A relict pronival (protalus) rampart in the Tararua Range, North Island, New Zealand

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ABSTRACT

Debris ridges in New Zealand are routinely assumed to be ‘moraines’ and used as key Southern Hemisphere paleoclimatic sites without detailed evaluation of ridge origin. Here we assess the origin of a debris ridge adjacent to Dundas Ridge in the Tararua Range, North Island, New Zealand, through measurements of ridge morphology and sedimentary properties. The ridge has a steep c. 35° distal slope (height 18 m), compared with the c. 19° proximal slope (height 6 m), and on all transects the distal slopes contain the coarsest material (median *b*-axis clast widths of 0.18-0.25 m), compared to distal samples (0.34-0.37 m). Clast shape (C_{40} range 40-60%) and angularity (RA>65%) indicate typically angular and ‘slabby’ clasts, and along with the lack of fines, and the c. 40-m-distance between the ridge crest and the foot of the backwall, lead us to reject a glacial (moraine) origin for the ridge. The single ridge morphology precludes a protalus rock glacier origin, while the lack of a broad hillslope scar and debris apron beyond the ridge excludes a landslide origin. Instead, we interpret the ridge as a pronival (protalus) rampart formed by supranival debris supply—from the c. 200 m-high southeastern slopes of Dundas Ridge—across a snowbed. Re-distribution of snow by prevailing westerlies from Mt Dundas Ridge into the basin would have nourished the snowbed, which is likely to have formed during the interval 24-18 kyr BP, when a minor alpine-style glaciation affected sectors of the Tararua Range. This is the first pronival rampart detailed in New Zealand, raising the possibility that debris ridges of pronival origin may also be present elsewhere in New Zealand’s mountains.

KEY WORDS: pronival rampart; protalus rampart; New Zealand; supranival; snowbed

INTRODUCTION

A pronival rampart is a ridge or ramp of debris formed at the downslope margin of a snowbed or firn-field (Shakesby, 1997; Hedding 2011). Such features are also known as protalus ramparts (Ballantyne and Kirkbride, 1986), although Shakesby (1997) advocated the use of the term ‘pronival’ (i.e. snow front) as this appropriately describes any firn-foot debris accumulations, regardless of slope position. Traditionally, pronival rampart formation has been attributed to the accumulation of clasts that have fallen from cliffs, and bounced, rolled or slid supranivally down a steep perennial firn-field, accumulating at the base as a rampart (White, 1981). Other workers have shown that a variety of additional mechanisms may contribute to rampart development, including supranival debris flows (Ono and Watanabe, 1986), wet-snow avalanches (Ballantyne, 1987), snowcreep (Gardner *et al.*, 1983) and bulldozing of unconsolidated sediments by basal sliding and firn creep (Shakesby *et al.*, 1999). Indeed, Curry *et al.* (2001) tested four hypotheses for the origin of one particular debris ridge: (1) a wholly pronival (protalus) rampart; (2) glacial; (3) landslide; and (4) protalus rock glacier, all leading to subsequent pronival rampart development.

Two basic models of rampart formation through supranival debris transport processes have been proposed. In the first model, Ballantyne and Kirkbride (1986) proposed that ramparts evolve via gradual and intermittent accumulation of rockfall debris on the downslope margin of a firn-field. The rampart crest migrates outwards away from the talus slope, with the distal slope formed at the angle of repose (34-38°) of the debris (Ballantyne and Kirkbride, 1986). In the second model, Hedding *et al*. (2007) proposed a retrogressive (upslope) model of rampart development under fluctuating, and possibly declining snowbed volumes. Coupled with a lack of data from actively-forming ramparts, this has led to uncertainty about interpreting the origin of relict forms (Gordon and Ballantyne, 2006), which have been confused with moraines, landslide deposits, and protalus rock glaciers (Ballantyne, 1987). One example is the arcuate ridge of large tabular boulders at Baosbheinn, northern Scotland, which has previously been interpreted as a protalus rampart and a talus rock glacier (Sissons, 1976; Ballantyne, 1986), but recently reinterpreted as rockslide debris (Ballantyne and Stone, 2009).

In New Zealand, while unconsolidated debris ridges forming key Southern Hemisphere paleoclimatic sites are often dated with high precision (Barrows *et al*., 2007; Schaefer *et al.*, 2009; Kaplan *et al.*, 2010), the exact process-origin of such features is rarely explored. Here, we investigate an unconsolidated debris ridge, which we hypothesise is a relict pronival rampart, in the Tararua Range on the North Island. The range was subjected to a minor alpine-style glaciation during the last glacial cycle, culminating in deglaciation around 18 kyr BP (Brook *et al*., 2008). In New Zealand, fragmentary moraine ridges, assumed to be formed at the limit of glacial advance, are the most widely used evidence for former glacier extents, and, by inference, Southern Hemisphere paleoclimate (Schaefer *et al*., 2009; Kaplan *et al*., 2010). Intriguingly, although a small number of pronival ramparts have been documented in the Southern Hemisphere (Valcárcel-Diaz *et al.*, 2006; Hedding *et al*., 2007), none have hitherto been described in New Zealand. Interest is now emerging in determining the exact process-origin of unconsolidated debris ridges in New Zealand's mountain zones (Tovar *et al*., 2008; McColl and Davies, 2011).

