On the identification, genesis and palaeo-environmental significance of pronival ramparts

By

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"*The poetry of the earth is never dead*."

John Keats (1795 – 1821)

On the Grasshopper and the Cricket

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Abstract

A pronival (protalus) rampart is a ridge, series of ridges or ramp of unconsolidated debris formed at the downslope margin of a perennial or semi-permanent snowbed overlooked by an exposed bedrock cliff. These landforms were traditionally regarded as simple and easily understood since the mechanisms of debris transport were intuitively considered to include supranival debris transport whereby clasts dislodged from the exposed cliffs above roll, bounce and slide over a snowbed under the influence of gravity. However, most studies focus on relict examples and few accounts document debris transport, or investigate rampart genesis, at actively-accumulating sites. This has led to circular reasoning and assumptions about rampart morphology, site characteristics, constituent material, genesis and palaeo-environmental significance. A review of existing literature reveals that rampart development was conventionally thought to extend downslope or outward below snowbeds of increasing thickness and extent but not all actively-accumulating ramparts fit this model.

Given the over-reliance of research on relict pronival ramparts, this thesis focusses on actively–accumulating examples in order to improve our understanding of their genesis, clarify rampart identification and re-evaluate their palaeo-environmental significance. Rampart genesis is addressed by focussing on active sites on sub-Antarctic Marion Island and at Grunehogna, Western Dronning Maud Land, Antarctica as well as all other actively-accumulating ramparts documented across the globe. An alternative model for genesis in the form of retrogressive (upslope) development under fluctuating, and possibly declining, snowbed volumes is presented and relative-age dating techniques are recognised as being particularly useful in aiding with the assessment of rampart genesis. It is also found that ramparts which exhibit a distal slope at repose do not necessarily develop below snowbeds which are increasing in extent and thickness. The different modes of rampart genesis demonstrate that environmental conditions may change during their development and maintenance. The morphology and position of pronival ramparts on a slope are found to closely resemble glacial moraines, rock-slope failures and other discrete talus-derived landforms such as protalus rock glaciers, protalus lobes, avalanche deposits as well as morphologically similar geological structures. As such, their identification can be difficult. In the past, studies have used the characteristics of relict pronival ramparts to develop diagnostic criteria to distinguish ramparts from glacial moraines, rock-slope failures and other talus-derived landforms. These diagnostic criteria are assessed against information gathered from actively-accumulating pronival ramparts and a focus is placed on site characteristics, rampart morphology and sedimentology. Evidence presented in this thesis shows that several of the previously suggested 'diagnostic criteria' are invalid and a new set of criteria, with an emphasis on using a multiple-working hypothesis, are proposed to facilitate the identification of relict (as well as actively-accumulating) ramparts in the field.

Classification of several landforms as pronival ramparts in southern Africa has been scrutinised in the past. The proposed diagnostic criteria are used to clarify their identification. Based on the criteria presented here, none of the landforms previously recognised as pronival ramparts in southern Africa should be regarded as pronival ramparts. The most morphologically compelling examples in southern Africa are the landforms at Mount Enterprise in the Eastern Cape Province though the site characteristics and the constituent material of the ridge do not suggest a rampart origin. Alternative origins which should be investigated for these landforms range from scree deposits and rock-slope failures to stone-banked lobes. As is the case in southern Africa, relict pronival ramparts are typically used to infer palaeo-environmental conditions. The absence of pronival ramparts at ideal topographic sites in southern Africa questions the persistence of late-lying snow along and on the Lesotho-Drakensberg escarpment during the Late Quaternary. This observation is in contrast with the notion of niche glaciation in preferential locations above 3000m a.s.l. and demonstrates that, although pronival ramparts can typically only be used to infer more snowy conditions, their presence or absence can, in certain contexts, be useful in palaeo-environmental reconstructions.

Declaration

I, David William Hedding declare that the thesis, which I hereby submit for the degree Doctor of Philosophy (Geography) at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

Signature:

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DATE:

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My parents, Donald and Alison, deserve a great deal of thanks for their constant love and support. Thank you for the freedom that you have given me to find my own way, and I hope this piece of work will make you proud.

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Last, I would like to thank the Lord who has blessed us with this beautiful world. I want to thank you Lord for taking us into your care and keeping us safe. *Psalm 23*

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Section A

Chapter 1: Introduction

Introduction

A pronival (protalus) rampart is defined as a ridge, series of ridges or ramp of unconsolidated debris formed at the downslope margin of a perennial or semi-permanent snowbed (Shakesby, 2004). These landforms are typically located near the base of a steep bedrock cliff in a periglacial environment and have long been considered to be “simple, easily understood features” (Thorn, 1988: 16). However, studies of actively-accumulating landforms (*e.g*. Harris, 1986; Ono & Watanabe, 1986; Ballantyne, 1987a; Pérez, 1988; Shakesby *et al*., 1995; Strelin & Sone, 1998; Shakesby *et al*., 1999; Anderson *et al*., 2001; Fukui, 2003) have demonstrated that rampart genesis and their palaeo-environmental significance is still poorly understood. Several authors (Shakesby, 1997; Shakesby *et al*., 1999; Mills *et al*., 2009a; Brook *et al*., 2011) have also noted that it is difficult to differentiate pronival ramparts from glacial moraines, rock-slope failures and other discrete talus-derived landforms (*i.e*. protalus rock glaciers, solifluction deposits and avalanche deposits) as well as morphologically similar geological structures. Much of the difficulty experienced with the identification of pronival ramparts is because no conclusive set of diagnostic parameters has hitherto been developed. This thesis intends to develop a set of diagnostic criteria for pronival ramparts as well as examine rampart genesis and palaeo-environmental significance. In order to understand why ramparts were originally considered to be simple, easily understood landforms and where some of the confusion may have arisen with regards to distinguishing ramparts from, glacial moraines, rock-slope failures and other talus-derived landforms, it is essential to first review why research on pronival ramparts started and how it has evolved.

Early work

According to Shakesby (1997) the first descriptions of pronival ramparts appear to be those of Drew (1873) and Ward (1873) from the Upper Indus Basin and the Lake District, United Kingdom, respectively. The overly simple concept describing the traditionally assumed supranival mode of genesis was first proposed by Drew (1873: 445), who suggested that “a talus of snow forms first… and then upon the snow-heap rolls down the loosened stuff, which therefore finds rest only at the foot… of the snow talus; melting of this in summer leaves a heap of stones which may be of considerable height”. Ward (1873: 426) describes "mounds of scree material formed at the base of a slope, by sliding fragments over an incline of snow lying at the base of crags". Unwin (1988) points out that later in the 19th Century, Kendal (1893: 69) described "a fringe of rock debris" formed at the base of a "talus of snow". In the following year, Kinahan (1894: 237) confusingly referred to the some Irish examples of ramparts as "terminal moraines" and to one specific example as "a massive esker-like high accumulation of shingle". Interestingly, Kinahan (1894: 236) states that he first examined these rampart-like features, 'some forty years' prior to his publication and, thus, he may well have been the first to recognise what we now call pronival ramparts. More importantly, Kinahan (1894: 238) described their mode of formation by stating "the slope in some years was covered by frozen snow, over which stones from the high ground slide". Kinahan (1894: 236) referred to these landforms as "snow stones" or "*cloghsnatty*" in Irish Gaelic, for which Warren (1979) provides *clogha snachta* as the correct spelling.

Later, Marr & Adie (1898) described 'snow slope detritus' which they differentiated from 'true moraine' in Snowdonia, Wales. Gatty (1906) envisaged a similar mechanism of rampart formation to Ward (1873) when he observed that 'blocks wedged off the cliffs by the winter's frost roll or slide down and come to rest at the foot of the snow-shoot' at a site on Ben Nevis, Scotland. Although this landform has subsequently been re-interpreted by Ballantyne (1989) as an avalanche rampart, the observation of Gatty (1906) remains interesting. Shakesby (1997) indicates that Cross & Howe (1905) referred to 'snowbank accumulations', while Howe (1909) referred to 'snow-bank deposits' which presumably are all ramparts. These accounts, together with the description of Chamberlain & Salisbury (1906: 472-474) who noted that the "disposition of talus appears to be due to snow banks at the bases of the mountains" whereby "descending talus rolls out over snow, lodging at its outer edge", appear to be the first descriptions of pronival ramparts in North America. Calkin *et al*. (1998) indicate that in 1906, Moffit (1913) unknowingly photographed landforms in Alaska that were subsequently identified as pronival ramparts (Kaufman *et al*., 1989). Matthes (1900: 184) also associated landforms in the Bighorn Mountains, Wyoming, North America with nivation processes when describing "morainal material, not in distinct heaps but rather spread out, lower down in the valley" which, due to a lack of striations, was not attributed to glacial motion. However, not enough evidence is presented to determine if these landforms are ramparts which led Thorn (1988) to suggest that these landforms are boulder pavements.

Daly (1912: 593; Plate 57) described “wall-like piles” that were “dependent on the formation of heavy snow-banks and a specially rapid frost-action before summer heat has melted the snow in large measure” as ‘winter-talus ridges’. This term was later adopted by Lahee (1931) and permeates through subsequent geology literature. Gregory (1917: 82) also provided an early description of ‘ramparts’ in North America when he noted “miniature embankments ... ascribed to nivation, operating at a time when a perennial snowcap occupied the highland”. Subsequently, Gordon & Ballantyne (2006) have reinterpreted these landforms as being characteristic of rock glacier creep. Bowman (1916: 287) recognised that “material ... rolls down a long incline of snow and comes to rest at the foot of it as a fringe of talus” and Behre (1933) indicates that Bowman (1916) incorrectly linked most of the waste material associated with the snowbanks to the erosive action of the snow. Nevertheless, Bowman (1916) appears to have been the first to note gravity-driven supranival debris transport and the formation of pronival ramparts in South America.

Gripp (1929) provides an interesting early description of rampart formation from Spitsbergen. Van der Meer (2004: 108) explains that Gripp (1929) envisaged rampart formation whereby “katabatic winds can deposit snow in front of an end moraine, where debris from the moraine can slide over the snow surface and accumulate as a block moraine overlying the sandur”. Such an accumulation of debris would mostly certainly be considered part of the moraine complex after deglaciation (Van der Meer, 2004). This may represent one of only two descriptions of rampart genesis in front of moraines. The other description of rampart genesis in front of moraine comes from Marr & Adie (1898: 56) who, while describing concentric ridges of moraine, noted that on most of the moraine ridges “rest sub-angular perched blocks, whilst the innermost crescent of the drift dam consists of angular blocks as though some at least of this material was rather of the nature of snow-slope detritus than true moraine”.

Following from the work of Daly (1912), Behre (1933) correctly identified the traditionally envisaged supranival gravity-driven mechanism of debris transport. Behre (1933: 630) observed that “talus blocks, breaking from rock ledges, roll down over the snow and continue bounding toward its lower edge”. This observation appears to be similar to the explanations of debris transport provided by Howe (1909) and Crawford (1913). Shortly thereafter, Russell (1933: 935) noted that “as boulders and spalls roll down a snow surface with greater ease than down similarly inclined talus, they accumulate below the lower margins of permanent or semi-permanent snow drifts, where they form conspicuous benches”. Howe (1909) observed that with larger or smaller snow banks, ridges would form at different distances from the cliff which, according to Gutiérrez (2013), led Sharpe (1960) to infer that ridges which are parallel to each other are indicative of parallel slope retreat. Boch (1946) discusses debris transportation associated with snowpatches from the northern part of the Urals and represents one of the earliest known references to supranival debris transport in modern-day Russia.

Evolution of the term ‘pronival rampart’

Behre (1933) introduced the term ‘nivation ridge’ which was subsequently adopted by Lewis (1966), Unwin (1975) and Butzer (1976). Recently, Luckman (2007: 571) has stated that “at some talus sites, a perennial firn (snow) patch may develop at the base of the slope. Rockfall or avalanche debris landing on this icy surface slides to the base, accumulating as a ridge which has been termed a protalus rampart or nivation ridge”. Other similar terms, such as nivation moraine (Imamura, 1937, 1940; Derbyshire *et al*., 1979) and nival moraine (Karczewski *et al*., 1981; Dzierżek & Nitychoruk, 1987) were also proposed. Shakesby (1997) points out that other, less popular, terms for these landforms can also be found in the Anglo-Saxon language literature. Examples include pseudo-moraines (Peev, 1966; Watson, 1966) and ‘firn pseudo-moraines’ (Bizubová & Škvarček, 1999), miniature moraines (Manley, 1949), talus terraces (Liestøl, 1962) and protalus ridges (Gardner *et al*., 1983). Derbyshire *et al*. (1979) preferred the term ‘nivation moraine’ to protalus rampart for fines-rich in contrast to boulder-rich examples , although Shakesby (1997: 396) highlights that “it is not always clear whether the landforms referred to (above) formed in the manner envisaged for ramparts”. Many of these terms are no longer used but Neuendorf *et al*. (2005: 724) have since defined the outdated term ‘winter protalus ridge’ as “a wall-like protalus rampart formed of blocks and boulders derived from cliffs above a snowbank-occupied cirque before the summer heat melts the snow across which the blocks roll”. This illustrates that the adoption of new terminology can be slow across different disciplines.

Bryan (1934) was the first to propose the term ‘protalus rampart’ when reviewing the article by Behre (1933) since nivation was perceived to be associated with erosion and not deposition around snowbank margins. Later, Knoll (1977: 14) defined a protalus rampart as “a linear to arcuate ridge, composed of unsorted blocky rubble, formed by the downslope gliding of rock fragments across a snow or firn bank to their site of deposition”. Knoll (1977) developed an elaborate scheme that sub-divides protalus ramparts according to form and suggested that ‘each term implies a mode of formation of the rampart that is different from the rest’ (Table 1.1) but, unfortunately, this is not the case as will be discussed later. The work of Knoll (1977) was cited by Butler (1984; 1986a) but not elsewhere and, thus, the terms used to sub-divide protalus ramparts have remained largely ignored by the geomorphology community working in periglacial and glacial environments. In the mid-1980s, Butler (1986b) advocated reintroducing the term ‘winter-talus ridge’ in place of ‘protalus rampart’, which was commonly used at the time (*e.g*. Richmond, 1962; Blagbrough & Breed, 1967; Rapp & Fairbridge, 1968; Flint, 1971; Embleton & King, 1975; Knoll, 1977; Washburn, 1979; Gray, 1982; Karte, 1983; Butler, 1984, 1986a; Ono & Watanabe, 1986; Harris, 1986 and Addison, 1987). Butler (1986b: 543) argued that the latter term “was not necessary, nor has it been since 1912” but its reintroduction received little support mainly because, as Porter (1987: 248) pointed out, the term was misleading due to the fact that “the release of rock debris from mountain slopes reaches a maximum frequency during mid- to late spring” and not in winter but also partly due to fact that the term ‘protalus rampart’ had become entrenched in the literature by then (Ballantyne, 1987b).

Table 1.1: Suggested sub-divisions of the term protalus rampart (Knoll, 1977).

<table>
<tr><td rowspan="6">Protalus rampart: a linear to arcuate ridge, composed of unsorted blocky rubble, formed by the downslope gliding of rock fragments across a snow or firn bank to their site of deposition.</td><td colspan="2">Protalus bar rampart: linear or broadly arcuate ridge, usually 100m to 600m long, composed of unsorted blocky rubble, formed along the edge of a snow or firn bank.</td></tr>
<tr><td rowspan="4">Protalus loop rampart: a tightly arcuate ridge, less than 100m long, composed of unsorted blocky rubble, formed along the edge of a snow or firn bank.</td><td>Single loop: isolated loop ramparts indicating an isolated snow or firn bank, and perhaps minimal periglacial conditions.</td></tr>
<tr><td>Cuspate loop: two or more single loops formed side by side with touching, but not overriding, flanks indicating two or more snow or firn banks that developed under extensive periglacial conditions than is represented by the single loop.</td></tr>
<tr><td>Compound loops: two or more single loops nested inside and upslope from the largest, outermost loop, but nowhere showing overriding relationships to lower loops. The compound form indicate depletion of a major snow or firn bank with hesitations in its ablation of sufficient duration to permit the production of a lesser protalus loop nested upslope from the major, outermost loop.</td></tr>
<tr><td>Complex loops: two or more single loops that display overriding relationships to each other, indicating two or more distinct periglacial episodes during which different snow or firn banks formed in the same general area.</td></tr>
<tr><td colspan="2">Protalus ridge rampart: Linear ridge, more than 600m long, composed of unsorted blocky rubble, formed along the edge of an extensive snow of firn bank.</td></tr>
</table>

Until the mid-1990s, 'protalus rampart' was used as the standard term because as Porter (1987) highlighted it was used 'as a descriptive, non-genetic designation'. Shakesby *et al*. (1995) then proposed that this term be replaced with 'pronival rampart'. They noted that 'protalus' was an inappropriate descriptor for ramparts in Romsdalsalpane, Norway, which lay at the foot of snowbeds occupying valley-side niches at the top, rather than the foot, of talus as indicated by the term 'protalus'. The descriptor 'pronival' (snow-front), therefore, provided a universally appropriate term that described these firn-foot debris accumulations, regardless of their position on the slope. The descriptor 'pronival' has largely gained acceptance in literature (*e.g*. Shakesby *et al*., 1999; Tanarro *et al*., 2001; Hughes *et al*., 2003; Harris *et al*., 2004; Gurney & Bartsch, 2005; Paasche *et al*., 2006; Hedding, 2008; Brook, 2009; Mandolla & Brook, 2010; Grab & Mills, 2011; Hall, 2012) and will be used henceforth in this thesis. Other studies use both descriptors (*e.g*. Shakesby, 1997, 2004; Wilson & Clark, 1999; Curry & Morris, 2004; Clark & Wilson, 2004; Shakesby *et al*., 2006; Hedding *et al*., 2007; Bartsch *et al*., 2008; De Beer & Sharp, 2009; Hedding *et al*., 2010, Hughes, 2010; Lilleøren & Etzelmüller, 2011; Trelea-Newton & Golledge, 2012; Jarman *et al*., 2013), but, many recent studies and books (*e.g*. Grab, 2000a; Whittow, 2000; Anderson *et al*., 2001; Lewis & Illgner, 2001; Ballantyne, 2002; Winchester & Chaujur, 2002, Fukui, 2003; Palacios *et al*., 2003; Wilson, 2004a; Wilson, 2004b, 2009; Serrano & González-Trueba, 2005; Lukas, 2006; Strelin *et al*., 2006; Valcárcel-Díaz *et al*., 2006; Murray, 2008; Osborn *et al*., 2008; Degenhardt, 2009; Whalley, 2009; Carrera-Gómez & Valcárcel-Díaz, 2010; Hall, 2010; Lewis, 2011; Hamilton & Labay, 2011; López-Martínez *et al*., 2012; Ruiz & Liaudat, 2012; Whalley, 2012) continue to only use the descriptor 'protalus'.

Barsch (1996) describes pronival ramparts as embryonic talus rock glaciers, based on the similarity between pronival ramparts and protalus rock talus glaciers, but Mills (2006: 57) notes that the difference between the two landforms may be "somewhat arbitrary". Scapozza *et al*. (2011) have recently proposed that the disused term 'protalus rampart' be used to define small permafrost creep phenomena (embryonic rock glaciers) in contrast to the traditional usage of the term. Previously, Shakesby *et al*. (1999) argued that if the term 'pronival rampart' were restricted to snowbed forms and protalus rampart to incipient rock glaciers it would lead to terminological confusion. Thus, this suggestion was not adopted in practice at the time of the proposed replacement of the term 'protalus rampart' with 'pronival rampart' (see Hedding, 2011; Appendix 1). Even though the term 'pronival rampart' has largely become entrenched in the literature, the proposal of Scapozza *et al*. (2011) may lead to further uncertainty in the literature because the differentiation of protalus ramparts (embryonic rock glaciers) from pronival ramparts may prove difficult, particularly in relict landforms. Thus, Hedding (2011) opposes the alternative usage of the term 'protalus rampart' to denote embryonic rock glaciers until such time that diagnostic criteria are identified by which pronival ramparts can be differentiated from other talus-derived landforms, specifically embryonic rock glaciers. Instead, Hedding (2011) recommended that protalus rock glacier be used to denote embryonic rock glaciers. This nomenclature is crucial to avoid the incorrect identification and associated palaeo-environmental inferences that have, in the past, crept into research on pronival ramparts, particularly since protalus rock glaciers could be used to infer former permafrost conditions whereas pronival ramparts do not require permafrost for their formation.

Use of the term 'pronival rampart' in Japanese and several European languages

In Japanese geomorphology, researchers do not believe that the term 'pronival rampart' has been accepted across the globe and, therefore, Japanese geomorphologists retain use of the term 'protalus rampart'[1]. In Japanese (Katakana script) the term used to describe protalus ramparts is 'プロテーラスランパート'[1]. Although supranival debris transport has been documented in the Japanese Alps (Matsuoka & Sakai, 1999), it is interesting to note that Japanese geomorphologists have recently expressed the view that almost all of the ramparts documented represent talus origin (protalus) rock glaciers[1]. In Polish literature, Sedláková & Bugár (2012) indicate that Kotarba (2007) and Raczkowska (2007) used the term '*waly niwalne*' to denote 'nival ramparts'. Jaworski & Weckwerth (2004) also use the term '*waly nivalne*' but it is unclear if it is used in the same context or how it differs from the term '*moreny niwalne*' which Zwoliński *et al*. (2013) describe as a "nival moraine rampart". Lukniš (1973) uses '*snehový/firnový sutinový val*' to describe 'nival (firn) debris ramparts' and attributes the first documentation of 'nival debris ramparts' in the Kôprová Valley, Slovakia to Partsch (1923). Marcu (2011) translates pronival ramparts as '*potcoave nivale*' in Romanian and the term '*nivomorena*' is used to denote pronival ramparts in Italian[2].

[1] Information from personal communication with Dr Kotaro Fukui, Tateyama Caldera Sabo Museum, 68 Bunazaka-Ashikuraji Tateyama-machi Nakaniikawagun, Toyama, Japan, October 2013

[2] Information from personal communication with Dr Francesco Brardinoni, Dipartimento di Scienze Geologiche e Geotecnologie, Università degli Studi Milano-Bicocca, Piazza della Scienza 4, 20126 Milano, Italy, January 2013.

According to Kotlyakov & Komarova (2006), pronival ramparts are referred to as 'осыпной вал (osypnoy val)' in Russian literature.

In Spanish, pronival ramparts are referred to as '*derrubios de nivación*'[3], '*morenna de nevero*' (Carrera-Gómez & Valcárcel Díaz, 2010), '*caballón de derrumbamiento*' (Kotlyakov & Komarova, 2006) and '*morennas de nevé*'. In German literature, Krebs (1924) and Morawetz (1933) used the term '*schneeschutkitwälle*', Grötzbach (1965, cited in Corte, 1976) employed '*hangblockwulst*', Rasemann (2003) notes that Höllermann, (1983) used '*haldenfußwall*' and, most recently, Kotlyakov & Komarova (2006) have used the term '*geröllwall*' to denote a pronival rampart. The most popular German term, however, appears to be '*schneehaldenmoräne*' used by Barsh (1993; 1996). Various terms, such as '*bourrelet de conger*' (Lengellé, 1970), '*bourrelet de névé*' (André, 1985), '*les bourrelets*' (Pancza, 1998), '*moraine de névé*' (Boyé, 1952; Nicod, 1968; Faugeres, 1969; Orengo, 1973; Francou, 1977a; Serrano & González-Trueba, 2005) and '*rempart de éboulement*' (Kotlyakov & Komarova, 2006) have been used in French literature. Of these, the most common appears to be '*moraine de névé*' which, according to Hughes (2007), typically refers to pronival ramparts and usually implies formation by nival processes. Interestingly in the French literature, Francou (1977b) indicates that Gignoux (1946) used the term '*moraine de névé*' incorrectly when actually describing a rock glacier which illustrates the potential for misunderstandings with regard to the different use of terminology across several languages.

Pronival ramparts and the continuum of talus-derived landforms

Much of the confusion surrounding the correct identification of pronival ramparts in the field is because these landforms resemble various talus-derived features (*i.e*. protalus rock glaciers, solifluction deposits and avalanche deposits). The close proximity of pronival ramparts to modified talus sheets and cones as well as protalus rock glaciers and moraines has led to speculation about the possibility of linkages between these landforms (Shakesby, 1997) for over a century. As an example, Howe (1909) initially suggested that ramparts were a transition stage between talus and rock streams (rock glaciers) but later changed his opinion and expressed the view that ramparts were in no way genetically related to rock glaciers (Sharpe, 1960).

3 Information from personal communication with Dr Javier Cia Chueca, Departamento de Geografía y Ordenación del Territorio, Facultad de Ciencias Humanas y de la Educación, Universidad de Zaragoza, Zaragova, Spain, July 2013.

