Diagnostic criteria for pronival ramparts: site, morphological and sedimentological characteristics

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ABSTRACT. Pronival ramparts are discrete debris accumulations found below steep rock faces at the foot of snowbeds or firn fields but they are often confused with moraines, protalus rock glaciers or rock-slope failure debris accumulations. This can be attributed to a poor understanding of the modes of rampart genesis, failure to recognise the significance of topography in their development and the use of inappropriate diagnostic criteria. Various characteristics have been suggested for identification of pronival ramparts but these are derived largely from relict features. Research on actively-accumulating ramparts has shown that some of the suggested criteria are no longer useful. This paper reviews existing criteria and shows that, for diagnostic purposes, more emphasis should be placed on the attributes of actively-accumulating features. A more robust set of criteria, derived from common characteristics of actively-accumulating ramparts, are proposed that assists in discriminating relict and active pronival ramparts from other discrete bedrock cliff-foot debris accumulations.

Key words: pronival rampart, protalus rampart, diagnostic criteria,

Introduction

A pronival (protalus) rampart is a ridge, series of ridges or ramp of debris formed at the downslope margin of a perennial or semi-permanent snowbed (Shakesby 2004). Until the mid 1980s, most of the research dealt with supposed relict (fossil) examples, with few studies focusing on actively-accumulating features and their observed processes (Shakesby 1997). Many relict pronival ramparts have been identified incorrectly (see Ballantyne and Harris 1994; Gordon and Ballantyne 2006; Ballantyne and Stone 2009). Ballantyne and Kirkbride (1986) proposed diagnostic criteria based on the morphometric regularity of nine relict ramparts in Great Britain but Ballantyne and Harris (1994) later note that two of the nine ramparts, namely the features at Lairig Ghru in the Cairngorns and Baosbheinn in the N.W. Highlands, may not be true ramparts. The pronival rampart on St Kilda (Ballantyne, 2002), along with several other features in Great Britain (*e.g.*

Wilson 2004), are now also considered products of large-scale rock-slope failures (see Jarman 2006) that 'mimic' pronival ramparts (Wilson 2009). Given the uncertainty of several rampart-like landforms in Great Britain, the proposed diagnostic criteria by Ballantyne and Kirkbride (1986) should be re-evaluated.

Due to inappropriate diagnostic criteria coupled with a generally poor understanding of their genesis, identification of pronival ramparts remains problematic (Scotti *et al*. 2013). The debate surrounding relict pronival ramparts in southern Africa (*e.g*. Shakesby 1997; Grab 2000; Sumner and de Villiers 2002; Lewis 2008; Hall 2010; Grab *et al*. 2012) provides further examples. Shakesby (1997; 394) argues that "only when further investigations on actively-accumulating ramparts have been carried out, will it be possible to compile a reliable list of criteria for distinguishing ramparts from moraines, protalus rock glaciers, and other bedrock cliff-foot depositional forms." A growing body of literature, based on studies of such landforms (*e.g*. Harris 1986; Ono and Watanabe 1986; Ballantyne 1987; Pérez 1988; Shakesby *et al*. 1995; Hall and Meiklejohn 1997; Strelin and Sone 1998; Shakesby *et al*. 1999; Fukui 2003; Hedding *et al*. 2007; Hedding *et al*. 2010; Margold *et al*. 2011; Matthews *et al*. 2011) now provides the opportunity to explore common characteristics of these features. This paper reviews the characteristics of actively-accumulating pronival ramparts in order to compile a revised set of diagnostic criteria which can then be used to identify ramparts and distinguish them from other discrete cliff-foot accumulations.

Site, morphological and sedimentological characteristics of pronival ramparts

Actively-accumulating pronival ramparts, although rare in comparison to other discrete bedrock cliff-foot debris accumulations, are found in periglacial and glacial environments across the globe. The morphological and sedimentological characteristics are summarised in Table 1. Given the uncertainty surrounding the identification and supposed characteristics of many relict ramparts only actively-accumulating ramparts are tabulated here. Common site, morphological and sedimentological characteristics are then identified in order to establish diagnostic criteria.