Widespread periglacial activity, both relict and active, forms an important component of the landscape evolution on the South Island of New Zealand, especially in the Central Otago highlands and on the eastern side of the Southern Alps (Soons and Price, 1990; Augustinus, 2002). In contrast, there is a paucity of documented relict and active periglacial landforms on the North Island. Cotton (1958) and Cotton and Te Punga (1955) identified solifluction deposits (angular, frost-shattered clasts in a silty matrix) on the higher slopes around the city of Wellington, thought to have formed during the Last Glacial Maximum (LGM). Other deposits postulated to be of relict periglacial (or possibly even permafrost) origin are colluvium-filled bedrock depressions (Stevens, 1957; Crozier *et al*., 1990), along with inactive fans along the coast to the north of Wellington, which Fleming (1970) reported as being of periglacial origin, formed during the LGM. Small solifluction lobes and terraces have been observed on the central volcanic peaks of the North Island by McArthur (1987), the only study to report active periglacial activity on the North Island. Allibone and Wilson (1997) and Brook (2009) reported the presence of an unconsolidated ridge on Stewart Island, but concluded it was of glacial origin on the basis of rounded clasts within a silty matrix. Thus, given the abundance of cold-climate landforms, in New Zealand, it is surprising that pronival ramparts (active or relict) have never been reported from either the North or South Islands.

Hence, given the often fragmentary nature of the glacial moraine record, and the emerging interest in New Zealand’s unconsolidated debris ridges as paleoclimatic proxies in the Southern Hemisphere (Kaplan *et al*., 2010), it is important and timely to determine the exact process-origin of debris-ridge deposits. The objectives of this paper are to analyse a ridge in the Tararua Range of the North Island according to ‘diagnostic’ morphological and sedimentological criteria suggested by Hedding *et al.* (2010). We measure and analyse clast shape, size and angularity, and ridge profiles and distances from the backwall.

STUDY AREA

The focus of this study is an unconsolidated debris ridge formed at 1220 m above sea level (asl) on the south-eastern side of Dundas Ridge (c. 1420 m) in the central Tararua Range (Figure 1). The Tararua Range (Figure 1) is a young, deeply entrenched mountain range, a result of major faulting and folding which began in the Pliocene (Pillans, 1986). In the vicinity of the study area the bedrock is composed of quartzofeldspathic metasediments of the Torlesse Terrane (Begg and Johnston, 2000). The debris ridge itself (40°43’06”S, 175°27’41”E) is located beneath partially-vegetated mature rockfall talus slopes, between the peaks of Dundas (1499 m) to the southwest and Pukemoremore (1474 m) to the northeast (Figure 1).

Present-day glacier activity on the North Island is limited to niche glaciers on the stratovolcanoes, Mt Ruapehu and Mt Taranaki (Figure 1A), with current equilibrium line altitudes (ELAs) of c. 2450 m and c. 2600, respectively (Richardson and Brook 2010; Brook *et al.*, 2011). Mean annual air temperature in the study area is estimated to be c. 6.1°C, based on the temperature data from 1990 and 1991 from Mt Bruce, 13 km east of Mt Dundas at 305 m asl (National Institute for Water and Atmospheric Research, 2012), and a temperature lapse rate of 6.5°C km^{-1}. However, during the Last Glacial Maximum (LGM), a minor valley and cirque glaciation affected six catchments in the Tararua Range to the west and south of the study site (Brook and Brock, 2005), with a reconstructed equilibrium line altitude (ELA) of c. 1050 m (Brook *et al.*, 2008). It would appear the ‘local’ LGM closely mirrored advances in the Southern Alps, with cosmogenic ^{10}Be ages indicating that glaciation culminated at c. 18-24 ka (Brook *et al.*, 2008). Though glacial activity during the Antarctic Cold Reversal (14.5-12.7 ka; Putnam *et al.*, 2010) and Late Holocene (Schaefer *et al.*, 2009) initiated glacier advances in the Southern Alps, the effects of post-LGM climate on cryogenic activity on the North Island are largely unknown. Although there are no meteorological stations in the central Tararua Range, the average annual rainfall has been estimated at c. 6200 mm on the peaks to the south of Dundas Ridge (Griffiths and McSaveney, 1983).

