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Formation of the Waiho Loop terminal moraine, New Zealand

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ABSTRACT: We present an analysis of the formation and evolution of the Waiho Loop terminal moraine. Recent work has shown that the Loop comprises mainly rock avalanche material, and suggested its formation was associated with a rock-avalanche-driven glacier advance. New evidence from shallow seismic studies between the range front and the Loop suggests (i) that the presence of a basal trough critically influences glacier behaviour and moraine formation; and (ii) that the volume of the Waiho Loop is significantly greater than previously thought. A one-dimensional dynamic ice flow model is used to test two rock-avalanche-based scenarios for the formation of the Loop: first, that a rock avalanche caused a significant advance of the glacier terminus from a location within the confined mountain valley to the Loop; and second, that the rock avalanche occurred while the glacier was retreating with its terminus close to the position of the Loop. It is shown that this terminal moraine was not the result of a glacier advance. Copyright © 2014 John Wiley & Sons, Ltd.

KEYWORDS: debris covered glacier; Franz Josef Glacier; numerical modelling; overdeepened trough; rock avalanche debris.

Introduction

Franz Josef Glacier, on the west of the South Island, New Zealand (Fig. 1), is one of the most intensively studied glaciers worldwide. The prominent, steep-sided arcuate piedmont terminal moraine of the Franz Josef Glacier, known as the Waiho Loop, has been of particular interest since it was identified as evidence of a Southern Hemisphere Younger Dryas event (e.g. Mercer, 1988; Denton and Hendy, 1994). The moraine has been interpreted to indicate inter-hemispheric connectivity and synchronicity of climate change (Denton and Hendy, 1994; Broecker, 2000) or not (Singer *et al.*, 1998). It has also been inferred to indicate a major Lateglacial cooling event in New Zealand (Anderson and Mackintosh, 2006).

More recent research has indicated that the moraine may be Early Holocene rather than Lateglacial (10.5 ± 0.2 ka; Barrows *et al.*, 2007), although this interpretation is controversial (e.g. Applegate *et al.*, 2008) and more recently the production rate for ^{10}Be in the Southern Hemisphere has been revised (Putnam *et al.*, 2010b) and true ages are likely to be ~15% older. More significantly, Tovar *et al.* (2008) and Shulmeister *et al.* (2009) suggested that the Loop moraine may not reflect climate variation at all. Attention was drawn to its composition dominated by rock-avalanche debris, and it was shown that it was the result of a landslide sourced from the upper Franz Josef catchment, because its lithology is dominated by angular quartzo-feldspathic sandstone found there (Tovar *et al.*, 2008). They suggested that ~0.1 km^3 of debris deposited onto the glacier ablation zone could have caused the glacier to advance 3 km from a position close to Canavan's Knob down-valley to the Waiho Loop location (Fig. 2), where the ~60-m-high terminal moraine was constructed. This was challenged by Vacco *et al.* (2010a, b), whose modelling suggested that the advance of the Franz Josef Glacier could not be a result of rock avalanche because there was no widespread, hummocky, glacial stagnation deposit up-valley of the Loop; however, hummocky moraine has been noted in river cuts within about 500 m of the inner margin of the Waiho Loop (Shulmeister *et al.*, 2010a) so this ablation moraine is present but is mostly buried by subsequent outwash deposits. Additionally, Vacco *et al.* (2010a) concluded that a rock avalanche of 4–20 times the estimated debris volume of Tovar *et al.* (2008) is required to construct the terminal moraine, as their model showed that only a small percentage (5–25%) of material from the rock avalanche will end up in the Loop moraine deposit.

This paper presents a detailed explanation for the formation and preservation of the Waiho Loop. This uses newly acquired shallow seismic reflection data to clarify the topographic context of the Loop. We also use an ice flow model to investigate the effects of rock avalanche debris on the behaviour of the Franz Josef Glacier and the development of the Loop, and we explain how it has survived erosion by the powerful Waiho River.

Approach

Seismic surveys

To investigate the subaerial topography into which the Waiho Loop was emplaced, shallow seismic reflection surveys were carried out to map subsurface structures upstream of, and across, the Waiho Loop (Figs 3 and 4). The surveys were carried out along one line (NW) west of the Tatare River and another (N) east of the Tatare. The latter continued on the downstream side of the Loop, but access difficulties prevented the former from doing so. The energy source used for acquiring seismic data was an accelerated weight drop of 25 kg, at an interval of 13.2 m. A StratVisor NZ (San Jose, CA, USA) receiver was used and data were processed using Landmark Geophysical's ProMAX processing software. The data from these two surveys are shown in Fig. 3 and interpreted in Fig. 5.

The clear reflectors in both sections, sloping upward towards the Waiho Loop, indicate the presence of an overdeepening west of the range front whose distal end coincides with the location of the Loop. This is supported by the presence of a surface outcrop of Greenland Group bedrock immediately north of the Loop (Fig. 5). The northward tectonic motion of the Australasian Plate relative to the Pacific Plate east of the range front Alpine fault takes place at about 30 m per millennium (e.g. Townend *et al.*, 2012), so

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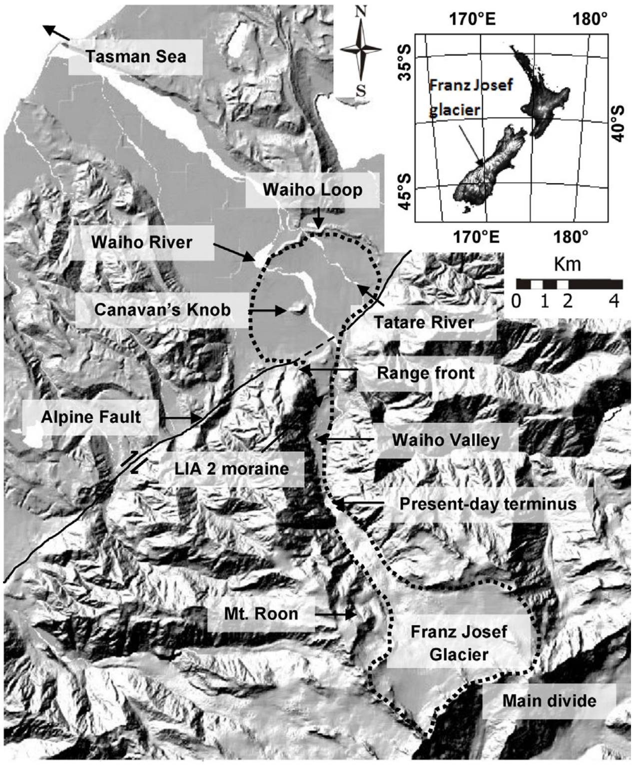