There are two contrasting views of pronival ramparts and the continuum of talus-derived landforms. One holds that pronival ramparts represent a morphological continuum of talus-derived landforms (*e.g.* Corte, 1976, 1987; Haeberli, 1985; Ballantyne & Kirkbride, 1986; Barsch, 1993; Lilleøren & Etzelmüller, 2011; Whalley, 2012). Ballantyne (2002) highlights that some authors view pronival ramparts as progenitors of protalus rock glaciers (*e.g.* Barsch, 1993) whereas Palacios & Sánchez-Colomer (1997) and Van Tatenhove & Dikau (1990) appear to link the development of ramparts with that of moraines. The other view considers pronival ramparts, protalus lobes, protalus rock glaciers and moraines as separate, independently produced forms of modified talus occurring in a non-developmental morphological continuum (White, 1981; Shakesby *et al*., 1987; Shakesby, 1997; Hedding *et al*., 2007; Degenhardt, 2009). The latter view appears to be favoured by most researchers (see Shakesby, 1997) and stems from the observation of Johnson (1983: 28) that the "morphological continuum is not necessarily a process continuum".

Hamilton & Whalley (1995) and Johnson *et al*. (2007) propose that protalus lobes (a progenitor to rock glaciers) should be distinguished from protalus ramparts on the basis that protalus ramparts are process specific and involve rocks transported by gravity over seasonal snow fields (Degenhardt, 2009). Also Hedding *et al*. (2007) question the inclusion of pronival ramparts as a transitional landform in the morphological continuum of talus-derived landforms since all actively-accumulating ramparts do not necessarily develop below snowbeds which are progressively increasing in extent and thickness and, therefore, do not always "grow" into protalus rock glaciers or moraines. These observations emphasise the sentiment of Whalley (2009) who, referring to the observation of Johnson (1983), notes that caution should be used when interpreting landforms, especially for the reconstruction of past climates since morphologically similar landforms may be produced by different processes resulting in so-called 'equifinality' or form-convergence.

Theoretical framework

A detailed theoretical foundation is necessary for all research in geomorphology, particularly when cognisance is made that any study, qualitative or quantitative, of landforms and land-forming processes in the context of environmental change is an enormously complex task (Meadows, 1988). The complexity of landforms and land-forming processes is due to the many variables (*e.g.* climate, lithology, structure and vegetation), past and present, that play a role in geomorphological processes, landform development and even maintenance, which can all be mutually exclusive. The mainly qualitative approach to investigate ramparts adopted in this thesis is done in recognition of the argument made by Thorn (1992: 5) that "… although form alone has no explanatory power, explained form provides us with our only opportunity to link past, present and future. Consequently, we must treat process and form symbiotically, while recognising that process is pervasive. However, the form we identify and treat discretely is only a portion of a much larger related continuum". Therefore, geomorphology is more than simply the description of contemporary landscapes; it is the elucidation and explanation of their histories (Meadows, 1988) and possible futures. The quantitative aspect of this thesis focuses on debris transport and accumulation in the context of rampart genesis. It feeds information into the qualitative approach of the thesis to explain rampart form.

The broad concept of climatic geomorphology postulates that different climates, through their effects on processes, produce unique assemblages of landforms (Meadows, 1988). Even though this concept is overly simplistic by sacrificing precision for generalisation (Fig. 1.1) this is not an error, providing it is done consciously (Thorn, 1992). Thus, notwithstanding its flaws, described in detail below, climatic geomorphology has become entrenched in geomorphology and dominated a good deal of geomorphological research in the past (*e.g.* Derbyshire, 1973; Derbyshire *et al.*, 1979), primarily, as climate has an influence on the rate or frequency of many geomorphological processes (Nyberg & Lindh, 1990). As such, much of the earlier research on pronival ramparts was undertaken under the paradigm of climatic geomorphology.

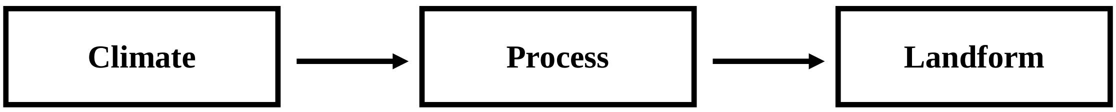

Figure 1.1: The concept of climatic geomorphology.

Contemporary periglacial and geomorphological research has turned to process-based studies since climatic geomorphology has many shortcomings (Thorn, 1992). Among the flaws cited are: the disparate and inappropriate criteria used to establish climatic zones; failure to establish climate-process links; inadequate corroboration of process-form links: and uncertainty of temporal relationships between meteorological and/or climatic inputs and geomorphological responses (Thorn, 1992). The same geomorphological processes can also occur under different climatic regimes and different processes within the same climatic regime can produce the same landforms or products (convergence of form) (Hedding, 2006). Sumner *et al*. (2004a) question the concept of process zonality by showing that the similarity of weathering products across different environments can be attributed to the recognition that thermal changes, the actual driving force behind thermally induced rock weathering, tend to be azonal. Moreover, if one uses a climatic geomorphological approach it is particularly pertinent to highlight that climate in itself is a complex phenomenon and as Stoddart (1969; p. 210, cited in Meadows, 1988) has noted: "… while climatic factors are important, they are not necessarily dominant: landform geometry results from a complex interplay of climate, lithology and structure and vegetation … To isolate a single group of factors is unrealistic and distorting …". In addition, geomorphological features are usually more sensitive to changes in precipitation than temperature but, as is noted above, the precise nature of a climate-landform relationship is rarely, if ever, clear (Meadows, 1988).

Climatic geomorphology founded the concept of the development of distinctive landforms (Brunsden & Thornes, 1979), which Priesnitz (1988: 64) expressed succinctly as “constant climates cause characteristic forms”. Such a view requires a one-to-one relationship between climate and geomorphological process as well as between process and form under ideal circumstances (Thorn, 1992) but, apart from landforms associated with glaciers and permafrost, this is almost never the case. Therefore, it follows that only in specific instances when certain climatic thresholds are maintained, or exceeded in certain environments, do specific landforms develop. However, it is pertinent to highlight that the time it takes processes to adapt to a different climate regime can take longer than the actual climate change itself (Brunsden, 1996). Therefore, it is imperative to examine these factors and take them into consideration when studying landforms as indicators of processes and ultimately climate. Brunsden (1996) illustrates this point through the theory of persistence of form where the lifetime of a landform can be defined as the sum of the successive time intervals between the formation and the erosion on the landform created, and that all landforms have a specific life expectancy. This concept is illustrated by the persistence of certain landforms on sub-Antarctic Marion Island (see Nel, 2001). Nevertheless, periglacial geomorphology has been strongly influenced by the concept of climatic geomorphology and usually seeks to specify the features characteristic of a given periglacial climate (Priesnitz, 1988). When identifying a landform a mode of genesis is assigned to the landform (*e.g.* nivation hollow) which, if correct, allows certain inferences about present (and past) processes and their linkages to current and palaeo-environmental conditions (Priesnitz, 1988).

Following from the section above, when first documented, pronival ramparts were investigated under the paradigm of climatic geomorphology. They were initially linked with late-lying snowbeds (*e.g.* Behre, 1933) and a simple gravity-driven mechanism of debris transport was inferred for rampart development (Behre, 1933). It was assumed that debris dislodged from an exposed cliff would fall onto a snowbed below, roll, slide and/or bounce down its icy surface and accumulate at its lower margin. This simple explanation remained unchallenged for approximately 50 years but, as Platt (1964) purports, even good ideas should be challenged. It is that challenge of the current body of knowledge that improves and refines it (Thorn & Hall, 2002). Johnson (1983) questioned the overly simple gravity-driven debris transport mechanism which led to the detailed studies of Pérez (1987) and, later, Shakesby *et al*. (1995). Matsuoka & Sakai (1999) have also conducted a detailed assessment of rockfall activity and documented supranival debris transport. The overly simple explanation given for rampart development and the relative abundance of relict landforms (particularly in Great Britain) led researchers to typically focus on the palaeo-environmental significance of pronival ramparts, grounded in the paradigm of climatic geomorphology. Some authors linked pronival ramparts with stable snowbeds (Sissons, 1979; Ballantyne, 1987) whereas others (*e.g.* Ballantyne & Kirkbride, 1986) associated rampart development with snowbeds that were increasing in extent and thickness. The considerable amount of research on relict pronival ramparts led to assumptions and circular arguments pertaining to their development, morphology and palaeo-environmental significance (Shakesby, 1997). It is only recently that research on pronival ramparts has started to focus on the processes responsible for rampart development; a rather late shift toward process studies on actively-accumulating landforms but it is hoped that this shift will lay the foundation for improving our understanding of the genesis and palaeo-environmental significance of pronival ramparts.

Aims and objectives

Much of the research on pronival ramparts has focussed on relict landforms which has led to circular reasoning and assumptions about process dynamics (genesis), typical rampart morphology, constituent material and topographic setting (see Shakesby, 1997). Studies on actively-accumulating pronival ramparts (*e.g.* Harris, 1986; Ono & Watanabe, 1986; Ballantyne, 1987a; Pérez, 1988; Shakesby *et al*., 1995; Strelin & Sone, 1998; Shakesby *et al*., 1999; Anderson *et al*., 2001; Fukui, 2003) have elucidated new knowledge on some of the aspects mentioned above but pronival ramparts are still poorly understood, specifically in terms of rampart genesis, identification and palaeo-environmental significance. This thesis aims to improve our understanding of rampart genesis, develop a set of diagnostic criteria which can assist in differentiating pronival ramparts from glacial moraines, rock-slope failures and other discrete talus-debris landforms as well as highlight the value (and limitations) of using pronival ramparts as palaeo-environmental indicators. The age of a rampart or stage of development also plays some role in determining the morphology of the landform and will be assessed in the context of palaeo-environmental significance.

Thus, the following objectives are identified:

- To adopt a definition of pronival ramparts and identify gaps in the current body of knowledge in terms of the genesis of pronival rampart, their identification and their use as palaeo-environmental indicators.
- To present advances in the understanding of rampart genesis, based on the studies of actively-accumulating ramparts (*e.g.* Hedding *et al*., 2007; Hedding *et al*., 2010).
- To explain rampart genesis, while taking cognisance of the fact that rampart development may occur across periods of stable, increasing and/or decreasing snowfall, and determine if rampart morphology can be used as evidence in palaeo-environmental reconstructions.
- To develop a robust set of diagnostic criteria to distinguish ramparts from other discrete debris accumulations (*e.g.* Hedding & Sumner, 2013).
- To apply the diagnostic criteria to relict pronival ramparts documented in southern Africa. This re-assessment will focus on the environmental conditions under which they developed, age or stage of development, site characteristics, underlying topography (slope angle), slope position, suggested debris transport mechanisms and their resultant morphology. An evaluation of the palaeo-environmental inferences derived from these landforms will also be conducted.

Contextual setting

In the past, research on pronival ramparts made little progress because much of the research was based on supposed relict landforms (Shakesby, 1997). This mired past is similar to the limited progress made in research on nivation and cryoplanation terraces. To illustrate, Hall (1997) highlights that although there is a substantial body of literature on cryoplanation (*e.g.* Dylik, 1957; Demek, 1969; Czudek, 1995) “the actual formative processes involved … is (*sic*) still far from clear”. This echoes Johnson (1983: 32) who states, when discussing debris transport processes involved in rampart genesis, that "extensive movement of debris over semi-permanent snowbanks has never been observed ... rampart accumulation (by this mechanism) must remain a question mark".

Thorn & Hall (2002: 534) state that nivation and cryoplanation "are severely debilitated by fuzzy conceptualisation, inconsistent usage and a lack of telling fieldwork". Research on nivation has struggled to settle on workable definition (Thorn, 1988; Thorn & Hall, 2002) and very few studies have been conducted on 'active' cryoplanation terraces (*e.g.* Hall, 1997; Hall & André, 2010). Nevertheless, 'nivation' has been studied in alpine (Rapp, 1984), Arctic (Nyberg, 1986; 1991) and Antarctic (Hall & André, 2010) environments and is generally associated with weathering and mass movement processes stemming from late-lying seasonal snow and the ensuing landforms (Thorn & Hall, 2002). Freeze-thaw weathering is traditionally regarded as the dominant process for debris breakdown and production (Embleton & King, 1975) but Hall *et al*. (2002) question the existence or pervasiveness of this form of weathering in cold regions. Similarly, although a large body of literature exists on pronival ramparts, very few studies have focussed on actively-accumulating landforms and a workable definition of pronival ramparts has been slow in its evolution as the term has changed from 'nivation ridge' to 'protalus rampart' and, most recently, to 'pronival rampart'.

Nivation and cryoplanation terraces, as is the case with pronival ramparts, are intrinsically associated with late-lying snowpatches but Thorn (1988) notes that pronival ramparts are usually discussed more as an aspect of talus development than as a component of nivation. The term 'nivation' was first coined by Matthes (1900: 183) when he stated that "the effects of the occupation by quiescent (*static*) névé are thus to convert shallow V-shaped valleys into flat U-shaped ones and to efface their drainage lines without material change of grade. These névé effects, which are wholly different from those produced by glaciation, I shall for the sake of brevity, speak of as the effects of nivation, the valleys exhibiting them having been nivated". Matthes (1900) is best known for introducing the term 'nivation' to periglacial geomorphology, but he also made a brief description of 'morainal material' associated with nivation processes (not glacial motion) which this author speculates may be an early description of pronival ramparts (see above).

The scant literature on 'active' cryoplanation terraces (Thorn & Hall, 2002) mirrors the paucity of literature on actively-accumulating pronival ramparts (Shakesby, 1997). In both instances, the research on supposed relict landforms led to circular reasoning and assumptions. Cryoplanation terraces are typically regarded as a manifestation of nivation and cryoplanation in periglacial environments. This brings to the fore some of the overlap regarding nivation and cryoplanation and their meaning which has led to much confusion as both process suites are similar (see Hall, 1998 for further discussion). Cryoplanation terraces vary in form from sickle-like to elongate stepped profiles and they are relatively narrow in shape (French, 2007). These features are then typically used to invoke inferences about formative processes and the environmental conditions through which they developed. In a similar manner, the identification of pronival ramparts has traditionally been used to infer the palaeo-environmental conditions under which the rampart developed with little understanding of the debris transport processes involved or the mode of rampart genesis itself.

Noting the similarities in the shortcomings of research on nivation and cryoplanation terraces with pronival ramparts, it is hoped that this thesis will provide some insights which will aid in the identifying appropriate questions for future studies on not only pronival ramparts but other periglacial landforms such as cryoplanation terraces.

Structure of the thesis

This thesis contains two sections. Section A comprises this introduction (Chapter 1) and a compilation of independent yet interrelated research papers (Chapter 2 and Chapter 3). Chapter one has introduced the reader to literature on pronival ramparts and specifically highlights the current gaps in the understanding of rampart genesis, diagnostic criteria and their palaeo-environmental significance. Chapter two comprises of two parts which present new findings with regard to rampart genesis and the associated importance of the different environmental conditions under which they form, the age or stage of rampart development, debris transport mechanisms involved in their formation and the topography over which they form (Hedding *et al*., 2007; Hedding *et al*., 2010). Chapter three is based on Hedding & Sumner (2013) and presents developments made by the author in the refinement of diagnostic parameters for the identification of (active and relict) pronival ramparts in the field. The assessment of the morphometric regularity of relict pronival ramparts by Ballantyne & Kirkbride (1986) and summary of diagnostic criteria by Shakesby (1997) provide the point of departure for this section.

In Section B diagnostic criteria are then used to re-assess relict pronival ramparts in southern Africa. In particular, chapter four draws from the advances in understanding of rampart genesis and the development of more robust diagnostic criteria presented in chapters two and three, respectively. Collectively, this information will then be used to highlight the use and limitations of pronival ramparts as palaeo-environmental indicators in chapter five. Chapter six summarises the body of work and presents avenues for possible future research. Some repetition occurs between chapters but, unfortunately, this is unavoidable as the three included articles which form the basis of chapters 2 and 3 primarily focus on various aspects of rampart genesis, diagnostic criteria and their palaeo-environmental significance. Relevant acknowledgements are included at the end of each research paper but all the references are included at the end of the thesis. One article by the author (Hedding, 2011) that is related to the thesis but not vital to the findings presented is included in Appendix 1.

Chapter 2: The genesis of pronival ramparts

Introduction

A working definition for a pronival rampart is a ridge, series of ridges or ramp of unconsolidated debris formed at the downslope margin of a perennial or semi-permanent snowbed that is overlooked by an exposed bedrock cliff. The genesis of pronival ramparts was, for many years, simply assumed to result from debris sliding, rolling and bouncing over a snowbed and therefore, actively-accumulating ramparts received very little attention. Rampart genesis was believed to occur in periglacial and glacial environments. Recent studies (*e.g*. Harris, 1986; Ono & Watanabe, 1986; Ballantyne, 1987a; Shakesby *et al*., 1995; Calkin *et al*., 1998; Shakesby *et al*., 1999) have shown that various mechanisms of debris transport may contribute to rampart genesis but few have address debris production. The following sections address debris production and explain the mechanisms of debris transport in order to provide the platform from which to address rampart genesis.

Debris production

Relict pronival ramparts were frequently described as comprising coarse angular rockfall material that was derived from the bedrock cliffs (backwall) which rose above the former supposed snowbed (Washburn, 1979; White, 1981; Oxford, 1985; Harris, 1986). This angular material was typically attributed to the supranival transport of frost-shattered debris (Shakesby & Matthews, 1993; Shakesby, 1997; Brook, 2009). One of the earliest descriptions of frost shattering occurring at the headwall comes from Lewis (1939) and this concept has become entrenched in the literature, particularly in textbooks. Frost-shattered debris is typically associated with frost or freeze-thaw weathering, although a review of weathering processes in cold environments by Hall *et al*. (2002) questions frost-weathering as a process or suite of processes and shows that frost weathering processes do not necessarily produce angular-shaped debris. Shakesby (1997: 397) notes that clasts of actively-accumulating ramparts are “by no means nearly all angular, as is thought typical of fossil ramparts”.

In general, very little research on debris production from exposed bedrock cliffs has been conducted in periglacial environments but Matsuoka & Sakai (1999) conduct a detailed assessment of rockfall activity in the Hosozawa Cirque, Japanese Alps. They indicate that factors influencing rockfall activity (debris production) include rock joint spacing, rock temperature (short-term temperature oscillations and seasonal freezing and thawing) and weather conditions (*i.e*. rainfall). Matsuoka & Sakai (1999) regard seasonal frost weathering to be the most important process responsible for the modification of the cirque wall. Matsuoka & Sakai (1999) also indicate that rockfall activity intensifies with regard to size of boulders and frequency of rockfalls in spring during the seasonal thawing period. This observation suggests that debris production may coincide with late-lying snow and that monitoring of debris production for rampart development should be intensified during spring.

Matsuoka (2001) observed frost wedging of alpine bedrock whereby macrocracks visible on the rock surface widened during two seasonal periods; namely during autumn and spring. This finding supports the observation of Porter (1987) who highlights that the release of rock debris from slopes in the formation of pronival ramparts takes place more frequently during mid- to late spring and not in winter. Debris may conceivably be wedged from the cliff face by ice but this could be regarded as a form of mass wasting or erosion (movement of debris) and not weathering (the breakdown of material). To the author's knowledge, no studies have hitherto investigated rockwall retreat in the context of debris production specifically for actively-accumulating pronival ramparts in periglacial environments. Several studies (*e.g*. Rapp, 1960; Ballantyne & Eckford, 1984; Ballantyne & Kirkbride, 1987; André, 1997; Bower, 1998; Hinchliffe & Ballantyne, 1999; Curry & Morris, 2004) have, however, assessed rockwall retreat under periglacial conditions with retreat rates of between 10^{-2} and 10^{-1}mm year^{-1} (French, 2007). Some studies have determined rockwall retreat through direct observations (*e.g*. Matsuoka & Sakai, 1999) but other studies have used the volume of the sediments at the base of the rockwall to infer long-term average rates (*e.g*. Ballantyne & Kirkbride, 1987; André, 1997; Hinchliffe & Ballantyne, 1999).

Based on the volumes of eight widely distributed stadial pronival ramparts, Ballantyne & Kirkbride (1987) indicate average stadial rockwall retreat of 1.14-1.61m y^{-1} (estimated average rockwall retreat rates of 1.5-4.0mm y^{-1}). However, Hinchliffe & 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. Ballantyne & Eckford (1984) document average present-day rockwall retreat rates of 0.015mm y^{-1} (excluding infrequent large-scale falls). Curry *et al*. (2001) note that had a pronival rampart origin been valid for the Nant Ffrancon landform in north 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 cast 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 notes the exceptionally large volume in relation to the potential backwall source area of some discrete debris accumulations in Britain led to questioning their classification as pronival ramparts.

A number of other slope processes (mass wasting) can contribute material in the formation of pronival ramparts (discussed in detail 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 indicate that we still know relatively little in terms of the debris production linked to debris transport for the genesis of pronival ramparts.

Debris transport mechanisms

Supranival processes

From the earliest descriptions of ramparts by Drew (1873) and Ward (1873) an overly simple mode of pronival rampart genesis 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 & Harris, 1994). Due to the implied simplicity of the supranival gravity fall process, it was accepted by almost all subsequent studies (*e.g*. Daly, 1912; Bryan, 1934; White, 1981; Goudie *et al*., 1994), with it becoming a textbook paradigm (*e.g.* Washburn, 1979). However, the work of Ono & Watanabe (1986), following on from the initial work of Sekine (1973), Harris (1986), Ballantyne (1987b), Shakesby *et al.* (1995) and Shakesby *et al.* (1999), have questioned the primacy of the simple gravity-driven mode of genesis. This point is highlighted in a critical review 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”. Other possible transport mechanisms including debris flows (Ono & Watanabe, 1986), slush avalanches (Ballantyne, 1987b), the reworking of till deposits from up-slope (Harris, 1986), solifluction and meltwater flows (Shakesby *et al*., 1995) and snowpush (Shakesby *et al*., 1999) have been identified (Fig. 2.1).

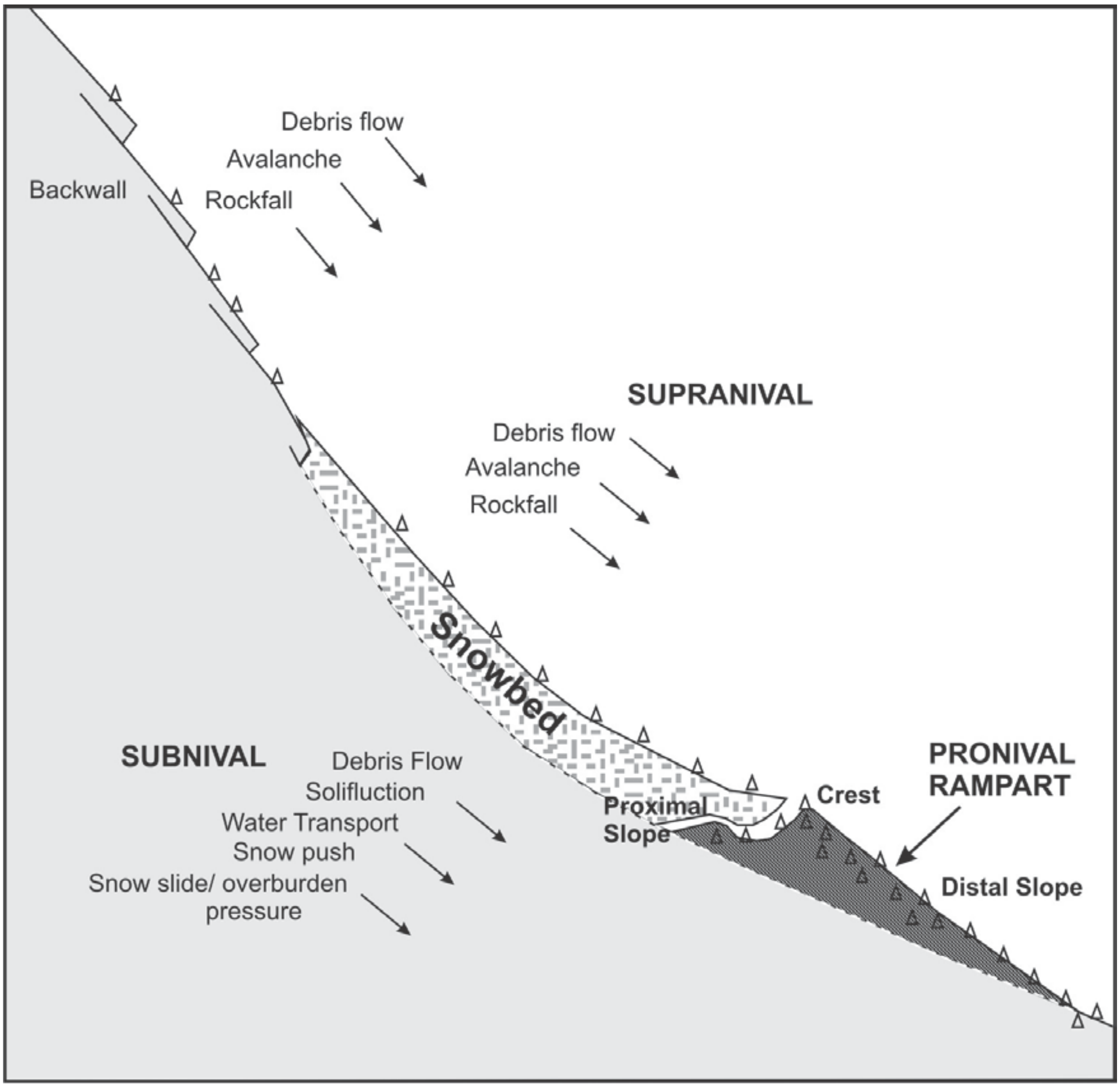

Figure 2.1: Supranival and subnival debris transport mechanisms responsible for rampart formation (adapted from Shakesby *et al*., 1995).