METHODS

To evaluate the morphology of the ridge, three longitudinal profiles were surveyed across the ridge using a laser rangefinder (Figure 3). Readings were taken at breaks of slope, with surveyed profiles used to calculate various dimensions following Ballantyne and Kirkbride (1986), including maximum downslope width (w), length (L), maximum height of the distal (h_1) and proximal (h_2) slopes and maximum horizontal distance from the crest of the feature to the foot of the (former) talus slope (d). Assuming a regular decline in slope it was possible to estimate the maximum thickness of the deposit (z), and mean proximal and distal slope angles were also calculated (Table 1). The sedimentology of the ridge was investigated following the example of Ballantyne (1987) and Curry *et al.* (2001), whereby measurements of the *b*-axis of 50 clasts at four sites along each of the three transects were made.

Following Benn and Ballantyne (1994), the lengths of the three orthogonal axes were measured for 10 sets of clasts (n = 50) in the size range 35-125 mm (*a*-axis) from the debris accumulation at the *b*-axis sample sites, and then compared with eight sets of clasts (n = 50) from the Park Valley moraine (Figure 1). The latter appears to be either a small ice-stream interaction medial moraine or a lateral moraine, and includes striated, actively-transported clasts (Brook *et al.*, 2008) of the same Torlesse Terrane quartzofeldspathic metasediments (Begg and Johnston, 2000). From these data, the indices RA (% angular + very angular) and C_{40} (% of clasts with a *c:a* axis ratio of ≤0.4) were calculated for each sample of 50 clasts. Finally, using the morphological measurements in Table 1, a reconstruction of the former firn-field was made in order to evaluate whether the firn-field was at the transition point from (stationary) snow to (mobile) ice (Ballantyne and Benn, 1994).

RESULTS

Morphological data for the debris ridge are reported in Table 1. The ridge is c. 250 m long (L), and roughly arcuate in planform, with a minor downslope ‘bulge’ toward the centre (Figures 1 and 2). The mean distance (d) from the centre of the ridge crest to the foot of the backwall is c. 40 m, indicating sufficient space for snow accumulation. The width of the ridge (w) is c. 33 m, with the distal slope rising from the valley side below the ridge at a gradient of 35°, and the proximal slope rising at an angle of c. 19° from the backing depression between the ridge and backwall (Figure 3). Maximum heights of the distal (h_1) and proximal (h_2) slopes of the ridge are c. 18 m and c. 6 m, respectively, and assuming a regular decline in slope under the ridge, it was possible to determine a maximum ridge thickness (z) of c. 9 m (Table 1). Given the height of the ridge, and distance to the backwall (40 m), following Ballantyne and Benn (1994), a snowslope angle (α) of $\geq 30^{\circ}$ would suggest that the stationary firn-field would have been close to transition into a small glacier. Figure 3 illustrates the morphology of the three transects measured. The bulging and flattening of the ridge toward its centre, as seen in transect B, is the most striking feature.

Although the debris ridge supports a partial vegetation cover developed locally in thin soil, the surface layers generally consist of openwork coarse clasts. Three clasts at the foot of the backwall exceed 2 m in diameter. Median clast widths (*b*-axis) for sites surveyed on the ridge indicate that on all transects the distal slopes contain the coarsest material (Figure 3). This is consistent with studies of actively-forming pronival ramparts (Ballantyne, 1987). Indeed, median clast widths vary from 0.18 to 0.25 m (range = 0.12 to 0.35 m) on proximal slopes, where they are well-sorted, to 0.34 to 0.37 m (range = 0.12 to 0.53 m) toward the distal side of the crest, where sorting is poor (Figure 3). On the distal slope of the ridge, clasts tend to increase in size downslope, up to 0.54 m for *b*-axes (Figure 3). The backing depression is partially infilled by a debris cone which emanates from a rockwall chute upslope (Figure 2A), and *in situ* bedrock is exposed as cliffed outcrops above most of the deposit (Figure 2B). In terms of clast shape and angularity (Figure 4), the eight sets of till samples from the Park Valley Moraine to the west are much more 'blocky' (C_{40} values range 16-26%) and more rounded (RA<21%) than the samples from the Dundas Ridge debris accumulation (C_{40} range 40-60%, RA>65%). While clasts from the Park Valley till are often striated (Brook *et al.*, 2008), striae were not found on clasts from the debris accumulation. Given the similar lithology between the two sites, this suggests that analysing the covariance of the RA and C_{40} indices, which is an established tool in discriminating the transport pathways of glaciogenic facies (Benn and Ballantyne, 1994), is useful in distinguishing between Park Valley morainic and Dundas Ridge debris-ridge deposits.

