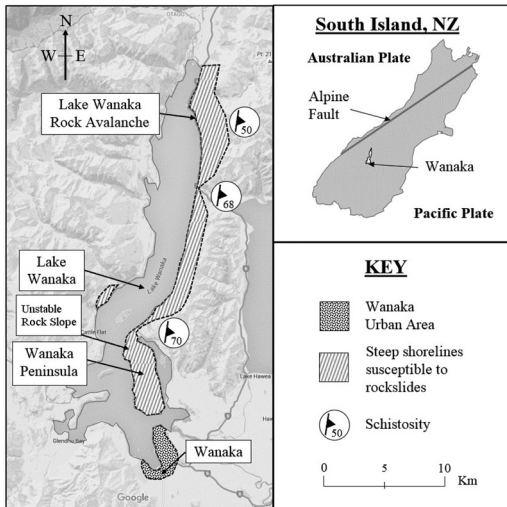


Figure 1. Lake Wanaka showing key locations and steep shorelines susceptible to rockslides.

An Mw 5.8 earthquake occurred in the Matukituki Valley 30 km northwest of Wanaka in 2015. There were no reports of shoreline rockslides, but seiche waves with an estimated height of 0.5 m were observed at Wanaka.

### 3 TOPOGRAPHY AND CLIMATE

The Lake Wanaka rock avalanche is located at Sheepskin Creek near the head of the lake, 40 km from Wanaka (Figs. 1, 2). The lake is at 280 m above sea level, and the surrounding mountains rise steeply to altitudes of over 1000 m.

Climate is cool temperate, with annual rainfall of about 2000 mm. The vegetation is scrub and regenerating forest near the lake, changing to tussock grassland at higher altitudes.

### 4 MORPHOLOGY OF THE ROCK AVALANCHE AND ADJACENT FEATURES

The deposit has been identified as a rock avalanche on the basis of surface morphology and internal stratigraphy. It is an open-slope, Type II feature (Nicoletti & Sorriso-Valvo, 1991), with a characteristic fan shape (Fig. 2).

Runout distance is about 1.4 km (excluding the submerged toe), and the ratio of H/L (Fall height/Run-out) for the sub-aerial section is 0.6. Both the

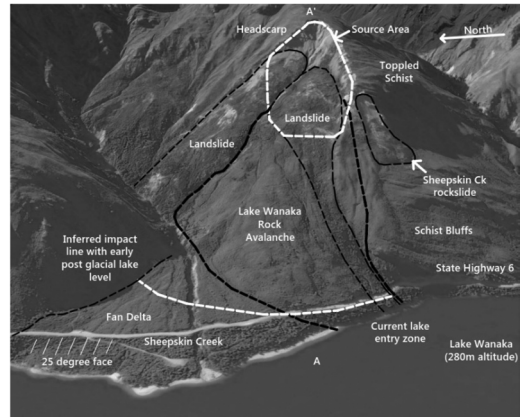


Figure 2. The Lake Wanaka Rock Avalanche.

source area and the deposit have been significantly modified by later geological processes.

#### 4.1 Source area

The location of the source area is shown on Figure 2. A prominent V shaped scarp up to 50 m high extends around the source area, and represents the original rockslide headscarp, albeit modified by retrogression and erosion. The floor of the source area is now partially occupied by two slowly creeping landslides.

One landslide is located above the rock avalanche debris, with a narrow extension down a stream gully to the lake. The surface is undulating, with numerous internal scarps and tension cracks.

The other slide extends downslope to Sheepskin Creek. It has several active internal scarps, and appears to be moving in response to erosion at the toe.

#### 4.2 Rock avalanche

The rock avalanche deposit is fan shaped, with radiating longitudinal ridges and depressions (Fig. 2).

The debris fan widens downslope, forming an arcuate depositional lobe with a slope of about 25°. The northern (left) side of the deposit extends beneath the adjacent fan delta of Sheepskin Creek.

Rock avalanche debris outcrops along a 300 m long arcuate section of the modern lakeshore (Figs. 2, 4). Prior to the deposition of the fan delta, it likely extended in an 800 m long arc along the early post-glacial shoreline that was 20 m higher than at present.

The deposit continues below the lake, but there is no obvious evidence of the underwater extent on existing bathymetry, probably due to the low resolution of the survey and fan delta deposition.

#### 4.3 Adjacent features

Steep schist slopes lie to the south of the rock avalanche (Fig. 2). Those adjacent to the source area have a rippled appearance due to deep-seated toppling (Halliday, 2010). Below the toppled zone are steep bluffs with inward dipping schistosity (50°) that extend down to the lake.