Table 1. Morphological and sedimentological characteristics of actively-accumulating ramparts (based on the criteria from Shakesby 1997).

Location	No. of ramparts	Slope angles (°) Distal	Proximal	Thickness (m)	Length (m)	Morphological characteristics	Plan form	Clast roundness	Reference
Okskolten, Norway	1	16-41	4-44	≤ 2	100	Main and minor ridges	Sinuous	'mainly angular'	Harris (1986)
Kuranosake, Japan	1	*c*. 24	*c*. 17	≤ 4	*c*. 110	Ridge and mound complex	Complex	'angular'	Ono and Watanabe (1986); Fukui (2003)
Lyngen, Norway	2	34-43	0-8	≤ 5	60-115	Single ridge	Arcuate	Sub-angular to very angular	Ballantyne (1987)
Lassen Peak, USA	1	33-39	25-30	≤ 4	150	Double ridge	Arcuate	Rounding by particle collisions	Pérez (1988)
British Columbia, Canada	9	25-35	*c*. 6	*c*. 10	n.d.	Double ridge	Sinuous	'highly angular'	Hall and Meiklejohn (1997)
Smørbotn and Romsdalsalpane, Norway	10	26-37	-20 to -32*	1-9	150-460	Single and multiple ridges and ramps	Arcuate	Sub-rounded to very angular	Shakesby *et al*. (1995); Shakesby *et al*. (1999)
James Ross Island, Antarctic	2	40-50	40-50	≤ 5	150	Single ridge	Sinuous	'angular volcanic fragments'	Strelin and Sone (1998)
Marion Island, South Africa	1	22	34	7-8	140	Single ridge with step	Sinuous	Angular	Hedding *et al*. (2007)
Grunehogna, Antarctica	1	20	-14*	≤ 1	85	Single ridge	Sinuous	'typically angular'	Hedding *et al*. (2010)
Krkonoše Mountains, Czech Republic	2	n.d.	n.d.	≤ 3	c. 40	Single ridge	Arcuate	'angular clasts'	Margold *et al*. (2011)
Smørbotn, Nystølsnovi and Alnesreset, Norway	7	23-27; 33-38	0 to -25*	≤ 6	≤ 300	Single ridge	Linear to Arcuate	'very angular to angular'	Matthews *et al*. (2011)

n.d. = no data

* negative values denote slope declination towards the valley floor.

In plan-form, it appears that actively-accumulating ramparts vary from single linear and curved features to complex and sinuous or festoon-shaped features comprising multiple ridges (Table 1). Lengths range from 40m (Margold *et al*. 2011) to 460m (Shakesby *et al*. 1995) and features can attain a thickness of 10m (Hall and Meiklejohn 1997). Table 1 demonstrates that active ramparts are typically not as large in terms of cross-profile form as many supposed relict features but the maximum lateral extent of snowbeds and their associated ramparts are greater than is generally assumed for relict features (Shakesby 1997). Distal and proximal slopes of ramparts can both form 'repose slopes'. The characteristics of distal and proximal slopes, which are dependent on snowbed attributes and underlying slope angle, can be indicative of downslope or upslope (retrogressive) development. Hedding *et al*. (2007) show a step feature in the proximal slope of a rampart possibly in response to decreased snowfall.

Genesis of ramparts is, in all cases, restricted to sites overlooked by a rockwall but the site or topographic setting has not received much attention in studies on active features. Hedding *et al*. (2007) and Hedding *et al*. (2010) report backwall heights of 52m and 120m respectively, which could enable investigations of backwall retreat and the growth rates of ramparts. Few of other such site data are available. When assessing actively-accumulating ramparts, more emphasis should thus be placed on the relationship of the source of debris production (backwall height and width) with the maximum rampart crest height and distance of from the backwall.