DISCUSSION

Several different explanations for slope-foot debris accumulations have been proposed, such as moraine ridges, pronival ramparts, protalus rock glaciers and rock slope failures (Shakesby, 1997). According to the 'diagnostic criteria' for pronival ramparts (Table 2) adapted from Hedding *et al.* (2010), the contention that the Dundas Ridge feature is a pronival rampart is plausible, and the following discussion justifies why this is the probable mode of origin. At a simple level, comparison of the debris ridge with fossil and actively-forming pronival ramparts indicates that the debris ridge is most likely of pronival origin. Several lines of evidence favour this explanation. The mean *d* value of 40 m is within the range of c. 30-70 m defined by the model of Ballantyne and Benn (1994). Likewise, the *d* = 40 m is within the typical range of *d* values reported from 33 pronival ramparts from northern Europe, North America and Japan (Curry *et al*., 2001). Ballantyne and Benn (1994) modelled the threshold conditions under which a snowbank begins to move and becomes an incipient glacier. Their work indicates that when the distance between the rampart crest and talus foot upslope exceeds 30-70 m, significant movement of the snowbank may occur. Given the crest-backwall distance (40 m), realistic snowslopes of ≥30º indicate that the firn field may have been close to deforming, and the small 'bulge' in the centre of the ridge may represent the resulting minor 'bulldozing'. Alternatively, the 'bulge' may have formed due to localised deformation of the rampart associated with firn-field ablation. However, a 'true' glacial origin for the ridge is unlikely as the ridge is outside mapped glaciated zones of the Tararua Range (Brook and Brock, 2005). Nevertheless, the ridge is at a similar elevation (c. 1160 m) to a Last Glacial Maximum (LGM) lateral moraine on the margin of Park Valley c. 5 km to the west, but the spatial and topographic positioning of the Dundas debris ridge is unlike that of a lateral moraine. This is because the ridge is located on a valley-side bench above a sinuous, V-shaped fluvial valley. Although the ridge morphology may reflect a small terminal moraine, the high RA values (cf. Glasser *et al*., 2006), the openwork nature of the debris with a lack of sandy-silty matrix characteristic of glacial diamict (Benn and Evans, 2010), and the limited distance of the ridge crest to the backwall indicate it is not a moraine.

A protalus rock glacier origin for the ridge is more plausible given the clast angularity, but protalus rock glaciers tend to be multi-ridged (Curry *et al*., 2001) and terminate at much greater distances from the talus foot than the Dundas debris ridge. Moreover, protalus rock glaciers often have a ridge-and-furrow relief with a crenulated or scalloped planform of their outer margins (White, 1981). In contrast, the ridge is arcuate with a single crest, and together with the other factors outlined, this suggests a protalus rock glacier origin is inappropriate. A rock-slope failure origin for the ridge also appears unlikely due to the lack of a whole-slope failure scar above the ridge, with only a minor (c. 40 m wide) recess in the southeastern slope of Dundas ridge indicative of a ‘failure scar’. Moreover, rock-slope failures tend to produce boulders that are much larger than adjacent talus accumulations (Curry *et al*., 2001), but the debris ridge material is similar in size to local talus slope clasts. Also, the 'rock-slope failure' hypothesis is further undermined by the moderate gradient of the rockwall (cf. Gordon and Ballantyne, 2006). The rampart has formed in a location with a southeasterly aspect, which would favour snow accumulation due to low insolation receipts. Furthermore, variability in snow accumulation on current New Zealand firn-fields is strongly influenced by atmospheric circulation, orography and redistribution of snow by westerly winds (Purdie *et al*., 2011), which would favour accumulation in southeast-facing basins. Indeed, wind deflation of snow from snow banks on the summit of Dundas Ridge to the west would have helped nourish the firn-field behind the rampart.

A pronival rampart origin of the debris ridge has implications for interpretations of debris ridges in New Zealand mountains, where pronival ramparts have not previously been identified. Indeed, fragmentary debris ridges forming 'moraines' are often used as key Southern Hemisphere paleoclimatic sites without detailed investigation of ridge sedimentology, or spatial and topographic positioning (Kaplan *et al.*, 2010). Recent work has highlighted the presence of rock avalanche deposits in glaciated zones of the New Zealand Southern Alps (McColl and Davies, 2011), and it was recently proposed that supraglacial rock avalanche debris can dominate glacial sedimentation (Tovar *et al*., 2008). This may lead to formation of 'moraines' that are difficult to distinguish from their more conventionally-formed equivalents (Shulmeister *et al.*, 2009), or rock glaciers (Kirkbride and Brazier, 1995). The implication is that without detailed analysis and application of 'diagnostic criteria' (Hedding *et al*., 2007), the process-origins of debris ridges may be wrongly designated, leading to potentially erroneous paleoclimatic extrapolations.