Figure 1. Location of the Franz Josef Glacier in Westland, New Zealand, based on a 1986 digital elevation model, with locations referred to herein indicated. Note the Waiho Loop has been offset ~500 m to the north-east due to motion of the dextral strike-slip plate-boundary Alpine Fault since it was emplaced. The dashed lines show the estimated extent of the glacier when its terminus was at the Loop.

the Franz Josef Glacier has formed and occupied this basin only in the last 200 000 years, i.e. during the last two major glaciations. Thus, the floor of the overdeepening seems likely to comprise bedrock overlain by glacial and glaciolacustrine deposits, assuming that a major glaciation would remove interglacial outwash deposits. In both sections (Fig. 4) the reflectors indicate accretion on the distal upslope of the overdeepening, and onlapping of surface-parallel deposits onto these accreted layers. The uppermost layer of material is known from near-surface exposures to be fluvial outwash from the Tatare River. The bedrock trough has an estimated maximum depth of 200–300 m, and the maximum depth to the prominent reflectors is about 150 m (Fig. 5). The only other information on the subsurface geology of the Waiho valley comes from the Waiho-1 borehole close to the sea about 10 km down-valley of the Loop (Sutherland, 1996); this showed 250 m of Quaternary gravels overlying older formations.

Both seismic sections indicate that the base of the Loop is ~80 m below the present outwash surface, so its cross-section is roughly as shown in Fig. 5, with a cross-sectional area of about 0.075 km^2. The present-day length of the Loop is ~6 km, and its original length may have been greater due to later erosion of its western end by the Waiho River, so the total volume is approximately 0.5 km^3. This does not include any rock avalanche debris that was deposited after the glacier stagnated and melted out *in situ*, so the volume of the rock avalanche that created the Loop was at least 0.5 km^3.

Model experiments

Mechanics

We use a simple one-dimensional ice flow model for Franz Josef Glacier to investigate the development of the Waiho Loop terminal moraine after deposition of rock avalanche debris on the glacier surface. The change in ice thickness at a cross-section ∂H_i over time ∂t is:

$$\frac{\partial H_\mathrm{i}}{\partial t} = b - \frac{\partial Q_\mathrm{ice}}{\partial x}, \tag{1}$$

where b is the climatic mass balance and $\partial Q_\mathrm{ice}/\partial x$ is the along-flow gradient in the ice flux. Ice moves by internal deformation and basal sliding. Internal flow due to ice deformation Q_def is

$$Q_\mathrm{def} = -\frac{1}{5} B H_\mathrm{i}{}^{(n+2)} \left[\rho_\mathrm{i} g \frac{\partial z}{\partial x}\right]^n, \tag{2}$$

where ρ_i is the density of ice for temperate glaciers (890 kg m^{-3}; Le Meur *et al.*, 2004), g is the gravitational acceleration

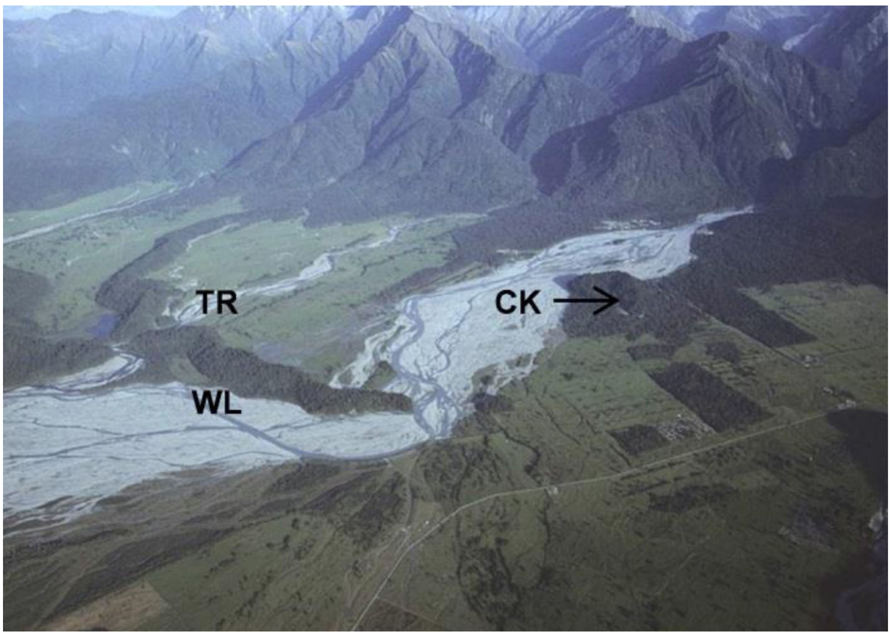

Figure 2. Waiho Loop (WL) terminal moraine, Franz Josef Glacier, Westland, New Zealand, centre-left, looking north-east (photo: G. Denton). The prominent hillock on the near bank of the river between the Loop and the range-front is Canavan's Knob (CK). The Tatare River (TR) is the smaller river on the far side of the Waiho River. For an aerial view of these locations, please refer to Fig. 1. This figure is available in colour online at wileyonlinelibrary.com.

