

## **Evidence for a landslide origin of the Waiho Loop Moraine, New Zealand.**

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**The formation of the Waiho Loop Moraine in South Island, New Zealand has been used as *prima facie* evidence for the inter-hemispheric connectivity and synchronicity of climate change<sup>1,2</sup> and has been inferred to imply a major late glacial cooling in New Zealand<sup>3</sup>. Recent work has challenged both the late-glacial timing of the event<sup>4</sup> and whether strong cooling is required to create the advance<sup>4,5</sup>. Here we show that the Waiho Loop was not caused by a climatic event, but instead represents the end product of a major landslide onto the Franz Josef glacier. These results preclude any significant climatic forcing of the Waiho Loop moraine including an alternative precipitation-driven model<sup>5</sup>. The results highlight the fact that glacial moraines are not necessarily climatic in origin, contrary to widespread practice in evaluating mass balance responses of glacial systems<sup>3,6</sup>.**

The Waiho Loop is a dramatic arcuate terminal moraine loop that rises more than 100 m above the plains on the foreland of the Franz Josef Glacier in South Westland, New Zealand (Fig. 1). It has been the focus of much international research since it was

recognised as a candidate for a Southern Hemisphere Younger Dryas (YD) event<sup>7</sup>. The first detailed chronological study<sup>8</sup> was based on wood in growth position from Canavan's Knob, a glacially sculpted granitic outcrop about 2 km behind the loop itself, and concluded that the moraine was immediately pre-YD in age. Subsequently, the Canavan's Knob deposit was re-dated and reinterpreted<sup>1</sup> and it was concluded that the Loop was early YD in age. These results appeared to confirm a YD signal in New Zealand<sup>9</sup> and seemed to support a global climate linkage through the atmosphere via greenhouse gases. This Waiho Loop interpretation has gained wide currency<sup>2,10</sup> but has also been widely debated and challenged both with respect to timing<sup>11</sup> and to the scale of the cooling implied<sup>5</sup>. Many workers have reverted to an immediate pre-YD interpretation which has been inferred to imply a Southern Hemisphere/Northern Hemisphere millennial scale climate offset and might suggest a thermohaline linkage in the climate system<sup>12</sup>. Most recently an early Holocene age has been proposed for the Waiho Loop based on cosmogenic ages<sup>4</sup>. These cosmogenic ages include a YD age result (WH-10) and if interpreted conservatively, still do not preclude a YD age for the feature. The issue of the occurrence and scale of cooling is still hotly debated as the interpretation of significant cooling from the glacial advance has long disagreed with data from other proxies<sup>13,14</sup>.

Despite the number and high profile of reports on the age and climatic implications of the Waiho Loop moraine, geomorphological data are surprisingly limited and no sedimentary descriptions have been published. Here we report the first systematic comparison of the sedimentology of the Waiho Loop with that of other moraines in the Franz Josef system.

A total of 18 outcrops through moraines were examined; seventeen sites are located within the extended Waiho System and one in the adjacent Whataroa System (Mt Hercules – Fig. 1 and Supplementary Data 1). Seven of the Waiho system sites are located in river cuts on or tracks through the Waiho Loop Moraine. It was immediately recognized that the lithology of the Waiho Loop was visually different to that of all the other moraines. Consequently, 1 m<sup>2</sup> sections of the outcrops were selected in a semi-random fashion (access to the face limited site selection) and 50 clasts per site were chosen randomly for lithological and roundness analyses. Clast analyses were also carried out on three sections of gravel bars in the rivers adjacent to the Waiho Loop outcrops and from a rock fall within the schist section of the Waiho Valley. The remaining sites were in other Franz Josef moraines.

Three distinct rock lithologies were recognized: a low grade quartzo-feldspathic sandstone, a high grade schist, and granite. The former two match the distinction between higher grade schists and lower grade meta-sediments mapped regionally east of the Alpine Fault in this area<sup>15</sup> (Fig 1) while the latter occurs only in samples downstream of Canavan's Knob. To quantify clast shape, a four point roundness scale was applied. For consistency, a single operator measured all samples.