CONCLUSIONS

The unconsolidated debris ridge on the southern side of Dundas Ridge, Tararua Range, has been investigated using 'diagnostic criteria' of debris-ridge morphology, spatial and topographic positioning, and sedimentology. Collectively, the openwork nature of constituent debris, angular clasts, single-crested ridge morphology and close proximity to the backwall are consistent with both relict and actively-forming pronival ramparts. Comparison with other studies shows that both rockslides and protalus rock glaciers tend to be multi-ridged and are found at greater distances from the backwall. Furthermore, the steep-sided, sinuous valley below the ridge has not been glaciated during the Quaternary, and so a lateral moraine mode of origin is discounted. Hence, it is most likely that the debris ridge is a relict pronival rampart that formed close (c. 40 m) to the base of the moderately steep, elevated backwall provided by Dundas Ridge, in a location with a southeasterly aspect that favoured snow accumulation due to low insolation receipts. The ‘bulging’ near the centre of the ridge may represent snow-push processes in addition to traditional supranival mechanisms, supporting the view that ramparts should be viewed as potentially a polygenetic product of a combination of one or more snowbed-related processes. The rampart possibly formed during cold-climate conditions within the interval 24-18 kyr BP, when a minor alpine-style glaciation affected valleys to the west and south.

This study has implications for paleoclimatic analyses in New Zealand, as fragmentary debris ridges are routinely assumed to be ‘moraines’ and are used as key Southern Hemisphere paleoclimatic sites. This is often without any detailed investigation of ridge geomorphology and sedimentology, and recent work has actually reclassified some ‘moraines’ as rock avalanche deposits (McColl and Davies, 2011). The corollary is that the apparent paucity of pronival ramparts in New Zealand may be artificial, given the high rates of debris supply, and ice and snow cover variability during the Quaternary.

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CAPTIONS

Figure 1: (A) Location of the study area in the southern Tararua Range on the North Island of New Zealand; (B) Location of the Dundas debris ridge in relation to the Park Valley lateral moraine (asterisked) described in Brook *et al.* (2008), and inferred ice limits (black lines) from Adkin (1911); (C) The debris ridge on the southeastern slopes of Dundas Ridge, showing the location of transect A to C in Figure 3. Note that the transects shown in Figure 3 only represent the morphology of the debris ridges in relation to the lowermost section of the backwall. Dashed lines represent hiking tracks.

Figure 2: (A) View of the roughly arcuate debris ridge from the northeast of the feature, arrows marking the lateral extent of the ridge; (B) Vegetated rockslopes above the northwestern end of the ridge, with the arrow marking Dundas Ridge, ~200 m above the debris ridge and marking the up-slope limit of the backwall; (C) Vegetated rockslopes above the southeastern end of the ridge, with large boulders (*a*-axis >1.2 m, arrowed) in the backing depression between the backwall and ridge crest.

Figure 3 Boxplots of clast *b*-axis length (on left) measured at four points along transects A to C, showing representative ridge cross-sections and the lower sections of the backwall (on right). Note that the Dundas Ridge source area actually extends ~200 m above the debris-ridge crest. Approximate position of each transect is shown in Figure 1. The box plots summarise the *b*-axis distributions (n=50), with the vertical lines representing the range, and horizontal lines defining the upper quartile, median and lower quartiles.

Figure 4 Plot of RA index (% of very angular or angular clasts) against C_{40} shape index (% of clasts with *c:a* axis rations ≤0.4) for 10 samples from the Dundas debris ridge and 8 samples from till in the glaciated Park Valley to the southeast.

Table 1 Dimensions and morphology of the Dundas debris ridge (see text for explanation of abbreviations).

Table 2 Diagnostic criteria for distinguishing pronival (protalus) ramparts from other talus-foot landforms (adapted from Hedding *et al*., 2010).

Table 1

Length (m)	Width (m)	h_1 (m)	h_2 (m)	z (m)	d (m)	Average slope (°)	
						Proximal	Distal
250	33	18	6	9	40	19	35

Table 2

Criteria		**Additional comments**
Glacial moraine		
Talus-foot location	✓	
Glacial erosional forms	×	
Striated clasts	×	
Linear plan form	×	Arcuate, central bulge
Ridge crest to cliff-foot distance > *c*. 30-70 m	✓	40 m
Landslide		
Talus-foot location	✓	
Hillslope scar	✓	
Debris aprons beyond the feature	×	Partial
Large masses of displaced hillside within or above the area of debris accumulation	×	
Protalus rock glacier		
Talus-foot location	✓	
Greater in length (downslope) than in width (across-slope)	×	
Convex distal slope	×	
Meandering and closed depressions, downslope ridges and furrows, and transverse ridges and depressions	×	
Pronival (protalus) rampart		
Large ridge to backwall summit inclination	✓	
Small ridge to backwall distance	✓	
Ridge crest to cliff-foot distance < *c*. 30-70 m	✓	
Restricted potential snow accumulation depth	✓	
Length <300 m	✓	
Openwork fabric with/without infilling fines	✓	
Single ridge	✓	
Ridge size increase with distance from cliff foot	✓	
Backwall and ridge same lithology	✓	