Constituent material of relict ramparts is typically described as angular, coarse debris (*e.g*. Washburn 1979; Colhoun 1981; White 1981; Lindner and Marks 1985; Oxford 1985; Harris 1986; Tinkler and Pengelly 1994; Shakesby *et al*. 1995; Shakesby *et al*. 1999; Shakesby 2004; Mills 2006) since it was envisaged that only such material could move across the snowbed surface, comprising firn and ice, by way of the simple supranival gravity fall process. Ramparts are thus frequently noted with angular-shaped clasts, which are then typically attributed to the supranival transport of frost-shattered debris (Shakesby and Matthews 1993; Brook 2009); although 'frost' weathering processes do not necessarily produce angular-shape debris (see Hall *et al*., 2002). The constituent material of pronival ramparts is not constrained to angular material with some studies of active features reporting appreciable quantities of fines (*e.g*. Pérez

1988; Shakesby *et al*. 1995; Shakesby *et al*. 1999). Pérez (1988) concluded that fines found in the rampart studied at Lessen Peak, California could have been produced by the impact of falling clasts, infranival meltwater flow within a sediment-rich layer, *in situ* weathering, avalanches or debris flows. Fines and clastic debris can be transported by avalanching (Ballantyne 1987; Matthews *et al*. 2011) and fines could be incorporated in the constituent material of actively-accumulating ramparts through alpine debris flows (Ono and Watanabe 1985). Shakesby (1997) also suggests that low frequency-high magnitude rockfall events might be responsible for rampart formation in favoured locations. Shakesby *et al*. (1999) have shown that densely packed snow, produced in maritime periglacial climates with heavy winter snowfall and rapid snow-firn conversion, may eventually begin to slide, pushing (snow-push) boulders of over 50cm in length but, as a process, this has not been reported elsewhere. Therefore, snow-push may only be possible as a mechanism for the genesis of pronival ramparts when the constituent material is suitable (*i.e*. not when large clasts are interlocking).

In some studies of relict examples (*e.g*. Lengellé 1970; Washburn 1979), fines were not found or were considered to only represent a very small fraction of the constituent material. White (1981: 131) asserted that very little, if any, fine debris ordinarily reaches the lower edge of the firn field. Hedding *et al*. (2007) only observed occasional interstitial fines in an active rampart which they attributed to wind-blown material and small debris flows on the surface of the snowbed, whereas Pérez (1988) reported a substantial quantity of fines in the rampart. Hall and Meiklejohn (1997) observed few fines in the inner (active) ridge of pronival ramparts in the Canadian Rockies and Ballantyne and Kirkbride (1986) indicate that even at depth fines form no more than a partial infill. In contrast, Hall and Meiklejohn (1997) describes the relict outer ridges of ramparts to comprise of both large blocks and fine material. Ballantyne and Kirkbride (1986) attribute the observation of fines within pronival ramparts to granular disintegration but Derbyshire *et al*. (1979) indicate that considerable fines can be transported through the process of supranival wash. Harris (1986) suggests that fresh clean surfaces and mechanical features such as ‘conchoidal fractures, meandering ridges, breakage blocks, and arc-shaped and parallel steps’ are characteristic of quartz grains (fines) on an active rampart in Norway. Lewis (1994) used these and other transport-induced microtextures of quartz grains as sedimentological evidence to identify a relict pronival rampart in South Africa. However, a recent study by Sweet and Soreghan (2010) shows that the transport-induced microtextures of quartz grains can be obtained through various transport/fracture processes in a variety of depositional environments and many other microtexture patterns such as dissolution etching, weathered surfaces and precipitation features can be attributed to diagenesis. Thus, characteristics of quartz grains possess no environmental significance (Sweet and Soreghan 2010) and are not useful as a diagnostic criterion.