Clark & Ciolkosz (1988) report that although Richter (1973) did not document evidence for protalus (pronival) rampart development, his drawings (Figure 19, p. 123; Figure 24, p. 131) clearly demonstrate that he understood the processes involved in the transport of rock debris over a snow cover. However, this mode of proposed accumulation remained unsubstantiated for over 100 years which led Johnson (1983: 32) to assert that since "extensive movement of debris over semi-permanent snowbanks has never been observed ... rampart accumulation (by this mechanism) must remain a question mark". Shakesby (1997) notes that exceptions to this came from Birnie (1978), Vincent & Lee (1982), Hall (1985) and Ward (1985) who all made exploratory observations on the movement of debris across snowbeds. Pérez (1988), and more recently Hedding *et al*. (2010), validated the traditional gravity fall mechanism of debris accumulation by demonstrating that clasts introduced at the top of a steep snowbed could reach its foot.

A range of supranival and subnival mechanisms of debris transport may contribute to rampart development (Fig. 2.1). Ramparts formed by subnival processes have received very little attention with only two studies having been conducted to date (Shakesby *et al*., 1995; 1999). Shakesby *et al*. (1995) provide evidence of solifluction enhanced by wet conditions beneath and at the periphery of snowbeds at actively-accumulating ramparts in Romsdalsalpane, Norway. Shakesby (1997: 401) notes that Shakesby *et al*. (1995) "found evidence of what they interpreted as debris flows emerging from beneath a snowbed which led them to deduce that they could be supplying debris together with meltwater action". Shakesby *et al*. (1995) also note snow creep which involves slow sliding of snow on an internal or, more likely, a basal shear plane (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. Shakesby *et al*. (1995) raise the possibility that subnival debris transport mechanisms may be as important as supranival mechanisms in rampart formation but no study has, as yet, specifically addressed this. Interestingly Shakesby *et al*. (1999) highlight that the ramparts formed by subnival debris transport mechanisms display 'distinct' rampart morphology in the form of asymmetrical ridges which take on a sickle shape in plan-form.

Supranival debris transport involves the traditionally envisaged gravity-driven mechanisms of debris transport for rampart formation. Drew (1873: 445) was the first to describe the process when he wrote that "a talus of snow forms first ... and then upon the snow- heap rolls down the loosened stuff, which therefore finds rest only at the foot ... of the snow talus; the melting of this in summer leaves a heap of stones which may be of considerable height". Later Kendall (1893: 69) stated that rockfall fragments "would find the base of the cliffs pre-occupied by a talus of snow, (and) would roll further out from the base and form a fringe of rock debris". Shakesby (1997) notes that this model was endorsed by Daly (1912) and later by Bryan (1934: 656) who argued that rampart debris "accumulated piecemeal by rock-fall or debris-fall across perennial snowbank" with bouncing and sliding being added to rolling as possible transport mechanisms. Washburn (1979), White (1981) and Goudie *et al*., (1994) accepted the supranival gravity fall process of rampart formation but the lack of evidence for supranival debris slide, bounce and roll prompted Johnson (1983: 32) to question this mechanism of debris transport for rampart genesis. The traditionally envisaged mechanism of gravity-driven supranival debris transport has subsequently been observed at actively-accumulating ramparts (*e.g*. Pérez, 1988; Hedding *et al*., 2007; Hedding *et al*., 2010). Pérez (1988) notes 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. Debris flows (Ono & Watanabe, 1986) and slush avalanching (Ballantyne, 1987a) have also been noted as supranival debris transport mechanisms.

Subnival processes

Shakesby *et al*. (1995) and Shakesby *et al*. (1999) provide evidence for subnival processes being at least as important as supranival debris transport processes from actively-accumulating ramparts in Romsdalsalpane, Norway. Shakesby *et al*. (1999) show that 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 50cm in length. However, the study of Shakesby *et al*. (1999) indicates that only four of the 50 randomly measured clasts were greater than 50cm in size with the majority of the clasts in the rampart being less than 20cm. The ramparts in Romsdalsalpane, Norway appear to be smaller than ramparts formed by supranvial processes and, thus, subnival processes would potentially be limited to ramparts which are matrix, rather than clast-supported.

Rampart genesis

Curry *et al*. (2001) indicate that various rampart origins exist (glacial, rampart, rock-slide and protalus rock glacier) and rampart origin and formation should be investigated using multiple working hypotheses (Harris *et al*., 2004). Although various observations had been made regarding rampart genesis (*e.g*. Sissons, 1979), Ballantyne & Kirkbride (1986) were the first to propose a model of rampart genesis. Their model of rampart development addresses rampart genesis under supranival debris transport and deposition (Fig. 2.1). Ballantyne & Kirkbride (1986) have proposed a model of downslope rampart extension at the foot of thickening snowbeds (Fig. 2.2A), which contrasts with the previous interpretation of Sissons (1979) in that 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 & Harris, 1994). A suggested morphological characteristic of ramparts which extend downslope was that the distal slope was formed at repose (34-38°) by the accumulation of cohesionless cascading debris (Ballantyne & Kirkbride, 1986; Gordon & Ballantyne, 2006). However, not all (active or relict) ramparts exhibit this characteristic (*e.g.* Wilson, 1990). Hall & Meiklejohn (1997) note that many ramparts in the Canadian Rockies had two crests with the outer one being older than the inner which does not conform to the model presented by Ballantyne & Kirkbride (1986). Similarly, Pérez (1988: 89) found that the outer rampart ridge on Lassen Peak, California had a more subdued topography, was stabilised by plants and was thus "clearly older and inactive". These observations allude to the possibility of retrogressive rampart development.

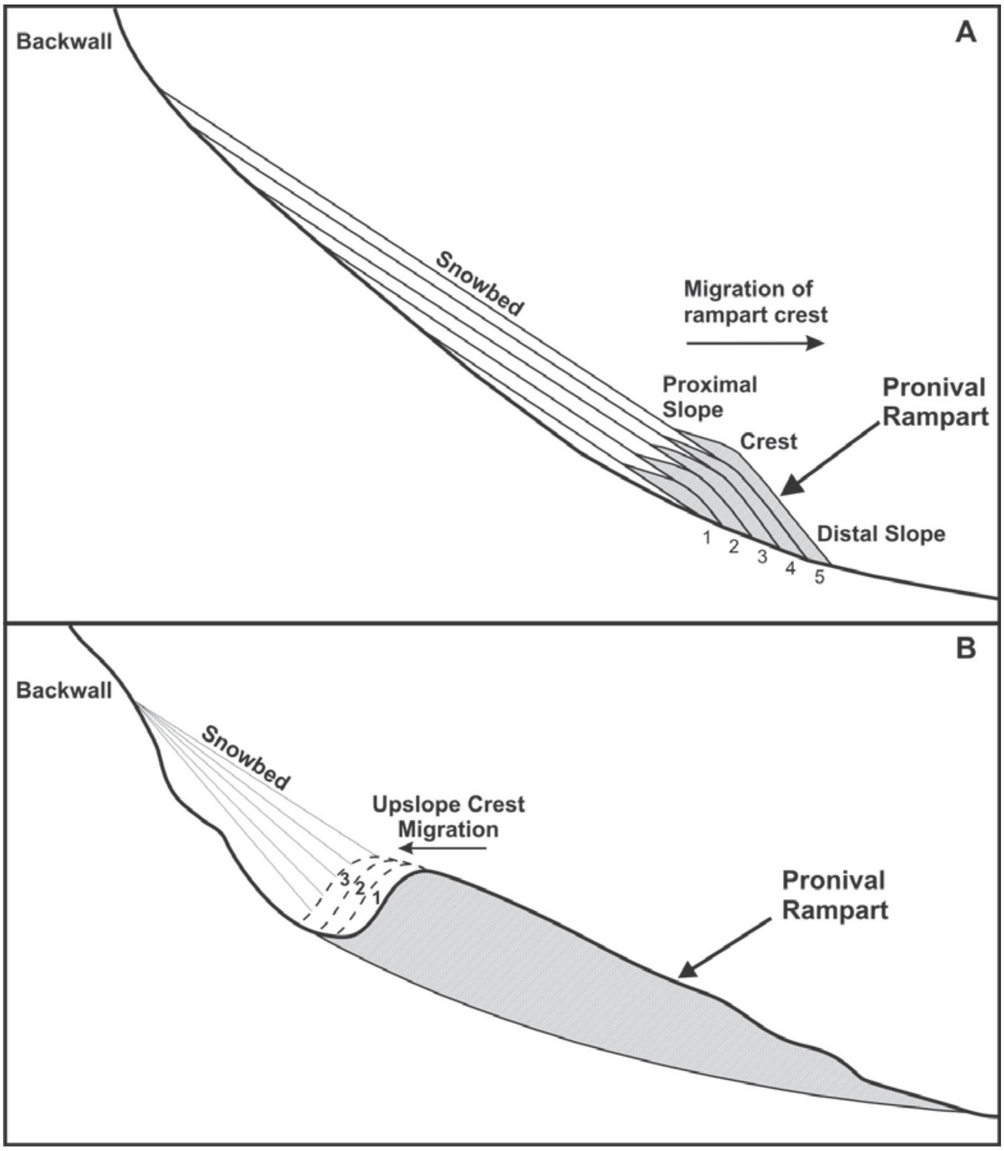

Figure 2.2: Figure A: the downslope model (outward extension) of rampart formation (adapted from Ballantyne & Kirkbride, 1986). Figure B: the retrogressive (upslope) model of rampart formation (adapted from Hedding *et al*., 2007).

Two studies led by the author are presented below. First, that of an actively-accumulating pronival rampart on Marion Island by Hedding *et al*. (2007) where a retrogressive (upslope) model of rampart development under fluctuating, and possibly declining, snowbed volumes is proposed (Fig. 2.2B). Second, the study of an actively-accumulating pronival rampart near to the Grunehogna Peaks in Western Dronning Maud Land, Antarctic by Hedding *et al*. (2010) is presented which uses data on site characteristics, rampart morphology and a debris accumulation field test, in terms of location of deposition, to evaluate rampart genesis. The findings of Hedding *et al*. (2010) indicate outward (downslope) rampart extension even though this rampart does not possess a distal slope at repose. This observation questions the assertion that in order for ramparts to extend outward (downslope) their distal slopes must be at repose. These findings not only elucidate rampart genesis but provide the foundation to reassess the environmental controls under which ramparts develop, the site, morphological and sedimentological characteristics of ramparts and their usefulness and limitations in palaeo-environmental reconstructions.

Retrogressive rampart genesis

Formation of a pronival rampart on sub-Antarctic Marion Island

D.W. Hedding, P.D. Sumner, S.D. Holness and K.I. Meiklejohn

Footnote

Stephen Holness assisted with fieldwork and supplied photographs, Paul Sumner assisted with fieldwork and provided critical theoretical input and Ian Meiklejohn stimulated discussion and funded the research through a National Research Foundation (NRF) - South African National Antarctic Programme (SANAP) grant.

The article appears as it did in print but it has been formatted to conform to the guidelines for the thesis. The references of the article are included in the reference list at the end of the thesis.

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Abstract

The formation of a pronival (protalus) rampart on sub-Antarctic Marion Island is investigated. Morphological attributes show debris at the angle of repose on the rampart's proximal slope and at a lower angle on the distal slope. Relative-age dating, based on the percentage moss cover and weathering rind thickness of the clastic component indicates accumulation mainly on the proximal slope and rampart crest, implying upslope (retrogressive) accumulation. This contrasts with a previously published model for pronival ramparts, which proposes rampart growth by addition of material to the distal slope. Development of the Marion Island rampart is suggested to result from the control exerted by a relatively low-angled surface and a shrinking snowbed. A small debris step formed on the proximal slope appears to be a response to decreased snowfalls due to changing climate over the last *c*. 50 years. Growth rate of the rampart is considered to be variable during the Holocene in response to changes in climate and debris supply.

Introduction

A pronival (protalus) rampart (Shakesby, 1997) is a ramp or ridge of debris formed at the downslope margin of a snowbed or firn field. Supranival transport of debris has traditionally been assumed to be the simplest source of material for the rampart (Shakesby, 1997). In areas where seasonal or permanent snow lies at the base of a cliff, mass-wasting of debris from a free-face falls on to a snow surface and slides, bounces and rolls across the snow to rest at the downslope fringe of the snowbed. Through time, debris accumulates, and when the snow melts a ridge or ramp of slope material is left at some distance from the cliff face.

Until the mid-1980s, research into pronival ramparts focussed on inactive examples (Shakesby, 1997). Since then, studies of actively-forming ramparts have improved the understanding of origin, morphology and mechanisms contributing to growth, clarified terminology, and determined rampart positions in relation to snowbeds and talus slopes (*e.g.* Ono & Watanabe, 1986; Harris, 1986; Ballantyne 1987a, 1987b; Shakesby *et al.*, 1995; Shakesby *et al.*, 1999; Hall & Meiklejohn, 1997). In particular, a diverse range of supranival and subnival mechanisms of debris transport have been identified as potential contributors to rampart formation. Owing to its apparent simplicity, the actual manner of rampart genesis has, however, received relatively little attention. Nevertheless, four modes of origin are recognised by Curry *et al*. 2001, namely a (1) wholly pronival (protalus) rampart; (2) glacial; (3) landslide; and (4) protalus rock glacier origin, all with subsequent pronival development.

Ballantyne & Kirkbride (1986) proposed the only general model of rampart genesis, derived from supposed exemplar or 'unequivocal' fossil features in the United Kingdom. The model describes gradual and continuous accumulation of intermittent rockfall debris on the downslope margin of a snowbed with mass-wasted debris from upslope accumulating at the rampart crest and down the distal (downslope) section. Subsequent growth in snowbed size enables material to be constantly added to the debris crest facilitating the downslope extension of the rampart with the distal slope maintained at the angle of repose for the debris. However, some ramparts have been found to have distal slopes that are not at repose, or where accumulation has occurred on the proximal (upslope) slope of the rampart (*e.g.* Harris, 1986; Pérez, 1988; Grab, 1996). The actively-forming rampart found on Marion Island, appears to differ from the model proposed by Ballantyne & Kirkbride (1986) and is investigated according to previously suggested diagnostic criteria for pronival ramparts (see Shakesby, 1997). Although Birnie & Thom (1982) noted protalus lobes and ramparts on South Georgia, the Marion Island rampart is the first active landform of its kind known to be documented in detail from the sub-Antarctic.

Environmental setting and study site

Marion Island (46°54'S, 37°45'E) is the larger of two land masses that constitute the Prince Edward Islands (Fig. 2.3.1) and lies north of the Antarctic Polar Front, 2130km from the southern tip of Africa and 2570km from Antarctica. The island has a subaerial extent of 293km^2 and rises to 1240m above sea level (a.s.l.). Geologically, it comprises older sequences of pre-glacial (Pleistocene) basaltic lavas overlain in places by post-glacial (Holocene) black lavas and scoria (Verwoerd, 1971; McDougall *et al*., 2001). Numerous scoria cones distributed across the island are associated with the black lava phase. Between three (Hall, 1978, 1980) and seven glacial periods (McDougall *et al.*, 2001) have been detected on Marion Island. The most recent glaciation ended at approximately 13 000 B.P., when Marion Island had an extensive ice cover (Hall, 2002). Deglaciation is thought to have caused radial faulting, eruptions, and the formation of horst and graben structures resulting in scoria cone eruptions, scarps, and debris slopes that post-date glaciation (Hall, 1978, 1980; Sumner *et al*., 2002).

Subsequent Holocene climate fluctuations have left a relict periglacial imprint on the landscape (Holness & Boelhouwers, 1998).

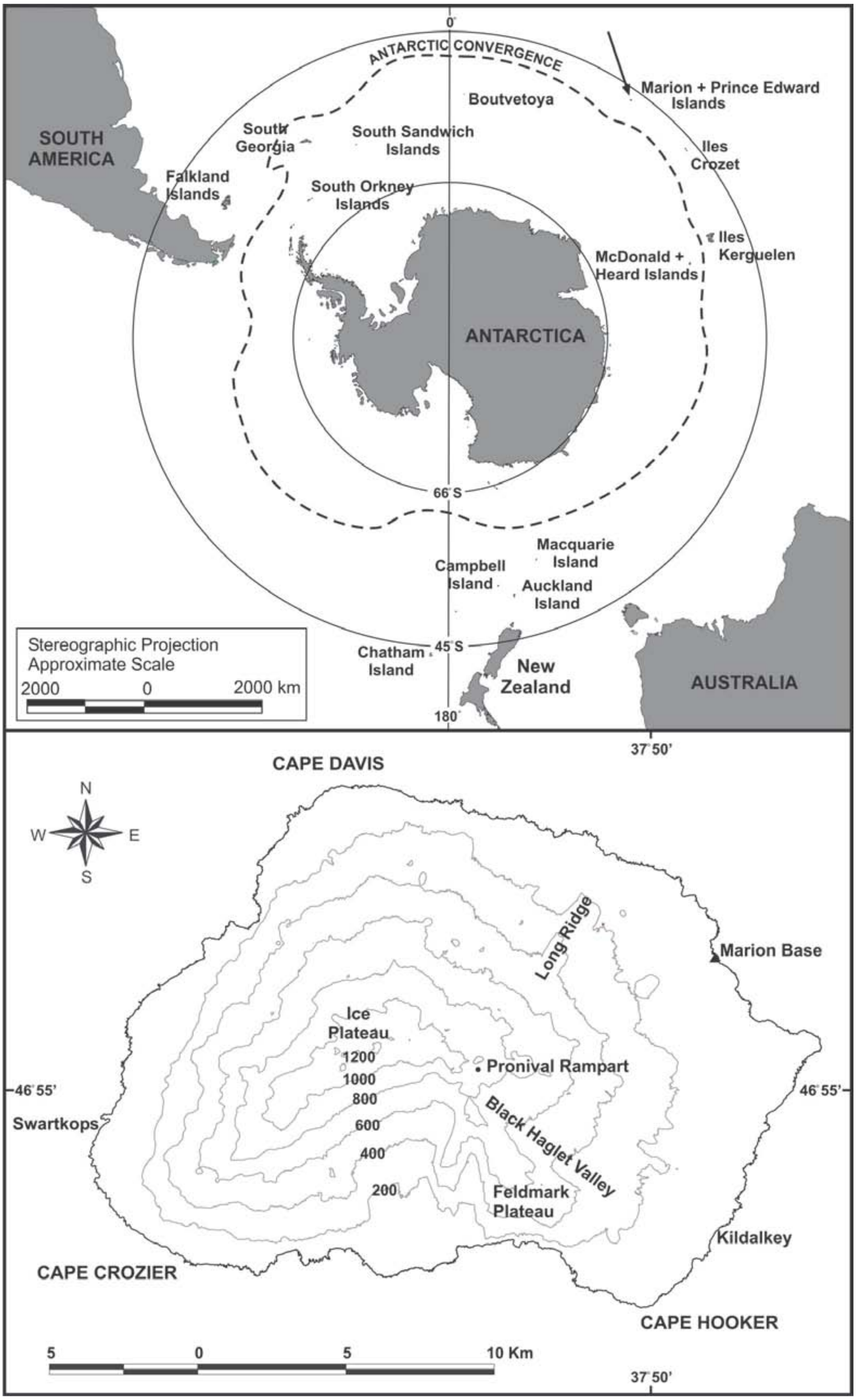

Figure 2.3.1: (a) Location of Marion Island within the sub-Antarctic region and (b) the location of the pronival rampart on Marion Island.

The Marion Island climate provides a hyper-maritime periglacial setting, characteristic of the sub-Antarctic islands (Boelhouwers *et al.*, 2003). Mean summer maximum and minimum temperatures on the east coast are 10.5 and 5.0°C, and the winter mean maxima and minima are 6.0 and 1.0°C, respectively. The meteorological station on the island experiences strong north-westerly winds (60% of occurrences) at an average speed of 32km/h. Average annual precipitation (at sea level) was 2576mm up to the late 1960s (Schulze, 1971) but has decreased to approximately 2000mm p.a. in the late 1990s (Smith, 2002) and has continued to decrease up to 2005 (Hedding, 2006). Snowfalls are currently recorded on approximately 50 days a year at sea level and are more frequent at higher altitudes (Holness, 2001; Hedding, 2006). Although snow is common, the permanent snow cover observed in the 1950's apparently disappeared by the mid 1980's (Sumner *et al.*, 2004b).

The pronival rampart of interest in this study, is situated at the head of the Black Haglet valley at an altitude of 900m a.s.l. (46°54'34.5"S, 37°45'14"E) (Fig. 2.3.1) and runs mostly north-south and parallel to the backwall (Fig. 2.3.2). Structural control in the form of a geological lineament, currently under investigation by one of the authors (KIM), appears to be aligned with the backwall and the associated destabilisation probably accounts for the enhanced mass-wasting activity of the valley head. The backwall comprises a lower grey lava layer, a middle pyroclastic (ash) layer, a highly jointed upper grey lava free-face that narrows from north to south topped by a scoria-covered ridge (Fig. 2.3.2a and 2.3.3). Rampart material comprises openwork clastic (long axis < 0.5m) and larger blocky material with intermittent interstitial fines. Two scree slopes flank and merge with the northern and southern lateral extremes of the rampart.

Field methodology

Observations on snow accumulation and debris movement were made between 1998 and 2000, in April 2003, April 2004 to May 2005, and in April 2006. Morphological attributes were measured, including rampart cross-profile and two longitudinal transects. Morphological dimensions were based on the measurements used by Ballantyne & Kirkbride (1986), including the maximum height of the distal (h_1) and proximal (h_2) slopes of the rampart ridges, the maximum rampart width (w) and the maximum horizontal distance from the rampart crest to the foot of the talus upslope (d). By extrapolation from the adjacent slope, the maximum rampart thickness (t) was estimated (Fig. 2.3.3). Rampart crest length (L) was measured and representative facet or spot angles recorded on both the proximal and distal slopes to provide an impression of the slope facets (Fig. 2.3.3).

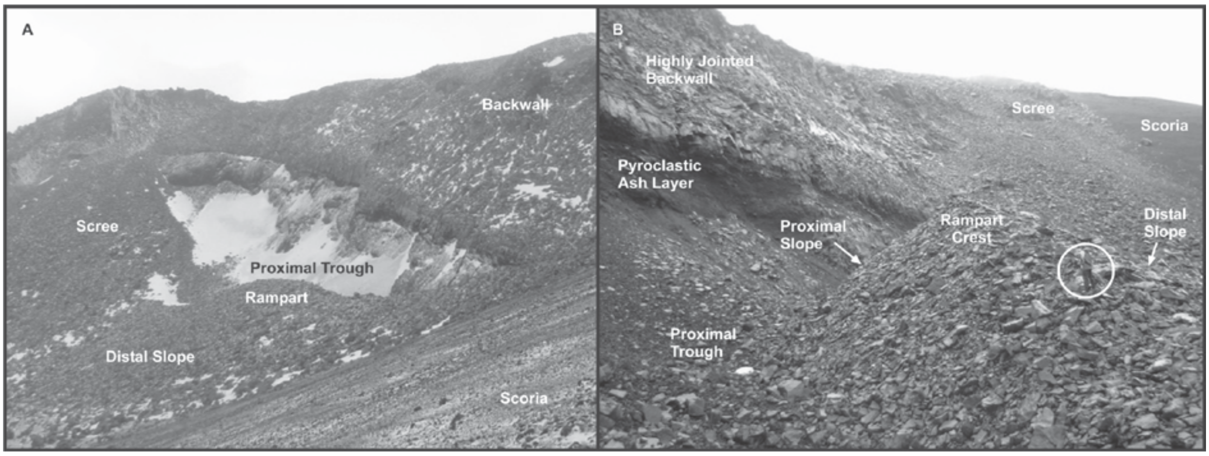

Figure 2.3.2: (a) Pronival rampart situated below a steep backwall; note the partial snow infill of the proximal trough and the thinning of the upper grey lava layer from north to south (right to left) (Hedding; April, 2005) and (b) the proximal trough devoid of snow (person circled for scale) (Hedding; April, 2003).