The samples from Waiho Loop are lithologically distinct ( $p > 0.005$ ; d.f. = 22: see Table 1 and Supplementary Data 2) from the clasts in the other moraines. Waiho Loop material has significantly less schist than all the other moraines and also has significantly less schist than the modern river samples. Within the loop the proportion of sandstone ranges from over 80% on the true left to c. 50% on the extreme true right; this may suggest a source for the sandstone on the true left (south side) of the

Waiho system. Waiho Loop material is significantly more angular than that of the other terminal moraines but is not distinctly different from all lateral moraine samples. Waiho Loop material is however much more consistently angular than any of the lateral moraines, which are (unsurprisingly) highly variable. The late Holocene terminal moraine materials in the confined Waiho Valley are almost as rounded as river material (see Supplementary Data 2).

Bedrock in the upper parts of the Franz Josef catchment is low grade metamorphosed sandstone. The lower reaches of the Waiho Valley are dominated by outcrops of high grade schist. The grade of the schist increases downvalley to the range front which is delineated by the Alpine Fault<sup>16</sup>. This major fault separates Australian plate rocks to the west from Pacific plate rocks to the east and has a total horizontal displacement of at least 500 km<sup>17</sup>. On the Australian plate, lithologies including granites and diorites as well as quartz-rich sandstones of the Greenland Group form the basement, but with the exception of bedrock highs like Canavans' Knob these rocks are buried tens to hundreds of metres below the outwash fans and moraines. Consequently all the moraines, except for the Waiho Loop, are dominated by schist.

To investigate the possibility that the Waiho Loop derived its sandstone-rich sediments from a bedrock high in Greenland Group (Australian Plate) sandstones, a limited number of samples were collected from the Waiho loop outcrops and thin sectioned. They were then point counted for petrological analyses. The high feldspar contents demonstrate an origin east of the Alpine Fault (see Fig 2). The absence of high grade minerals precludes a source close to the fault.

In summary, the Waiho Loop moraine is unlike moraines downstream and upstream of it; it is dominated by clasts derived from low-grade sandstones of eastern provenance. Rocks of this composition and metamorphic grade are mapped c. 13 km up-valley of the Waiho Loop on a southeast line between Crawford Knob and Mount Roon (see Fig 1) and the source of the rock comprising the Waiho Loop moraine is at least this distance up-valley.

In addition to its sedimentology, the arcuate form of the Waiho Loop resembles neither the complex topography of the major last glacial moraines which form hill ranges of lateral moraines along the edges of the valleys, nor the Holocene terminal moraines in the Waiho Valley. The divergence with the younger smaller moraines is more striking. Each of the latter is characterized by a small dump moraine capping the back of a large aggradation fan built up by the advancing glacier. Large rocks are rare. In contrast, the Waiho Loop is steep-sided and the top of the moraine is capped by extremely large boulders. Steeply dipping foreset beds are also recorded on the outside margin of the loop (see Supplementary Data 3). Latero-frontal fans and ramps are widely recognized as features associated with dumping from supra-glacial positions in the ice<sup>20</sup>.

Any explanation of the Waiho Loop moraine must reconcile the sedimentological difference between the Waiho Loop and the other moraines in the system. It requires a mechanism that can deliver a large volume of material from one part of the glacier's catchment to the moraine without significantly incorporating material from intermediate sites and without significantly rounding the material. There is one

obvious candidate, a landslide depositing a large supraglacial debris load onto the glacier.

Glacial advances in response to landslides are well known<sup>21</sup>. The basic principle is that the debris cover reduces the surface melt from the glacier by insulating it, thereby modifying the mass balance. In addition, a large landslide adds mass to the glacier increasing flow rates<sup>22</sup>. Hewitt<sup>23</sup> has developed a series of criteria by which landslide-derived moraines can be distinguished from typical glacially-derived moraines (recognizing that most glacial moraines contain some landslide material). High angularity and uniform lithology are two of the key criteria. The Waiho Loop satisfies these criteria, so we conclude that it is the product of a major landslide and not of a climatically triggered re-advance. The lack of a corresponding feature in the adjacent Fox glacier system, which is otherwise very similar to the Franz Josef in all respects, also suggests a local trigger, such as a large landslide, rather than a regional event such as climate variation.

Landslides of the magnitude required to form the Waiho Loop ( $> 10^8 \text{ m}^3$ ) are recorded by deposits in several parts of the Southern Alps (e.g. the  $5 \times 10^8 \text{ m}^3$  Craigieburn deposit<sup>24</sup>; the  $26 \times 10^9 \text{ m}^3$  Green Lake deposit in Fiordland<sup>25</sup>). These are inferred to result from the frequent intense seismicity of the range ( $M > 8.0$  earthquakes are known to occur on the Alpine Fault several times per millennium<sup>26,27</sup>). The landslide origin we suggest for the Waiho Loop thus fits the local geomorphic environment extremely well.