Towards a revised set of diagnostic criteria

Studies that focus on actively-accumulating ramparts (*e.g*. Harris 1986; Ono and Watanabe 1986; Ballantyne 1987; Pérez 1988; Shakesby *et al*. 1995; Hall and Meiklejohn 1997; Strelin and Sone, 1998; Shakesby *et al*. 1999; Fukui 2003; Hedding *et al*. 2007; Hedding *et al*. 2010; Margold *et al*. 2011; Matthews *et al*. 2011) have begun to provide the body of knowledge needed to improve our understanding of rampart genesis, morphology, sedimentology and palaeo-environmental significance. Hedding *et al*. (2010) indicate that the morphological characteristics and environmental conditions under which ramparts develop may be more varied than conceived in current models, particularly when rampart age or stage of development, underlying slope angle, the different mechanisms of supranival (and subnival) debris transport and the possibility of 'form-convergence' for discrete debris accumulations (Whalley 2009) are taken into account. Given the uncertainty around some of the diagnostic criteria and the confusion over the origins and nomenclature of pronival ramparts (Shakesby and Matthews 2012) the diagnostics presented here are based on actively-accumulating features and adopt multiple-working hypotheses when investigating the origins of landforms (Shakesby 1997; Curry *et al*. 2001; Harris *et al*. 2004) (Table 2).

Table 2. Proposed diagnostic criteria for the differentiation of pronival ramparts from moraines, protalus rock glaciers and landslide deposits.

Criteria	Reference
Pronival (Protalus) Rampart	
Ridge crest to cliff-foot distance <c.30-70m	Ballantyne and Benn (1994)
Insufficient cross-section depth for snow to glacier ice transformation	Watson (1966); Shakesby and Matthews (1993); Ballantyne and Benn (1994); Bower (1998)
Underlying slope gradient that will facilitate snow/firn bed angle >20°	Ballantyne and Benn (1994)
No glacial erosional forms or evidence of overdeepening of the associated backwall area through sapping and subglacial erosion	Bower (1998)
Openwork fabric; absence of fines (<2mm)	Hedding *et al*. (2007); Brook (2009); Hedding *et al*. (2010)
Backwall and ridge same lithology (no erratics)	Unwin (1975)
Absence of striated clasts	Shakesby and Matthews (1993); Curry *et al*. (2001)
Glacial Moraine	
Glacial erosional forms	Benn and Evans (2007)
Striated clasts	Shakesby and Matthews (1993); Curry *et al*. (2001)
Broadly arcuate in plan-form but in detail are often irregular and winding	Benn and Evans (2007)
Ridge crest to talus-foot distance >c.30-70m	Ballantyne and Benn (1994)
Presence of fines (<2mm)	Brook (2009)
Rock-slope Failure	
Recognizable source cavity or distinct scar of comparable volume, linked to the deposit by a feasible trajectory	Curry *et al*. (2001); Jarman *et al*. (2013)
Debris aprons beyond the feature	Curry *et al*. (2001)
Debris much larger than adjacent talus accumulations	Curry *et al*. (2001)
Large masses of displaced hillside within or above the area of debris accumulation	Curry *et al*. (2001)
Minimum size thresholds: 0.01 km^2 in areal extent (source and deposit); 0.1 Mm^3 in gross volume; and 5m depth of formerly intact bedrock	Jarman *et al*. (2013)
Protalus Rock Glacier	
Greater in length (down-slope) than in width (across-slope)	Curry *et al*. (2001)
Convex distal slope	Curry *et al*. (2001)
Typically terminate >70m from the talus slope	Curry *et al*. (2001)
Lobate or crenulated of the outer margins in plan form	White (1981); Wilson (1990)
Meandering and closed depressions, downslope ridges and furrows, and transverse ridges and depressions	White (1987); Curry *et al*. (2001)