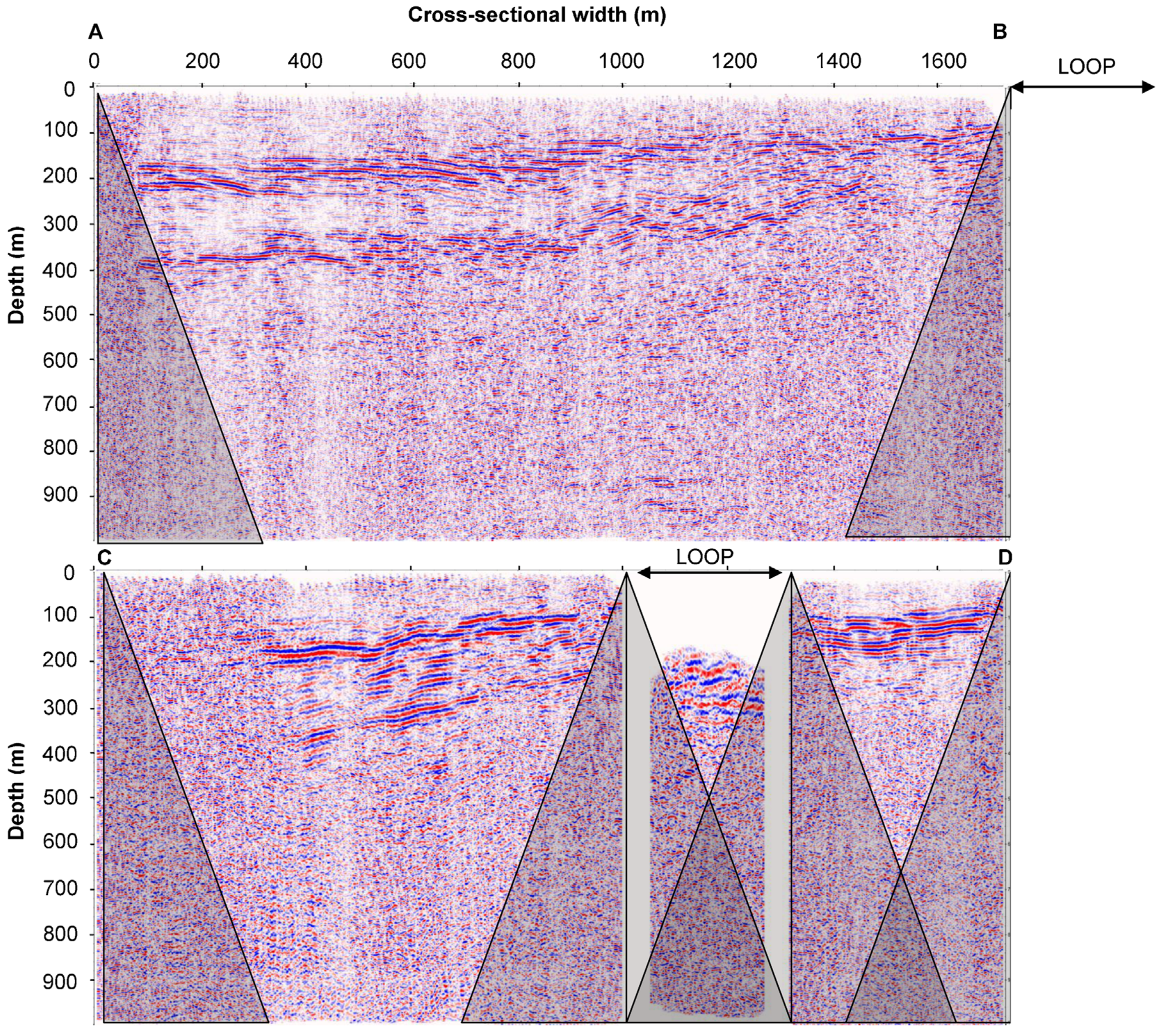

Figure 3. Waiho Loop seismic sections: top is the NW section and bottom is the N section. Shaded areas indicate where data are unreliable. Locations are shown in Fig. 4. This figure is available in colour online at wileyonlinelibrary.com.

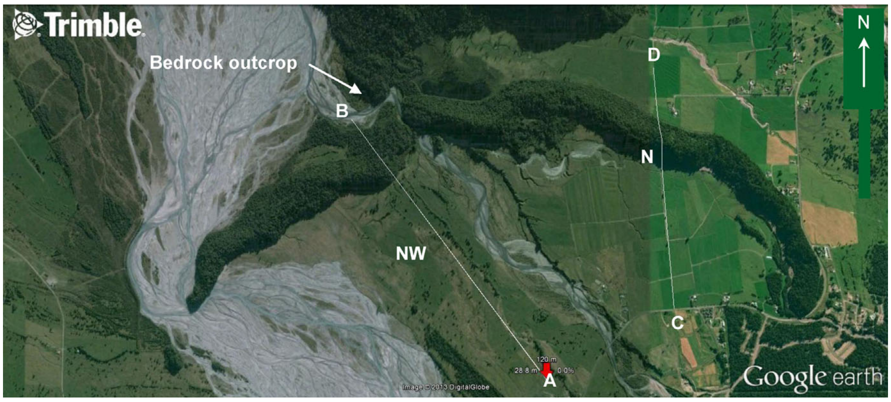

Figure 4. Locations of the Waiho Loop seismic sections N and NW with longitudinal profile from Google Earth (2006) for the NW section. This figure is available in colour online at wileyonlinelibrary.com.

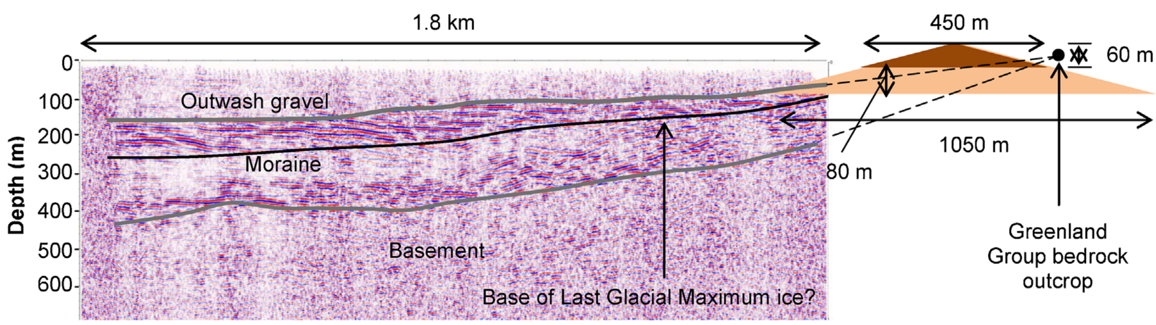

Figure 5. Seismic section NW interpreted and related to Loop position and bedrock outcrop north of Loop with an approximate cross-section of Waiho Loop (top right). Moraine, which possibly represents the base of LGM ice, is overlain by outwash gravels. The level of the moraine (black line) is used for the depth of overdeepening. This figure is available in colour online at wileyonlinelibrary.com.