We have identified a possible landslide source in the form of a deep depression 0.4 km<sup>2</sup> in area and 0.4 km deep on the east face of Mt Roon on the true left side of the glacier. This source is large enough ( $> 10^8 \text{ m}^3$ ) to generate the Waiho Loop moraine. We calculate that with an ice front at or near Canavan's Knob this landslide from this source would have fallen onto the glacier and spread sufficiently to cover the estimated 19 km<sup>2</sup> of the Franz Josef glacier to an average depth of ~ 5m. Furthermore, most ablation occurs in the lower reaches of the glacier. If total ablation were reduced by an average of 70% due to the debris cover, about  $1.5 \times 10^8 \text{ m}^3$  of extra ice would be added to the glacier each year. In order to reach the Waiho Loop from an existing terminus at Canavan's Knob, the glacier needed to advance 3 km, so about 2.4 km<sup>3</sup> of extra ice is required to fill this area to an average depth of 200 m. This could have been provided from the névé in about twenty years. (See Supplementary Data 4 for detailed analysis).

We note that the true left of the moraine has a particularly high percentage of sandstone but the whole moraine is composed of more angular material. We conclude that it is highly probable that less voluminous landsliding occurred in the schist section of the valley at the same time and contributed more material to the true right as well as many of the capping schist boulders.

Many previous studies have assumed a major retreat of the glacier up-valley of Canavan's Knob, prior to a significant YD or pre-YD readvance. There is, however, no evidence for such an earlier large-scale retreat, and this assumption is model driven. Based on the new ages for the Waiho Loop<sup>4</sup> and the existing ages for Canavan's Knob<sup>1,8,12</sup>, the simplest model for the Franz Josef glacier is a gradual

retreat to Canavan's Knob by about 13,000 years ago followed by a landslide-driven re-advance to the Waiho Loop either at or significantly later than 13,000 years ago (see Supplementary Data 5). No climate forcing is required.

With the elimination of the Waiho Loop as a climatic feature, the scale of late glacial cooling in New Zealand converges on low estimates. Neither oceanic<sup>4,28</sup> nor terrestrial<sup>29</sup> bio-proxies suggest a cooling event in excess of  $\sim 2^{\circ}\text{C}$  during the transition from the last ice age. Such subtle changes are within the range of modern climate variability, indicating that the whole concept of inter-hemispheric climate linkage during the last deglaciation needs careful re-examination. Furthermore, the landslide origin for this moraine reinforces the need for careful geomorphological and sedimentological work to support climatic inferences based on chronological studies. In high mountain areas not all glacial advances have a climatic origin.

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## Figure Legends

Figure 1. Location of study area with all sites referred to in the text marked. The Alpine Fault is marked in red. Metamorphic grade aligns parallel to the fault. High grade schists lie immediately east of the fault (purple), while lower grade sandstones (green) crop out further up glacier<sup>15</sup>. The Waiho Loop is 13 km down valley of the last outcrop of lower grade meta-sandstones. These sandstones dominate the Waiho Loop moraine lithology. The approximate limits of the Waiho ancient glacial and fluvial system is highlighted in orange.

Figure 2. Petrological point counts of Waiho Loop sandstones (red dots) against Torlesse derived sandstones (Pf series-grey boxes) and Greenland Group sandstones (blue squares). Each apex of the triangle represents 100% composition. Q = quartz, F = feldspar and L = lithics. The Waiho Loop samples are all clearly Torlesse in origin<sup>18,19</sup>.

## Table

Sample locations	Slightly metamorphosed Sandstone	Schist	Granite	Chi <sup>2</sup> Score
Mt Hercules	23	27	0	6.16
Okarito Beach	13	37	0	1.01
Okarito 1A	6.64	43.16	0	7.53

<b>Okarito 1B</b>	1.66	48.14	0	18.05
<b>Waiho mouth 1</b>	15	33	2	4.55
<b>Waiho mouth 2</b>	12	36	2	5.23
<b>Waiho beach</b>	14	34	2	4.59
<b>Lake Mapourika</b>	22	28	0	4.79
<b>The 'Mummy'</b>	16	34	0	0.55
<b>1750's moraine</b>	15	35	0	0.51
<b>Franz Josef</b>	8	42	0	5.57
<b>2003 moraine</b>				
<b>Waiho Loop</b>	35.3	14.7	0	<b>38.55</b>
<b>Average</b>				

Table 1. Compositional data for moraines of the Franz Josef system, counts normalized to 50. All moraines except Waiho Loop are dominated by schist and the next highest  $X^2$  score (Okarito 1B) is due the lack of sandstone at that site and is the result of crushing a schist rich unit. Both the '1750' and the Franz Josef 2003 moraines are significantly closer to the nearest source of low grade meta-sandstone than the Waiho Loop is.