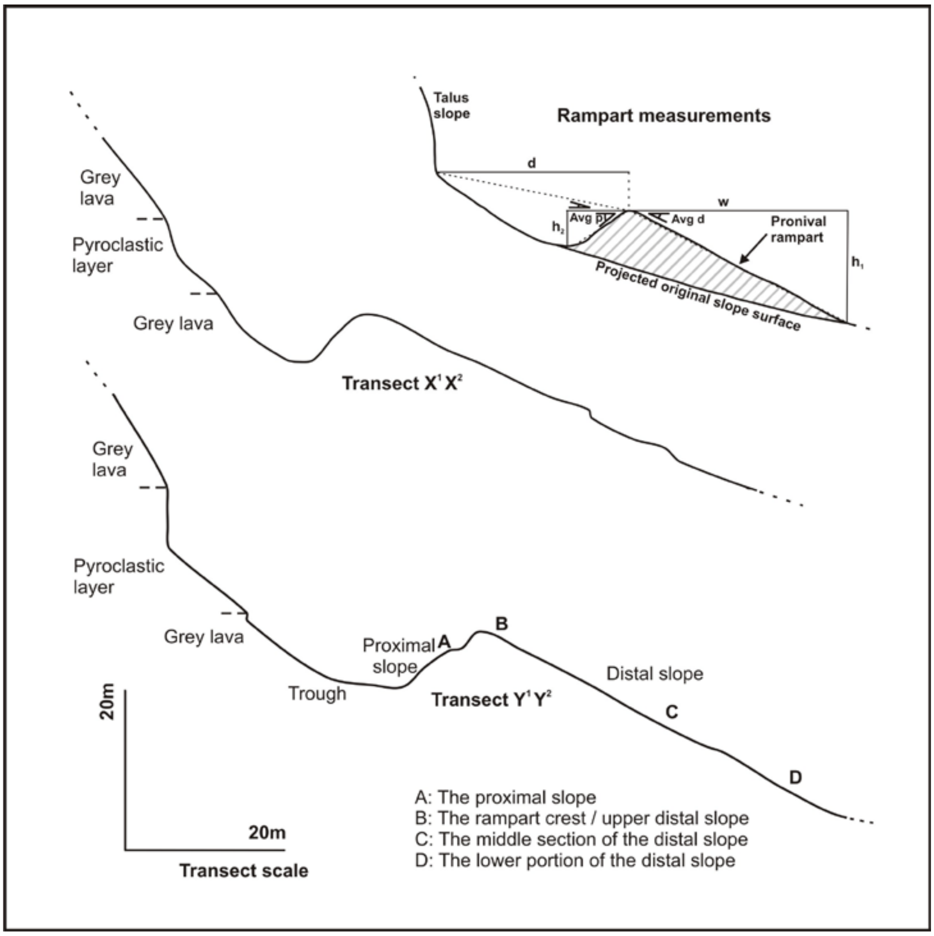

Figure 2.3.3: Surveyed transects, sample sites and schematic representation of morphological dimension measurements following Ballantyne & Kirkbride (1986).

Weathering rind thickness and moss cover were determined at four sites (A to D; Fig. 2.3.3) on the southern downslope transect (Y^1Y^2); the proximal slope, ridge crest, and two sites on the distal slope (*i.e.* middle and lower distal slope). Weathering indices have been successfully used for relative-age dating of grey lavas on the island (Sumner *et al.*, 2002); similar methods have been used on blocks elsewhere (*e.g.* McCarroll, 1989, Boelhouwers *et al.*, 1999). Twenty five measurements of upper-surface weathering rind thickness were made with a calliper (0.05mm resolution) at each of the sites by breaking clasts in the field. Upper surface moss cover of individual blocks was recorded to indicate where fresh debris was accumulating. Moss coverage was based on visual division of the collected data and the categories chosen were as follows: moss free, 1 – 9%, 10 – 24%, 25 – 49% and > than 50% for the nearest 50 blocks to the sites.

Observations and measurements

Snow accumulation was found to be enhanced east of the cliff where there is shade and protection from wind-scouring during storms, particularly in winter. Under the present-day snowfall regime, the trough has little snow infill in summer but in winter it reaches the rampart crest in places (Fig. 2.3.4a). Where the rampart crest is farthest from the backwall, the snowbed tends to fill the trough to a step visible at A on transect Y^1Y^2 (Fig. 2.3.5). A large snow bed and hard snow was observed to facilitate supranival clastic debris movement (Fig. 2.3.4b). No pyroclastic (ash) material has been incorporated into the rampart. However, fines consisting of wind-blown scoria, which settled on the snowbed and pyroclastic (ash) sediment, and transported by small debris flows from the ash layer on the backwall, were noted on the snow surface. In the absence of a snowbed in the late summer of 2003, small debris flows, similar to those found elsewhere on the island (Boelhouwers *et al.*, 2000), carried pyroclastic (ash) material into the trough on the lower backwall. Fresh clasts or larger blocks were notably absent in the trough above the proximal slope in the vicinity of the debris flows suggesting that snow-free conditions are infrequent.

Figures 2.3.3 and 2.3.5 illustrate crest, backwall, lateral and longitudinal extent of the rampart, representative facet angles, and the position of the longitudinal transects. Maximum rampart thickness, from the base of the proximal trough to the crest (Fig. 2.3.3) is 8m and coincides with the maximum height of the upper layer of grey lava, which in this case represents the source material in the backwall (Fig. 2.3.2a). The distance of the rampart crest from the backwall also corresponds with the availability of source material in the backwall

(Fig. 2.3.2a and 2.3.5). The north-south thinning of the upper layer of grey lava results in a decline in source material in the same direction, which, in turn, has resulted in the southern section of the rampart crest being situated farther away from the backwall. A discontinuous step running along the proximal slope, particularly evident on Transect Y, is found where the rampart is farthest from the backwall (A, transect Y^1 Y^2, Fig. 2.3.3). Facet angles measured adjacent to the crest give an average angle of 34° for the proximal slope, similar to that of adjacent scree slopes at their repose angles, and an average representative facet angle of the rectilinear distal slope of 22° (Table 2.1, Fig. 2.3.5). At no point on the distal slope is material at angle of repose of the scree adjacent to the rampart. The width of the rampart was 79m (Transect Y, Table 2.1) and maximum crest-talus distance was 47m.

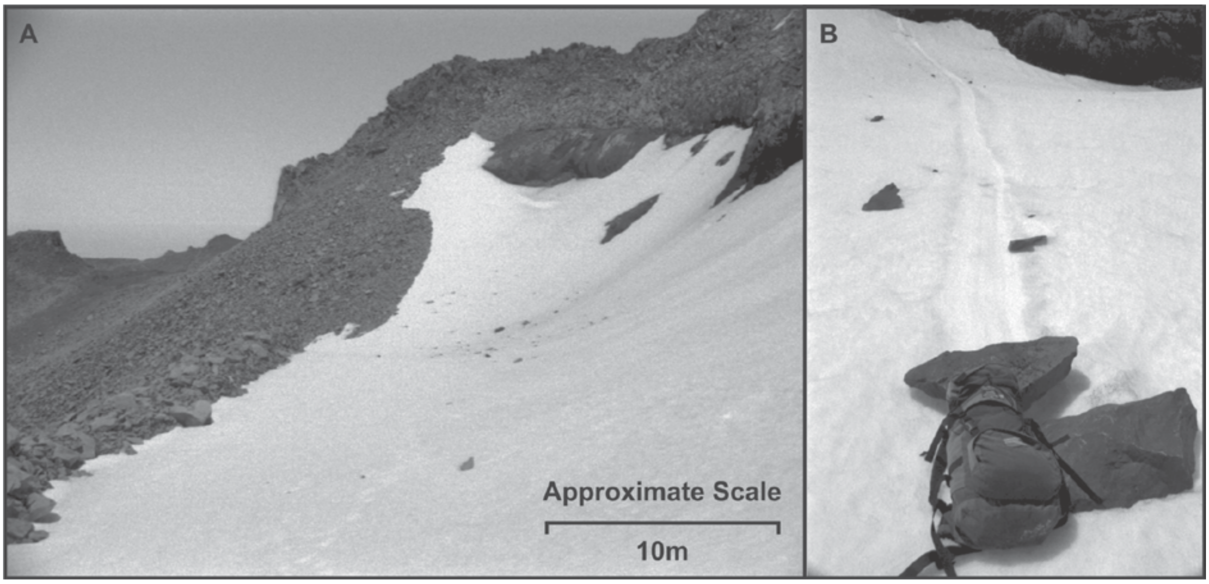

Figure 2.3.4: (a) Snow infill of the proximal trough nearly reaching the rampart crest; note the debris lying on the snowbed and (b) evidence of supranival debris movement (Holness; December, 1998).

Table 2.1: Rampart morphological dimensions derived from measurements noted in Figure 2.3.3.

Transect	Type	L (m)	w (m)	h_1 (m)	h_2 (m)	d (m)	Average slope (°) Proximal	Distal
X	Sinuous	140	67	22	7	11	34	22
Y			79	25	8	13		

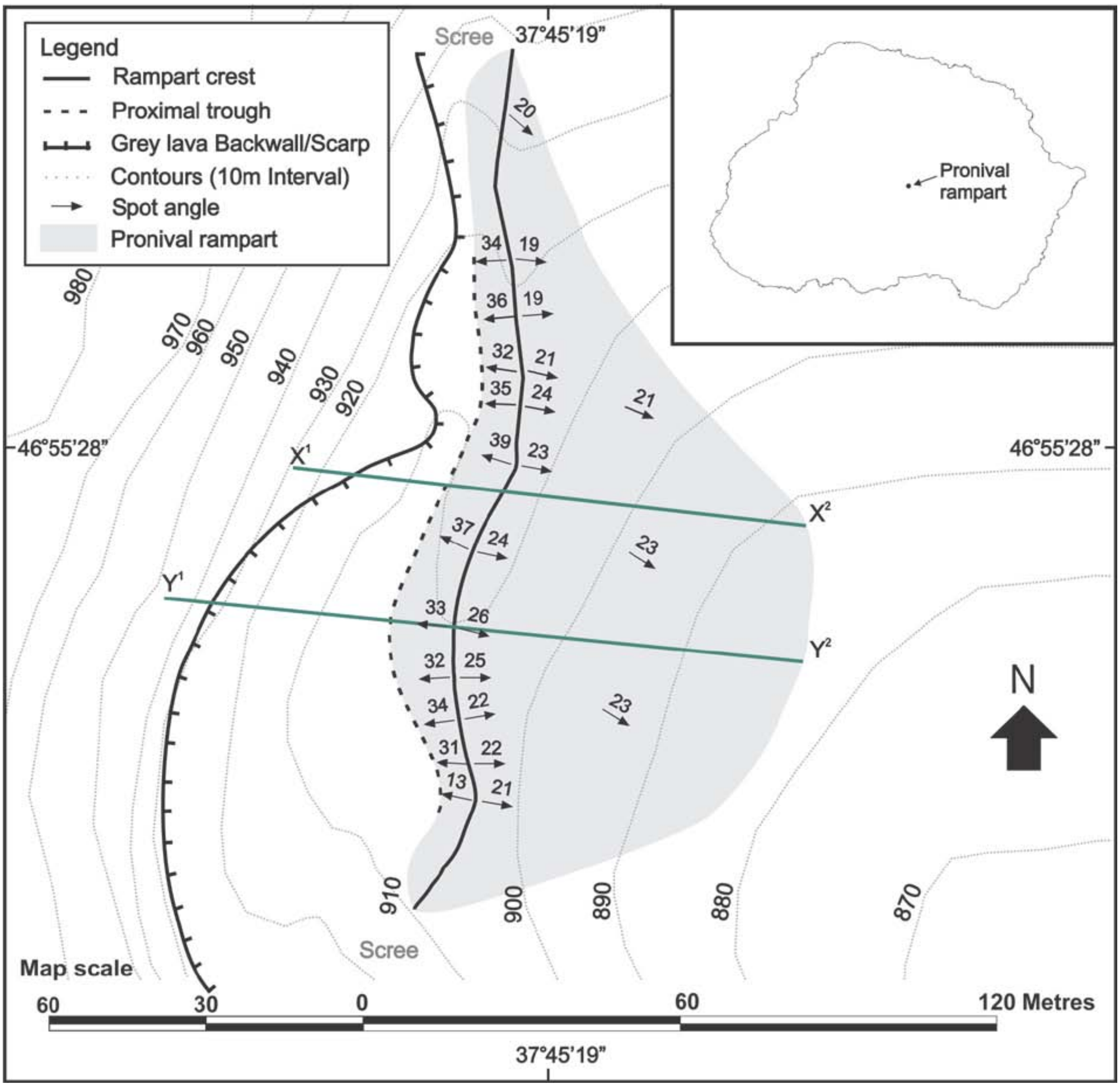

Figure 2.3.5: Plan view of the pronival rampart and surrounding area.

Few clasts in the vicinity of the rampart crest (B, Table 2.2) and extending into the trough (A, Table 2.2) had surface weathering rinds. Where clasts had weathering rinds at these two locations, the measured mean rind thicknesses were 0.39mm and 0.40mm respectively; probably reflecting pre-depositional, as opposed to *in situ* weathering. The number of clasts showing rinds increased down the distal slope and this is considered a function of both pre-weathering and *in situ* weathering. A mean value of 0.37mm was found mid-way down the distal slope, which is similar to that found for the clasts with rinds higher upslope. On the lower distal slope, fewer rind-free clasts were found, and the mean value for rinds measured was notably higher at 0.67mm and is suggested to be a result of longer exposure.

Table 2.2: Weathering rind thickness (mm) measured for the proximal slope (A), rampart crest (B), middle of distal slope (C) and lower distal slope (D) positions noted in Figure 2.3.3. Sample size is 25.

Site	No. without rinds	Mean weathering rind width (no. of rinds measured)
Proximal Slope (A)	23	0.40 (2)
Rampart Crest (B)	21	0.39 (4)
Middle of Distal Slope (C)	12	0.37 (13)
Bottom of Distal Slope (D)	6	0.61 (19)

The extent of moss cover decreased noticeably in the vicinity of the ridge. An additional sampling point (B2, Fig. 2.3.6) was used 5m down the distal slope and site B1 in Figure 6, therefore, corresponds with site B in Table 2. On the proximal slope, most clasts are moss-free or less than 10% covered (Fig. 2.3.6). Moss cover increases at the ridge crest (B1) and down the proximal slope to the lower distal slope where most clasts are more than 50% covered (Fig. 2.3.6). The above data illustrate frequent deposition in the upper region of the rampart, specifically the crest and proximal slope, similar to the findings of Sancho *et al.* (2001) for lichen on a pronival rampart in Spain.

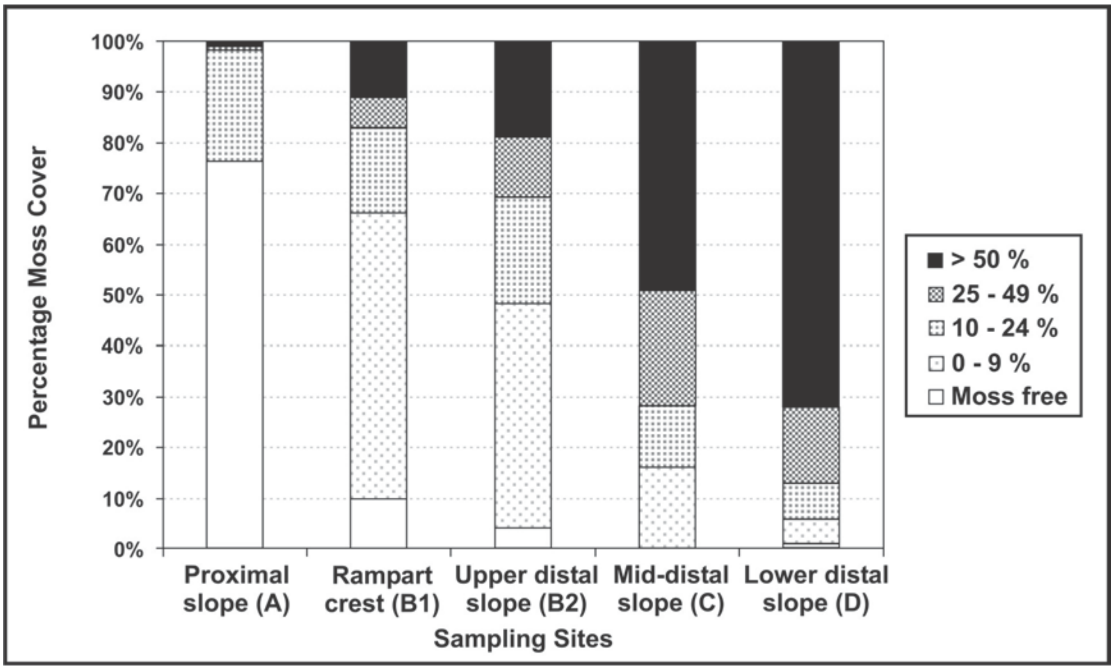

Figure 2.3.6: Mean moss cover (n=50 per site) at the sample sites; point B1 corresponds to the ridge crest and B2 is located 5m down the distal slope.

Rampart origin and growth

Any landform regarded as periglacial, including pronival ramparts, may be periglacial only in origin, growth, or maintenance, or it may be periglacial throughout its development (Thorn, 1992). Consequently, various modes of rampart evolution have been suggested (see Curry *et al*., 2001). Justification for regarding the Marion Island landform as a pronival rampart, according to diagnostic criteria (see Shakesby, 1997), are presented in Table 2.3 and the following discussion serves to identify its origin and formative processes. The landform on Marion Island is clearly not a moraine due to the limited distance of the rampart crest to the backwall, and climatic conditions on the island exclude an origin through the deformation of ice-rich permafrost (rock glacier creep). A landslide origin is also negated, even though the backwall appears to be aligned on an island-scale lineament or fault, since no pyroclastic (ash) material from the middle section of backwall is incorporated within the landform. The distinctly sinuous crest of the Marion Island landform is not typical of a landslide and supports a pronival origin and development. Supranival transport of material was frequently observed and the rampart appears not to conform to diagnostic criteria for other landforms. Moreover, rampart thickness and the rampart crest distance from backwall show a relationship to backwall source material; explained through upslope growth of the pronival rampart.

The rampart has formed in a location that favours snow accumulation, while on either side of the rampart, at sites that do not favour snow accumulation, scree slopes have developed. In addition, rampart crest length and cross-profile asymmetry are consistent with suggested ‘diagnostic’ criteria reviewed by Shakesby (1997) (Table 2.3). However, this rampart exhibits shallower distal (19-26°) than proximal slope angles (31-39°) in contrast to the characteristics suggested by Ballantyne & Kirkbride (1986). The original underlying slope angle and basal slope region may play a greater role in determining where debris accumulates on the rampart than has previously been addressed. A shallow original underlying slope angle would tend to only support a shallow snowbed slope angle inhibiting clasts from reaching the rampart crest and being deposited on the distal slope. Debris accumulation would not necessarily occur on the distal slope of the rampart thus preventing the distal slope from developing at repose. It is proposed that the original underlying slope can control whether the distal slope or proximal slope will become the ‘repose slope’ of the rampart, particularly when coupled with a variable snowbed size.

Table 2.3: Diagnostic criteria for distinguishing a rampart from other talus landforms (Table adapted from Shakesby, 1997).

Criteria		Additional Comments
Glacier		
Talus-foot location	✓	
Glacial erosional forms	x	
Striated clasts	x	
Linear plan form	✓	Sinuous
Asymmetrical cross-profile	✓	
Symmetrical cross-profile	x	
Clasts dip away from backwall	x	
Landslide		
• Talus-foot location	✓	
• Hillslope scar	x	
• Debris apron beyond the feature	x	
• Large masses of displaced hillside within or above the debris accumulation	x	
Protalus Rock Glacier		
• Talus-foot location	✓	
• Multiple arcuate ridges	x	Step on proximal slope
• Greater in length (down-slope) than in width (across-slope)	x	
• Crenulate or lobate plan form of the outer margins	x	
• Convex distal slope	x	Rectilinear
• Meandering and closed depressions, downslope ridges and furrows, and transverse ridges and depressions	x	
Pronival (Protalus) Rampart		
• Talus-foot location	✓	
• Large ridge to backwall summit inclination	✓	
• Small ridge to backwall distance	✓	
• Ridge crest to talus-foot distance <*c*.30-70m	✓	
• Restricted potential snow accumulation depth	✓	
• Length <300m	✓	
• Openwork fabric with/without infilling fines	✓	
• Single ridge	✓	Step on proximal slope
• Ridge size increase with distance from talus foot	✓	
• Backwall and ridge same lithology	✓	
• Angular clasts	✓	

Moss cover and weathering rind data indicate that material is 'younger' on the upper, and 'older' on the lower part of the rampart. Thus, the accumulation of debris on the proximal slope of the pronival rampart at the foot of a non-permanent snowbed combined with the evidence that the distal slope is not at 'repose' indicates that this rampart cannot develop following the model of downslope migration proposed by Ballantyne & Kirkbride (1986). An upslope direction of accumulation is apparent, with the crest of the rampart acting as the zone for material deposition; debris is deposited in the area of the crest or on the proximal slope of the rampart. During seasonal snowbed melt, even if only partial, the crest material falls as scree down the proximal slope. Scattered fresh debris, decreasing in quantity towards its base, occurs over the distal slope and is probably derived from rockfalls. Upslope (retrogressive) growth of the rampart explains the rectilinear morphology of the distal section and the existence of a recently formed step on the proximal slope. The step on the proximal slope is probably due to variability in both the snowbed size, largely as a result of reduced snowfall in the latter half of the twentieth century (see Smith, 2002, Sumner *et al*., 2004b) and production of debris from the backwall.

The maximum distance of the rampart, from the rampart crest to the foot of the distal slope is approximately 65m. Weathering rind thicknesses on the lower (oldest) part of slope are in accord with the grey lava surface data for immediate post-glacial (Holocene) surfaces found elsewhere on the island (Sumner *et al.*, 2002). However, the absolute age of the rampart is not known and may, therefore, have been created and destroyed many times during the Holocene. It is also pertinent to highlight that the growth rate would probably have experienced some variation in response to fluctuations in the Holocene climate and debris supply; as indicated by other periglacial landforms on the island (Holness & Boelhouwers, 1998).

The observation of rockfall debris transport and accumulation at the foot of a non-permanent snowbed is extremely significant in the use of pronival ramparts as palaeoclimatic indicators. Shakesby (1997) highlights the hazards in using fossil pronival ramparts for palaeoclimatic reconstruction, because the contemporary climatic conditions necessary for rampart formation are not yet fully understood. In addition, the mode of development may not follow a specific model. It is noteworthy that on Marion Island recent warming has caused the disappearance of permanent snow on the island (Sumner *et al*., 2004b), further complicating observations and possibly slowing the rate of debris accretion. Grab (1996) highlights the apparently similarly rapid retreat of the snowline in the late twentieth century at the approximate altitude of a pronival rampart on Mount Kenya, which is used to infer fairly recent pronival rampart development. An upslope (retrogressive) mode of rampart growth could, however, provide an alternative mode of development rather than recent genesis. In Spain, Sancho *et al.* (2001) considered that the Hoya pronival rampart was completely inactive since the snowbed was too small to facilitate rampart growth, but this is only applicable to downslope rampart development. Lichenometric data presented by Sancho *et al.* (2001) for the constituent material of the proximal slope of rampart suggests a possible upslope manner of rampart growth initiated by the decreasing size of the snowbed as a plausible alternative.

Conclusion

Few actively-forming pronival ramparts have been described worldwide and none in detail from the sub-Antarctic. An actively-forming pronival rampart investigated on Marion Island at 900m a.s.l. consists of clastic material with occasional interstitial fines, is of a wholly pronival rampart origin and has grown by upslope rather than downslope accretion. Relative-age dating, in the form of percentage moss coverage and weathering-rind thickness, and the active accumulation on the rampart crest and proximal slope, where the snowbed has decreased in thickness, support the proposed upslope extension mode. A reduction in snowbed height on the proximal slope of the rampart is, therefore, seen as a key component of the proposed retrogressive mode of development. Since the most recent glaciation ended at approximately 13 000 B.P., debris accumulation has probably fluctuated throughout the Holocene in response to changing climate and debris supply. A step on part of the proximal slope is interpreted as a function of recent declining snowfalls on island.