In 2002, a rapid translational rockslide of 100,000 m<sup>3</sup> (Sheepskin Creek rockslide) occurred on a 35° slope in toppled schist adjacent to the source area (Halliday, 2008). It travelled over a steep bluff, and continued 300 m downslope, coming to rest on a glacial bench (Fig. 2).

A prominent, debris-flow dominated fan delta from Sheepskin Creek adjoins the rock avalanche, and overlies the northern toe of the deposit. It slopes at about 10°, and has large surface and sub-surface boulders. The creek is entrenched 10–15 m into the fan, and the channel is a conduit for debris flows.

The slope steepens in the frontal section of the fan between State Highway 6 and the shoreline, with the gradient changing at about 20 m above lake level. This steepening is most apparent along the northern 300 m section of the fan (Fig. 4), where the slope is locally up to 25°, but also occurs to a lesser extent to the south.

It is inferred that the fan delta originally formed when the lake was 20 m higher in the early post-glacial era. With subsequent falling lake levels, the original delta face was modified by continuing debris flows and erosion.

The age of the fan delta constrains the timing of the prior rock avalanche to the early post-glacial era.

## 5 VOLUME AND INTERNAL STRUCTURE

The inferred subsurface geology of the rock avalanche is shown on cross section A-A' (Fig. 3). There is no data available on the extension beneath the lake, and this part of the model is speculative.

Estimates of rock avalanche volume must therefore be based on the source area rather than the deposit. Using the approximate dimensions shown in the model, volume is estimated at 5–10 × 10<sup>6</sup> m<sup>3</sup>.

Because of the uncertainties involved, this volume is considered provisional only. More accurate estimation would require subsurface geological data and a high resolution bathymetric survey.

Exposures of the internal structure of the deposit are limited. In the toe region, shoreline outcrops and road cuts above SH6 show the near-surface debris is composed of gently dipping, highly fragmented but relatively un-disaggregated schist (Fig. 5). The original stratigraphy of quartz-rich and mica-rich layers can occasionally be traced, with finer fragmentation evident in the

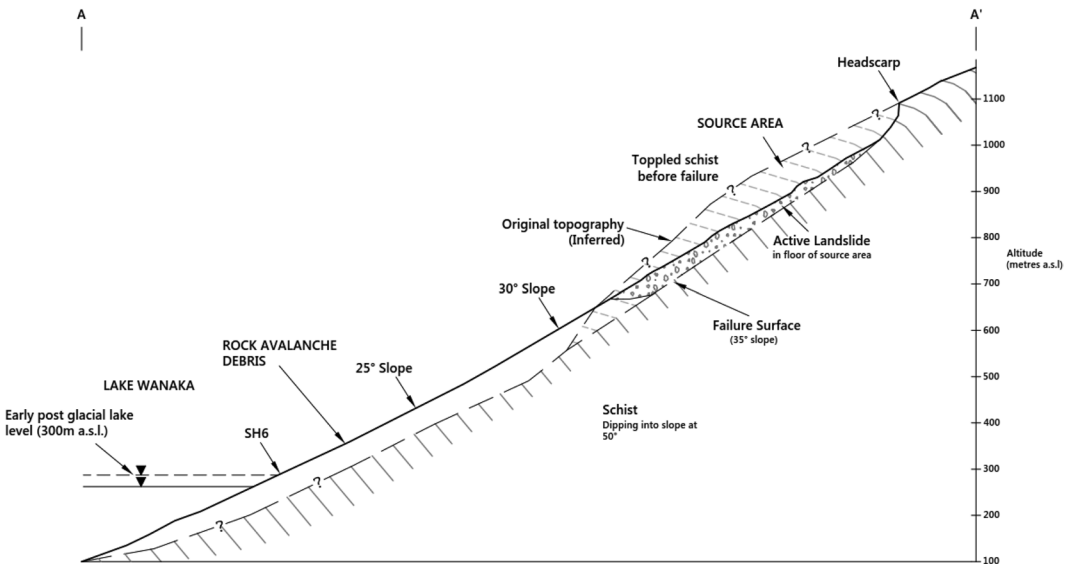


Figure 3. Cross section AA' through the rock avalanche source area and deposit.

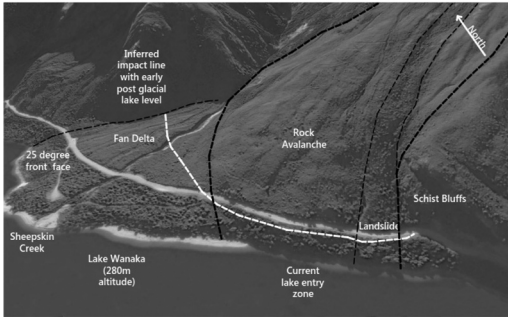


Figure 4. Oblique aerial view of the rock avalanche toe area.