## Supplementary Information

Five sets of supplementary data are provided. These are:

- 1) The scale of the location figure does not allow for sample sites from the figure to be accurately located and GPS locations in New Zealand map grid are provided.
- 2) Clast angularity data comparing angularity between the moraines within the Waiho system (Table 2) and also demonstrating the similarity of younger moraines to river material (Table 3).
- 3) A photograph of part of a cut through the loop demonstrating the steeply dipping forest beds of a latero-terminal fan.
- 4) We have scaled the effects of a documented large landslide on to the Bualtar Glacier (in Hewitt, 2008 in press) to the Franz Josef and applied the scaling to a putative landslide from a visible landslide scar on the upper slopes of Mt Roon, the northern-most possible source area for the inferred landslide. We have also related the location of the landslide to the lithology and clast shape characteristics of the Waiho Loop, and suggested further explanations for the lack of other such moraines in Westland.
- 5) A short discussion of the timing and climatic implications of the recent Barrows et al (2007 – ref 4) paper has been added to demonstrate that the proposed age for the feature does not resolve the issue of the origin and climatic implication of the Waiho Loop.

**1) GPS locations for outcrops described in the field based on New Zealand map grid.**

The 1m<sup>2</sup> sample grids occur in these outcrops.

1750 moraine E2281413, N5750325

Franz Josef 2003 moraine E2281200, N5747300

Lake Mapourika 5 samples - one site

1. E2281475, N5760510; 2. E2281793, N5760842; 3. E2281502, N576049;

4. E2281946, N5753680; 5. E2282788, N5763054 (sites pooled for analyses purposes because initial counts were <50)

The 'Mummy' landslide scarp - E2281098, N 5759711

Mt Hercules E2302744, N5777716

Okarito Beach 3 samples

1. Okarito Beach = E2278476, N5771662

2. Okarito 1A = E2278780, N5771863

3. Okarito 1B = 20 m below Okarito 1A

Waiho River mouth moraine - E2271089, N5764810

Waiho River mouth moraine 2 - E2271089, N5764810



Waiho River beachfront scarp - E2271010, N5764931

Waiho Loop 7 samples:

1. Waiho Loop Center = E2280323, N5757657
2. Waiho Loop West 1 = E2278901, N5756648
3. Waiho Loop West 1A = 40m west of sample Waiho Loop West 1
4. Waiho Loop West 2 = E2278910 N5756471
5. 4WD track on Waiho Loop = E2282563, N 5757514
6. 4WD track 2 = E2281098, N5757572
7. Rata Knob = E2278817, N 5755803

Franz Josef Glacier landslide - E2280648, N 5749465

Rivers (Waiho, Callery and Tatare) 3 sites -

1. Callery River = E2278901, N5756648 next to sample WW1
2. Tatare River = E2280323, N5757657 next to Waiho Loop Center
3. Waiho River = gravel bar at entry to Waiho Loop

2a) Lithological composition of gravel bars in local rivers where they cross the Waiho Loop contrasted with the composition of the Loop moraine itself and a rock fall deposit in the lower (schist bedrock) reach of the constrained Waiho Valley. Note the

dominance of schist (80%) in contrast to the prevalence of sandstone in the Loop itself.

