



Pronival ramparts: A review

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Abstract

Pronival ramparts are debris ridges formed at the downslope margins of perennial or semi-permanent snowbeds beneath bedrock cliffs. These landforms, also previously known as protalus ramparts, are located in periglacial environments, but the apparent simplicity of rampart formation made these landforms far less interesting than other modified forms of talus in cold environments. As a result, limited research, use of supposed relict examples and assumed formative mechanisms led to the misidentification of ramparts, circular arguments regarding genesis and inappropriate palaeo-environmental inferences. Several advances have, however, been made in the past few decades, particularly where actively-forming ramparts have been studied. Thus, this paper provides a review of research on pronival ramparts. In particular, focus is placed on the advances made in our understanding of rampart genesis, identification (diagnostic criteria) and palaeo-environmental significance. Notable advances include the development of a retrogressive model of rampart genesis to supplement the conventional downslope model of development, revised diagnostic criteria for field identification and the use of calibration equations during Schmidt-hammer exposure dating of pronival rampart. The use of pronival ramparts as palaeo-environmental indicators is also examined to determine what relict examples of these landforms may reveal about past climates.

Keywords

Pronival rampart, protalus rampart, snowbed, snow, genesis, diagnostic criteria, palaeo-environmental significance

1 Introduction

A pronival rampart is a ridge, series of ridges or ramp of debris formed at the downslope margins of a perennial or semi-permanent snowbed overlooked by a bedrock cliff (Figure 1). These landforms were formerly referred to as protalus ramparts. Scappoza et al. (2011) and Scappoza (2015) have recently proposed that the term ‘protalus rampart’ be used to designate small permafrost creep phenomena in the lower part of a talus slope that can be considered as active embryonic rock glaciers. This proposal makes a distinction between nivo-gravitational landforms (pronival ramparts) and a permafrost-

related landform (protalus ramparts) (Scappoza, 2015) but Matthews et al. (2016) prefer the term ‘embryonic rock glacier’ over protalus rampart since these landforms can develop entirely by permafrost creep without the development of a pronival rampart first. In addition, Hedding (2011) cautions that since the terms ‘pronival rampart’ and ‘protalus rampart’ have been used

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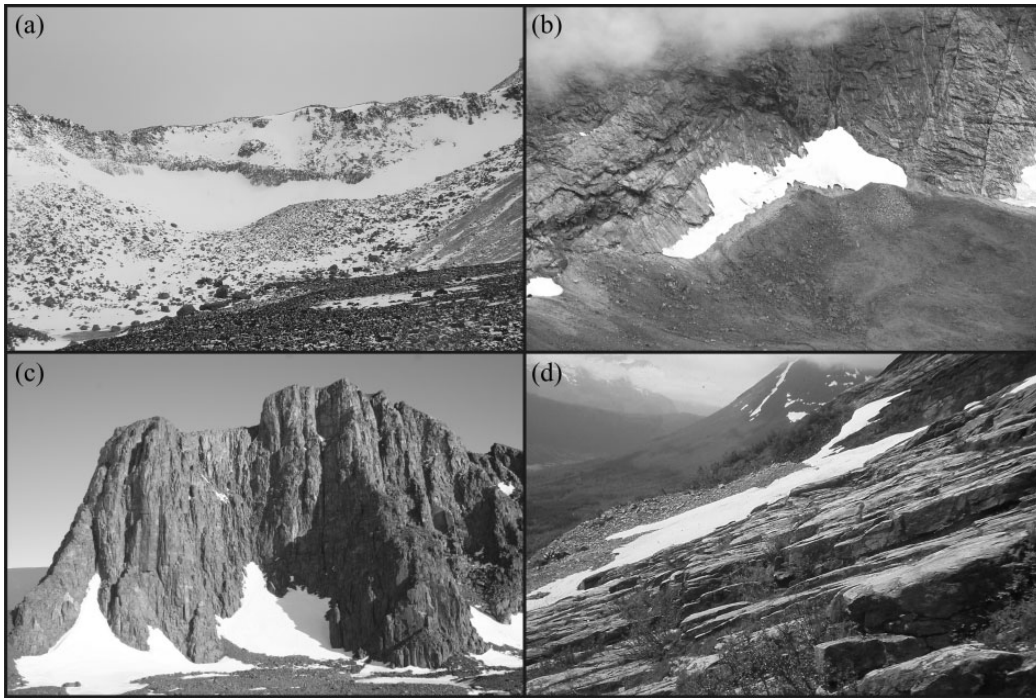


Figure 1. Examples of actively-accumulating pronival ramparts. (a) a rampart on sub-Antarctic Marion Island. (b) a rampart at Smørbotn, Norway (Photograph: JA Matthews; used with permission). (c) a rampart at Grunehogna Peaks, Western Dronning Maud Land, Antarctica. (d) a rampart at Taskedalen, Norway (Photograph: R Shakesby; used with permission).

interchangeably over the past two decades, it may lead to further confusion. Moreover, the inability to distinguish between relict pronival ramparts and protalus ramparts, as envisioned by Scappoza et al. (2011) and Scappoza (2015), may make it difficult to adopt this suggestion in practice. For instance, Colucci et al. (2016) acknowledge that, when investigating relict protalus ramparts and pronival ramparts using remote sensing data, both suggested forms must be considered together owing to the difficulty in distinguishing the real origin.