The proposed mode of development contrasts with those suggested for pronival ramparts elsewhere, where accumulation and extension occur in a downslope direction. A lower underlying basal slope gradient combined with a seasonally fluctuating, possibly generally declining, snowbed volume are proposed as the controlling factors in rampart growth direction. Active formation of a pronival rampart at the foot of a non-permanent snowbed also highlights the importance for a clear understanding of the climatic thresholds governing rampart origin and development. This study illustrates the potential, highlighted by Boelhouwers & Hall (2002) that a hyper-maritime (sub-Antarctic) perspective may have in improving the understanding of the basic driving mechanisms and boundary conditions in permafrost and periglacial processes. Observation of a seemingly similar manner of debris accumulation of a pronival rampart on Mount Kenya (Grab, 1996) and reinterpretation of lichenometric data for a pronival rampart in the hollow of the Gredos Cirque in Spain (Sancho *et al*. 2001), of which both are associated with disappearing snowlines in their vicinity, suggest that these landforms may provide other examples of a landscape process-response to climate change, manifested in an upslope (retrogressive) mode of rampart development.

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Outward rampart genesis (extension)

Some observations on the formation of an active pronival rampart at Grunehogna Peaks, Western Dronning Maud Land, Antarctica

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Footnote

Jay Le Roux and Michael Loubser assisted with debris transport fieldwork and supplied photographs, Jacqueline Davis assisted with mapping of the pronival rampart and Ian Meiklejohn provided funding for the research through a National Research Foundation (NRF) - South African National Antarctic Programme (SANAP) grant.

The article appears as it did in print but it has been formatted to conform to the guidelines of the thesis. The references of the article are included in the reference list at the end of the thesis

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Abstract

Summer observations of the morphology and the debris accumulation processes at an actively-forming pronival rampart at Grunehogna Peaks, Western Dronning Maud Land, Antarctica, demonstrate that rockfall debris accumulation is causing downslope (outward) rampart extension even though the distal slope is not at the angle of repose. Field experiments show that the vast majority of rocks can traverse a stable firn surface to reach the proximal slope of the rampart and more than half end up on the distal slope or beyond. The formation processes indicate that the morphological characteristics and environmental conditions under which such features develop may be more varied than conceived in current models. Consequently, caution must be employed when fossil ramparts are used to infer palaeo-environmental conditions.

Introduction

A pronival rampart is a ridge or ramp of debris formed at the downslope margin of a snowbed or firn field (Shakesby, 1997). These features are also commonly known as protalus ramparts (*e.g.* Strelin & Sone, 1998; Anderson *et al*., 2001; Whalley, 2009) but Shakesby (1997) has advocated the replacement of 'protalus' with 'pronival' (snow-front) since the latter provides a universally appropriate term that describes firn-foot debris accumulations, regardless of their position on the slope. Curry *et al*. (2001) indicate that various rampart origins exist (*i.e*. glacial, rampart, rockslide and protalus rock glacier) and rampart origin and formation, therefore, should be investigated using multiple working hypotheses (Harris *et al*., 2004). Other studies (*e.g*. Harris, 1986; Ono & Watanabe, 1986; Ballantyne, 1987; Shakesby *et al*., 1995; Shakesby *et al*., 1999) have shown that a range of supranival and subnival mechanisms of debris transport may contribute to rampart development. Ramparts formed by supranival debris transport mechanisms accumulate partly through debris cascading down and piling up on the distal slope, and partly by entrapment of moving debris against the proximal slope (Ballantyne, 1987; Pérez, 1988). However, relatively little research has been conducted on the genesis of actively-accumulating pronival ramparts (Shakesby, 1997; Anderson *et al*., 2001) in part because ramparts are typically seen as "simple, easily understood features" (Thorn, 1988: 16).

Two models have been proposed for rampart development through supranival debris transport and deposition. The model of Ballantyne & Kirkbride (1986) proposes downslope rampart extension at the foot of thickening snowbeds, and contrasts with the previous interpretation of Sissons (1979) that the snowbed (firn field) maintained fairly stable dimensions during the period of rampart formation. In this model, rampart crests migrate outwards away from the talus as the ramparts accumulate at the foot of thickening snowbeds (Ballantyne & Harris, 1994). A suggested morphological characteristic of ramparts which extend downslope is that the distal slope is formed at repose (34-38°) by the accumulation of cohesionless cascading debris (Ballantyne & Kirkbride, 1986; Gordon & Ballantyne, 2006). However, not all ramparts exhibit this characteristic (*e.g*. Wilson, 1990), and Hedding *et al*. (2007) proposed a retrogressive (upslope) model of rampart development under fluctuating, and possibly declining, snowbed volumes based on observations on Marion Island. A rampart described by Strelin & Sone (1998) also experiences variable snowbed volumes and though the distal slope is at repose, so is the proximal slope, which may be an indication of retrogressive development.

A small number of pronival ramparts have been documented for the sub-Antarctic region (*e.g*. Valcárcel-Diaz *et al*., 2006; Hedding *et al*., 2007 and Boelhouwers *et al*., 2008) and James Ross Island off the Antarctic Peninsula (*e.g*. Strelin & Sone, 1998) but as far as we know, none have hitherto been described in detail for the Antarctic continent. This paper provides the first detailed investigation of the formation of an actively-forming pronival rampart found at Grunehogna Peaks, Western Dronning Maud Land, Antarctica. The objective is to compare this feature's formation to existing models of supranival rampart development using observations on (1) rampart morphology, (2) the associated firn field size from the austral summers of 2006/7 and 2008/9 and (3) debris accumulation locations through field experiments. In addition, the use of fossil ramparts in palaeo-environmental reconstruction is discussed.

Environmental setting and study site

The actively-forming pronival rampart (72°03'13"S; 2°42'47"W) is located at approximately 1090m above sea level on the north-eastern periphery of the Grunehogna Peaks, a group of nunataks some 200km inland of the Southern Ocean (ice-shelf front), at the southern end of the Ahlmannryggen (range), Western Dronning Maud Land, Antarctica (Fig. 2.4.1). Geologically, these nunataks are mostly composed of Borgmassivet intrusives, which are of Precambrian age and have undergone metamorphosis. Most nunataks in this region of Antarctica exhibit wind-scoured hollows on their leeward sides where debris can accumulate and geomorphological processes can operate without being destroyed by glacial erosion. The firn-foot debris accumulation is situated within such a wind-scoured hollow and can be found below a precipitous (approximately 120m high) backwall at the foot of a perennial firn field where there is a marked reduction in gradient (Fig. 2.4.2). The backwall appears to be aligned along a geological lineament (dyke) which may have facilitated debris production. The rampart incorporates some intermittent interstitial fines but comprises predominantly openwork clastic material (long axis <0.5m). The rampart faces north-west and exhibits a sinuous 'crest' (Fig. 2.4.3). The firn field is concave in cross-profile and from visual observations during field visits from the austral summers of 2006/7 and 2008/9, its size appears to be stable at present. No detailed meteorological data exists for Grunehogna Peaks, but data between 2000 and 2006 for the South African Base (SANAE IV) atop the Vesleskarvet nunatak (71°40'22"S; 2°50'25"W), approximately 50km farther north, at 845m above sea level give a mean annual air temperature of -17°C.

Morphological measurements

The "diagnostic criteria" suggested by Shakesby (1997) and tabulated by Hedding *et al*. (2007) are adapted here to identify the landform under investigation as a pronival rampart (Table 2.4.1). A transverse profile along the rampart firn field boundary and four longitudinal transects were surveyed to determine the downslope width, cross-slope length and the general surface morphology of the rampart and firn field (Fig. 2.4.3). The distances from rampart and firn field boundaries to the foot of the cliff and angle of snow slope were also measured.

Measurements of the morphology of the pronival rampart are summarised in Table 2.4.2. The four longitudinal transects and spot angles were then used to determine the cross-profile form of the firn field (Fig. 2.4.3). The average firn field angle is 34° and the mean distance from rampart crest to foot of the backwall is 24m, indicating very limited space for snow accumulation. All spot angles on the firn field are larger than the minimum value of 20° required for debris movement over firn (Ballantyne & Benn, 1994). The cross-slope length of the rampart is 85m and its downslope width averages 23m from the rampart-firn field boundary to the foot of the distal slope. The average slope angles of the proximal and distal slopes are 14° and 20° respectively (Table 2.4.2).

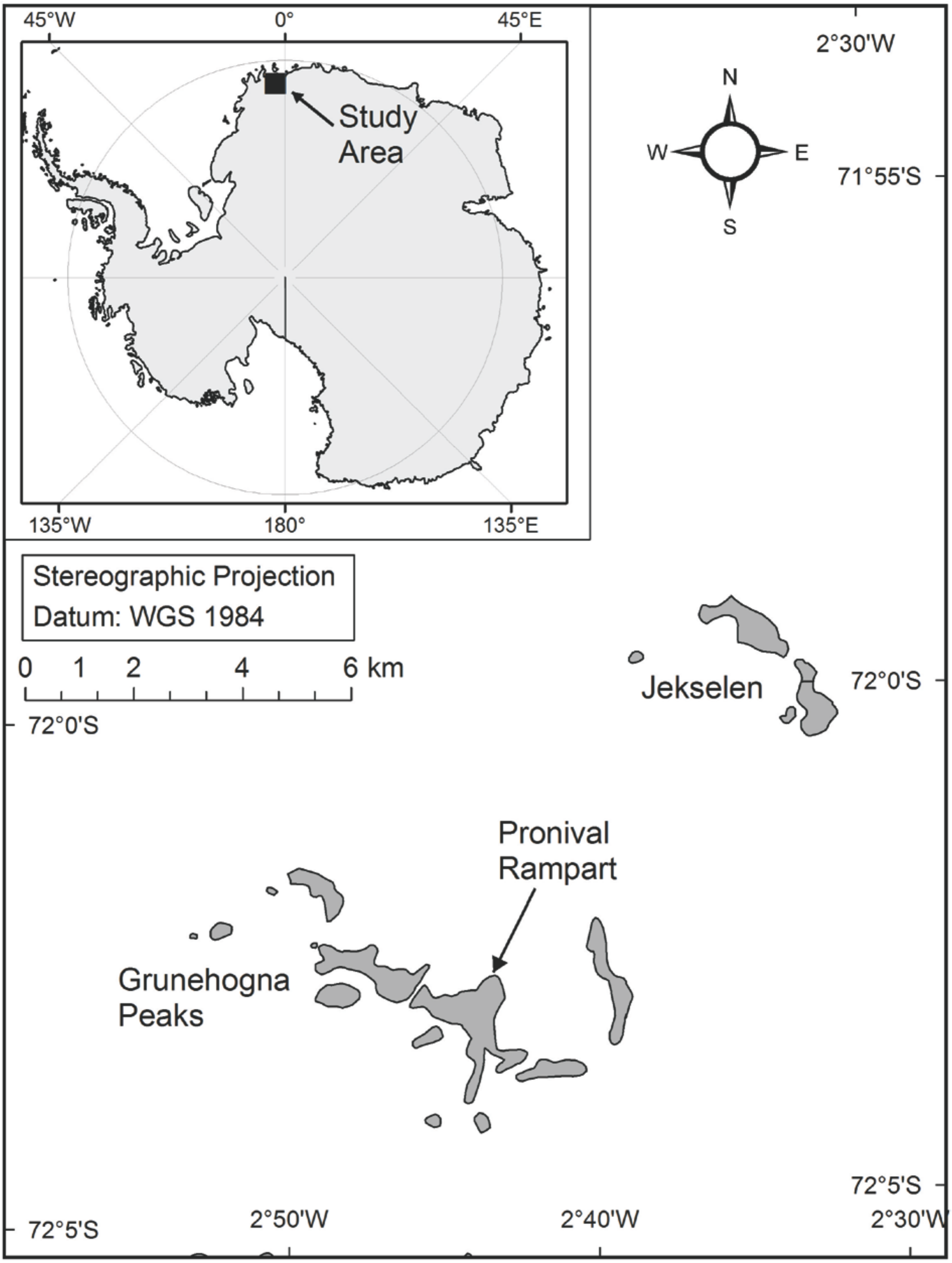

Figure 2.4.1: Location of the Grunehogna Peaks nunataks in Western Dronning Maud Land, Antarctica, and location of the pronival rampart at Grunehogna Peaks.

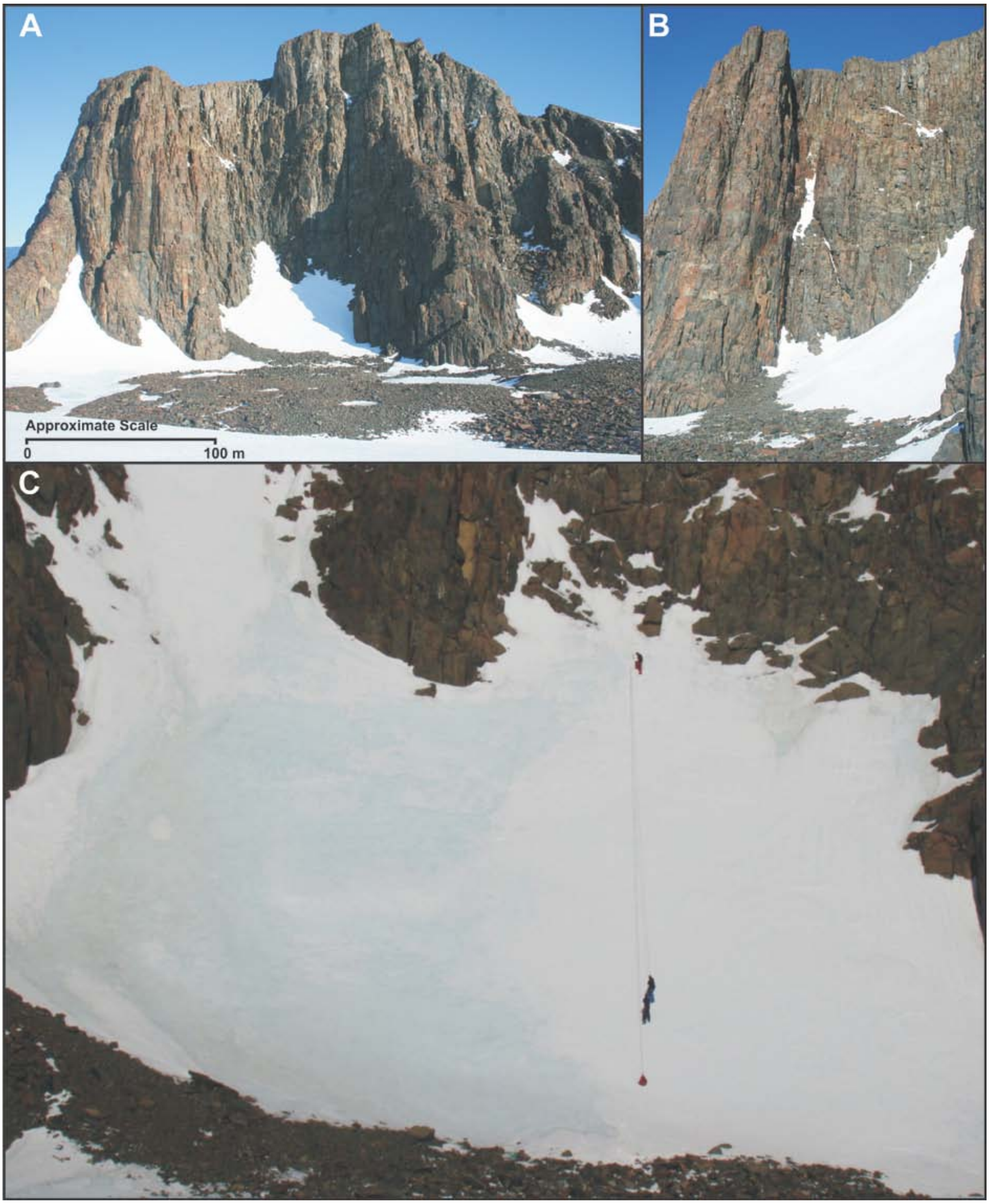

Figure 2.4.2: Photo A: View of the pronival rampart, firn field and cliff-face from the north of the feature. The backwall is approximately 120m high. Photo B: View of the pronival rampart, firn field and backwall from west of the feature. Photo C: Releasing clasts from approximately 5m below the top of the firn field (Photo: J.J. Le Roux). In places, the firn (ice) was hard enough to use crampons. Note the people for scale.

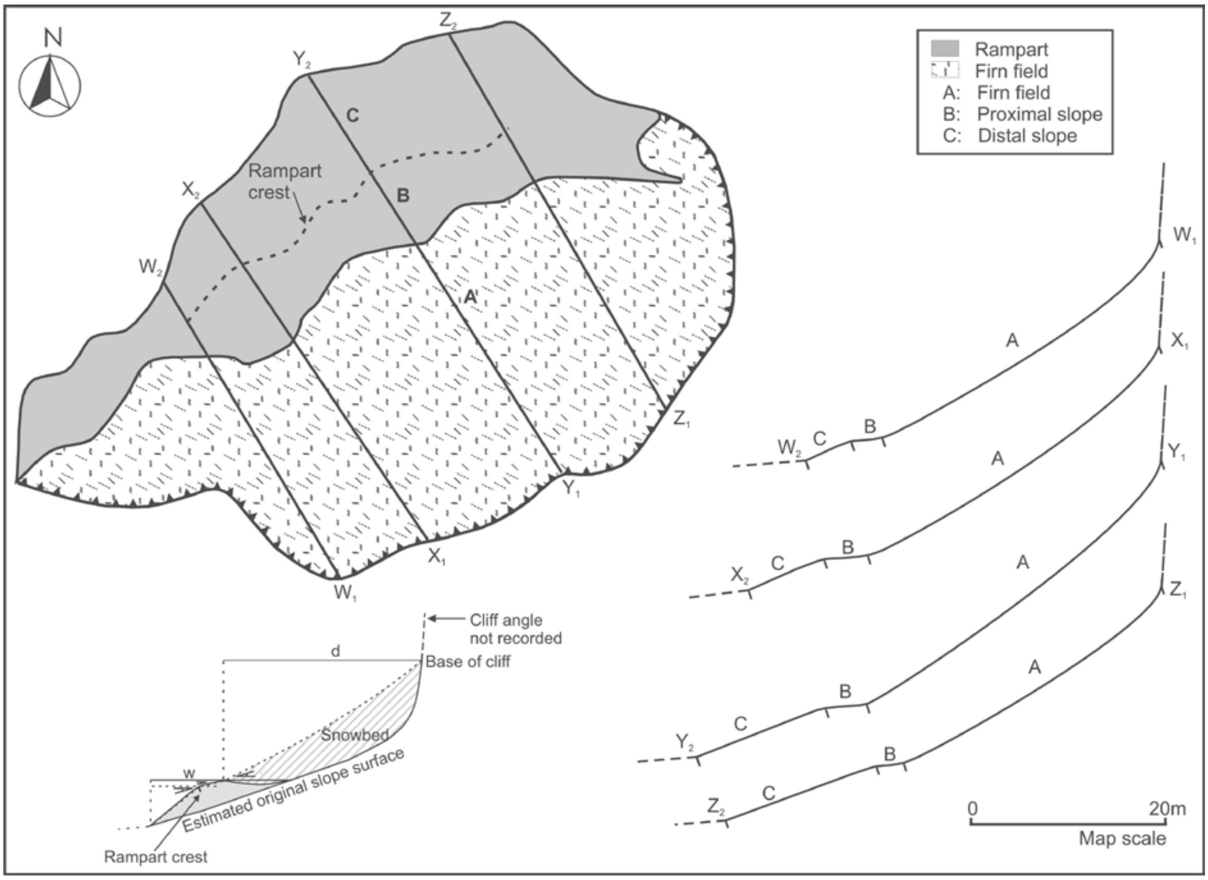

Figure 2.4.3: Plan view and surveyed transects of the pronival rampart.

Debris transport and deposition

Mechanisms of debris transport and locality of accumulation were investigated by releasing fifty clasts from approximately 5m below the upper limit of the firn field, which represents the lowest possible height from which debris could break away from the backwall naturally (Fig. 2.4.2). Clasts were randomly collected from the rampart itself but with a limiting mass of 25kg. Clasts were typically angular and, although released with far less potential energy than rockfall debris supplied by the backwall above, only two (4%) of the clasts did not have enough momentum to reach the foot of the firn field.

Table 2.4.1: Diagnostic criteria for distinguishing a pronival (protalus) rampart from other talus landforms (Adapted from Hedding *et al.*, 2007).

Criteria		Additional Comments
Glacial Moraine		
• Talus-foot location	✓	
• Glacial erosional forms	x	
• Striated clasts	x	
• Linear plan form	x	Sinuous
• Clasts dip away from backwall	x	
• Ridge crest to cliff-foot distance >*c*.30-70m	x	
Landslide		
• Talus-foot location	✓	
• Hillslope scar	x	
• Debris aprons beyond the feature	✓	Partial
• Large masses of displaced hillside within or above the area of debris accumulation	x	
Protalus Rock Glacier		
• Talus-foot location	✓	
• Greater in length (down-slope) than in width (across-slope)	x	
• Convex distal slope	x	Rectilinear
• Meandering and closed depressions, downslope ridges and furrows, and transverse ridges and depressions	x	
Pronival (Protalus) Rampart		
• Large ridge to backwall summit inclination	✓	
• Small ridge to backwall distance	✓	
• Ridge crest to cliff-foot distance <*c*.30-70m	✓	
• Restricted potential snow accumulation depth	✓	
• Length <300m	✓	
• Openwork fabric with/without infilling fines	✓	
• Single ridge	✓	
• Ridge size increase with distance from cliff foot	✓	
• Backwall and ridge same lithology	✓	

Table 2.4.2: Dimensions and morphology of the Grunehogna rampart.

Length (m)	Width (m)	Height (m)	Snow slope (°)			Proximal slope (°)			Distal slope (°)		
			Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
85	23	24	25	34	54	13	14	19	17	20	24

Clasts travelled down the firn field by rolling, bouncing and gliding, as previously observed by Pérez (1988), thus confirming supranival debris transport as the mechanism for the delivery of material for rampart formation. No evidence of debris from wet snow avalanches or supranival debris flows was observed. Even the clasts that came to rest on the firn field could later melt into the snow and ice through black-body radiation (cf. Ono & Watanabe, 1986) and melt their way downslope, contributing debris to the rampart. Nineteen (38%) and fifteen (30%) of the clasts came to rest on the proximal and distal slopes, respectively. A further fourteen clasts (28%) overshot the rampart, making it difficult to identify a clear downslope margin. In summary, 58% of the clasts released down the firn field surmounted the rampart 'crest' (between the proximal and distal slopes). Both average weight and roundness of the released clasts increased with distance from the backwall (Table 2.4.3).

Table 2.4.3: Summary of locality of debris deposition.

Position of Deposition	No. of Clasts (sample size = 50)	Average Weight of Clasts (kg) (Std Dev.)	Sphericity (Std Dev.)
Firn field	2 (4%)	6.5 (0.7)	0.57 (0.03)
Proximal slope	19 (38%)	6.5 (4.4)	0.64 (0.11)
Distal slope	15 (30%)	8.9 (6.7)	0.64 (0.10)
Below the rampart	14 (28%)	9.9 (6.7)	0.69 (0.11)

Discussion

According to the 'diagnostic criteria' for pronival ramparts adapted from Hedding *et al*. (2007), the lack of striated clasts and glacial erosional forms coupled with the feature's location in a wind-scoured hollow away from the influence of glacial processes preclude a glacial origin. Although the feature exhibits a partial debris apron below it, the lack of a hillslope scar and large masses of displaced hillside within or above the area of debris accumulation argue against a landslide origin. The lack of a convex distal slope, meandering and closed depressions, downslope ridges and furrows, and transverse ridges and depressions as well as a greater across-slope distance than down-slope distance suggest that the feature is not a protalus rock glacier. A pronival rampart origin is deemed valid given that the landform is composed of the same rock type (*i.e.* Borgmassivet intrusives) as the backwall, has a rampart crest to backwall distance of less than *c*.30-70m, and is being affected by supranvial debris transport. The feature appears relatively small in relation to the debris source area which may indicate that the feature and firn field are relatively young or that debris production from the backwall is particularly slow.

Assessment of where debris deposition occurs indicates that the rampart is extending downslope through supranival debris transport, following the model proposed by Ballantyne & Kirkbride (1986). However, unlike this model, the distal slope is not at repose. In addition, the short-term observations of the apparently stable size of the firn field raises questions regarding the necessity for the continuous growth of a snowbed or firn field for the downslope extension of ramparts (*cf*. Ballantyne & Kirkbride 1986). Thus the rampart morphology and the environmental conditions under which ramparts extend downslope may be more varied than previously recognised, particularly when the underlying slope angle, rampart age or stage of development and the different mechanisms of supranival (and subnival) debris transport are taken into account. Another implication is that caution should be employed when using the morphology of fossil pronival ramparts in palaeo-environmental reconstructions, particularly in light of the possibility of ‘form-convergence’ for discrete debris accumulations (Whalley, 2009). Lastly, depending on which of the existing models of rampart development fit the morphology of the feature, very different palaeo-environmental conditions can be inferred.