Supplementary Table 1 – Lithology of river and rockfall deposits compared to the Waiho Loop

	<b>Slightly metamorphosed Sandstone</b>	<b>Schist</b>	<b>Granite</b>
<b>Callery River</b>	14	36	0
<b>Tartare River</b>	4	46	0
<b>Waiho River</b>	11	39	0
<b>River average</b>	9.67	40.33	0
<b>Waiho valley rock fall</b>	0	50	0
<b>Average Waiho Loop</b>	35.3	14.7	0

Supplementary Table 1 – Lithology of river and rockfall deposits compared to the Waiho Loop

2b) Clast roundness data for moraines of the Franz Josef system, counts normalized to 50. The Waiho Loop sites contain more angular and sub-angular material than the other terminal moraine sites (T). Note that the ‘2003’ moraine is our terminology and is the approximate age of the moraine. It may alternatively relate to a 2002 glacial limit. The moraines beyond the Waiho Loop are in lateral (L) or latero-terminal (LT) positions and these are highly variable in angularity over short vertical and horizontal distances. For example, the two beds examined at the Waiho mouth outcrop are metres apart in the same vertical section. Sample 1 is the most angular sample

encountered whereas sample 2 is dominantly sub-rounded. The occurrence of angular material in lateral moraines is predictable as these moraines are built from supraglacial debris which will be dominated by rockfall. The wide internal variability of angularity in these lateral deposits (e.g. Waiho Mouth and Okarito) contrasts with the consistently more angular nature of Waiho Loop deposits.

<b>Sample locations</b>	<b>Angular</b>	<b>Sub-angular</b>	<b>Sub-rounded</b>	<b>Rounded</b>	<b>Chi<sup>2</sup> Score</b>
<b>Mt Hercules (LT)</b>	0	2	35	13	33.39
<b>Okarito Beach (L)</b>	5	3	39	3	11.7
<b>Okarito 1A (L)</b>	9.96	14.94	24.9	0	7.30
<b>Okarito 1B (L)</b>	0	0	49.8	0	41.51
<b>Waiho mouth 1 (L)</b>	23	12	11	4	37.99
<b>Waiho mouth 2 (L)</b>	3	14	26	7	6.12
<b>Waiho beach (L)</b>	16	15	15	4	15.75
<b>Lake Mapourika (LT)</b>	7	14	26	3	2.06
<b>The 'Mummy' (LT)</b>	12	17	15	6	12.59
<b>1750's moraine(T)</b>	0	7	34	9	15.40
<b>Franz Josef</b>	1	10	36	3	9.38
<b>2003 moraine(T)</b>					
<b>Waiho Loop</b>	19.42	13.57	15.86	1.14	<b>24.50</b>

<b>Average(T)</b>				
<b>Overall averages</b>	8.03	10.21	27.31	4.43

Supplementary Table 2. Clast roundness data for moraines of the Franz Josef system.

<b>Sample locations</b>	<b>Angular</b>	<b>Sub-angular</b>	<b>Sub-rounded</b>	<b>Rounded</b>
<b>Rata Knob</b>	34	13	2	1
<b>Waiho Loop</b>	11	17	22	0
<b>West - 1</b>				
<b>Waiho Loop</b>	12	18	20	0
<b>West – 1B</b>				
<b>Waiho Loop</b>	15	19	16	0
<b>West – 2</b>				
<b>Waiho Loop</b>	18	8	24	0
<b>centre</b>				
<b>Waiho 4WD</b>	22	11	15	2
<b>drive track</b>				
<b>Waiho 4WD</b>	24	9	12	5
<b>drive track-2</b>				
<b>Waiho Loop</b>	19.42	13.57	15.86	1.14
<b>Average</b>				

Supplementary Table 3. Clast roundness data for Waiho Loop sites

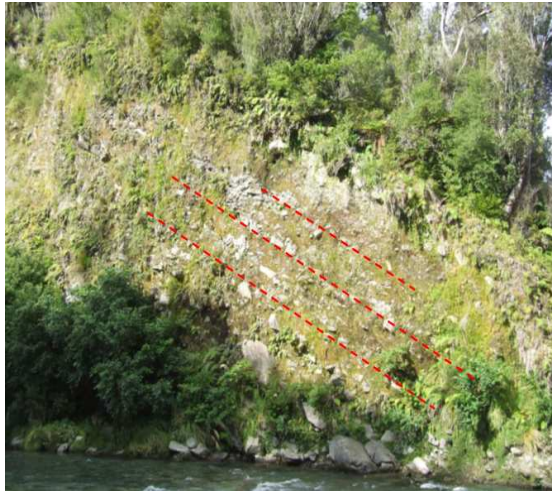
Angular data for river and landslide sites against Waiho Valley and Waiho Loop terminal moraines. Note the strong similarity between terminal moraines within the confined Waiho Valley reach and river sediments. The Waiho Loop is intermediate between these moraines and an unmodified rock fall deposit. The very high angularity of the rock fall is partially because of its 100% schist composition.