Shakesby (1997, 2004) and Hedding (2011, 2016) chronicle the development of the terminology used to describe pronival ramparts. Whalley (2015) notes that the choice of words and terms associated with pronival ramparts and protalus features needs particular attention in both terrestrial and non-terrestrial

environments. Active ramparts are located in periglacial environments but the apparent simplicity of rampart formation made these landforms far less interesting than other modified forms of talus in cold environments (Shakesby, 1997). As a result, limited research, use of supposed relict examples and assumed formative mechanisms has led to the misidentification of ramparts, circular arguments regarding genesis and inappropriate palaeo-environmental inferences (c.f. Shakesby, 1997; Hedding, 2014). Several advances have, however, been made in the past two decades, particularly where actively-forming ramparts have been studied (e.g. Fukui, 2003; Hall and Meiklejohn, 1997; Hedding et al., 2007; Hedding et al., 2010; Margold et al., 2011; Matthews and Wilson, 2015; Matthews et al., 2011; Matthews et al., 2015; Shakesby et al., 1999; Strelin and Sone,

1998;). Thus, this paper provides a review of research on pronival ramparts since the seminal review by Shakesby (1997). In particular, focus is placed on the advances made in our understanding of rampart genesis, identification (diagnostic criteria) and palaeo-environmental significance, but, first, an overview of the distribution and characteristics of relict and actively-accumulating pronival ramparts is presented.

1. Distribution and characteristics of pronival ramparts

Both active and relict pronival ramparts have wide geographic and altitudinal distributions. Relict ramparts have been documented primarily in Britain and Ireland, but some of these have been misinterpreted (see Shakesby, 1997). Examples of relict ramparts have also been identified in Norway (e.g. Shakesby et al., 1987), Africa (e.g. Lewis and Illgner, 2001) and Australia (Slee, 2015) (Table 1). The putative relict pronival rampart at Guyra in mainland Australia identified by Slee (2015) is particularly interesting in terms of the uniqueness of the site. Relict examples have also been mapped in the Central Andes (e.g. Trombotto, 2000) and Africa (e.g. Grab, 1996) with little morphological detail provided. Active ramparts are more widespread (Table 2), but none have been documented in Africa (Hedding, 2014), Australia (Slee, 2015) or New Zealand (Brook and Williams, 2013). Given the current and former global distribution of cold climates, pronival ramparts are probably underrepresented in the literature. For instance, relict pronival ramparts perched on valley sides may have been misinterpreted as former moraines of valley glaciers due to a lack of understanding of rampart genesis and morphometrics.

Actively-accumulating pronival ramparts are found in a variety of environmental conditions (Table 3). Mean annual air temperatures at sites range from -17°C (Hedding et al., 2010) to

0.9°C (Hedding et al., 2007). Precipitation is typically above ~ 800 mm p.a. but can vary greatly from almost none in the Antarctic (Hedding et al., 2010) to above 3000 mm (water equivalent of snow) (Fukui, 2003). Shakesby (1997: 410) noted that ‘fossil ramparts provide little useful palaeo-environmental information other than indicating the obvious; that climatic conditions were formerly cooler and/or more snowy’. However, the absence or presence of relict pronival ramparts, specifically in areas which experienced marginal glaciations, may be particularly useful in palaeo-environmental reconstructions (see Hedding, 2014).

II Rampart genesis

Relict pronival ramparts are frequently described as comprising coarse angular rockfall material derived from the bedrock cliffs (back-wall) above the snowbed (e.g. Harris, 1986). This angular material is typically attributed to the supranival transport of frost-shattered debris (Brook, 2009). One of the earliest descriptions of frost shattering occurring at the headwall comes from Lewis (1939) and this concept has become largely entrenched in the literature. Shakesby (1997: 397) noted, however, that clasts of actively-accumulating ramparts are ‘by no means nearly all angular, as is thought typical of fossil ramparts’ and highlights the limited understanding of debris production for the genesis of ramparts.

1. Debris production

In general, very little research on debris production from exposed bedrock cliffs has been undertaken in periglacial environments (see Krautblatter and Dikau, 2007; Luckman, 2013). Matsuoka and Sakai (1999) regard seasonal frost weathering to be the most important process responsible for the modification of a cirque wall and show that rockfall activity intensifies in spring during the seasonal thawing period. Matsuoka (2001) observed frost

Table 1. Morphological and sedimentological characteristics of some relict (fossil) ramparts (adapted from Curry et al., 2001, and updated to the present).

Location	No. of ramparts	Slope angles (°)		Height / thickness (m)	Length (m)	Morphological characteristics (Plan form)	Debris transport mechanisms	Clast roundness	Reference
		Distal	Proximal						
Grampians, Scotland	2	34 and 37.5	-13.5 and -12	2 and 1/4 and 6	33 and 150	Single ridge (arcuate – truncated)	Supranival: Rockfall	Angular	Ballantyne and Kirkbride (1986)
Lake District, England	2	34 and 34	-11 and -21.5	2 and 3/10 and 10	225 and 300	Single ridge (linear and arcuate)	Supranival: Rockfall	Angular	Ballantyne and Kirkbride (1986)
NW Highlands, Scotland	1	36	\$	4 / 34	120	Single ridge (arcuate)	Supranival: Rockfall	Angular	Ballantyne and Kirkbride (1986)
Rondane, Norway	4	30*	-19.5*	3-7 / 6-56	280-590	Single and double ridges (ND)	Supranival: Rockfall Subnival: Snow push and snow creep	Angular	Shakesby et al. (1987)
Errigal, Ireland	2	20 and 31.5	-4 and -14	5 and 13 / 4 and 10	150 and 325	Single ridge (linear to gently arcuate)	Supranival: Rockfall	Coarse and openwork	Wilson (1990)
Lake District, England	1	24-32	-7- -18	1-2 / ND	140	Single ridge (linear)	Supranival: Rockfall	ND	Wilson and Clark (1999)
Magillicuddy's Reeks, south-west Ireland	1	35-39	-10-15	1.5 / 40-75	125	Single ridge (linear)	Supranival: Rockfall	Angular to very angular	Anderson et al. (2001)
Mount Enterprise, South Africa	2	37	-27	3 / ND	55 and 80	Single ridge (linear)	Supranival: Rockfall	ND	Lewis and Illgner (2001)
Thabana Ntelyana, Lesotho	3	45	-15	0.6-0.7 / 4-6	15-22	Single ridge (arcuate)	Subnival: Snow push and snow creep	Sub-angular to sub-rounded	Grab and Mills (2011)
Guyra, Australia	1	5	-5	2-2.5 / c. 10	c. 90	Single ridge (arcuate)	Supranival: Rockfall	Openwork clasts	Slee (2015)

ND = No data, \$ = No proximal slope, * denotes average.