The suggested threshold values for the self-limiting model of Ballantyne & Benn (1994), applicable to the rampart under investigation, indicate that for a snow slope angle of 35° and assuming an average firn field density of 800 kg/m^3, the transition from stationary firn into a dynamic, small incipient glacier will take place between 25-40m. It is pertinent to highlight that the model of Ballantyne & Benn (1994) used an estimated average density of perennial firn fields in non-polar environments and average shear stress of 70-100kPa at the base of the glacier when the base of glaciers in polar regions typically exhibit an average shear stress of 150kPa. Therefore, the transition distance from stationary cold-based firn into a moving body of ice would be even greater in polar environments. The average snow slope angle is 34° and the horizontal distance from the rampart crest to backwall is 24m, which indicates that, at present, the cold-based firn field is stationary. Thus the rampart is currently extending downslope without being destroyed or modified by moving glacier ice. It is unknown if the rampart is being affected by permafrost creep (Fukui, 2003) or creep of firn (Shakesby *et al.*, 1999) but this appears unlikely given the very cold climate of the site which means that the firn must be cold-based and permafrost is very cold.

Ramparts extending downslope on a shallow underlying slope angle under stable snowbed or firn field conditions will only continue to do so as long as the majority of clasts have enough kinetic energy to surmount the rampart crest. Should the firn field grow through increased snow accumulation, as a result of climate change in the region, the stationary firn field may transform into a small incipient glacier which could consequently destroy or modify the rampart (Ballantyne & Benn, 1994). This would support the contention that pronival ramparts can be viewed as a stage in the formation of either rock glaciers or moraines (Shakesby, 1997). Strelin & Sone (1998) suggest that protalus lobes and pronival ramparts are genetically related and Harrison *et al*. (2008) suggest that a continuum of form and size exists between moraines, protalus ramparts and rock glaciers. However, the ramparts described by Strelin & Sone (1998) and Hedding *et al*. (2007) illustrate that ramparts do not necessarily require the growth of steeply inclined firn fields. Therefore, it appears that pronival ramparts, protalus rock glaciers and moraines could also be viewed as separate, independently produced forms of modified talus occurring in a non-developmental morphological continuum.

Future studies should focus on active features and, where possible, incorporate additional data such as relative-age dating to infer rampart formation (*e.g*. Hedding *et al*., 2007). Furthermore, since so few active features have been described, a comparison of documented ramparts could generate interesting insights into rampart development. These could be used when investigating previously undocumented features such as a 'rampart-like ridge' on sub-Antarctic Macquarie Island (Selkirk *et al*., 2008). Re-investigation of previously documented 'pronival ramparts' (*e.g*. Gordon & Ballantyne, 2006) could also provide some useful insights; particularly for palaeo-environmental reconstructions. Finally, geomorphological studies, particularly in the Southern Circumpolar Region, should focus more attention on ice-free areas (*e.g*. wind-scoured hollows around nunataks) since these areas may represent preferential locations for rampart development.

Conclusion

The pronival rampart on the north-eastern periphery of the Grunehogna Peaks, Western Dronning Maud Land represents the first active pronival rampart to be documented in detail for the Antarctic continent. Data on rampart morphology and debris accumulation, in terms of locality of deposition, indicate downslope rampart extension even though this rampart does not possess a distal slope at repose. Observations from the austral summers of 2006/7 and 2008/9 suggest that the firn field size is stable and stationary at present. Collectively, the findings indicate that the morphological characteristics of ramparts and the environmental conditions under which their downslope extension occurs may be more varied than previously proposed (Ballantyne & Kirkbride, 1986). Consequently, the use of morphology of fossil features alone to infer rampart formation appears questionable, since landforms that are similar morphologically might be produced by different processes.

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Summary

Hedding *et al*. (2007) propose a retrogressive (upslope) model of rampart development under fluctuating, and possibly declining, snowbed volumes based on observations on Marion Island (Fig. 2.3.1). Retrogressive rampart development is based on the cumulative evidence from relative-age dating of constituent material, assessment of ridge morphology and location of the rampart in relation to its surrounding topography. The moss cover and weathering rind data presented by Hedding *et al*. (2007) indicate that material is ‘younger’ on the upper, and ‘older’ on the lower part of the rampart which can be explained by a seasonally fluctuating, and possibly declining, snowbed. As the snowbed fluctuates and generally recedes (diminishes) it would expose the constituent material of the rampart on which moss can grow and weathering rinds can develop. Also, as the snowbed fluctuates and generally recedes (diminishes) and due to the steep proximal slope of the rampart, material would be exhibit less moss cover and smaller weathering rinds than that of material on the lower reaches of the rampart. The retrogressive model opens rampart genesis to a far wider range of environmental conditions. Hedding *et al*. (2010) then question the assertion that in order for ramparts to extend outward (downslope) their distal slopes must be at repose. These studies also support 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". Thus, the studies of Hedding *et al*. (2007) and Hedding *et al*. (2010) illustrate that ramparts do not necessarily extend downslope and, therefore, should not be regarded as part of a linear developmental continuum in the formation of rock glaciers or moraines. Finally, Hedding *et al*. (2007) and Hedding *et al*. (2010) highlight that the site, morphological and sedimentological characteristics of ramparts differ from what has previously been suggested which has implications for the establishment of diagnostic criteria. The following chapter will assess the site, morphological and sedimentological characteristics of ramparts and interrogate their usefulness as diagnostic criteria.

Chapter 3: Site, morphological and sedimentological characteristics of pronival ramparts: implications for diagnostic criteria

Introduction

Pronival ramparts are difficult to identify because the morphological characteristics of these landforms and their position on a slope resemble the characteristics of glacial moraines, rock-slope failures and various other talus-derived landforms. Positive identification of pronival ramparts is further complicated by a poor understanding of their genesis coupled with the use of inappropriate diagnostic criteria. Initially, much of the research on pronival ramparts focussed on supposed exemplar fossil (relict) landforms which presented different views on their genesis and characteristic attributes. This led Shakesby (1997: 394) to state 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 & Watanabe, 1986; Ballantyne, 1987; Pérez, 1988; Shakesby *et al*., 1995; Hall & Meiklejohn, 1997; Strelin & Sone, 1998; Shakesby *et al*., 1999; Fukui, 2003; Hedding *et al*., 2007; Hedding *et al*., 2010; Margold *et al*., 2011; Matthews *et al*., 2011), is now providing the opportunity to develop a more robust set of diagnostic criteria with which pronival ramparts can be distinguished from other discrete bedrock cliff-foot debris accumulations.

Hedding *et al*. (2007) and later Hedding *et al*. (2010) analysed the diagnostic criteria summarised by Shakesby (1997) as well as the criteria presented by several other authors (*e.g.* Lewis, 1966; Unwin, 1975; Curry *et al*., 2001), to construct a set of diagnostic criteria with which to distinguish ramparts from other bedrock cliff-foot debris accumulations. Although the criteria proposed by Hedding *et al*. (2007) and Hedding *et al*. (2010) are presented in Chapter 2, they are not discussed in any detail and are instead addressed in this chapter. The diagnostic criteria presented by Hedding *et al*. (2010) have, recently, been employed to identify a relict (fossil) pronival rampart in New Zealand (Brook & Williams, 2013). However, research on pronival ramparts since 2010 (*e.g.* Hedding, 2011 in Appendix 1) has led the author to realise that some of the diagnostic criteria can be revised (Hedding & Sumner, 2013) to further facilitate the identification of ramparts.

Ballantyne & Kirkbride (1986) analysed the morphometric regularity of relict pronival ramparts in Great Britain to develop the outward (downslope) extension model of rampart genesis and suggest characteristics and relationships by which ramparts can be identified. Some authors (*e.g.* Lewis, 1994) used these characteristics and relationships to assist with the identification of pronival ramparts. Therefore, it is also necessary to examine the relationships of morphometric regularity as a method to assist in the identification of pronival ramparts. This chapter will thus assess the morphometric regularity and then re-evaluate existing diagnostic criteria based on actively-accumulating landforms (*e.g.* Hedding *et al*., 2007; Hedding *et al*., 2010).

Morphometric regularity

Ballantyne & Kirkbride (1986) analysed relationships from morphometric regularity of nine relict pronival ramparts in Great Britain which were believed to represent unequivocal examples of this type of landform. Ballantyne & Kirkbride (1986) identified strong linear correlations between rampart thickness and rampart width, rampart thickness and crest to talus foot distance, and rampart width and crest to talus foot distance. However, Ballantyne & Harris (1994) indicate that two of the landforms used by Ballantyne & Kirkbride (1986) have, subsequently, been reinterpreted as having alternative origins. Lewis (1994) used the morphometric relationships to assist in the identification of a rampart-like feature in South Africa. Shakesby (1997) highlights that Lewis's (1994) comparison of the relationships based on morphometric regularity demonstrate more differences than similarities. More importantly, however, is that Shakesby (1997) notes that the use of relict ramparts to assess relationships based on morphometric regularity is inappropriate because of the questionable identification of some relict ramparts. In addition, not all ramparts extend (grow) downslope (*i.e.* Hedding *et al*., 2007) and post-depositional modification of relict features is often not taken into consideration. Thus, morphometric regularity should ideally be assessed based on information on actively-accumulating ramparts.

Since the late 1990s research has shifted to actively-accumulating landforms. This has led to progress in terms of improving our understanding of rampart genesis and the site and morphological characteristics and the opportunity to reassess the morphometric parameters and assist in the identification of pronival ramparts is now apparent. Ballantyne & Kirkbride (1986) state that, if a snowbed maintained fairly stable dimensions during the period of formation (*e.g.* Sissons, 1979; Ballantyne, 1987; Hedding *et al*., 2010), rampart size would be conditioned only by the height of the rockwall source area, rockfall rate and the period of snowbed survival, irrespective of extent and thickness of the snowbed. This alludes to the importance of topographic control in rampart genesis which includes a backwall of exposed bedrock being large (high) enough to produce sufficient debris for transport and subsequent accumulation, a steep underlying slope on which the snowbed rests to facilitate debris transport and, lastly, the rampart being close enough to the backwall to prevent the static snowbed from transforming into dynamic ice. The steeper the slope angle, the shorter the distance the rampart crest can be from the backwall (source of debris) before the firn (ice) becomes dynamic and starts to move downslope under the influence of gravity. According to Ballantyne & Benn (1994), the maximum distance of the rampart crest from the source of debris (backwall) is *c*. 30 to 70m at a slope gradient of 35° and 25°, respectively. It is pertinent to highlight that the model of Ballantyne & Benn (1994) used an estimated average density of perennial firn fields in non-polar environments and average shear stress of 70–100kPa at the base of the glacier whereas the base of glaciers in polar regions typically exhibit an average shear stress of 150kPa. 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).

Although there are problems with the morphometric regularity of pronival ramparts, suggested by Ballantyne & Kirkbride (1986), generating some field parameters may help address the identification of some ramparts. It would also provide a starting point in the field before application of the diagnostic criteria developed by Hedding & Sumner (2013). One way to approach the development of basic field parameters for distinguishing landforms as pronival ramparts would be to assess rampart ridge height in relation to backwall height (zone of debris production), the distance of the rampart crest from the backwall and the average slope angle. Rampart genesis is a function of debris production from the backwall and transport across a snowbed. Therefore, rampart height will, in part, be linked to debris production, the underlying slope length and slope angle between the rampart and backwall. Although debris production and transport will vary across the width of the backwall and snowbed and notwithstanding the difficulty of determining the height of an actively-accumulating rampart, average rampart height will be best associated with the average backwall height; a function of debris production. It is expected that the average backwall height will far exceed maximum rampart height as is traditionally envisaged for pronival ramparts (Shakesby, 1997). From the information provided by Hedding *et al*. (2007) and

Hedding *et al*. (2010), the ratio of backwall height to average rampart height is 52/7 (7.5) and 120/2 (60), respectively. This is in keeping with notion that ramparts are overlooked by steep exposed bedrock cliffs. Unfortunately, not many studies on pronival ramparts have documented backwall height in relation to rampart height but it is proposed that the ratio of backwall height to rampart height should exceed 4-5. This value takes cognisance of the fact that incidences of rockfall will also play a role in rampart genesis.

Ballantyne & Benn (1994) indicate that the slope angle of a snowbed must be more than 20° to facilitate debris transport across the snowbed. This threshold value can, therefore, be regarded as the absolute minimum slope angle for the snowbed and by association underlying slope. Ballantyne & Benn (1994) also indicate that the slope length between the talus foot and rampart may not exceed *c*.30-70m depending on slope angle. Thus the maximum distance of a rampart from the source of debris may probably not exceed 70m. The threshold values above provide simple field parameters to assist with identifying landforms as pronival ramparts. If a landform is not excluded by the field parameters provided above then a more detailed assessment of the feature in the context of its surroundings and palaeo-environment (history) can be conducted to assess the origin of the landform. It is imperative that appropriate site, morphological and sedimentological characteristics are assessed in combination and to use multiple-working hypotheses when identifying the origin of a landform; namely a discrete debris accumulation on a slope. Various combinations of diagnostic criteria for pronival ramparts have previously been suggested (*e.g*. Unwin, 1975; Ballantyne & Kirkbride, 1986; Shakesby, 1997; Hedding *et al*., 2007; Hedding *et al*., 2010) but some of the suggested criteria are based on supposed relict ramparts which have been reinterpreted as having alternative origins (*e.g*. Ballantyne & Kirkbride, 1986; Ballantyne & Harris, 1994). Thus some diagnostic criteria are now thought to be inappropriate. Other potential diagnostic criteria, such as the widely-used RA-C_{40} co-variance approach (see Lukas *et al*., 2013), should also be reviewed for their use as a diagnostic criterion used in the identification of pronival ramparts. The article presented below by Hedding & Sumner (2013) discusses these aspects in detail and presents a new set of diagnostic criteria.

Site, morphological and sedimentological characteristics as diagnostic criteria

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

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Footnote

Paul Sumner assisted with conceptualisation and editing of the paper.

The article appears as it did in print but it has been formatted to conform to the formatting guidelines of the thesis. The references of the article are included in the reference list at the end of the thesis.

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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.

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 ramparts and their observed processes (Shakesby, 1997). Many relict pronival ramparts have been identified incorrectly (see Ballantyne & Harris 1994; Gordon & Ballantyne 2006; Ballantyne & Stone, 2009). Ballantyne & Kirkbride (1986) proposed diagnostic criteria based on the morphometric regularity of nine relict ramparts in Great Britain but Ballantyne & 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 & Kirkbride (1986) should be re-evaluated.

Due to inappropriate diagnostic criteria coupled with a generally poor understanding of their genesis (Hedding, 2011), identification of pronival ramparts remains problematic (Scotti *et al.*, 2013). The debate surrounding relict pronival ramparts in southern Africa (*e.g.*

Shakesby, 1997; Grab, 2000a; Sumner & de Villiers 2002; Lewis, 2008a; 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 & Watanabe, 1986; Ballantyne, 1987a; Pérez, 1988; Shakesby *et al*., 1995; Hall & Meiklejohn 1997; Strelin & 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.

In plan-form, actively-accumulating ramparts vary from single linear and curved features to complex and sinuous or festoon-shaped features comprising multiple ridges (Table 3.1). Lengths range from 40m (Margold *et al*., 2011) to 460m (Shakesby *et al*., 1995) and features can attain a thickness of 10m (Hall & 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

Table 3.1: 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 & 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 & 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 & 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.

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 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 & Marks, 1985; Oxford, 1985; Harris, 1986; Tinkler & 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 & Matthews, 1993; Brook, 2009); although 'frost' weathering processes do not necessarily produce angular-shaped 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 & Watanabe, 1986). 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 50 cm 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) 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 & Meiklejohn (1997) observed few fines in the inner (active) ridge of pronival ramparts in the Canadian Rockies and Ballantyne & Kirkbride (1986) indicate that even at depth fines form no more than a partial infill. In contrast, Hall and Meiklejohn (1997) describe the relict outer ridges of ramparts to comprise of both large blocks and fine material. Ballantyne & 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 & 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 & 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 & Watanabe, 1986; Ballantyne, 1987; Pérez, 1988; Shakesby *et al.*, 1995; Hall & Meiklejohn, 1997; Strelin & 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 & 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 3.2).

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 & Sone, 1998). The diagnostic criterion 'Large ridge to backwall inclination' introduced by Lewis (1966), and used recently by Brook & 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 & 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 & 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 and 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 & 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).

Table 3.2: Proposed diagnostic criteria for the differentiation of pronival ramparts from moraines, protalus rock glaciers and rock-slope failure deposits.

Criteria	**Reference**
Pronival (Protalus) Rampart	
Ridge crest to cliff-foot distance <*c*.30-70m	Ballantyne & Benn (1994)
Insufficient cross-section depth for snow to glacier ice transformation	Watson (1966); Shakesby & Matthews (1993); Ballantyne & Benn (1994); Bower (1998)
Underlying slope gradient that will facilitate snow/firn bed angle >20°	Ballantyne & 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 & Matthews (1993); Curry *et al*. (2001)
Glacial Moraine	
Glacial erosional forms	Benn & Evans (2007)
Striated clasts	Shakesby & Matthews (1993); Curry *et al*. (2001)
Broadly arcuate in plan-form but in detail are often irregular and winding	Benn & Evans (2007)
Ridge crest to talus-foot distance >*c*.30-70m	Ballantyne & 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: 0.01km^2 in areal extent (source and deposit); 0.1Mm^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)

Mills (2006) indicates that clasts of pronival ramparts have a slabby particle shape (Ballantyne & 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 ascertion 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 & Matthews, 1993; Shakesby, 1997). Benn & 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 & 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, 2000a; Sumner & de Villiers, 2002; Lewis, 2008b; 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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Summary

Chapter 3 first reviews the use of morphometric regularity as a means to assist with the identification of pronival ramparts. The morphometric regularity identified by Ballantyne & Kirkbride (1986) among nine supposed relict pronival ramparts across Great Britain is questioned. However, the benefits of investigating morphometric relationships and site (topographic) and morphological characteristics of actively-accumulating features against suggested thresholds values (*i.e*. Ballantyne & Benn, 1994) is highlighted. Focus is placed on the site and morphological characteristics of actively-accumulating features that are significant in terms of rampart genesis. These include backwall height in relation to rampart height, slope length and slope angle and provide simple field parameters to distinguish landforms as pronival ramparts that fall within these parameters. In particular, a call is made for studies to include an assessment of the height of the exposed backwall (cliff) in relation to the maximum height of the rampart.

Chapter 3 then presents a set of diagnostic criteria proposed by Hedding & Sumner (2013) with which pronival ramparts can be distinguished from other discrete bedrock cliff-foot debris accumulations. It adopts a multiple-working hypothesis when investigating the origins of landforms (Shakesby, 1997; Curry *et al*., 2001; Harris *et al*., 2004) and incorporates criteria which are not limited to ridge morphology but rather focus on characteristics of ridge morphology, sedimentology and topographic setting or location of actively-accumulating landforms. Shakesby (1997: 407) indicates that the absence of fines “cannot be used to distinguish ramparts from moraines” since Shakesby *et al*. (1995) found that matrix supported clasts can occur in active ramparts. Also fines are required to enable debris flows and solifluction to deliver material to ramparts but fines will only constitute a very small percentage of the volume of the constituent material of ramparts. When the ‘absence of fines’ is coupled with ‘openwork fabric’ in the diagnostic criteria proposed by Hedding & Sumner (2013) it recognises that (interstitial) fines can be included in ramparts (*e.g*. Hedding *et al*., 2007) but that fines will not represent a significant fraction of the constituent material of ramparts, as is the case with moraines (Brook, 2009). Thus, ‘limited fines’ coupled with

'openwork fabric' may represent a better diagnostic criterion for the identification of pronival ramparts.

The diagnostic criteria presented by Hedding & Sumner (2013) are applied, in the following chapter, to supposed relict (fossil) pronival ramparts in southern Africa (Nicol, 1973, 1976; Marker, 1986, 1990; Lewis, 1994; Lewis & Illgner, 2001; Mills, 2006; Grab & Mills, 2011). Much debate surrounds the identification of relict pronival ramparts in southern Africa and their use in palaeo-environmental reconstructions (Shakesby, 1997; Grab, 2000a; Sumner & de Villiers, 2002; Lewis, 2008a; Hedding & Nel, 2010; Grab *et al.*, 2012; Hall, 2012). Thus, application of the diagnostics presented may assist in resolving their origin.

Section B

Chapter 4: Relict pronival ramparts in southern Africa re-examined

Introduction

Several relict (fossil) ramparts have been reported in southern Africa (Nicol, 1973, 1976; Marker, 1986, 1990; Lewis, 1994, 2008a, 2008b; Lewis & Illgner, 2001; Mills, 2006, Grab & Mills, 2011) and have also been included in various regional syntheses of Quaternary periglacial and glacial landforms (Marker, 1995; Grab, 2000a; Sumner & Meiklejohn, 2000; Boelhouwers & Meiklejohn, 2002; Hall, 2010; Hall & Meiklejohn, 2011; Grab *et al*., 2012). Geographically, relict pronival ramparts have been identified across the mountainous regions of southern Africa (Fig. 4.1) and Table 4.1 summarises the ridge morphology, interpreted age, aspect, geology and sedimentology of published accounts. Ramparts are documented in the Amatola Mountains (Marker, 1986), on the escarpment in the Eastern Cape (Lewis & Illgner, 2001), in the Golden Gate Highlands National Park (Nicol, 1973, 1976; Marker, 1990) and at the highest peak in the southern Africa, Thabana Ntlenyana (Grab & Mills, 2011). The altitudinal range of the ramparts is 1750m to 3440m a.s.l., all are regarded as relict, and most are thought to have developed during the Late Pleistocene (Marker, 1986; 1990) or roughly between 27 000yr BP and 10 000yr BP (Lewis, 1994; Lewis & Illgner, 2001). Grab & Mills (2011) suggest the most recent period of rampart genesis on Thabana Ntlenyana in Lesotho during a relatively cold, yet moist period ~ A.D. 300-1000.

Lewis (1994) was the first to question the identification of ramparts in southern Africa. Lewis (1994: 37) stated that “Nicol (1973) and Marker (1990) have described features in South Africa that they call protalus ramparts, although since they possess few of the attributes of protalus ramparts they will not be discussed further… ”. Later, Shakesby (1997: 408) also queried certain ramparts (*e.g*. Nicol, 1973; Marker, 1990; Lewis, 1994) and was particularly critical of the rampart identified by Lewis (1994) (discussed later) and stated that “other ‘ramparts’ in South Africa have probably had alternative origins”. Sumner & de Villiers (2002) re-examined the pronival ramparts of Marker (1986) and proposed that the landforms are openwork scree deposits; an interpretation which is also re-examined here. Mills (2006) provides a brief review of some of the ramparts in South Africa (*i.e*. Marker, 1990; Lewis, 1994) but does not critically evaluate the identification of these landforms. Lewis (2008a) reinterprets the Killmore rampart (Lewis, 1994) as a glacial moraine but the true origin remains speculative (see also Mills, 2006: 42). Hedding & Nel (2010) also express doubts regarding both pronival and glacial origin for the Killmore landform which will be expanded upon later in this Chapter. Finally, Hall (2012) questions the existence of ramparts in southern Africa within a broader debate on the glaciation of the Lesotho-Drakensberg region during the Late Quaternary.