	Angular	Sub- angular	Sub- rounded	Rounded
Callery River	0	0	47	3
Tartare River	0	3	40	7
Waiho River	0	9	30	11
River average	0	4	39	7
Waiho valley rockfall	40	10	0	0
1750's moraine	0	7	34	9
Franz Josef 2003	1	10	36	3
Average Waiho Loop	14	15.5	20.5	0

Supplementary Table 4. Clast roundness data for river and rockfall sites compared against moraines.

A comparison of roundness between the younger moraines (excludes LGM) and the modern rivers sampled where they pass through Waiho Loop. The two Late Holocene moraines are much more similar in roundness to the river material than they are to Waiho Loop material.

### 3) Morpho-sedimentology of Waiho Loop

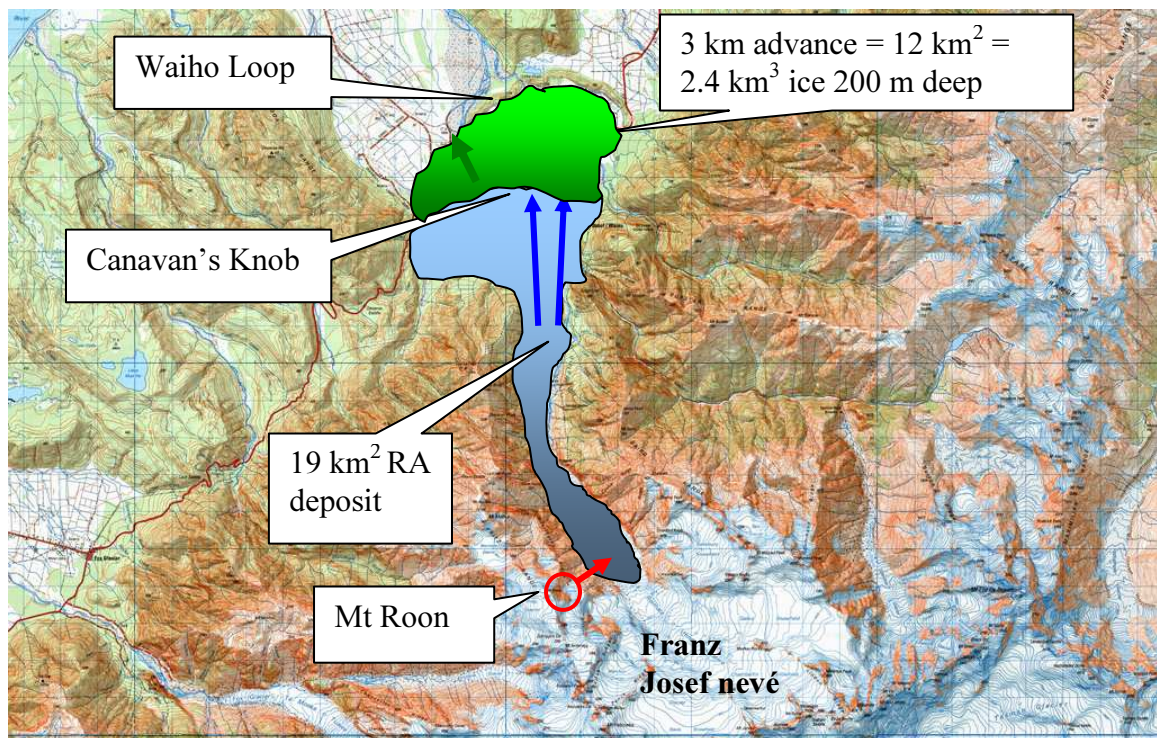


Supplementary Data Figure 1. Steeply dipping foreset beds on the outside margin of the Waiho Loop. Waiho Loop Center site, where the Tataru River crosses the Loop. Crude bedding has been highlighted on photograph.





Supplementary Data Figure 3(b) Google Earth view of east face of Mt Roon



Supplementary Data Figure 4 Rock avalanche from Mt Roon: runout and effects on Franz Josef glacier



Modelling the behaviour of rock avalanches on glaciers, and then the consequent changes in ice dynamics, cannot yet be done reliably using numerical models. Here we utilise instead data from the effects of a similar but smaller event in the Himalayas reported in detail by Hewitt<sup>1</sup>, scaling up the deposit dimensions according to dimensional homogeneity. Both the Bualtar and the Franz Josef valleys are about 1 km wide at the rock avalanche sites, and have similar gradients, and these are the major determinants of both rock avalanche and glacier behaviour. We acknowledge the imprecisions inherent in this approach, but suggest that they are less significant than those involved in the use of current-generation numerical models<sup>2</sup>.