Table 2. Morphological and sedimentological characteristics of actively-accumulating ramparts (Adapted from Shakesby, 1997, and updated to the present).

Location	No. of ramparts	Slope angles (°)		Height / thickness (m)	Length (m)	Morphological characteristics (Plan form)	Debris transport mechanisms	Clast roundness	Reference
		Distal	Proximal						
Okskolten, Norway	1	16–41	–44––4	≤ 2 / 10	100	Main and minor ridges (sinuous)	Supranival: Rockfall	'mainly angular'	Harris (1986)
Kuranosake, Japan	1	c. 24	c. –17	≤ 4 / 52	c. 110	Ridge and mound complex (complex)	Supranival: Rockfall and debris flows	'angular'	Ono and Watanabe (1986); Fukui (2003)
Lyngen, Norway	2	34–43	–8–0	≤ 5 / 32–42	60–115	Single ridge (arcuate)	Supranival: Rockfall	Sub-angular to very angular	Ballantyne (1987)
Lassen Peak, USA	1	33–39	–30––25	≤ 4 / 5–30	150	Double ridge (arcuate)	Supranival: Rockfall and debris flows	Rounding by particle collisions	Pérez (1988)
Romsdalsalpene, Norway	10	26–37	–20–32	1–9 / 21–84	150–460	Single and multiple ridges and ramps (sickle-shaped)	Subnival: Debris flows, meltwater, snow push and solifluction	Sub-rounded to very angular	Shakesby et al. (1995); Shakesby et al. (1999)
British Columbia, Canada	9	25–27; 25–35	–12––6; c. –6	10 / ND	ND	Double ridge (sinuous)	Supranival: Rockfall	'sharp' and 'highly angular'	Hall and Meiklejohn (1997)
James Ross Island, Antarctic	2	40–50	–40––50	≤ 5 / c. 20	150	Single ridge (sinuous)	Supranival: Rockfall, debris flows and avalanche	'angular volcanic fragments'	Strelin and Sone (1998)

(continued)

Table 2. (continued)

Location	No. of ramparts	Slope angles (°)		Height / thickness (m)	Length (m)	Morphological characteristics (Plan form)	Debris transport mechanisms	Clast roundness	Reference
		Distal	Proximal						
Marion Island, South Africa	1	22	-34	7-8 / 67-79	140	Single ridge with step (sinuous)	Supranival: Rockfall	Angular	Hedding et al. (2007)
Grunehogna, Antarctica	1	20	14	< 1 / 5-23	85	Single ridge (sinuous)	Supranival: Rockfall	'typically angular'	Hedding et al. (2010)
Krkonoše Mountains, Czech Republic	2	c. 32-48	c. -40-18	3 / c. 10-20	40	Single ridge (arcuate)	Supranival: Rockfall	Angular	Margold et al. (2011)
Smørbotn, Norway	2	33-36	-26-27	2.5-3 / c. 10-70	300-360*	Single ridge (linear to arcuate)	Supranival: Rockfall and snow-avalanche	'very angular to angular'	Matthews et al. (2016)

* Matthews et al. (2011) note that other ramparts extend for >2 km around the cirque headwall.
 ND = No data.

Table 3. Environmental characteristics of actively-accumulating pronival ramparts.

Location (Latitude; Longitude)	Author(s)	Altitude (a.s.l.)	Air Temperature (°C)	Precipitation (mm) / mean snow cover (days)	Note
Okskolten, Norway (66°30'N; 14°20'E)	Harris (1986)	900 m	-3°C (data cited from Worsley and Harris, 1974)	1032 mm (data cited from Harris, 1974) / 210 (data cited from Harris, 1974)	Temperature data from Okstindsjøen (710 m a.s.l.); Precipitation data from Hattfjellidal (380 m a.s.l)
Kuranosake, Japan (36°36'N; 137°36'E)	Ono and Watanabe (1986); Fukui (2003)	~2500 m	-2.8°C (data cited from Fukui and Iwata, 2000)	Summer precipitation > 1000 mm; Winter precipitation > 3000 mm (water equivalent of snow) (Fukui, 2003) / ND	Data from Muroda (2454 m a.s.l)
Lyngen, Norway (69°35'N; 20°15'E)	Ballantyne (1987)	760 m	-1.8°C (Ballantyne, 1987)	600–850 mm (Ballantyne, 1987) / ND	Temperature data from Tromsø and Skibotn (700 m a.s.l.); Precipitation data from Jøvik and Lyngseidet (0 m a.s.l)
Lassen Peak, USA (40°29'N; 121°30'W)	Pérez (1988)	2615 m	<0°C (winter: November to April) (Pérez, 1989)	1650–1700 mm (Pérez, 1988) / ND	Data from Lessen Peak, California
British Columbia, Canada (54°14'N; 120°50'W)	Hall and Meiklejohn (1997)	1850 m	High summer temperatures (\geq 20°C) (Hall and Meiklejohn, 1997)	ND / High winter snowfall (Hall and Meiklejohn, 1997)	Observations from Canadian Rockies (1850 m a.s.l.)
Smørbotn and Romsdalsalpene, Norway (62°25'N; 27°35'E)	Shakesby et al. (1995); Shakesby et al. (1999)	800 m	~1.5°C (Shakesby et al., 1999)	1211 mm (Shakesby et al., 1999) / ND	Data from Åndalsnes (20 m a.s.l.)
James Ross Island, Antarctic (63°52'S; 57°48'W)	Strelin and Sone (1998)	100 m	~-6.5°C (Strelin and Sone, 1998)	~200 mm (water equivalent) / ND	Data from James Ross Island (0 m a.s.l.)