Hedding *et al*. (2010) adapted the criteria of Hedding *et al*. (2007) by removing ‘Erratics’ from the set of diagnostics since not all moraines contain erratics. They also did not consider the criteria ‘Asymmetrical cross-profile’ and ‘Symmetrical cross-profile’ as diagnostic since actively-accumulating ramparts can display either of these characteristics depending on debris production, snowbed attributes and consequently rampart genesis (*e.g*. Hedding *et al*. 2007; Strelin and Sone 1998). The diagnostic criteria ‘Large ridge to backwall inclination’ introduced by Lewis (1966), and used recently by Brook and Williams (2013), has not been considered here since it is based on relict features that have been reinterpreted as scarp-foot ridges by Shakesby (1992) and Shakesby and Matthews (1993). Hedding *et al*. (2010) dropped the criterion ‘Crenulate or lobate plan form of outer margins’ tabulated by Hedding *et al*. (2007) but it is reintroduced here as a valid criterion for the identification of protalus rock glaciers (White 1981; Wilson 1990). The criterion ‘Ridge size increase with distance from cliff foot’ used by Hedding *et al*. (2010) and Brook and Williams (2013) is discarded because the retrogressive genesis of an actively-accumulating rampart on sub-Antarctic Marion Island (Hedding 2008) indicates that size does not necessarily increase with distance from cliff foot. Rather, rampart size is dependent on debris production and snowbed size and shape thus ridge size cannot be regarded as diagnostic. Similarly, the criteria ‘Length <300m’ and ‘Single ridge’ used by Hedding *et al*. (2007) and Hedding *et al*. (2010) are not regarded as diagnostic for actively-accumulating features. Phrasing of the criterion ‘Ridge crest to cliff-foot distance <c. 30-70m’ has been adapted in contrast to ‘Ridge crest to talus-foot distance <c. 30-70m’ introduced by Ballantyne and Benn (1994) to accommodate ramparts that accumulate between the bedrock valley side and the top (not base) of the talus slope (Shakesby *et al*. 1995; Shakesby *et al*. 1999; Matthews *et al*. 2011).

Mills (2006) indicates that clasts of pronival ramparts have a slabby particle shape (Ballantyne and Kirkbride 1986), have no preferred orientation (Washburn 1979; Pérez 1988), are aligned oblique to the ridge crest (Shakesby *et al*. 1999; Harris 1986) and dip downslope (Lewis, 1966; Harris 1986). The criterion ‘Clasts dip away from backwall’ used by Harris (1986), Mills (2006) and Hedding *et al*. (2010) has not been considered here because, in contrast to the ascertain of Lewis (1966) that the upward transport of debris forming moraines would cause clasts to dip toward the backwall, material may also slide over a steep glacier surface and dip away from the backwall. Therefore, it is unlikely to be a very useful criterion (see also Shakesby and Matthews 1993; Shakesby 1997). Benn and Ballantyne (1994) note the usefulness of using the C_{40} index to differentiate clasts with different erosional “histories” but this criterion has not been adopted widely. A comparison of the co-variance of clast RA (angularity) and C_{40} shape of constituent ridge debris has been proposed by Benn and Ballantyne (1994) to provide a method to differentiate pronival ramparts from moraines, but low C_{40} and RA values only imply sub-glacial glacial transport of clasts while moraines can also comprise supraglacial debris represented by high C_{40} and RA values. The use of this criterion is thus questionable. Introduction of the absence/presence of fines (<2mm) in the set of diagnostic criteria is based on comparison of constituent material of moraines and pronival ramparts by Brook (2009).

Conclusion

The proposed set of diagnostic criteria presented here adopt multiple-working hypotheses when investigating the origins of landforms (Shakesby 1997; Curry *et al*. 2001; Harris *et al*. 2004) and incorporate characteristics which are not limited to ridge morphology but also focus on sedimentology and topographic setting of actively-accumulating features. This is proposed as a starting point for the identification of pronival ramparts in the field and may also facilitate the reappraisal of questionable relict examples (see Shakesby 1997; Grab 2000; Sumner & de Villiers 2002; Lewis 2008; Hall 2010; Grab *et al*. 2012). Since few studies document the scale of the rampart in relation to the surrounding topography, this aspect should also be investigated in more detail in future studies of actively-accumulating ramparts.

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