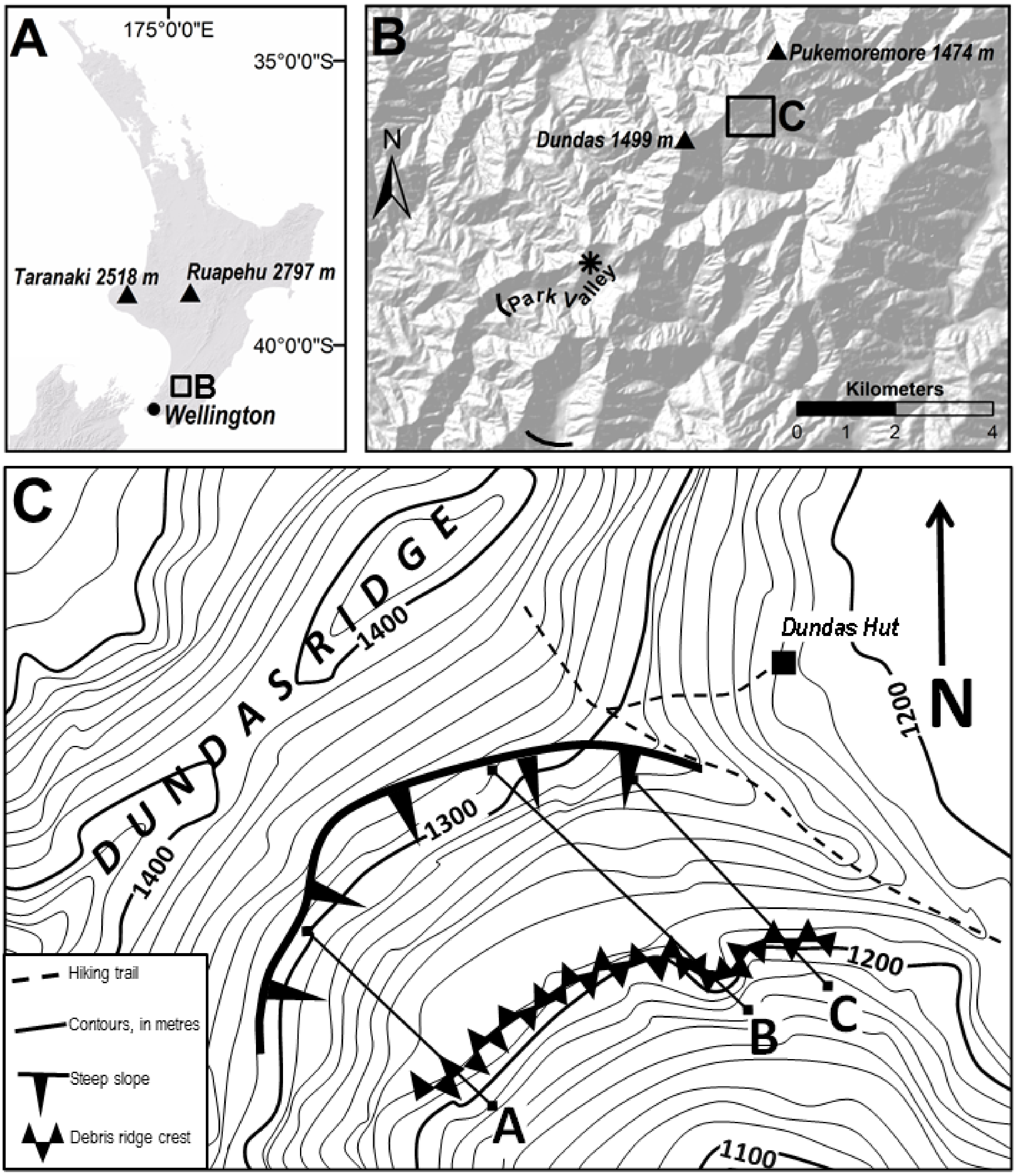
A
175°0'0"E
35°0'0"S
Taranaki 2518 m
Ruapehu 2797 m
40°0'0"S
B
Wellington
B
Pukemoremore 1474 m
C
Dundas 1499 m
N
Park Valley
Kilometers
0
1
2
4
C
DUNDAS RIDGE
1400
1400
1300
1200
1200
1100
Dundas Hut
N
A
B
C
Hiking trail
Contours, in metres
Steep slope
Debris ridge crest