(continued)

Table 3. (continued)

Location (Latitude; Longitude)	Author(s)	Altitude (a.s.l.)	Air Temperature (°C)	Precipitation (mm) / mean snow cover (days)	Note
Marion Island, South Africa (46°54'S; 37°45'E)	Hedding et al. (2007)	900 m	0.9°C (Hedding, 2008)	~1000 mm (data cited from Blake, 1996; Hedding, 2006) / snow cover from May to October (data cited from Hedding, 2006)	Temperature data from Delta Kop (1000 m a.s.l.); Precipitation data from Katedraalkrans (750 m a.s.l.)
Grunehogna, Antarctica (72°03'S; 2°42'E)	Hedding et al. (2010)	1090 m	-17°C (Hedding et al., 2010)	ND / ND	Temperature data from Vesleskarvet (845 m a.s.l.)
Krkonoše Mountains, Czech Republic (50°41'N; 15°39'E)	Margold et al. (2011)	1500 m	0.3°C (data cited from Glowicki, 1997)	> 1500 mm (data cited from Spusta et al., 2003) / snow cover from November to April (data cited from Spusta et al., 2003)	Temperature data from Sněžka (1602 m a.s.l.); Precipitation data from Sněžka (1602 m a.s.l.)
Smørbotn, Nystølsnøvi and Ainesreset, Norway (62°29'N; 7°45'E)	Matthews et al. (2011)	800–900 m; 400 m; 850 m	~1.5°C (Shakesby et al., 1999)	1211 mm (Shakesby et al., 1999) / ND	Data from Åndalsnes (20 m a.s.l.)

ND = No data.

wedging of alpine bedrock whereby macrocracks visible on the rock surface widened during two seasonal periods; namely, during autumn and spring. Pancza (1998) notes that during spring, the surface of the snow hardens and acts as a slideway for the rocks detached from the cliffs above, which can facilitate rampart development. These observations support the assertion that the formation of ramparts takes place more frequently during mid to late spring and not in winter (Porter, 1987). In contrast, Krautblatter and Moser (2009) have reported that over 90% of the rockfall events in the German Alps were triggered by precipitation events. These rockfall events are ascribed to the remobilization of stored debris on the rockslope, which Krautblatter and Dikau (2007) consider to be a significant link between backwearing and rockfall deposition.

Several studies (e.g. Anderson et al., 2001; André, 1997; Bower, 1998; Curry and Morris, 2004; Hinchliffe and Ballantyne, 1999) assess rockwall retreat under periglacial conditions with retreat rates of between 10^{-2} and 10^{-1} mm year⁻¹ (French, 2007). Matsuoka and Sakai (1999) determine rockwall retreat through direct observations, and other studies (e.g. André, 1997; Hinchliffe and Ballantyne, 1999) have used the volume of the sediments at the base of the rockwall to infer long-term average rates of rockwall retreat. Although some studies have used the volume of ramparts in relation to the source area of the backwall to infer rates of rockwall retreat (e.g. Anderson et al., 2001; Ballantyne and Kirkbride, 1987), no studies have specifically investigated rockwall debris production at actively-accumulating pronival rampart sites. In addition, when determining rates of rockwall retreat at pronival ramparts, a critical factor which should be considered is how much of the rockwall is exposed. Anderson et al. (2001) indicate that the principal source of error when using rampart volume to calculate rockwall retreat is the estimation of the rampart cross-sectional area because it is necessary to

assume that there is a regular decline in the gradient of the underlying slope. Based on the volumes of eight widely distributed Loch Lomond Stadial pronival ramparts, Ballantyne and Kirkbride (1987) suggested average stadial rockwall retreat of 1.14–1.61 m (estimated average rockwall retreat rates of 1.5–4.0 mmy⁻¹). However, Hinchliffe and Ballantyne (1999) indicate that these rates of rockwall retreat are two orders of magnitude greater than those implied by recent rockfall accumulation on relict talus slopes. Using a relict pronival rampart, Anderson et al. (2001) estimate that rockwall retreat rates during the Younger Dryas Stadial varied between 13 and 195 mmy⁻¹, but Ballantyne and Eckford (1984) document average present-day rockwall retreat rates of 0.015 mmy⁻¹ (excluding infrequent large-scale falls) and, therefore, rates of rockwall retreat (and debris production) based on relict landforms differ greatly from rates based on active processes.

A number of other slope processes (mass wasting) can contribute material in the formation of pronival ramparts (discussed in the next section). Rapid mass wasting in the form of snow avalanches and debris flows can deliver a wide range (in size) of material downslope, including fines. Fines are found in many actively-accumulating ramparts and can also result from in situ breakdown of constituent material, debris flows delivering fines or aeolian transport of fines. These observations show that we still know relatively little in terms of the debris production linked to debris transport and the genesis of pronival ramparts. Nevertheless, the volume of material deposited in relation to the rockwall retreat and the age of the landform can be useful when identifying relict examples. Curry et al. (2001) noted that a pronival rampart origin had been valid for the Nant Ffrancon landform in northern Wales, assessment of the volume of the landform and surface area of the backwall implies that the average rockwall retreat would have been four times greater than

that indicated by pronival ramparts developed in Britain during the Loch Lomond Stade. This calculation casts doubt on the classification of the landform as a pronival rampart and was one of the aspects which prompted the reinvestigation of the Nant Ffrancon landform by Curry et al. (2001). Bower (1998) also noted that the exceptionally large volume in relation to the potential backwall source area of some discrete debris accumulations in Britain led to questioning the landforms' classification as pronival ramparts.

2. Debris transport mechanisms

From the earliest descriptions of ramparts by Drew (1873) and Ward (1873), an overly simple mode of pronival rampart genesis by supranival processes has been assumed. Rampart development was traditionally attributed to the progressive accumulation of clasts that fall from cliffs upslope and roll, bounce or slide to the foot of the snow (firn) (Ballantyne and Harris, 1994). Pérez (1988) noted that ramparts formed by supranival debris transport mechanisms accumulate partly through debris cascading down and piling up on the distal slope, and partly by the entrapment of moving debris against the proximal slope. Owing to the implied simplicity of the supranival gravity fall process, this process was accepted by almost all subsequent studies (e.g. Goudie et al., 1994) and has become a textbook paradigm (e.g. Ballantyne and Harris, 1994). The traditionally envisaged mechanism of gravity-driven supranival debris transport has subsequently been observed at actively-accumulating ramparts (e.g. Hedding et al., 2007; Hedding et al., 2010; Pérez, 1988).