Mt Roon lies within the surface exposure of the Torlesse group metamorphosed sandstones in the Waiho catchment (Supplementary Figure 2). The upper east face of Mt Roon (Fig. SI 3) is a deep depression  $\sim 0.4 \text{ km}^2$  in area and  $\sim 0.4 \text{ km}$  in depth, morphologically similar to a rock avalanche source area<sup>3</sup>. Erosion in  $\sim 10^4$  years will not have altered its vertical dimensions by more than 100 m, and probably much less. A rock avalanche from this source area would have had a volume of at least  $10^8 \text{ m}^3$  (the volume of material in the Waiho Loop above present fan surface level), so it is a possible source for the Waiho Loop material. The base of the depression is about 400 m above the present glacier surface. If the rock avalanche occurred when the glacier terminus was at about the 250 m asl summit of Canavan's Knob, 7 km farther advanced than at present, then assuming conservatively (since the basal shear stress of valley glaciers is often constant at about  $1 \text{ bar}^4$ ) that the slope of the glacier surface was equal to that of its bedrock base, the ice surface below Mt Roon would have been at  $\sim 1500 \text{ m asl}$ ; close to the base of the suggested source area, but probably not above

it. The surface area of the glacier downstream of Mt Roon would then have been  $\sim 19$  km<sup>2</sup> (SD Fig. 4).

Hewitt<sup>1</sup> reports the behaviour and effects of the  $\sim 10^7$  m<sup>3</sup> Bualtar I rock avalanche in the Karakoram in 1987; this fell into the narrow valley of the Bualtar glacier, which is comparable in width and gradient to the Franz Josef. Its deposit covered an area of 4.8 km<sup>2</sup>. Dimensional homogeneity requires that, assuming the dynamics of the two landslides were comparable, the deposit area scales with the volume to the two-thirds power<sup>5,6</sup>, so a  $> 10$  times bigger Mt Roon rock avalanche would have covered an area of  $> 4.8 \times 10^{2/3}$  or  $> 19$  km<sup>2</sup>. Mt Roon debris could thus have covered the whole of the Franz Josef glacier downstream of the rock avalanche source. Greater than  $10^8$  m<sup>3</sup> of debris would cover 19 km<sup>2</sup> of ice to an average depth of  $> 5$  m; the debris depth would have decreased in the distal direction so it could have varied from a maximum of  $> 10$  m to close to zero. This is sufficient to reduce the surface ablation under the debris very substantially<sup>1,7,8</sup>. Ablation from the Franz Josef glacier does not occur only at the surface, however; voluminous rain- and melt-water cause substantial en- and subglacial ablation also. Hence the reduction of ablation due to debris cover would have been less than that in a drier system. We now try to estimate roughly how long the suggested advance to the Waiho Loop may have taken, by assuming 100% reduction of ablation to give a lower bound, and 50% reduction of ablation to give a likely upper bound

The accumulation area of the Franz Josef glacier is  $\sim 25$  km<sup>2</sup><sup>9</sup>. If say 70% of its  $\sim 10$  m water equivalent of precipitation each year<sup>10</sup> convert to ice, then  $\sim 2 \times 10^8$  m<sup>3</sup> of ice

are added to the névé each year. If total ablation is reduced by an average of 50% by insulation due to the debris cover, about  $10^8 \text{ m}^3$  of ice is added to the glacier each year. In addition,  $> 5 \text{ m}$  depth of rock debris is equivalent to  $> 10 \text{ m}$  of ice, adding to the downvalley driving force on the ice; the glacier will clearly tend to advance in response. In order to reach the Waiho Loop from a terminus at Canavan's Knob, the glacier needed to advance  $3 \text{ km}$ , so about  $12 \text{ km}^2$  of new ice area was required and, at a depth of say  $200 \text{ m}$  (assuming that a substantial depth of the original Loop is buried by postglacial outwash), a volume of  $\sim 2.4 \times 10^9 \text{ m}^3$ . If all ablation ceased, this volume could have been provided from the névé in about 12 years; if ablation was reduced by 50% then about 24 years would have been required. However, the Bualtar glacier in fact surged following the rock avalanche of 1987, advancing  $2.5 \text{ km}$  within its valley and increasing in area by about  $2.5 \text{ km}^2$  by 1992<sup>1</sup>, so the Franz Josef glacier may also have surged. Scaling the surge area suggests that the Franz Josef surge may have been  $> 2.5 \times 10^{2/3}$  or  $> 11.6 \text{ km}^2$  – close to the  $12 \text{ km}^2$  needed to reach the Waiho Loop from Canavan's Knob. In that case, ice storage in the mid-valley would have reduced rapidly, allowing the advance to the Loop to have been completed much more rapidly. It appears likely that the Waiho Loop advance was of the order of decadal in duration, but possibly shorter if surging dominated the behaviour.