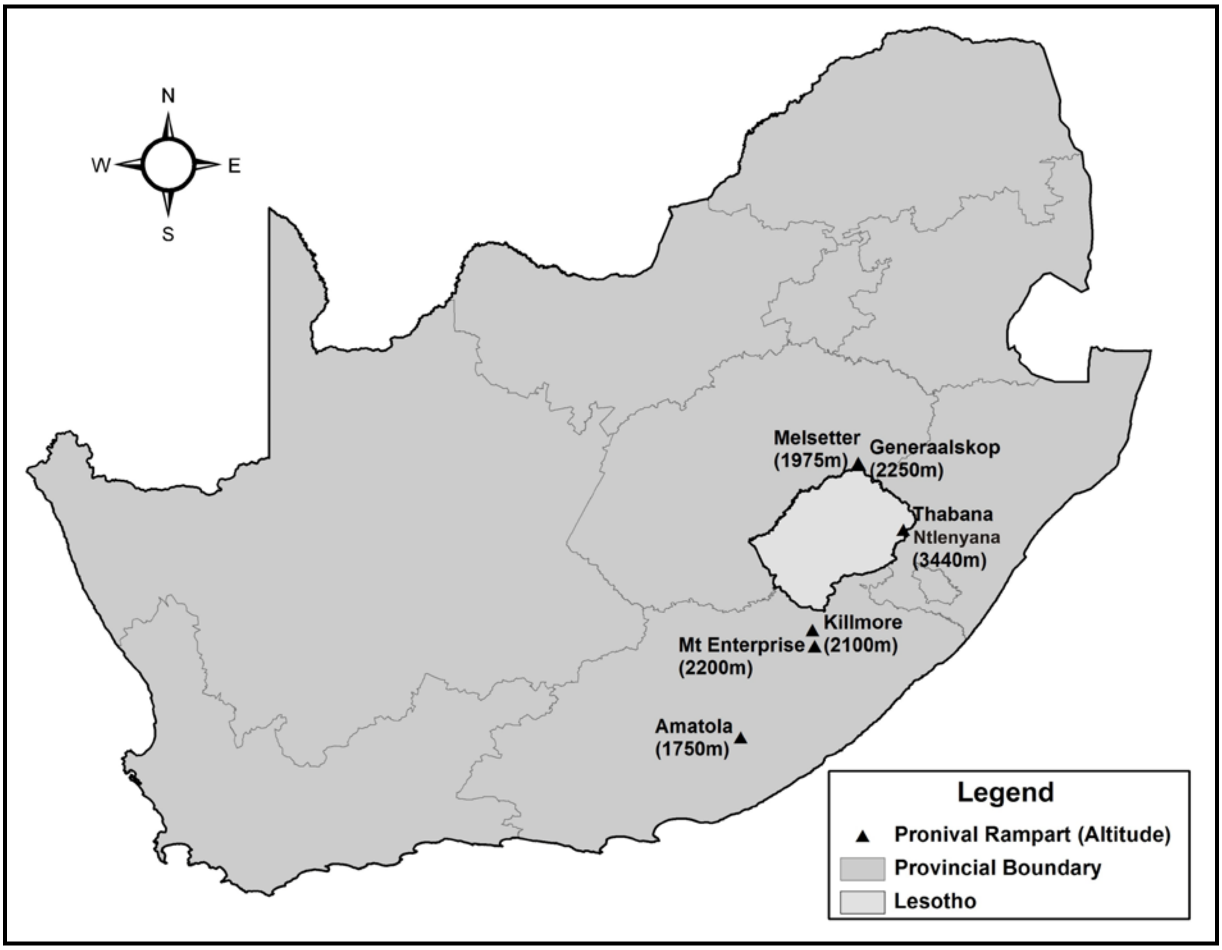

Figure 4.1: Locations of supposed relict pronival ramparts in southern Africa. The approximate altitude of landforms is given in metres above sea level.

Table 4.1: General characteristics of pronival ramparts in southern Africa as given by the respective authors.

Rampart	Latitude	Longitude	Author(s)	Interpreted Age	Diagnostic Criteria	Lithology; Geological setting	Slope gradient	Ridge morphology	Aspect
Melsetter (Golden Gate Highlands National Park)	28°29’51” S	28°36’16” E	Nicol (1973, 1976)	Pleistocene	None	Amygdaloidal basalt and sandstone; just below the boundary between underlying sandstone and basalt	27°	Single rampart; arcuate	south-facing
Generaalskop (Golden Gate Highlands National Park)	28°31’47” S	28°37’31” E	Marker (1990)	“Last cold phase some 20 000 years ago”	None	Dolerite; just above the boundary between underlying sandstone and dolerite	26-30°	Three separate discontinuous ridges; somewhat linear	north, north-east facing
Amatola	32°30’46” S	26°53’48” E	Marker (1986)	“Pleistocene cold phase”	None	Dolerite	18-28°*	Single rampart	south, south-west facing
Killmore	30°56’48” S	27°56’27” E	Lewis (1994)	“no direct evidence of the age of the rampart” but later indicates that the “Killmore protalus rampart is of Last Glacial rather than of older age: it probably formed in the stadial that occurred after 27000 BP and before 13000 BP”	Ridge morphology and sedimentology (Ballantyne & Kirkbride, 1986)	Basalt; just above the boundary between underlying sandstone and basalt	25°	Single ridge; slightly sinuous or festoon-shaped	east-facing
Mt Enterprise	31°10’52” S	27°58’34” E	Lewis & Illgner (2001)	Post-date ”between 22 000yr BP and 10 000yr BP”	No striae visible on clasts of either ridge.	Basalt; just above the boundary between underlying sandstone and basalt	27°	Single discontinuous ridge; slightly sinuous	east-facing
Thabana Ntlenyana	29°27’55” S	29°16’20” E	Grab & Mills (2011)	~AD 300-1000	Backwall and ridge same lithology Ridge morphology?	Basalt	17-21°	Three discrete ridges; arcuate	southerly-facing slopes

* The gradient is only 18° for the first 25m but steepens through to 24° in the middle section and 28° on the lower tongue.

Doubts regarding pronival ramparts in southern Africa have also been expressed elsewhere (*e.g.* Grab *et al*., 2012) but Sumner & de Villiers (2002) remains the only published study, to date, which specifically re-assesses a pronival rampart in southern Africa. This illustrates the view of Mills & Grab (2005) that, although considerable geomorphological work has been undertaken on periglacial and possible glacial landforms in eastern Lesotho highlands and along the Drakensberg escarpment of southern Africa, their origin, process mechanisms and associated climatic implications in many cases remain controversial and unresolved.

Using the diagnostic criteria proposed by Hedding & Sumner (2013), this chapter will re-evaluate pronival ramparts in southern Africa to ascertain whether these landforms have been identified correctly. Each site will be re-investigated as an independent case study and site, morphological and sedimentological characteristics will be verified during field visits. Although not a specific objective of the thesis alternative origins for the discrete debris accumulations are proposed where possible. In many instances the palaeo-environmental inferences drawn from the presence of pronival ramparts in southern Africa does not fit well with other palaeo-environmental reconstructions for the Quaternary (*e.g.* Meadows, 2001; Thomas & Shaw, 2002; Chase & Meadows, 2007). Thus the palaeo-environmental inferences derived from pronival ramparts at each site will also be re-assessed in the following chapter.

Golden Gate Highlands National Park - Melsetter

Nicol (1973) was the first to suggest a rampart origin for debris accumulations in southern Africa. When describing a ridge of unconsolidated material in the Melsetter Hollow (Fig. 4.2a) in the Golden Gate National Highlands Park (G.G.H.N.P.) Nicol (1973: 60) states that “this feature remained a puzzle until a paper by E. Watson (1966) came to the writer’s possession. In his investigation of examples of nivation cirques, Watson encountered similar boulders accumulations and has interpreted them as the protalus ramparts of Bryan (1934) and the *moraine de névé* of Boyé (1952)”. Nicol (1973), using the observations of Watson (1966), explains rampart formation and its potential use to infer the lowest extent of perennial snow within a nivation hollow. Since the studies of Nicol (1973; 1976) primarily focussed on explaining the nature and origin of hollows in the G.G.H.N.P. only the Melsetter rampart is documented in any detail but the heights above sea level and aspect (orientation) of twelve other pronival ramparts in the G.G.H.N.P. are documented by Nicol (1976). Nicol (1976: 266) notes that “it would be repetitive to list the exact details of all the examples (of hollows) as far

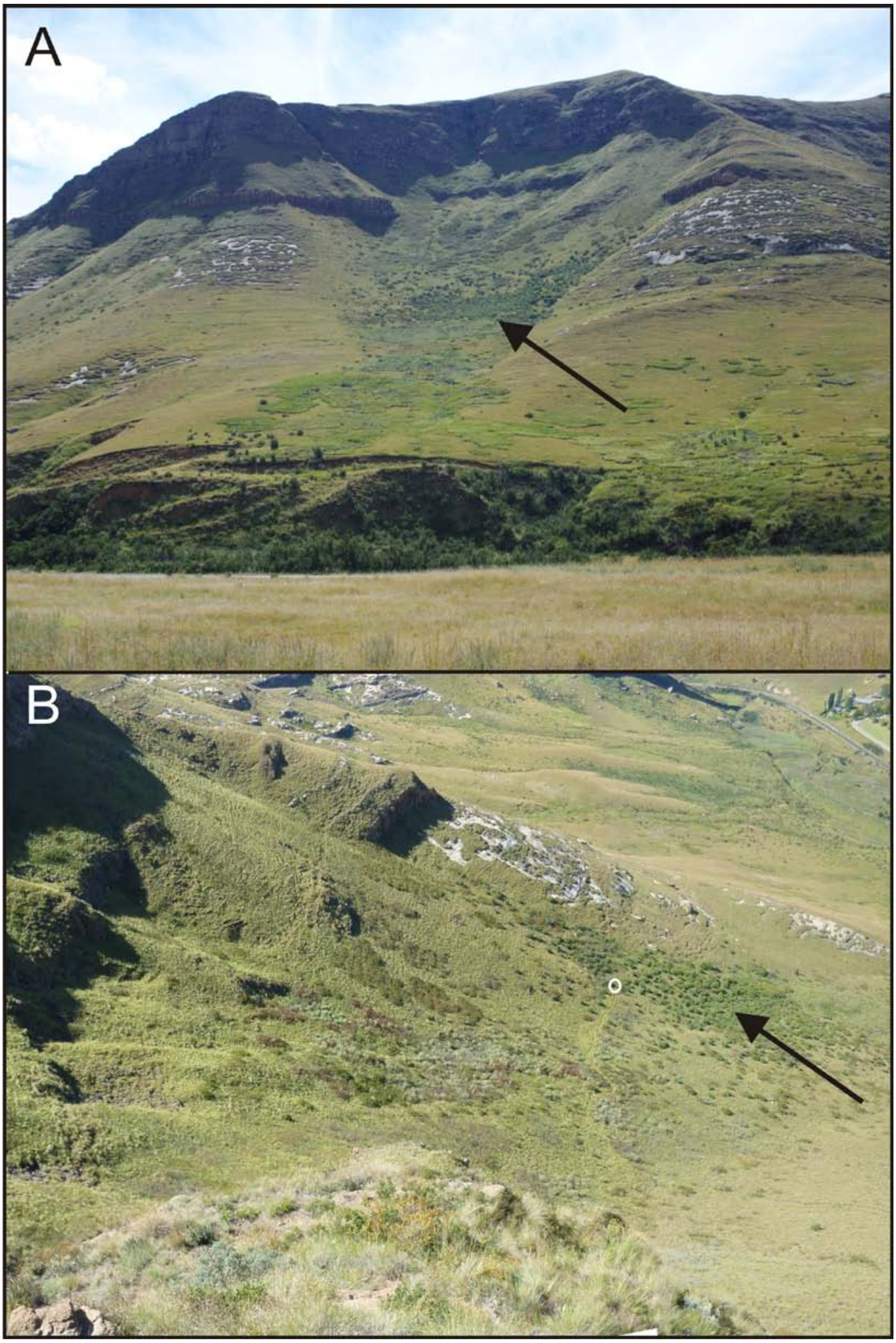

Figure 4.2: Photograph A: view looking north into the Melsetter hollow in the Golden Gate Highlands National Park. The debris accumulation is located below the sandstone-basalt contact. The height difference between the valley floor and the top of the backwall is approximately 280m. Photograph B: view looking east across the Melsetter hollow. Person is circled for scale.

as slope angles changes are concerned – they do not differ so markedly that any one stands out in comparison with the rest and all show the same basic pattern as the Melsetter hollow”. Nicol (1976) took photographs of several other hollows with associated ramparts (see Figures 7.5; 7.6; 7.7 in Nicol, 1976: 262) but only the Melsetter rampart is re-examined here in any detail.

The debris accumulation within the Melsetter hollow is depicted in Figure 4.2a and Nicol (1973; 1976) indicates that it is comprises sub-angular amygdaloidal basalt clasts. Field investigations of the debris accumulation, however, reveal that not only does it comprise sub-angular amygdaloidal basalt clasts but some sub-angular sandstone clasts can also be found amongst the debris strewn across the hillslope. The clasts typically have an a-axis length of between 0.5-1m (Fig. 4.3) and well-developed weathering rinds present on the sandstone clasts indicate that these clasts have not been deposited recently (*i.e.* since the study of Nicol, 1973; 1976). Figure 7.2 in Nicol (1976: 260) displays a pronounced ridge of debris which he notes “forms a sudden steep break in slope” but this appears to have been exaggerated in the figure as field investigations did not reveal this pronounced ridge. In addition, observations from the field indicate that the material is a debris apron rather than a discrete ridge as claimed by Nicol (1973; 1976). The debris is located approximately 230m from a backwall which is 53m high and near vertical (73°) at approximately 1974m a.s.l. (Fig. 4.4). Debris is found just below the contact between sandstone and basalts (Fig. 4.2b). Although, Nicol (1976: 264) used the phrase “talus slide” in the caption of Figure 7.9 to describe the rampart in the Wilgehof hollow and notes various examples of mass movements from landslides to earthflows, rock fall or rock-slope failure are not considered as possible mechanisms of genesis for the landform in the Melsetter hollow. Later, Marker (1990) states that the pronival ramparts identified by Nicol (1973) were superimposed on solifluction deposits within the nivation hollows.

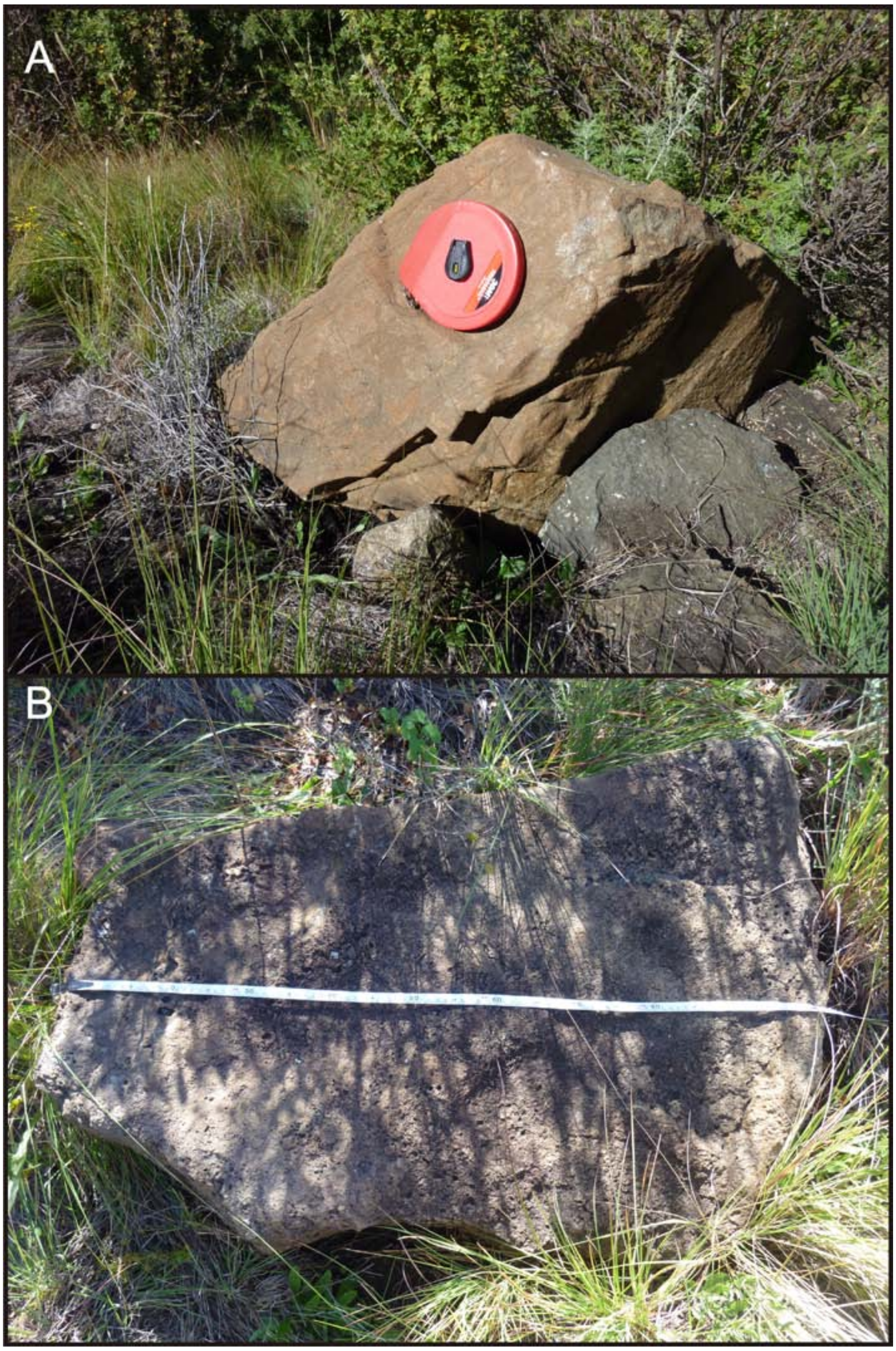

Figure 4.3: Debris comprising the debris accumulation within the Melsetter hollow in the Golden Gate Highlands National Park. Photograph A: A sub-angular sandstone clast amongst sub-angular amygdaloidal basalt clasts. Photograph B: A sub-angular amygdaloidal basalt within the debris accumulation. A-axis length is 1.05m. Clasts are strewn (scattered) over the hillslope and do not form a cohesive debris accumulation.

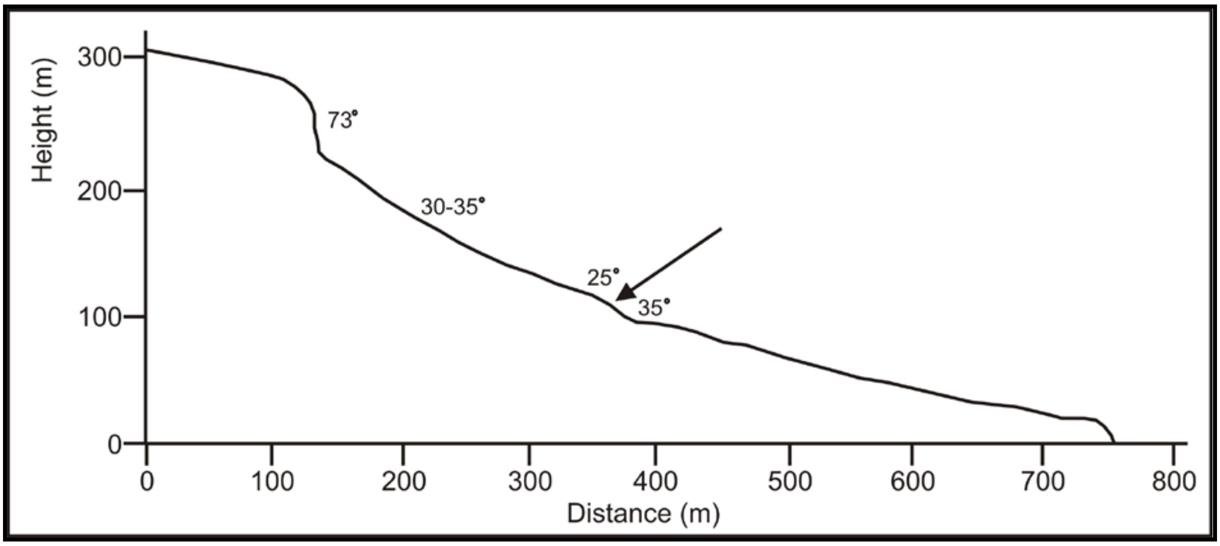

Figure 4.4: Cross profile of the Melsetter rampart identified by Nicol (1973, 1976) (Adapted from Nicol, 1976). The arrow indicates the position of the ‘rampart’. The height of the backwall is 53m and the landform is approximately 230m from the backwall which is 53m high and near vertical (73°).

Nicol’s (1973, 1976) ramparts in the Golden Gate National Highlands Park have been questioned by Lewis (1994) and Shakesby (1997). Re-examination of the cross-profile of the Melsetter hollow (see Fig. 4.4) illustrates that the supposed ridge is approximately 230m from the backwall. This horizontal distance far exceeds the threshold value of between 30-70m for the conversion of stationary to dynamic ice calculated by Benn & Ballantyne (1994). Nicol (1976) recognised that if an adequate vertical thickness of snow could accumulate in a hollow, the lower layers would undergo transformation from firn into the early stages of dynamic glacial ice. Nicol (1976) used the suggested threshold value of 37.8m (125 feet) by Watson (1966) to infer that some movement by plastic deformation under gravitational force may have occurred in the Melsetter hollow resulting in the initial stages of a rudimentary glacier to develop. This observation represents one of the earliest of pronival ramparts as part of a continuum of talus-derived features (see Shakesby, 1997).

Re-examining the debris accumulation within the Melsetter hollow (Fig. 4.5) using the diagnostic criteria for pronival rampart proposed by Hedding & Sumner (2013) it becomes clear that this landform is not a pronival rampart. The main evidence which points away from a rampart origin is the fact that the debris is over 200m from the backwall. This implies, on theoretical grounds (see Benn & Ballantyne, 1994), that the ice making up the snowbed would have started to move downslope under the force of gravity. Based on the diagnostic criteria,

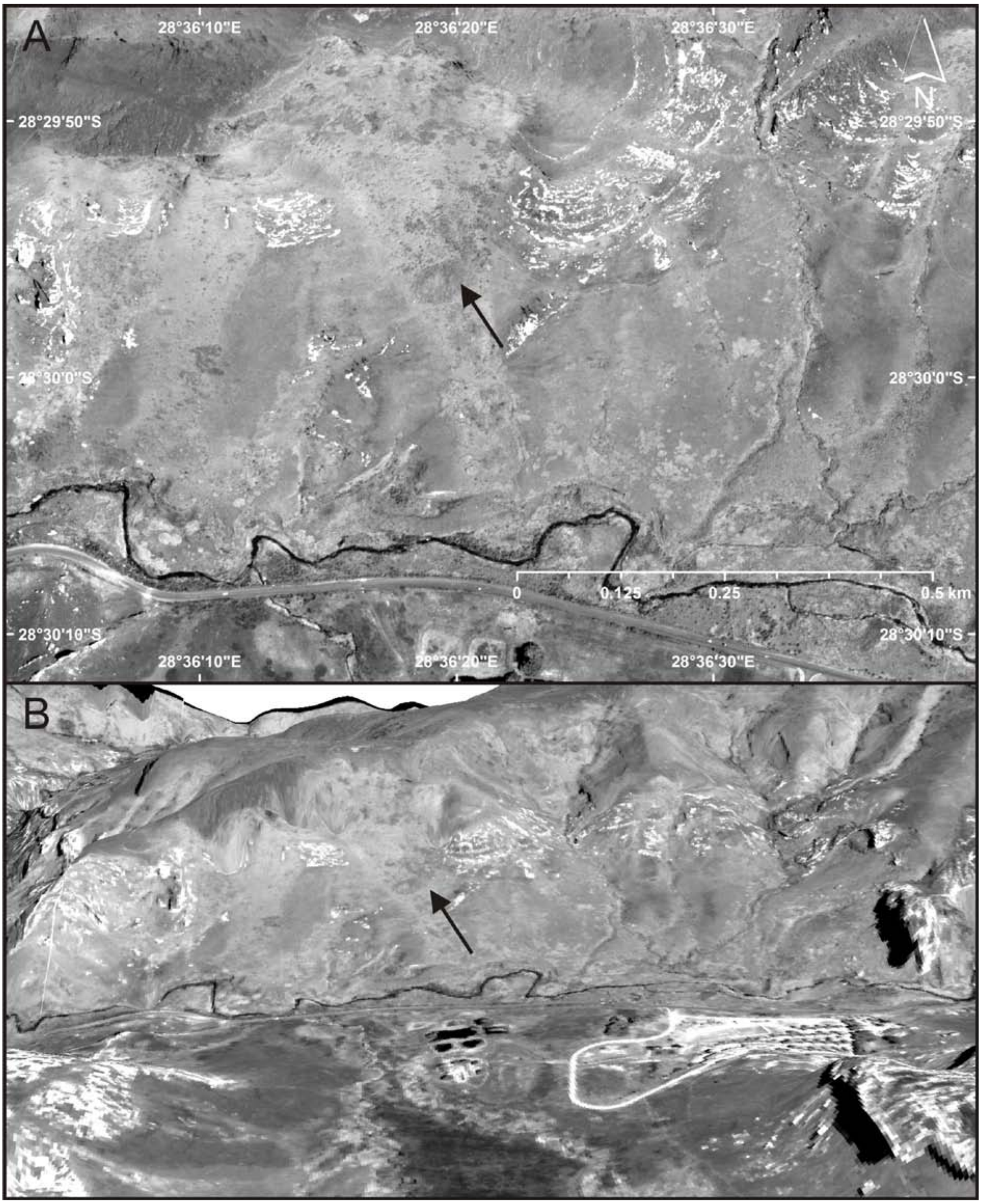

Figure 4.5: Image A: Worldview-2 satellite image of the Melsetter debris accumulation within the Little Caledon Valley of the Golden Gate Highlands National Park documented by Nicol (1973; 1976). Image B: 3D visualisation of the debris accumulation documented by Nicol (1973, 1976). View looking north.

the landform is not a glacial moraine, protalus rock glacier or rock-slope failure. The lack of striated clasts, glacial erosional forms and recognisable ridge precludes classification as a moraine, absence of a recognisable source cavity or distinct scar in conjunction with the size thresholds proposed by Jarman *et al*. (2013) negate a rock-slope failure origin (Table 3.2). Also, the debris accumulation resembles an apron of debris rather than a distinct landform with a lobate or crenulated margins with a convex distal slope which points away from identification as a protalus rock glacier (Table 3.2). Thus the piecemeal accumulation of rockfall debris (scree), which does not require ice or snow to form, should be investigated for the landform within the Melsetter hollow. Owing to the 'armchair' shape of the Melsetter hollow, rock fall debris is funnelled into its present location. Interestingly, the apparent hollow in which the debris accumulation is found is at the intersection of two dolerite dykes and the contact between basalt and underlying sandstone. It is asserted that this intersection of lithologies (structural control) has created the weaknesses which weathering and subsequently erosion have exploited to create the Melsetter hollow (Fig. 4.2a; 4.5). Hollows in the Golden Gate Highlands National Park have traditionally been attributed to nivation and have been used in palaeo-environmental reconstructions for the region during the Quaternary (Nicol, 1973; 1976; Marker, 1990) but many of these hollows in the Golden Gate National Highlands Park are located at similar intersections of lithology and the structural control of their origins and the debris contained in them should be investigated further.