Figure 5. Highly fragmented but relatively un-disaggregated schist with fine gravel to boulder sized clasts, exposed above State Highway 6.

micaceous horizons. The clasts are slabby due to fragmentation along schistosity, and range in size from fine gravel to boulders. Individual boulders near the surface of the deposit show a “jig-saw” pattern of incipient fragmentation. This combination of geological features is characteristic of the “body facies” of rock avalanche deposits (Dunning, 2004).

Exposures in the banks of Sheepskin Creek on the extreme northern lateral flank of the deposit, show weakly stratified slabby schist gravel, with a variable content of boulders lacking “jig-saw” fragmentation.

Boulders up to several metres in diameter are scattered over the surface of the rock avalanche deposit, and a thin sub-surface bouldery layer is evident in some exposures. These may possibly represent a superficial “carapace facies”.

The basal contact between the rock avalanche debris and the underlying substrate is not exposed. On cross section A-A’ (Fig. 3) the deposit is inferred to lie on schist, but glacial and post-glacial deposits may be locally present.

## 6 FAILURE MECHANISM AND GEOLOGICAL HISTORY

The failure is inferred to be a rapid translational slide in toppled schist, with a similar mechanism to the adjacent small 2002 Sheepskin Creek rock-slide (Halliday, 2008). It is thought that failure was likely to have been progressive, with strain weakening lowering the friction angle on a highly micaceous failure surface to a residual value of 20–25°. This eventually resulted in rapid sliding on the 35° sloping hillside.

The final trigger was probably a seismic event such as an Alpine Fault earthquake or extreme rainfall. Timing is inferred to be early post-glacial.

The rock avalanche spread as it travelled downslope, due to lack of lateral confinement. It widened further at the base of the slope, forming a broad arcuate lobe that impacted the lake, then 20 m higher than current level. The length of impact was possibly up to 800 m, and a large displacement wave is inferred.

Slow landslides subsequently developed in the evacuated source area, with one slide extending in a narrow strip down to the lake, and the other to Sheepskin Creek.

The creek built a fan delta out into the lake, dominated by debris flows from the landslide and other areas of the catchment. As the lake level fell in post-glacial times, the creek entrenched into the fan.

## 7 TSUNAMI GENERATION

A large displacement wave would be expected from the impact of the rock avalanche. However, it cannot be accurately quantified due to lack of data on the submerged volume and impact velocity.

Hancox et al. (2012) adopted an empirical approach to estimation of landslide generated tsunami.

nami wave height. Using data from international and New Zealand examples, they established a linear log-log relationship between entry volume and near-field (within about 1 to 5 km) maximum vertical wave run-up height. This relationship applies to rapid landslides, including rock avalanches, with fall heights of 200–400 m or greater.

Cross section A-A' (Fig. 3) shows an interpretation of the subsurface geometry of the rock avalanche. The projection below original lake surface is speculative, but based on the total volume estimate of  $5\text{--}10 \times 10^6 \text{ m}^3$ , an entry volume of up to several million cubic metres appears feasible.

The Volume/Wave height graph in Hancox et al. estimates maximum near-field wave run-up heights of 25 m for an entry volume of  $1 \times 10^6 \text{ m}^3$ , and 40 m for  $2 \times 10^6 \text{ m}^3$ . These examples illustrate the potentially large size of a tsunami wave from the rock avalanche.

## 8 DISCUSSION

The evidence of a past rock avalanche impact on Lake Wanaka illustrates the tsunami risk posed by the steep, unstable schist slopes of the lake. The risk is currently elevated by the high probability of an Alpine Fault earthquake in the next 50 years.

The rock avalanche and the adjacent rapid Sheepskin Creek rockslide, both originated on  $35^\circ$  scarp slopes weakened by toppling. They illustrate the rapid rockslide potential of steep scarp slopes along the eastern shoreline of the lake.

Shoreline areas considered susceptible to rockslides are shown in Figure 1. An estimated 20% of these areas have slopes of about  $35^\circ$  or greater directly above the shoreline, likely to be susceptible to rapid failure and tsunami generation.

The shoreline area presenting the greatest rockslide tsunami risk to Wanaka is likely to be the Wanaka peninsula, at the nearest point 1.5 km from the residential area, and 5.5 km from the low lying town centre (Fig. 1). Steep slopes around the peninsula are susceptible to rapid failure, and show geomorphic evidence of past rockslide events (Fig. 6). Due to the closeness of Wanaka, seismically triggered rockslide tsunamis could reach the town within minutes of the cessation of shaking, leaving little or no time for effective response.

Potential hazards on the peninsula are illustrated by an unstable, 400 m high,  $45^\circ$  sloping rock slope, 9 km up the lake from the nearest Wanaka residential area, and 12.8 km from the town centre (Fig. 6). It forms a residual spur between the evacuated source areas of two previous large rockslides.