($9.8\,\mathrm{m\,s^{-1}}$) and B is the temperature-dependent ice creep parameter. For temperate ice $B = 2.4\times10^{-24}\ \mathrm{s^{-1}\ Pa^{-3}}$ and n is commonly assumed to equal 3 (Cuffey and Paterson, 2010). The surface slope is $\partial z/\partial x$, where the x axis points down-glacier and the z axis points upward. The bed slope in the confined valley is taken from bedrock depth estimates by Anderson *et al.* (2008), while the bed slope on the foreplain is constrained by seismic data. The basal sliding component of flow Q_{slide} is approximated by

$$Q_{\mathrm{slide}} = U_s H \tau_b{}^{n-1}, \tag{3}$$

where τ_b is the basal shear stress ($-\rho_i g H_i \partial z/\partial x$). U_s is a coefficient of sliding taken as $3.5\times10^{-7}\,\mathrm{m\,Pa^{-2}\ a^{-1}}$ to yield realistic sliding velocities of 50–75% of the surface velocities, as there is probably a high water table within the glacier due to the temperate perihumid climate. Internal deformation and basal sliding are tuned to match the present-day observations of Herman *et al.* (2011). The model is one-dimensional, so the change in lateral constraint from the confined valley onto the foreplain must be taken into account when modelling ice discharges and flow rates. Ice discharge on the foreplain Q_f is calculated from:

$$Q_f = Q\left(\frac{A_c}{A_f}\right), \tag{4}$$

where A_c is the mean area in the confined valley at each length step x ($\sim5\times10^5\ \mathrm{m^2}$) and A_f is the area at each length step in the foreplain.

The climatic balance b in Eqn (1) depends on the mass balance gradient $\partial b/\partial z$ and the equilibrium line altitude (ELA):

$$b = \frac{\partial b}{\partial z}(z - \mathrm{ELA}). \tag{5}$$

A balance maximum of $8\,\mathrm{m\ a^{-1}}$ is used, reflecting the high precipitation rates in the upper Franz Josef catchment (Griffiths and McSaveney, 1983). A steep mass balance gradient of $0.015\ \mathrm{a^{-1}}$ is required to match present-day surface melting rates on the order of $20\,\mathrm{m}$ w.eq. $\mathrm{a^{-1}}$ at the 2000–2010 terminus, 10.5 km from the main divide, with a present-day ELA of 1850 m a.s.l. (Anderson *et al.*, 2006).

Basal and englacial melting

Basal and englacial melting are commonly ignored in mass and energy balance models, with melting parameterizations for the surface only (e.g. Nakawo and Young, 1982; Han *et al.*, 2006; Reid and Brock, 2010). However, when the ablation zone is covered by debris, the influence of basal and englacial melting on glacier length and mass balance may increase significantly, because a glacier that acquires a debris cover thick enough to suppress surface ablation (Reznichenko *et al.*, 2010) will have a greater proportion of basal and englacial melt to total melt.

Basal melt m_b due to geothermal heat flux and frictional heat follows Cuffey and Paterson (2010):

$$m_b = \frac{G + \tau_b u_b - \kappa_i \Theta_b}{L\rho_i}, \tag{6}$$

where G is the geothermal heat flux (typically $0.05\,\mathrm{W\,m^{-2}}$), u_b is the basal sliding velocity (Q_{slide}/H_i), κ_i is the thermal conductivity of ice ($2.2\,\mathrm{W\,m^{-1}\,K^{-1}}$), and L is the latent heat of fusion for ice ($3.4\times10^5\,\mathrm{J\,kg^{-1}}$). The basal temperature gradient of ice Θ_b is typically $\sim$0.015–0.025 $\mathrm{K\,m^{-1}}$ (Budd *et al.*, 1970; Hooke, 2005). Englacial melting due to strain heating m_s, based on Glen's Flow Law for ice (Nye, 1952; Glen, 1955), is:

$$m_s = \frac{B\tau_{xz}{}^n \tau_{xz}}{L\rho_i}, \tag{7}$$

where τ_{xz} is the englacial stress ($\tau_{xz} = \rho_i g[H_i - z]\partial z/\partial x$). Englacial stress reduces linearly from a maximum at the glacier bed where $\tau_b = \tau_{xz}$ to the surface where $\tau_{xz} = 0$.

Water from rainfall and snowmelt entering Franz Josef Glacier from the surrounding non-glaciated catchments (a total discharge Q_w of approximately 2.0 $\mathrm{m^3\ s^{-1}}$) causes melting due to the advection of heat from relatively warm water to the cooler ice m_{ad} (Shreve, 1972):

$$m_{ad} = \frac{Q_w \rho_w c_w \frac{\partial T_w}{\partial s}}{L\rho_i}, \tag{8}$$

where ρ_w is the density of water ($1000\,\mathrm{kg\,m^{-3}}$), c_w is the specific heat capacity of water ($4180\,\mathrm{J\,kg^{-1}\,K^{-1}}$) and $\partial T_w/\partial s$ is the rate of temperature reduction along the glacier (negative in the direction of flow). When the glacier is near the Waiho Loop, the mean water temperature is estimated as $\sim$6.0°C, based on a mean ablation zone elevation of 700 m a.s.l. Runoff travelling through the glacier from surface melt and from the glacier sides causes melting due to viscous dissipation in the flow water m_f (Shreve, 1972):

$$m_f = \frac{Q_w \rho_w H_i g}{L\rho_i} \tag{9}$$

The modelled glacier-averaged basal and englacial melt is $0.75\,\mathrm{m\ a^{-1}}$ when the debris-covered glacier extends to the Waiho Loop. This is 25% of the total melt discharge in the time (30 years) between the rock avalanche debris covering the ablation zone and all glacier debris advecting past the transient climatic terminus 3 km upstream of the Loop at Canavan's Knob. Glacier-averaged melting caused by geothermal heat flux is $0.01\,\mathrm{m\ a^{-1}}$, melting due to friction at the ice-bed interface is $0.2\,\mathrm{m\ a^{-1}}$, melting due to strain heating is $0.4\,\mathrm{m\ a^{-1}}$, melting due to heat advection is $0.1\,\mathrm{m\ a^{-1}}$ and melting due to viscous dissipation in flowing water is $0.05\,\mathrm{m\ a^{-1}}$. If basal and englacial melting are ignored, the modelled ice thickness would increase by 25 m. Interestingly, if the same quantity of mean basal and englacial melt ($0.75\,\mathrm{m\ a^{-1}}$) is incorporated into a one-dimensional model with a terminus at the Tasman Sea, with the same basal topography used by Vacco *et al.* (2010a), the glacier length reduces by 5 km, which would reduce the overrun of their model (see Shulmeister *et al.* (2010a) for further comment).