In general, a slope gradient of at least 20° (see Ballantyne and Benn, 1994) is required for gravitational transport of debris over firn surfaces. The work of Ono and Watanabe (1986), which follows on from the initial work of Sekine (1973), questions the primacy of the simple gravity-driven mode of genesis (see also

Ballantyne, 1987; Harris, 1986, Johnson, 1983; Shakesby et al., 1995; Shakesby et al., 1999). This point is highlighted by Shakesby (1997: 414) where it is stated that 'gravity movement of rockfall debris across a snowbed surface has been shown to be only one of several possible modes of transport capable of contributing debris to ramparts'.

A range of supranival and/or subnival mechanisms of debris transport may also contribute to rampart development. Other possible transport mechanisms include debris flows (Ono and Watanabe, 1986), snow avalanches (Ballantyne, 1987; Colucci, 2016; Matthews et al., 2011), the reworking of till deposits from upslope (Harris, 1986), solifluction and meltwater flows (Shakesby et al., 1995) and snow push (Kirkbride, 2016; Shakesby et al., 1999). Recently, Matthews et al. (2011) have demonstrated that rockfall is not the only primary debris transport mechanism in the formation of pronival ramparts. The position of each rampart studied by Matthews et al. (2011) and irregularly-shaped ramparts with gaps and gullies (Colucci, 2016) suggests that snow avalanches can play a significant role in rampart genesis. Shakesby et al. (1995) and Shakesby et al. (1999) also provide evidence for subnival processes being at least as important as supranival debris transport processes from actively-accumulating ramparts in Romsdalsalpane, Norway. However, ramparts formed by subnival processes have received very little attention, with only three studies having been conducted to date on actively-accumulating examples (see Matthews et al., 2011; Shakesby et al., 1995, 1999). Evidence of solifluction enhanced by wet conditions beneath and at the periphery of snowbeds at actively-accumulating ramparts has been identified by Shakesby et al. (1995). Shakesby et al. (1995) also found evidence of what they interpreted as debris flows emerging from beneath a snowbed, which led them to deduce that debris flows could be supplying debris together with meltwater action.

Shakesby et al. (1995) attributed rampart development to snow creep, which involves slow sliding of snow on an internal or, more likely, a basal shear plane (see Thorn, 1978). Later, Shakesby et al. (1999) revisited the ramparts at Romsdalsalpane, Norway, and noted snow push through the basal sliding of a snowbed acting on deformable, fines-rich diamicton as another form of subnival debris transport responsible for the development of small, distinct snowbed ridges. Ramparts formed by subnival debris transport mechanisms typically display 'distinct' rampart morphology in the form of asymmetrical ridges which take on a sickle shape in plan form (Shakesby et al., 1999). The ramparts in Romsdalsalpane, Norway, appear to be smaller than ramparts formed by supranival processes and, thus, subnival processes would potentially be limited to ramparts which are matrix, rather than clast-supported. Limiting factors in the genesis of ramparts formed by subnival processes are the slope or snowbed gradient, size of the snowbed and size of constituent material.

Kirkbride (2016) provides evidence that pronival landforms (snow push ridges) can also be associated with the deformation and/or bulldozing of sediment by late-season snowbeds through the gravitational sliding of snowbeds. Densely packed snow, produced in maritime periglacial climates with heavy winter snowfall and rapid snow-firn conversion, may eventually begin to slide, pushing boulders of over 50 cm in length (a-axis) in a matrix of clasts where the majority are less than 20 cm in length (a-axis) (Shakesby et al., 1999). Similarly, Grab and Mills (2011: 185) propose that 'snowcreep [sic] and snowpush [sic] may cause considerable localized stresses and initiate boulder movement where snow-basal frictional forces are sufficiently low', but shallow slope gradients and the interlocking of large clasts may arrest the movement of clasts downslope and is likely a limiting factor at their site in Lesotho, southern Africa. Ballantyne (2002) noted that although

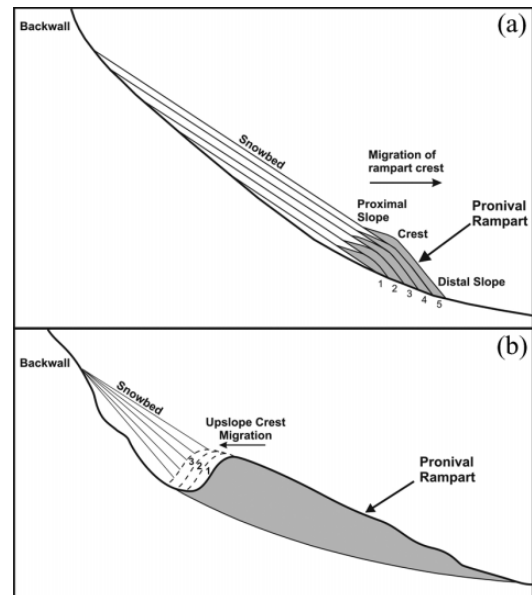


Figure 2. Models for rampart genesis. (a) the downslope model of rampart formation (adapted from Ballantyne and Kirkbride, 1986). (b) the retrogressive upslope model of rampart formation (adapted from Hedding et al., 2007). Numbers in the figure refer to sequential stages in rampart development.

bulldozing of debris by snow creep may produce small debris ridges less than one meter high, it cannot explain the formation of large ramparts several meters high.