Fig 1

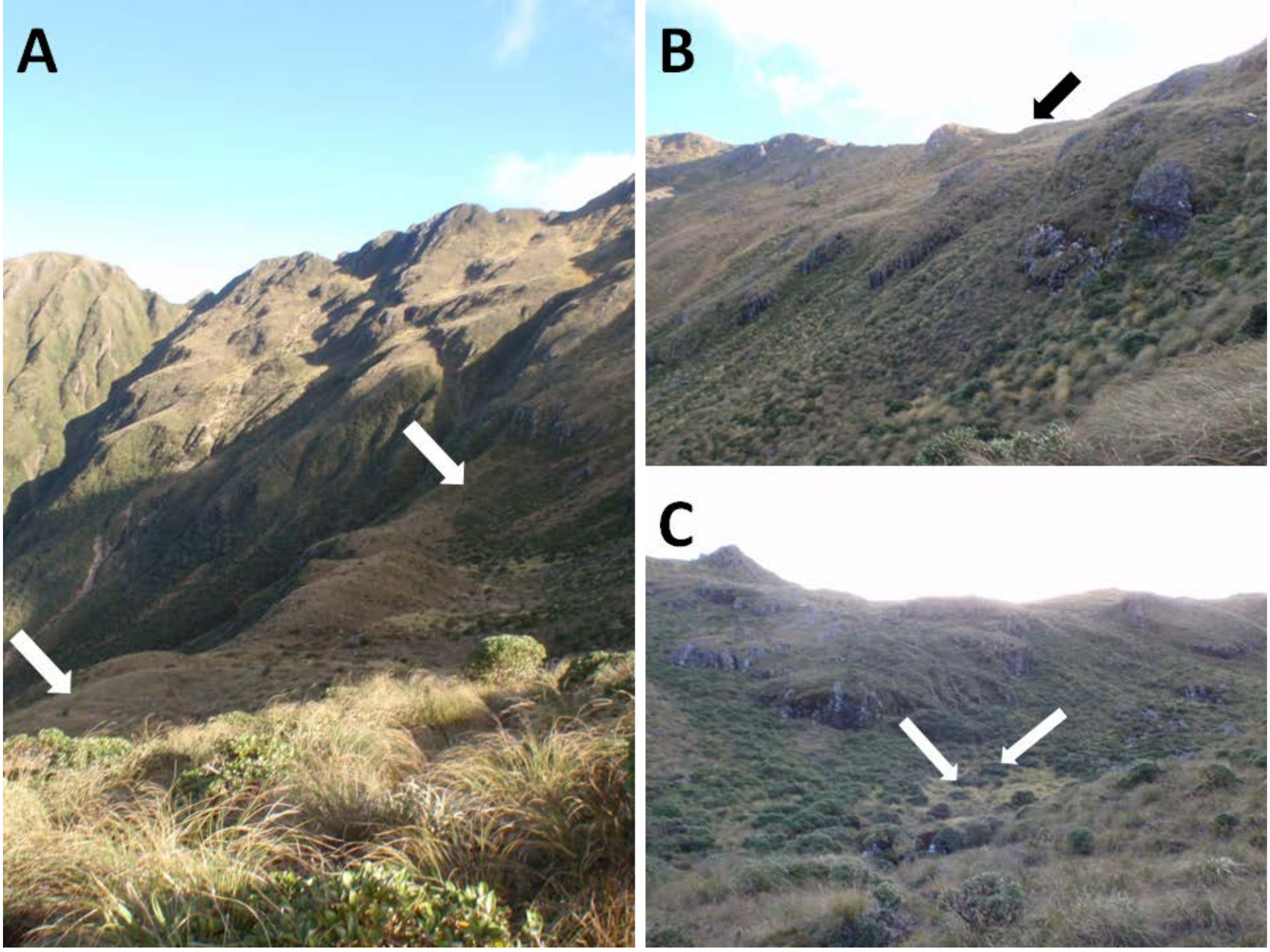

Fig 2

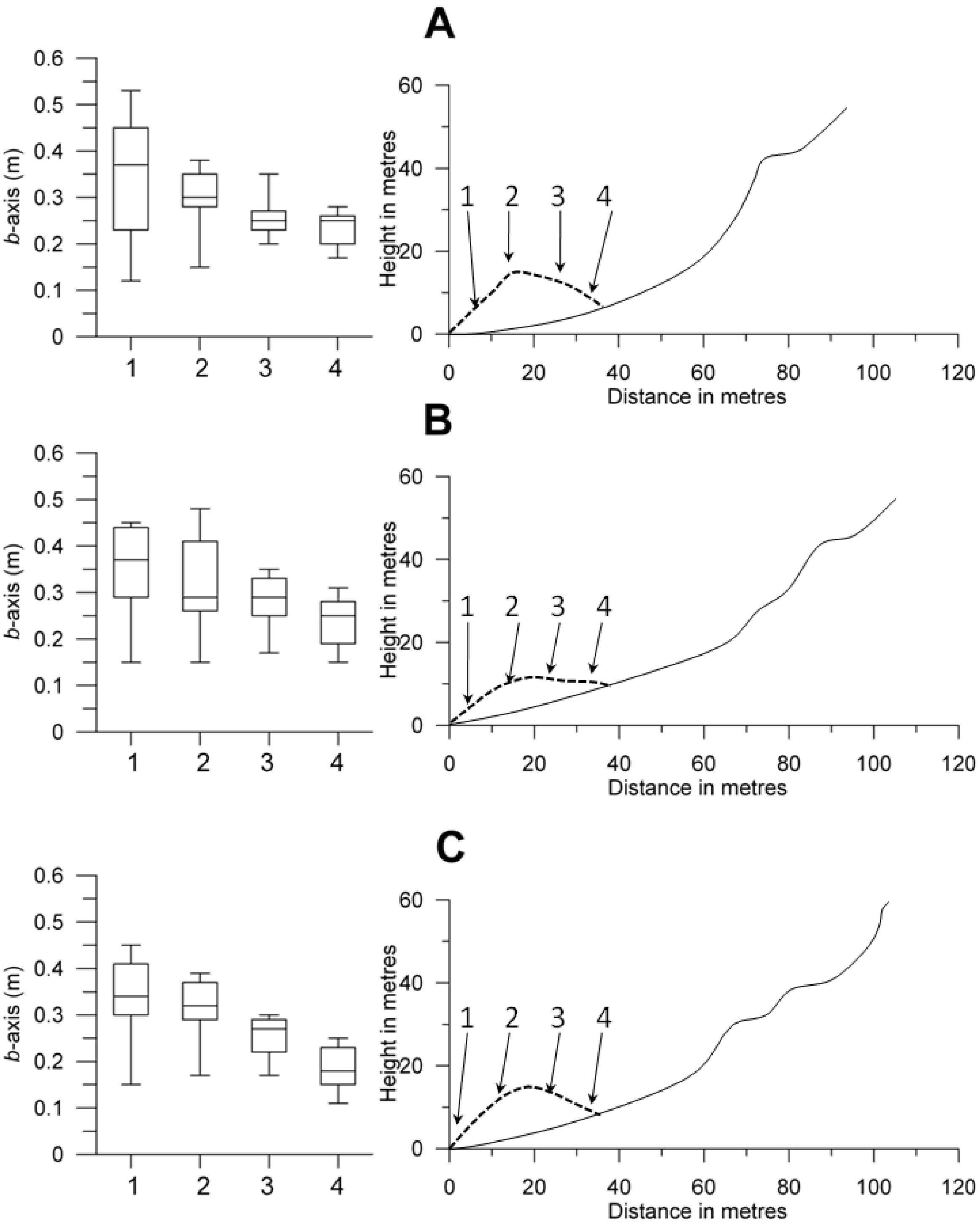
A
B
C
b-axis (m)
0
0.1
0.2
0.3
0.4
0.5
0.6
1
2
3
4
Height in metres
0
20
40
60
Distance in metres