Model calibration

The model was initially calibrated by locating the Franz Josef Glacier in its 2000–2010 position. Input variables include ELA, mass balance gradient and ice flow velocities, which are determined by recent observations. Experiments were initialized (i.e. $t = 0$) by finding the steady-state position of the glacier under a constant climate with no rock avalanche debris. At $t = 0.01$, rock avalanche debris covers the entire ablation zone. Any rock avalanche debris deposited above the ELA is assumed to become englacial and to not affect the mass balance gradient. As supraglacial debris is advected

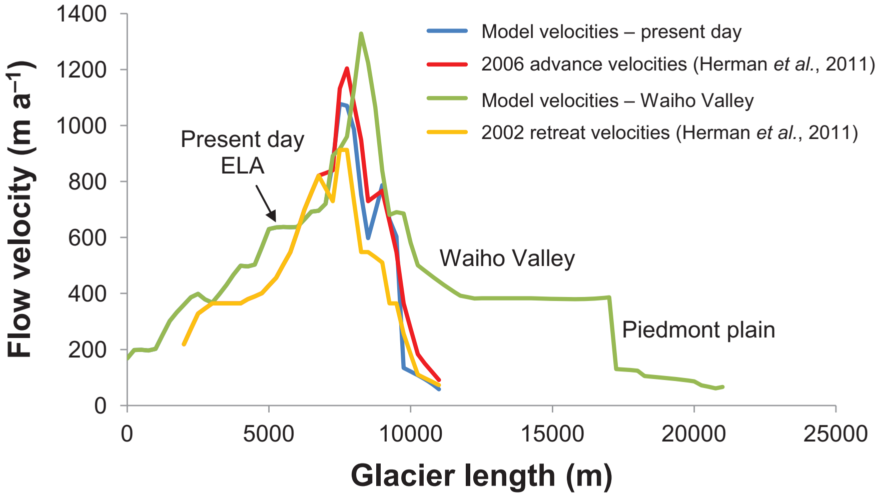

Figure 6. Comparison between observed and modelled flow velocities for the Franz Josef Glacier. Modelled present-day velocities fit closely both observed advance and retreat velocities. Modelled flow velocities for the Waiho Valley are for the glacier when it occupies the Loop position. This figure is available in colour online at wileyonlinelibrary.com.

down-valley, the ablation zone becomes progressively uncovered and surface ablation returns to previous rates. Debris cover also increases basal shear stress slightly due to a rock avalanche debris density of ~2000 kg m^{-3}. In both scenarios outlined below, the period over which the model is run is based on the time taken for debris to advect past the climatic terminus.

Observed ice flow velocities of Franz Josef Glacier during retreat and advance phases in the early 21st century are highest immediately down-valley of the ELA (Herman *et al.*, 2011). Figure 6 compares these observed retreat and advance values with modelled flow velocities for the present-day glacier and for the glacier extended to the Waiho Loop. Flow velocities reduce as the glacier enters the lower Waiho valley (currently non-glaciated), and further slow dramatically once past the range front (15 km from the main divide), where it diverges onto its piedmont plain. Any ice-surface-advected debris disperses in a similar way. Because no flow velocity data are available beyond the present terminus, we use the modelled velocity pattern for the present day and extrapolate these velocities down-valley of the present terminus.

Scenarios

Two previous studies have inferred that advances due to a rock avalanche depositing debris on the glacier surface formed a glacier terminus at the Loop position. First, Tovar *et al.* (2008) postulated that a rock avalanche could have caused an advance from Canavan's Knob to the Loop. Second, Vacco *et al.* (2010a) found that modelling an advance of the glacier with ~9-km-long, 90-m-thick debris cover (which is much greater than has ever been reported for a supraglacial rock avalanche) from a starting glacier length of 12 km (ELA = 1600 m) generates a terminal moraine 4 km down-valley of the actual Loop. Both these theories are tested using our model.

Our hypothesis is that formation of the Loop terminal moraine did not involve an advance. This requires that the glacier terminus must have been at, or very close to, the Loop position, 21 km from the main divide (ELA = 1100 m), at the time the rock avalanche occurred. Like many eastern valley glaciers of New Zealand, the terminus of the Franz Josef Glacier is thought to have retreated to its overdeepened trough margin during the Last Glacial Interglacial Transition (13.0–11.0 ka; Shulmeister *et al.*, 2010b), having extended many kilometres beyond this point at the Last Glacial Maximum (LGM; 23 ka). We suggest that, to develop the Waiho Loop from the landslide debris as a 'dump' moraine (Benn and Evans, 2010) in its present location, the glacier terminus was very close to the present Loop position at the time of the landslide, and the rock avalanche debris would have covered most of the glacier ablation zone and run out past the terminus. At the time of the rock avalanche, it is anticipated that the glacier terminus was retreating from its long occupied (decades to centuries) position near the trough end.

Empirical evidence indicates that the depth of a rock avalanche deposit on a glacier is rarely >20 m (e.g. Hewitt, 2009; Shulmeister *et al.*, 2009; Reznichenko, 2012). The 20-m debris thickness is applied over the approximately 30-km^2 ablation zone. This corresponds to 0.6 km^3 of rock avalanche debris material, but only approximately 0.4 km^3 would contribute to forming the Waiho Loop, because the model demonstrates that debris at the proximal end to the rock avalanche will not be advected to the Loop. As the Loop has an estimated volume of 0.5 km^3, an initial deposit of rock avalanche debris at the terminus of up to 25 m high is required at the onset of ice thickening to cause the moraine to build up to the observed present-day height. The model does not consider the effects of disconnected ice downstream of the climatic terminus continuing to flow towards the Loop under its (small and reducing) surface gradient, nor does it consider that the outwash fan elevation may have been higher. This would reduce the initial deposit height or the ablation zone debris thickness.