3. Rampart development

Although various observations were made regarding rampart genesis (e.g. Sissons, 1979), Ballantyne and Kirkbride (1986) were the first to develop a model for rampart genesis through supranival debris transport and deposition (Figure 2A). Their model proposed downslope rampart extension at the foot of thickening snowbeds, which contrasts with the previous interpretation of Sissons (1979) whereby the snowbed (firn field) maintained fairly stable dimensions during the period of rampart formation. In the downslope rampart extension model,

the rampart crest migrates outwards away from the talus as the debris accumulates at the foot of thickening snowbeds (Ballantyne and Harris, 1994). A suggested morphological characteristic of ramparts which extend downslope was that the distal slope was formed at the angle of repose (34–38°) by the accumulation of cohesionless cascading debris (Ballantyne and Kirkbride, 1986; Gordon and Ballantyne, 2006). Not all (active or relict) ramparts exhibit this characteristic (e.g. Wilson, 1990) and Hall and Meiklejohn (1997) noted that ramparts in the Canadian Rockies have two crests with the outer one being older than the inner. Pérez (1988: 89) also found that the outer rampart ridge on Lassen Peak, California, had a more subdued topography, is stabilized by plants and is thus ‘clearly older and inactive’. These observations allude to the possibility of alternative modes of rampart development.

Hedding et al. (2007) proposed a retrogressive (upslope) model of rampart development under fluctuating, and possibly declining, snowbed volumes based on observations on sub-Antarctic Marion Island (Figure 2B). The retrogressive (upslope) model of rampart development model opens rampart genesis to a wider range of environmental conditions. Later, Hedding et al. (2010) used data on site characteristics, rampart morphology and a debris accumulation field test, in terms of locality of deposition, to evaluate rampart genesis. Thus, outward (downslope) rampart extension is possible even when ramparts do not possess a distal slope at the angle of repose. Hedding (2014) also supports the notion expressed by Howe (1909: 36) over a century ago that ‘the slightly different forms and the varying size that the snow banks would have from year to year would undoubtedly cause an unequal distribution of the debris’.

III Identification and interpretation of pronival ramparts

Nearly a century ago, Marr (1916) recognized the difficulty in discriminating pronival

ramparts from cirque moraines. Harris (1986), Shakesby and Matthews (1993) and Brook et al. (2011) highlight that ramparts are notoriously difficult to identify since their morphological characteristics and position on a slope resemble the characteristics of glacial moraines, rock-slope failures and various other talus-derived landforms. Much of the initial research on pronival ramparts focused on supposed exemplar fossil (relict) features, which presented different views on their genesis and characteristic attributes (see Shakesby, 1997). Shakesby (1997: 394) then noted 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’.

Early in the 21st century, much of the research on pronival ramparts shifted to actively-accumulating landforms and has improved our understanding of rampart genesis and their site and morphological characteristics. When a snowbed maintains fairly stable dimensions during the period of formation (e.g. Ballantyne, 1987; Sissons, 1979), rampart size will be conditioned only by the height of the rock-wall source area, rockfall rate and the period of snowbed survival, irrespective of extent and thickness of the snowbed (Ballantyne and Kirkbride, 1986). This highlights the importance that the surrounding topography has on rampart genesis. Cliff or backwall height has, however, received little attention in studies on pronival ramparts. Hedding (2014) has proposed that, as a function of debris production, the ratio of backwall-to-rampart height should exceed 1: 4–5, but this requires further supporting evidence. More detail is forthcoming for the size of snowbeds above ramparts. Ballantyne and Benn (1994) give the maximum distance of the rampart crest from the source of debris (backwall) at c. 30 to 70 m on slope gradients of 35° and 25°, respectively. Ballantyne and Benn’s (1994) model uses an estimated average density of

perennial firn fields in non-polar environments and average shear stress of 70–100 kPa at the base of the glacier, whereas the bases of glaciers in polar regions typically exhibit an average shear stress of 150 kPa. Therefore, the transition distance from stationary cold-based firn into a moving body of ice would be even greater in polar environments (Hedding et al., 2010). Nevertheless, the model of Ballantyne and Benn (1994) to differentiate glaciers (dynamic ice) from snowbeds (static ice) remains a useful tool, but the importance of ice characteristics, surrounding topography and area (height) of source material cannot be understated.

1. Diagnostic criteria

A growing body of literature, based on actively-accumulating ramparts (e.g. Fukui, 2003; Hall and Meiklejohn, 1997; Hedding et al., 2007; Hedding et al., 2010; Margold et al., 2011; Matthews et al., 2011; Shakesby et al., 1999; Strelin and Sone, 1998) has provided the opportunity to develop a more robust set of diagnostic criteria by which pronival ramparts can be distinguished from other discrete bedrock cliff-foot debris accumulations (Hedding and Sumner, 2013; Table 4). Hedding and Sumner (2013), and later Hedding (2014), adopt a multiple-working hypothesis when investigating the origins of landforms (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. The diagnostic criteria presented in Table 4, in conjunction with the assessment of morphometrics in relation to the surrounding topography (back-wall), are not regarded as definitive (see Matthews et al., 2016) but are rather proposed as the starting point for the identification of pronival ramparts in the field, which may also facilitate the reappraisal of some relict examples. Scappoza (2015) proposes ‘diagnostic’ criteria to define active embryonic rock glaciers

(protalus ramparts) in Alpine environments, which supports genesis by permafrost creep of matrix supported landforms in the lower part of a talus slope.

IV Palaeo-environmental significance

Regardless of changing snowbed dimensions, rampart genesis is dependent on the existence of a long-lasting snowbed (probably several months). When the snowbeds disappear seasonally or through climatic amelioration, and ramparts become inactive, relict pronival ramparts are conspicuous landforms from which useful inferences may be drawn. Relict ramparts have been used in various palaeo-environmental reconstructions for Great Britain (e.g. Ballantyne and Harris, 1994; Ballantyne and Kirkbride, 1986) and southern Africa (e.g. Grab and Mills, 2011; Grab et al., 2012; Lewis, 1994; Lewis and Illgner, 2001). However, Hedding (2014) has reinterpreted the origin of several relict pronival ramparts in southern Africa. Ballantyne and Kirkbride (1986) used relict ramparts to mark the positions of former snowbeds that accumulated under colder (more snowy) conditions and then inferred palaeo-environmental (temperature and precipitation) estimates for the Late Quaternary. However, some of the previously identified relict ramparts are now considered to represent dubious examples (see Hedding, 2014; Shakesby, 1997) and, therefore, the palaeo-environmental inferences drawn must be viewed with caution.