0
20
40
60
80
100
120

Fig 3

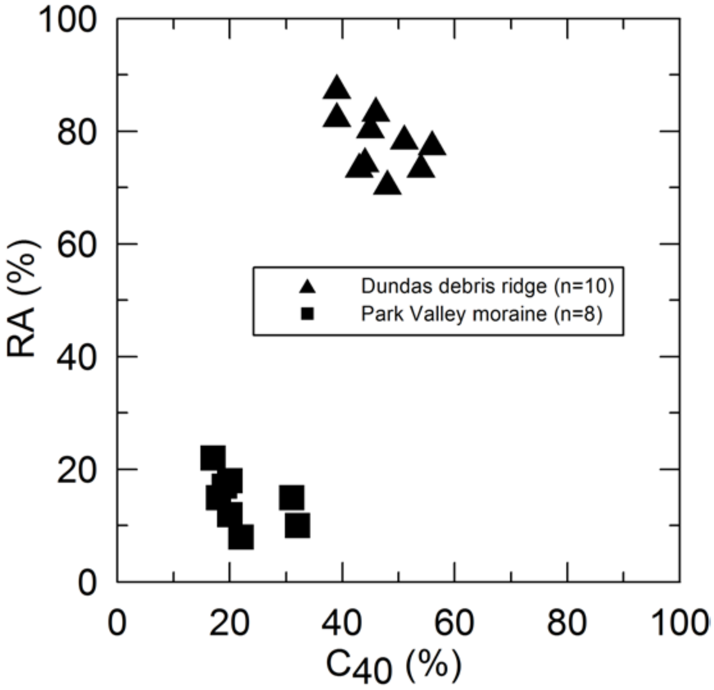
100
80
60
40
20
0
RA (%)
0
20
40
60
80
100
C_{40} (%)
▲ Dundas debris ridge (n=10)
■ Park Valley moraine (n=8)

Fig 4