Rock avalanche debris at least 25 m deep immediately beyond the terminus is realistic based on three possible terminus profiles illustrated in Fig. 7: (i) the glacier front is steep with rock avalanche debris deposited immediately downstream of the terminus forming an obstacle to glacier advance; (ii) the glacier surface is level with the bouldery foreplain, but the rock avalanche debris is thicker on the foreplain because it decelerates on leaving the ice; (iii) the glacier has retreated into the trough and the rock avalanche debris deposits between the terminus and the trough end, again forming an obstacle to an advance. Scenario (iii) is most likely because:

1. rock avalanche debris will slow down faster on the upward slope of the trough than on the flatter foreplain;
2. the glacier at the time of the rock avalanche is in a state of retreat (but still active), and retreating piedmont glaciers typically have a gentle surface slope in the terminus region (e.g. Malaspina Glacier; Bylot Island Glacier); this is reflected in the numerically modelled glacier (see Fig. 9 at $t = 0$); and

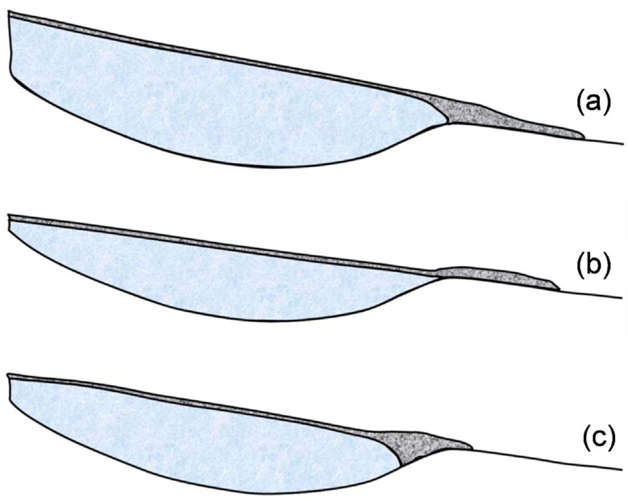

Figure 7. Three possible scenarios for the Franz Josef Glacier terminus upon deposition of rock avalanche debris: (a) the glacier has a steep front with rock avalanche debris forming an obstacle to glacier advance; (b) the glacier surface elevation is the same as the foreplain but the rock avalanche debris is thicker on the boulder forefield forming an obstacle to the advance; and (c) the glacier has retreated into the trough with the rock avalanche debris forming an obstacle to an advance. This figure is available in colour online at wileyonlinelibrary.com.

3. the rate of terminus retreat will reduce with increasing trough depth due to thicker ice taking longer to melt, so (iii) is statistically more likely than (i) or (ii).

Rock avalanche debris can resist bulldozing by a glacier. Numerous glaciers confined by high lateral moraines of similar cross-section to the Waiho Loop and formed by similar dumping processes (e.g. Fig. 8) demonstrate that the lateral ice pressure can be resisted while the glacier ice elevation is increasing. As ice is a non-linear viscous fluid with viscosity proportional to stress (Cuffey and Paterson, 2010), it is unlikely that it can exert significantly higher longitudinal than lateral forces. The bed shear stress exerted by Franz Josef Glacier is about 150 kPa (Anderson *et al.*, 2008); assuming that rock avalanche debris has a static friction coefficient of 1.0 (corresponding to an internal static friction angle of 45°), then a mound of rock avalanche debris 5 m high will be able to resist this pressure. This may explain why push moraines are commonly metre-scale in height and generally no more than 10–20 m (Bennett, 2001); any higher moraine is overtopped rather than pushed.

Figure 8. An example of high, steep lateral moraines near Missoula, Montana, USA. These moraines are similar in cross-section to the Waiho Loop, formed by dumping of supraglacial debris from an elevated ice surface (photo: L. Dodge; formontana.net/moraine.html). This figure is available in colour online at wileyonlinelibrary.com.

Results

Scenario 1: Rock avalanche-driven advance from Canavans Knob

Our model suggests that a glacial advance to the Loop with a starting length of 12 km is not physically possible. Assuming constant ice discharge, we model the volume of ice in the ablation zone as $\sim$0.4 km^3, so when the terminus reaches the Loop, the mean ice thickness will be only $\sim$15 m upstream of the Loop. Moreover, the debris-covered glacier is unable to advance significantly down-valley because the upper ablation zone becomes relieved of debris at a rate significantly greater than the rate terminus advance (ice flow velocities from the ELA to the present terminus are approximately 400–1100 m a^{-1}, in contrast to flow rates of $\sim$200 m a^{-1} in the lower confined valley; Fig. 6).

Our model also contradicts the theory of Tovar *et al.* (2008) that a rock avalanche caused an advance from Canavan's Knob to the Loop. If the ablation zone has a uniform debris thickness <20 m, the volume of material on the surface of the ablation zone is significantly less than our new volume estimate for the Loop. At unrealistically high debris thicknesses of 30–40 m, the modelled glacier reaches the Loop with sufficient surface debris to generate a terminal moraine only of approximately 0.05 km^3.

Scenario 2: No advance: terminus at the Loop position

The climatic terminus is defined as the terminus of the glacier given by the *prevailing* climate. Thus, it may be *transient* and is not necessarily the steady-state terminus. Its location is determined by running the model without debris on the glacier to determine the length of retreat over the modelled period (30 years). The numerical model indicates that the drastic mass balance alteration due to the rock avalanche caused a negligible advance (<250 m) before the rear of the debris-covered ice passed the transient climatic terminus at Canavan's Knob (Figs 1 and 2). The presence of the trough and the rock avalanche debris obstacle reduced mean ice flow velocity at the terminus to 50 m a^{-1} and thus prevented the glacier from advancing significantly; the glacier responded by thickening. Without the trough, and using the profile of the present-day fan as the glacier bed, the modelled glacier advances 1.5 km farther down-valley of the Loop over the time taken for the debris to pass the transient climatic terminus, and did not develop a prominent terminal moraine.

After 10 years, the rear of the debris has advected down-valley about 6 km from the ELA; modelled ice at the terminus is higher than the top of the developing moraine, which is beginning to form (Fig. 9) by dumping material from the top of the terminus. The glacier thins where the ice surface is free of debris but continues to thicken where the glacier is debris covered until 25 years after the rock avalanche.