Lukas (2006) uses relict pronival ramparts, in conjunction with laterally terminating thick talus sheets along slopes, to reconstruct a distinct glacial limit. Similarly, the presence of numerous rock glaciers and pronival ramparts in valley head areas have been used to indicate that the climatic conditions and the steep relief that is unsuitable for widespread glaciation favour the development and preservation of Alpine permafrost (Sattler et al., 2011).

Table 4. Proposed diagnostic criteria for the differentiation of pronival ramparts from moraines, protalus rock glaciers and rockslope failure deposits.

Criterion	Reference
Pronival (Protalus) Rampart	
Ridge crest to cliff-foot distance <c.30–70 m	Ballantyne and Benn (1994)
Insufficient cross-section depth for snow to glacier ice transformation	Ballantyne and Benn (1994); Bower (1998); Shakesby and Matthews (1993); Watson (1966)
Underlying slope gradient that will facilitate snow/firn bed angle >20°	Ballantyne and Benn (1994)
No glacial erosional forms or evidence of over deepening of the associated backwall area through sapping and subglacial erosion	Bower (1998)
Openwork fabric; absence of fines (<2 mm)	Brook (2009); Hedding et al. (2007); Hedding et al. (2010); Rapp (1984)
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	Curry et al. (2001); Shakesby and Matthews (1993)
Broadly arcuate in plan form, but in detail are often irregular and winding	Benn and Evans (2007)
Ridge crest to talus-foot distance >c.30–70 m	Ballantyne and Benn (1994)
Presence of fines (<2 mm)	Brook (2009)
Rockslope 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 5 m depth of formerly intact bedrock	Jarman et al. (2013)
Protalus Rock Glacier	
Greater in length (downslope) than in width (across-slope)	Curry et al. (2001)
Convex distal slope	Curry et al. (2001)
Typically terminate >70 m 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 aligned ridges and furrows, and transverse ridges and depressions	Curry et al. (2001); White (1987)

Recently, Colucci et al. (2016) have used high resolution orthophotos and a high resolution digital terrain model, interpolated from airborne

laser scanning (LiDAR), to differentiate pronival ramparts and protalus ramparts. Using the ‘steepness of the front’ and the contingent

presence or absence of a perennial or semi-permanent snow/*firn* field, Colucci et al. (2016: 116) suggest that the contingent presence or absence of a perennial or semi-permanent snow/*firn* field could be considered as indicators of activity in the case of pronival ramparts, while the presence of long-lasting summer snow fields associated with a pro talus rampart (embryonic rock glacier) could be an indicator of permafrost presence. However, Shakesby (1997: 413) stresses that ‘permafrost is not normally viewed as a requirement of rampart formation’ and this is supported by the absence of permafrost at several active sites (e.g. Hedding et al., 2007; Table 3). In addition, Matthews et al. (2016) note that embryonic rock glaciers can develop entirely by permafrost creep without the prior development of a pronival rampart.

Matthews and Wilson (2015) highlight that the legacy of glaciers, glacier–permafrost interaction and the specific type of periglacial environment must all be considered when assessing the palaeo-environmental and palaeo-climatic significance of pronival ramparts. For example, Colucci (2016) notes the importance of the damming effect of pronival ramparts and moraine ridges at the snout of small ice bodies, as the damming effect represents a geomorphological control on the evolution (and persistence) of such ice masses in relation to climatic warming. Therefore, in some instances, pronival ramparts may occur at lower altitudes than might be expected and may remain active for longer during periods of climatic warming.

Pronival ramparts can, under certain climatic conditions, transform into pro talus rock glaciers (e.g. Corte 1976; Ballantyne and Kirkbride, 1986) and even moraines (Ballantyne and Benn, 1994; Van Tatenhove and Dikau, 1990), but this is not a ubiquitous occurrence. Hedding et al. (2007) show that pronival ramparts can also develop under fluctuating, possibly declining, snow falls, while climatic amelioration can also lead to the incorporation of the ridges within

scree deposits. This transformation may occur as the snowbed disappears and rockfall debris fills the proximal trough to create a continuous apron of debris from the foot of the rockwall. Thus, the difficulty of positively identifying relict pronival ramparts and a poor understanding of the topographic and climatic thresholds governing rampart genesis can limit the potential for specific palaeo-environmental inferences. The wide range of temperature and precipitation characteristics at actively-accumulating pronival ramparts (Table 3) substantiates this view. In contrast, White (1981: 135) indicates that the study of pronival ramparts enables ‘a series of past episodes of refrigeration to be determined in a detail that cannot be obtained from larger and more bulky moraines’. The existence of relict ramparts is usually used in conjunction with independent information such as glacier reconstructions to infer palaeo-environmental conditions (e.g. Grab, 1996). Palaeo-environmental information can also be derived from estimating rampart volumes (e.g. Bower, 1998), but the growth rate during the formation of a rampart should be considered to be variable in response to changes in climate and debris supply (Hedding et al., 2007).

Rampart ridge morphology in the context of site characteristics (topography) and sedimentology may also be of value. Ridge morphology coupled with relative-age dating or calibrated-age dating (see Matthews and Wilson, 2015) of the constituent material of the rampart can be used to infer up- or downslope rampart genesis and the associated snowbed conditions during rampart genesis (e.g. Hedding et al., 2007; Hedding et al., 2010). Several studies (e.g. Matthews and Wilson, 2015; Matthews et al., 2011; Matthews et al., 2015; Shakesby et al., 2006) adopt calibrated-age dating techniques to provide a developmental history of ramparts in relation to their surroundings, while other studies use relative-age dating techniques to assess rampart genesis (Hedding et al., 2007;

Hedding et al., 2010). The use of calibration equations in Schmidt-hammer exposure dating of pronival ramparts, described by Matthews and Wilson (2015), is an important advance in determining the timing of their development and use as palaeo-environmental indicators. The establishment of a calibration equation quantitatively describes the relationship between a mean Schmidt-hammer R-value and rock-surface age (see Matthews and Wilson, 2015). It requires at least two surfaces of known age (control points) which are comparable in respect of lithology of the rock surfaces being dated (Matthews and Wilson, 2015). As such, its application should be considered when studying supposed examples of relict ramparts. Determination of the absolute age of pronival ramparts is complicated by the absence of datable component material within the landform (Anderson et al., 2001), but most ramparts are thought to post-date the Last Glacial Maximum. Grab and Mills (2011) use radiocarbon dating to determine the age of a palaeosol beneath a rampart in Lesotho. They date the palaeosol to AD 300–1000, which would imply very recent rampart development. However, the pronival ramparts identified by Grab and Mills (2011) have been reinterpreted as solifluction lobes (see Hedding, 2014).