These calculations are obviously approximate and indicate only orders of magnitude of the calculated quantities. Taken together with the lithological and grain shape evidence, and the anomalous cross-section, however, they demonstrate the feasibility of the hypothesis that the Waiho Loop formed as a result of a coseismic rock avalanche from Mt Roon, causing the glacier to surge from a position near Canavan's Knob to the Loop position.

#### (ii) Lithology of the Loop

Rock avalanche deposits tend to retain the lithological disposition of their sources, so the preponderance of low-grade metamorphosed sandstone on the west part of the Waiho Loop suggests that this material may have been sourced from the west side of the Waiho valley. The larger proportion of schist on the east part of the Loop could be explained by significant, but lower volume, landsliding from the schist comprising both sides of the lower part of the valley.

#### (iii) Grain shape and size distribution

Rock avalanche debris contains large quantities of finely fragmented rock; > 90% of the grains in the supraglacial deposit of the 1991 Mt Cook (New Zealand) rock avalanche were less than 10  $\mu$  in diameter<sup>11</sup>. The alteration to rock avalanche debris during supraglacial transport has been described by Hewitt<sup>1</sup>: “individual clasts tend to become less angular and more compact as they tumble, slide and impact other debris, and are weathered. Finer matrix materials are winnowed and flushed away, leaving materials of more uniform calibre”. The lower angularity of the Waiho Loop material compared with the Franz Josef glacier carpark landslide can thus be attributed to supraglacial transport and weathering, as can the small proportion of very fine material present.

#### (iv) Uniqueness of the Loop

The absence of features corresponding to the Waiho Loop in other parts of the West Coast, such as the otherwise very similar Fox glacier valley, may be the result of either (i) absence of large landslides in other valleys or (ii) preservation of the Waiho

Loop while other such features were eroded by river action in the ~ 10ky since emplacement.

#### **5. Comments on new ages and estimated duration of the Waiho Loop by Barrows et al.<sup>12</sup>. (ref 4 of main paper)**

In our opinion, the recent publication of the Holocene ages<sup>12</sup> does not resolve the issue of the age of the Waiho Loop Moraine. While it is fairly conventional to present cosmogenic ages as means, it is widely recognized that the likely cosmogenic age of a moraine is the *oldest* age derived from the feature (that is not an outlier). The reason for this is that moraines are highly unstable after deposition – the crests are at the angle of repose and the moraine contains buried ice that melts out over the succeeding centuries to millennia – causing the boulders to roll and topple which resets the cosmogenic clock. When attempting to date a single feature such as the Waiho Loop a more conservative approach would be to accept the oldest age or an average of oldest ages. The critical non-outlier age is that of WH-10 (11.77 ka +/- 1.22 ka). This age comfortably overlaps the Younger Dryas chron (13-11.5 kyr ago) and means that a YD age cannot be discounted from these data.

Compounding this is the fact that there is no correction for erosion. This is quite normal when reporting cosmogenic ages but while erosion corrections on relatively young samples like this are typically not large (c 3-5% of the age), the true ages are likely to be c. 200-500 years older than reported. In short, not only does the data not preclude a Younger Dryas age it does not preclude an Antarctic Cold Reversal age (a period preceding the Younger Dryas) either.

Consequently, all that can be stated from supplementary ref 12 is that the advance occurs at some stage during the deglaciation or early Holocene. The 2300 year duration for the advance suggested in that paper (p87, column 3, lines1-3) represents an upper limit, not an accurate duration of advance. The advance could equally well be decadal in scale. The Waiho Loop is not particularly large for a West Coast NZ moraine - the LGM moraines in the same system are orders of magnitude larger – and no extended duration is required to produce it.

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