The model indicates that no substantial advance occurred, but the terminus surface elevation increased by about 140 m over 30 years, before the rear of the debris-covered ice passed the transient climatic terminus and ice supply to the piedmont lobe ceased. The terminal moraine was not overtopped by ice, but increased in elevation by dumping of supraglacial debris. Following cessation of ice supply to the piedmont lobe the ice front ceased to increase in height and the ice body slowly downwasted leaving ablation moraine between the new terminus and the Loop (Fig. 9; $t = 30$). After

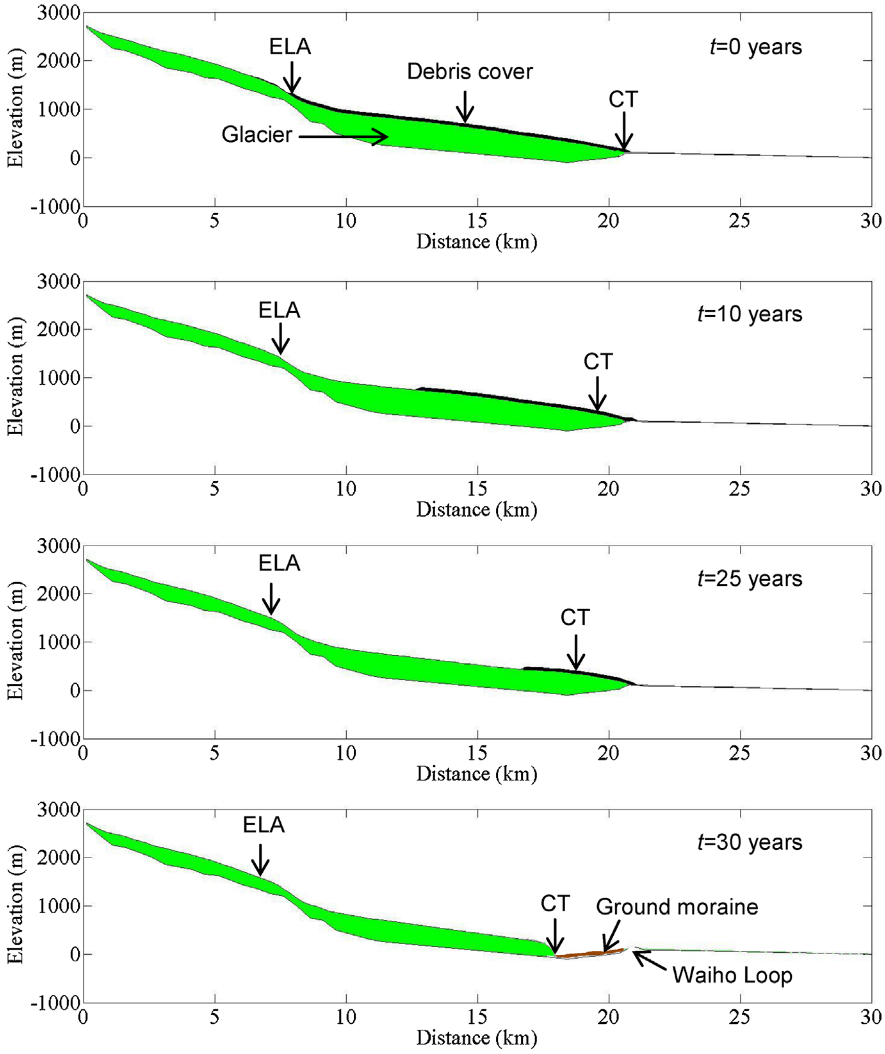

Figure 9. Model outputs for a 'no advance' scenario for the formation of the Waiho Loop. The rock avalanche debris thickness of 10 m is exaggerated 6× on the cross-sections for clarity. CT refers to the (transient) climatic terminus. After 10 years, the debris has been advected down-valley by a maximum of 6 km due to high ice flow velocities and the terminal moraine is building up. By 25 years, the debris covers the lower glacier tongue and the return to normal ablation rates in the upper to mid ablation zone results in relative thinning of the glacier there. After 30 years, the rear of the debris has passed the transient climatic terminus and building of the terminal moraine ceases. Note that the present-day elevation of the alluvial fan is used down-valley of the Loop. This figure is available in colour online at wileyonlinelibrary.com.

an additional 75 years, the climatic terminus re-established a further 4 km upstream at the location of the Little Ice Age 2 moraine (Fig. 1).

In summary, our geophysical and model data suggest that the Waiho Loop formed from a large (~1 km^3) rock avalanche covering the entire ablation zone of the Franz Josef glacier at a time when the terminus was at the position of the Loop, at the distal end of the trough. Our modelling demonstrates that substantial advances from terminus positions both in the confined valley and a short distance onto the piedmont plain (i.e. Canavan's Knob) cannot generate the large terminal moraine at the Loop, because most of the rock avalanche debris cannot then be transported to the terminal position to form it. For the Loop to form and grow high, the terminus must remain near the distal end of the overdeepened trough for an extended period.

Discussion

Canavan's Knob ^{14}C dates

In a quarry on the north (downstream) side of Canavan's Knob wood fragments were found and dated to 13.1 cal ka BP (Mercer, 1988; Denton and Hendy, 1994; Turney *et al.*, 2007); this is about 1000 years before the formation of the Loop. The fragments were stated by Denton and Hendy (1994) to have been emplaced by a re-advance of the Franz Josef glacier 'snout' over the site from a position upstream. Our scenario requires that the glacier terminus was at or close to the Loop position when the proposed rock avalanche occurred just before 12.1 cal ka BP (Barrows *et al.*, 2007), which appears to conflict with the terminus location recorded by the wood.

At the time of wood emplacement the glacier base adjacent to Canavan's Knob was substantially lower than present-day ground level, because the 400-m-deep fiord that occupied the lower Waiho valley at the LGM (Sutherland, 1996) was in the process of being infilled with sediment, and sea level was significantly lower than at present (Barrell, 2011). Figure 4 suggests that the ice base at Canavan's Knob was hundreds of metres below present-day ground level. Thus, the wood was emplaced at a considerable height above the glacier base. Mobilization of the wood by an advancing terminus is most unlikely to have resulted in its emplacement at a much higher level. An alternative explanation is that the wood emplaced on the ice surface by a valley-wall landslide and deposited at Canavan's Knob by rising and advancing ice, and there is no requirement for the glacier snout to have been advancing past Canavan's Knob at the time.