A 300 m long scarp crosses the crest of the spur, observed directly from the air and on aerial photographs. The scarp indicates incipient downslope

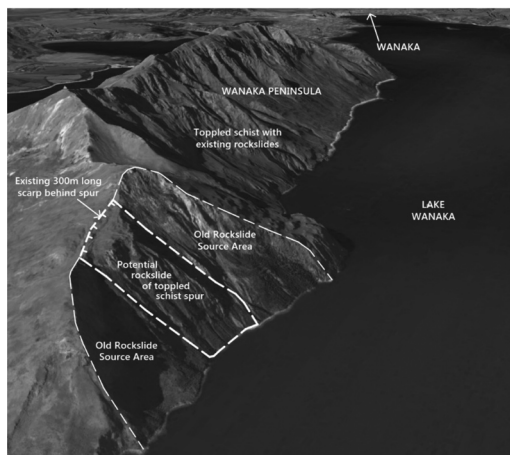


Figure 6. The Wanaka Peninsula showing existing rockslides and a potential future rockslide in the foreground. Note the location of the town of Wanaka in the background.

displacement of the weak, toppled schist rock mass, probably occurring along steep outward dipping joints. Failure of the spur could possibly result in a rapid rockslide of up to about  $3 \times 10^6 \text{ m}^3$  impacting the lake, generating a large tsunami. More detailed studies are clearly required to estimate the potential tsunami run-up height at Wanaka from the failure of this and other unstable slopes.

Scarp slope failures in schist are generally considered atypical, with most reported failures associated with dip slopes. Both types can be slow or rapid, depending on detailed geology and slope.

Many large, slowly creeping landslides that develop in the Otago schist terrain form on dip slopes. These landslides, including several on the eastern side of the Wanaka peninsula, have moved many tens of metres, and residual strength conditions pertain. They are generally more obvious than steep, potentially active scarp slopes, and have in recent years been subject to what could (arguably) be disproportionate focus in hazard evaluations.

Now that toppling failure mechanisms in schist are well understood, the importance of giving due regard to the potential for a rapid “first-time” slide in what may appear to be a “stable” scarp slope, should be an integral part of any seismic hazard evaluation.

No previous studies of tsunami risk on Lake Wanaka have been published, although many of the alpine lakes in the lower South Island have been assessed eg. Hancox et al., 2012. A future detailed study should address the full range of tsunami generators, including potential “first-time” scarp and

dip slope rockslides, delta collapse, lake-bed fault movements and seiching. A valuable adjunct to this work would be high resolution bathymetric data to detect past rockslide deposits on the lake bed.

Future “first-time” rockslides around the lake will most likely be triggered without prior warning by seismic events, although non-seismic failure due to rainfall or progressive strength loss is possible. The most effective means of risk reduction is probably to ensure the public are well informed. Disaster preparedness for Wanaka and surrounds should include reminders of the importance of retreating from the lakeshore to higher ground immediately following any strong earthquake. This is similar to the tsunami response advice provided to New Zealand coastal residents in the event of a strong earthquake.

Real-time monitoring of identified unstable rock slopes such as that on the Wanaka Peninsula, could be an additional tsunami risk management tool, providing possible early warning of impending failure from non-seismic causes. Such monitoring has been installed on schist landslides in the reservoir of the nearby 60 m high Clyde Dam (Gillon & Hancox, 1992), and is also used in the Norwegian fiords to manage rockslide tsunami risk (Harbitz et al., 2014).

## 9 CONCLUSIONS

A rock avalanche impacted Lake Wanaka in the early post-glacial era, generating a large displacement wave.

The failure began as a translational slide on a steep mountainside, pre-conditioned by deep-seated toppling in a schist scarp slope. Total debris volume is provisionally estimated at  $5-10 \times 10^6$  m<sup>3</sup>, with a large but undetermined volume entering the lake and generating a tsunami. The final trigger may have been a seismic event such as an Alpine Fault earthquake or extreme rainfall.

There is evidence of many past rockslides and areas with rockslide susceptibility around the steep-sided lake. More detailed study of tsunami risk from “first-time” landslides developing on steep scarp slopes is needed, particularly in view of the high probability of strong shaking in this district from the next Alpine Fault earthquake.

The most effective means of risk management is ongoing publicity emphasising that in steep

schist terrain (especially where shoreline slopes exceed 35°), tsunamis present a significant risk to lake shorelines. The necessary response is to retreat from the lakeshore to higher ground immediately following any strong earthquake.

Real-time monitoring of high risk rock slopes could also be utilised, to give early warning of potential rapid failure from non-seismic causes.

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