V Summary and future research

Pronival ramparts were initially considered to represent simple, easily understood landforms (Thorn, 1988), but they are now considered to be more complex landforms (see Hedding, 2014). Research shows a variety of debris transport mechanisms exist and that the environmental controls under which ramparts develop may be more varied than previously thought. Unfortunately, this review shows that we still know relatively little in terms of the debris production linked to debris transport and the genesis of pronival ramparts. This aspect should receive more attention, particularly in terms of how

debris production and debris transport affect rampart genesis. Advances in the understanding of rampart genesis include the addition of the retrogressive model of rampart genesis (see Hedding et al., 2007), which supplements the conventional downslope model of rampart development and the observation that the crests of pronival ramparts can migrate downslope under stable snowbed conditions (Hedding et al., 2010).

Another recent advance is the proposal of a set of diagnostic criteria by Hedding and Sumner (2013) and Hedding (2014), which focus on the characteristics of actively-accumulating ramparts and provide the basis to differentiate ramparts from other discrete debris accumulations. The set of 'diagnostic' criteria proposed by Hedding and Sumner (2013) place more emphasis on site and sedimentological rather than morphological characteristics and should be tested on supposed active and relict ramparts. In addition, the importance of using a multiple-working hypothesis (see Curry et al., 2001) when distinguishing active (and relict) ramparts is highlighted. Scappoza (2015) proposes diagnostic criteria to define protalus ramparts (active embryonic protalus rock glaciers), but the use of the term 'protalus rampart' to refer to permafrost-related phenomena may be problematic (see Hedding, 2011).

The value of ramparts as palaeo-environmental indicators has, in some instances, been seen to be limited (Shakesby, 1997), but the absence or presence of relict pronival ramparts, specifically in areas which experienced marginal glaciations, may be particularly useful in palaeo-environmental reconstructions (see Hedding, 2014). Relative-age dating techniques have been used successfully in research on pronival ramparts (see Hedding et al., 2007; Matthews et al., 2011; Shakesby et al., 2006). The use of relative-age dating techniques will be particularly important for research on rampart genesis; as is demonstrated by Matthews et al. (2011). Also, the use of calibration equations in

Schmidt-hammer exposure dating, described by Matthews and Wilson (2015), is a significant step forward for dating landforms, including pronival ramparts. Its application when studying supposed relict examples of pronival ramparts may be extremely useful in resolving the timing of rampart development and its palaeo-environmental significance. Anderson et al. (2001) noted that the absence of datable component material complicates absolute age determination of relict ramparts, but it is hoped that improvements in cosmogenic dating will improve to the stage where inheritance (pre-exposure) can be eliminated in the dating process of depositional landforms (Anderson et al., 1996). This is yet another exciting avenue for research on pronival ramparts.

Use of a combination of techniques such as ground radar, climate modelling and sedimentology (see Slee, 2015) coupled with relative-age dating or calibrated-age dating could be particularly useful when analysing the probable mode of origin for pronival ramparts. Several other techniques adapted from engineering geology could also be particularly useful when assessing the genesis of actively-accumulating ramparts. For instance, kinematic analyses and micro-seismicity could be used to investigate debris supply and debris transport, respectively. Finite elements modelling of the slopes, or use of terrestrial laser scanning or structure from motion (SfM) from drones, or satellite imagery could be used to map the extent of ramparts and associated snowbeds (Martin S. Brook, 2016, personal communication).

Research should focus on mechanisms of debris transport and the scale of ramparts in relation to the backwall and on the potential of snow avalanching in the formation of ramparts (see Matthews et al., 2011). Ballantyne (2002) doubts the efficacy of snow push as a mechanism for the development of large ramparts, several metres high, but it is necessary to establish whether active snowbeds can produce (snow push) large ramparts or landforms with the scale

and sedimentological characteristics of push moraines (see Shakesby et al., 1999). In some instances, there is a lack of appreciation in literature of just how large the source area (backwall) must be to facilitate the development of fairly small pronival ramparts. Hedding (2014) proposes that, as a function of debris production, the ratio of backwall-to-rampart height should exceed 1: 4–5, but this requires further research.

Rampart morphology should also receive further attention since differing modes of rampart genesis can result in various rampart morphologies. Therefore, it is worth investigating if rampart morphology may represent an expression of the environmental conditions under which they form. However, rampart morphology is dependent on the mechanism of debris transport, topographic setting (e.g. underlying slope gradient), the nature and size of constituent material and the rate of debris production, which may explain why rampart morphology varies so greatly. Superimposition of ramparts on other talus landforms and post-depositional change of relict ramparts also needs to be taken into account when assessing the morphology of relict fossil features. Also the possibility of ‘form-convergence’ for discrete debris accumulations, as suggested by Whalley (2009) should be considered. Ramparts can accumulate downslope of snowbeds which are increasing, stable or decreasing in volume. Ramparts may also develop downslope of snowbeds which fluctuate in volume throughout the period of debris accumulation. Based on these recent findings, questionable examples of ramparts should be reinvestigated and further detailed studies of actively-accumulating ramparts may construct the body of knowledge needed to resolve disagreements over the interpretation of landforms; particularly in light of post-depositional changes in morphology.

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