The wood at Canavan's Knob lies at an elevation of about 140 m a.s.l. (Burrows and Gellatly, 1982), so at 13.1 cal ka BP the ice surface was at this level or higher. This means that the terminus at the time was downstream of Canavan's Knob, given the much lower elevation of the valley floor at that time. The survival of the wood and the overlying till does not require that ice has not been substantially higher than 140 m a.s.l. since the wood was emplaced; the section is in the lee of Canavan's Knob, and could have survived burial by ice without being eroded. Our model shows an ice depth of ~ 150 m above the top of Canavan's Knob when the terminus was at the Loop position just before the rock avalanche, and the Franz Josef glacier terminus was at an elevation of about 160 m at the Loop 1000 years after the wood was emplaced, indicating even deeper burial. Furthermore, the 'till' is undated so may post-date the wood; it may indeed be rock avalanche debris.

The Canavan's Knob wood fragments can be explained if the Antarctic Cold Reversal (14.5–12.8 cal ka BP; Putnam *et al.*, 2010a) caused the Franz Josef glacier to advance from an unknown terminus position to or beyond the Waiho Loop position by about 12.8 cal ka BP. The Waiho Loop is not evidence for this advance. This advance emplaced the Canavan's Knob wood fragments at about 13.1 cal ka BP. Despite the ice surface later reaching 150 m above the top of Canavan's Knob, the wood was not eroded. Following the Antarctic Cold Reversal the terminus was near the Loop position, with the ice-surface elevation adjacent to Canavan's Knob gradually falling, until the rock avalanche occurred shortly before 12.1 cal ka BP. The consequent ice thickening associated with building of the Loop then further increased the ice depth above the wood sample, but again did not erode the deposit.

Significance of overdeepened troughs

The overdeepened trough revealed by seismic investigation is crucial to the presence and dimensions of the Waiho Loop. Overdeepened troughs are inferred to be present in every major glaciated valley in South Island, New Zealand. Often, the trough is now occupied by a lake (e.g. Lake Pukaki, Lake Ohau, Lake Hawea). Although less obvious in the landscape, troughs also occur west of the Alps and their presence is again marked by lakes (e.g. Lake Mapourika) and there is also geophysical evidence for overdeepening of the Whataroa Valley (Davey, 2010). The rapid tectonic advection of the western lowlands past the Alps east of the Alpine fault, however, suggests that troughs in Westland are likely to be less deep than those east of the Alps where no equivalent tectonic motion is known to occur. Troughs indicate the down-valley limit of effective glacial erosion and some valleys display more than one trough relating to different phases of glaciation. An example is the Rakaia Valley where one trough terminates about 8 km up valley from the Rakaia Gorge (Shulmeister *et al.*, 2010b), while an older trough downstream is partly filled by younger sediments (Shulmeister *et al.*, 2010c).

A modern example of an overdeepened trough margin is the Tasman Glacier margin in New Zealand. Here a lake over 200 m deep (Dykes and Brook, 2010) abuts the back of a large fan complex with moraines on its lakeside margin. The trough age is unknown but it pre-dates the Little Ice Age maximum (AD 1725; Winkler, 2000). Since the 1880s the glacier has gradually thinned (Hochstein, 1995) but the onset of terminus retreat was delayed by more than a century. A similar delayed retreat is likely to have also occurred when the Franz Josef Glacier was occupying its overdeepened trough before rock avalanche emplacement.

Preservation of the Waiho Loop

Preservation of the Waiho Loop, approximately 11 000 years after it was emplaced, in the very active high-stream-power fluvial environment of the Waiho River, can be explained by the presence of the Tatare River, just north of the Waiho River (Figs 1 and 2):

1. When the glacier receded from the foreland west of the range front, the Loop formed a barrier to the flow of the Tatare. A lake occupied the trough behind the Loop, and discharged west into the Waiho River.
2. Sediment from the Tatare catchment infilled this lake and increased in elevation faster than the Waiho River bed, because the latter, despite its larger catchment, had to infill a much larger valley area and volume. Thus, the Tatare fan was always at a higher level than the adjacent Waiho fan as both aggraded following deglaciation, preventing the Waiho from eroding any part of the Loop except its western end.
3. About 1000 years BP (McSaveney and Davies, 1998), the distal Tatare fan reached the elevation of the lowest point of the Loop; the Tatare River flowed over the Loop, and downcut through it to the level of the Waiho outwash surface downstream of the Loop. This downcut then retrogressed upstream along the Tatare to the range front, widening to form the present 500-m-wide Tatare arroyo.

This explanation suggests that other prominent terminal moraines may have formed in the Early Holocene but, if not protected by a nearby tributary, would not have survived subsequent fluvial erosion. Thus, the uniqueness of the Loop may owe more to unusual preservation circumstances rather than to unusual formation circumstances. Certainly, large coseismic rock avalanches occur occasionally in active orogens, and several deposits of the required size exist in the Southern Alps; so a number are likely to have fallen onto valley glaciers with piedmont lobes during deglaciation. Several prominent but smaller arcuate moraines also exist within moraine complexes elsewhere in South Westland (e.g. Mapourika, Okarito, Waitaha), but none has been investigated to date.

Conclusions

- Numerical modelling demonstrates that a rock avalanche could not have generated a significant *advance* of the Franz Josef Glacier that resulted in the formation of the Waiho Loop.
- The Waiho Loop is located at the distal end of an overdeepened trough, which allowed the terminus to remain in this position for an extended period during ice retreat.
- A major rock avalanche occurred while the glacier was in a period of retreat with its terminus at or very close to the Loop. Modelling demonstrates that the formation of the Waiho Loop took at least 30 years.
- The presence of the Waiho Loop does not reflect a climate-driven glacier advance; it actually represents no advance whatsoever.
- The preservation of the Loop is due to the protection provided by the alluvial fan of the Tatare River. The preservation of such a moraine is rare in New Zealand, as fluvial action typically removes them, especially in confined valley settings.

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Abbreviations. ELA, equilibrium line altitude; LGM, Last Glacial Maximum.

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