Golden Gate Highlands National Park - Generaalskop

Marker (1990) identified a series of transverse ridges below the cliffs, formed from a dolerite dyke, running up to Generaalskop in the Golden Gate Highlands National Park as pronival ramparts. These three largely parallel ridges occupy a narrow hillslope just above the sandstone-basalt contact. They are somewhat linear (depending on the scale at which they are viewed) but discontinuous across the predominantly north-facing slope (Fig. 4.6). The uppermost transverse ridge is the most pronounced and consists of two adjacent similar features which are separated by a seepage incision. This incision demonstrates that the ridge comprises closely-packed boulders to a depth of 3m (Marker, 1990). The boulders are up to $1m^3$ with the bulk of the clasts sampled by Marker (1990) between $0.5\text{-}1.0m^3$ and almost cubic in shape. The ridges are found below cliffs that are 6-7m in height (Marker, 1990). A dolerite dyke forms a minor cliff between the main ridge and cliff face. The main ridge occurs between 145-170m from the cliff face with two less distinct transverse ridges further downslope (Fig. 4.7).

Figure 4.6: A view upslope toward Generaalskop (looking south). A hummocky terrain comprising multiple ridges can be observed on the north-facing slope.

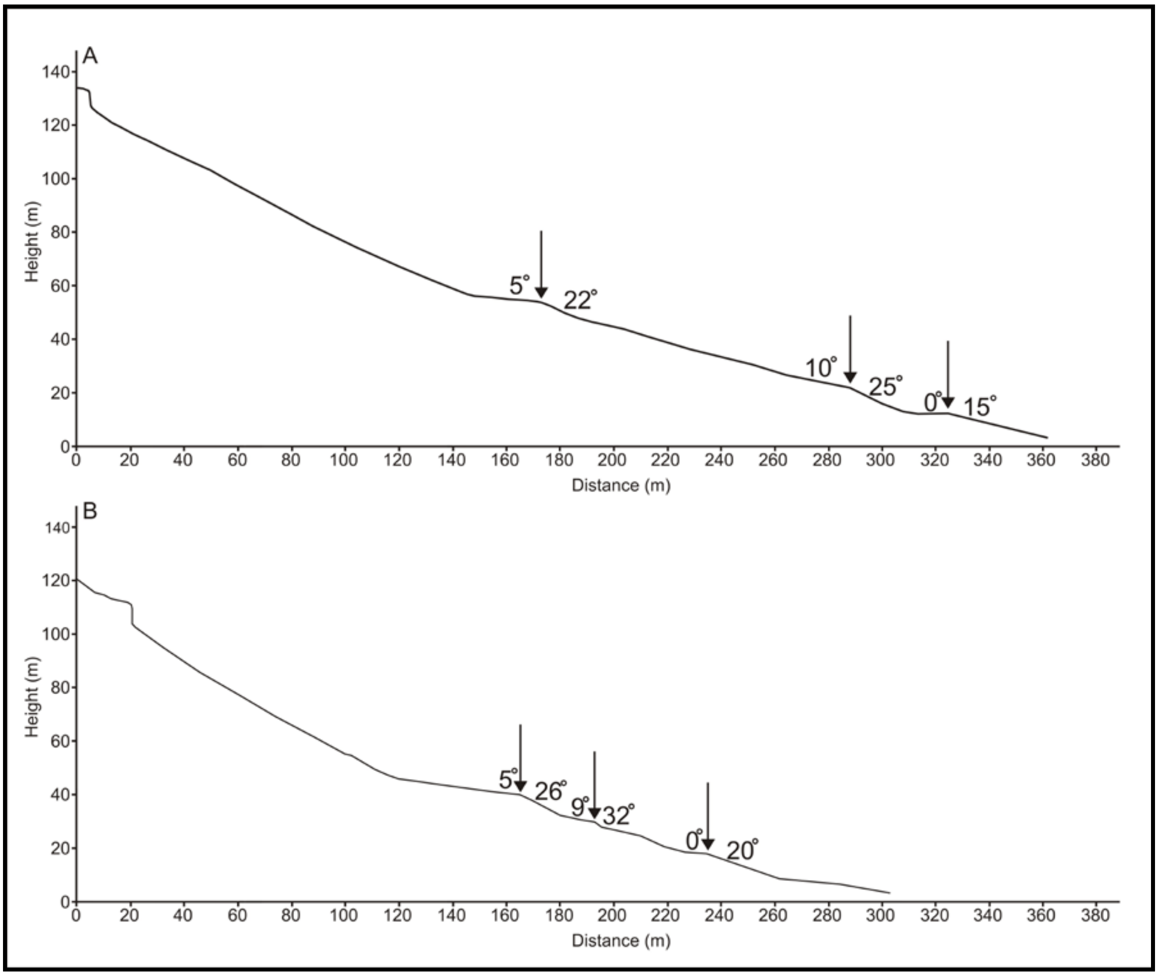

Figure 4.7: Cross profiles of features identified as pronival ramparts by Marker (1990) (adapted from Marker, 1990). Arrows demarcate the ridges. The uppermost ridge is the main ridge and is between 145m and 170m from the backwall which is a 6-7m vertical cliff face.

Marker (1990: 17) states that "the general characteristics of the landform at first suggest a slump feature caused by slope failure" but then proceeds to present the following arguments to oppose this statement:

- Slope failures on basalt are rare since soils and overburden are typically thin;
- Slope failures are unlikely to result in the linear arrangement of boulders aligned at right angles to the maximum gradient;
- The continuity of the minor cliff that provided the debris and the lack of failure planes in the basalt on the upper rock slope point away from a slump feature; and
- The absence of blocks (debris) on the intervening bedrock slope does not suggest a slope failure.

As an alternative, Marker (1990) suggests a rampart origin for the three ridges and attributes debris production to frost shattering from the cliff face under colder than present environmental conditions. According to Marker (1990: 18) "this slump-like landform" is similar to ramparts described by Nicol (1973) but highlights that the topographic setting differs. The ridges are not found in a hollow, the slope does not exhibit evidence of solifluction lobes, the ridges occur on a predominantly north-facing instead of south-facing slope and concavities of the hillslope are far less than those on the opposite side of the valley. Marker (1990: 17) also indicates "the thickness of the weathering rinds on the boulders making up the ridges, the redistribution of smaller debris composing the hummocky terrain and its remnant position as a thin lag on convexities in the toe area all indicate that the landforms are not of recent origin" and, thus, current slope processes are incapable of generating these ridges. Using the information presented above, Marker (1990) suggests that the lower ridges pre-date the upper more pronounced ridge and that components of the ridges have undergone considerable disintegration *in situ* and rearrangement downslope. This characteristic suggests retrogressive (upslope) development.

Using the diagnostic criteria proposed by Hedding & Sumner (2013) to re-evaluate the origin of the features documented by Marker (1990) it becomes apparent that the ridges are not pronival ramparts. With respect to a glacial origin (Table 3.2), the ridges are too far from the backwall to prevent the conversion of static ice of a snowbed into dynamic ice (see also Benn & Ballantyne, 1993). There is no conclusive evidence to suggest that the ridges are a glacial moraine or protalus rock glacier (see Table 3.2) but use of criteria for a rock-slope failure indicate that the ridges are most closely associated with a rock-slope failure or slump as was initially alluded to by Marker (1990). The evidence presented by Marker (1990) highlight more similarities with slumping as a process for formation than supra- and/or sub-nival processes responsible for the formation of pronival ramparts. Ground-proofing of the site indicates, similar to the findings of Sumner & de Villiers (2002), that boulders can also be found within a matrix of fines between the cliff face and the ridges described as rampart crests. Marker (1990) notes that fluvial incisions of the main upper ridge reveals that the ridge comprises closely-packed boulders to a depth of 3m. However, observations during field visits indicate that the ridges are not unconsolidated openwork deposits but rather that this material is consolidated material which has fractured during slumping and later weathered *in situ* (Fig. 4.6). In addition, the hillslope is littered with large boulders (some up to 1m^3) above, between, below and adjacent to the ridges documented by Marker (1990). The ridges are, therefore, considered here to represent evidence of retrogressive slumping, which was facilitated by the dolerite dykes between the uppermost ridge and the cliff-face (Fig. 4.6, 4.8). Subsequent rockfall material has been superimposed on the ridges.

Amatola Mountains, Eastern Cape Province

Marker (1986) interpreted 'scree tongue' features on Elandsberg in the Amatola Mountains of the Eastern Cape as pronival ramparts. Marker (1986: 905) notes that "the scree tongues are formed of Karoo System dolerite boulders derived from the cliffs immediately above them and little or no fines are trapped between boulders" and "individual scree tongues never abut directly onto the cliff above them". This observation then leads Marker (1986: 909) to remark that "Since protalus blocks emplaced by sliding across snow patches are features of the Caledon nivation niches, it seems probable that the large boulders associated with specific levels of the Elandsberg scree, are also protalus ramparts. Deposition downslope of a snow patch banked against a shaded cliff would also explain the absence of scree from the cliff foot flat".

The landforms described by Marker (1986) occur below 60m sub-vertical cliffs on the south-western slopes of Elandsberg (Fig. 4. 9). Ground proofing during field visits and evidence presented by Sumner & de Villiers (2002) dispute the existence of the "cliff foot flat" described by Marker (1986). The colluvium slopes are largely rectilinear and abut the cliffs above, with the screes commencing at varying distances (30-200 m) from the foot of the

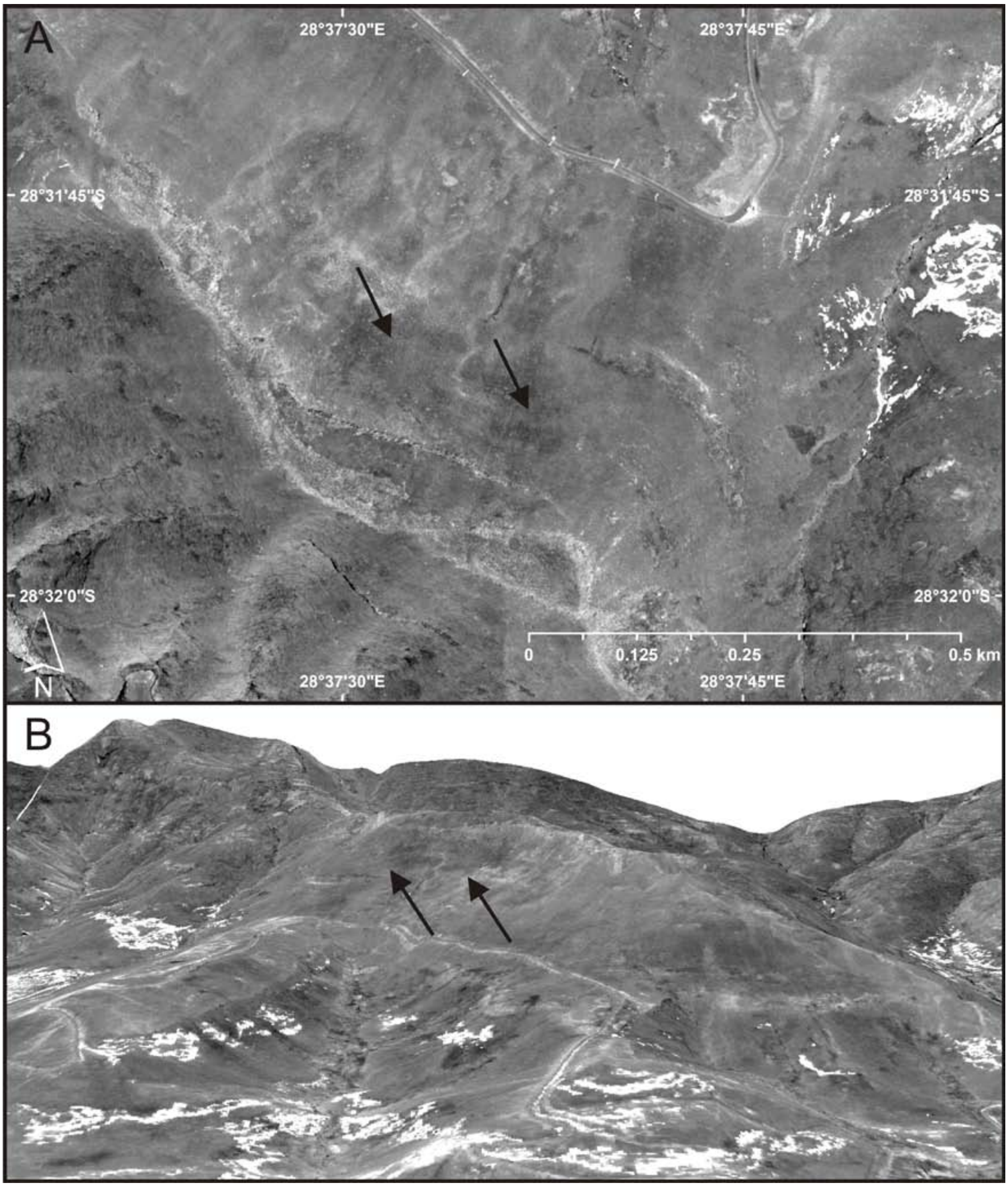

Figure 4.8: Image A: Worldview-2 satellite image of the ridges within the Highlands Golden Gate National Park documented by Marker (1990). Image B: 3D view visualisation of the ridges documented by Marker (1990). View looking south.

cliffs. In addition, Sumner & de Villiers (2002) indicate that the debris accumulations do not lie preferentially within former gullies or topographic hollows but rather typically occur on rectilinear slope segments or spurs. The constituent material of the features comprises boulders 0.5 to 2.0m (a-axis) with some blocks exhibiting *in situ* weathering (Sumner & de Villiers, 2002).

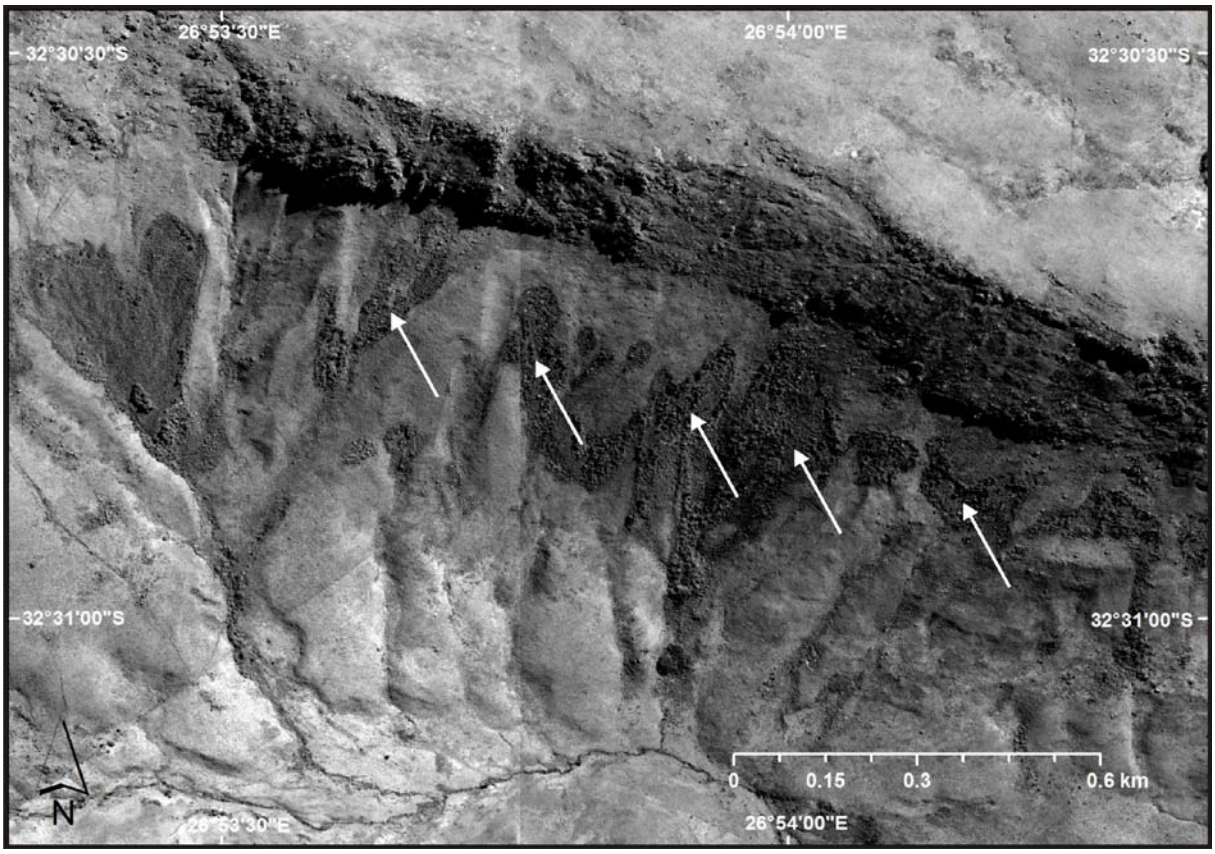

Figure 4.9: Worldview-1 satellite imagery (resolution 2m) of the Amatola screes. The proposed "pronival ramparts" are identified with arrows. The distinctive "Heart" is visible on the western edge of the satellite imagery.

Sumner & de Villiers (2002) reinterpret these landforms as openwork remnants of a gradual infill of the scree slopes. Although some of the landforms are within the prescribed distance from the cliff-line for the formation of pronival ramparts, boulders can be found within a matrix of fines between the cliff face and uppermost sections of the scree deposits. No evidence of recent rockfall material was observed between the cliffs and screes during a visit to the site (Fig. 4.10a). Thus, the presence of debris between the cliff and screes negates a rampart origin. A break in slope can be observed on the slopes exhibiting the scree deposits (Fig. 4.10b) but it occurs below the scree deposits and results from a structural bench. Using the diagnostic criteria of Hedding & Sumner (2013), a pronival rampart or glacial moraine, protalus rock glacier and rock-slope failure origins are excluded. The landforms are, as indicated by Sumner & de Villiers (2002), openwork remnants of a gradual infill of the scree deposits. Enhanced block production may have occurred during colder Pleistocene phases but no evidence for enhanced periglacial activity in the form of frost action or late-lying snow can be inferred.

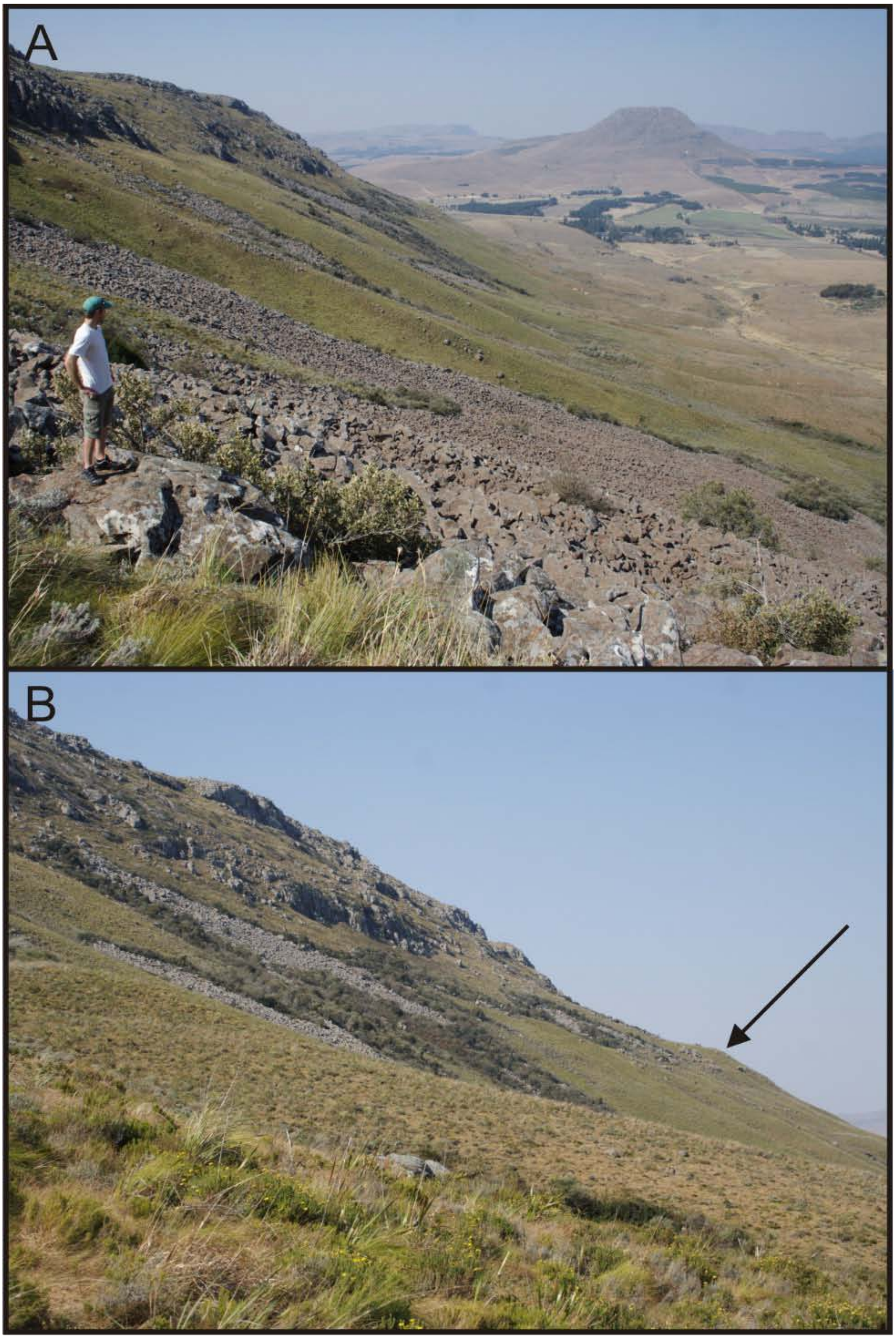

Figure 4.10: Photograph A: View from the "Heart" looking east across the scree deposits. Note the rectilinear slope and absence of 'cliff foot flat'. Photograph B: looking north-east upslope below the "Heart". The break in slope indicated by the arrow below and to the east of the scree deposits results from a structural bench.

Killmore, Eastern Cape Province

A ridge is found at ~2100m a.s.l. on a bench below cliffs on the western side of a left-bank tributary of the Bokspruit on the farm of Killmore (Fig. 4.11a). It is situated immediately above the contact between the basalts and underlying sandstone. Geologically, the landform comprises basalt and extends for almost 1.5km in a generally north-south direction. It is overlain with vegetation and three soils pits dug along the crest of the ridge reveal that it exhibits a soil profile of approximately 0.5m in depth. In places, the ridge is up to 17m high and 83m wide (Lewis, 2008a). The trough is covered with rockfall material and some rockfall debris has surmounted the ridge and extends downslope. The ridge (and trough between the ridge and upper valley slope) drops in altitude from north to south, in opposition to the gradient of the valley and terminates at its southern end (Fig. 4.11b). The ridge is situated on a bench near the top of the valley side-wall and thus the location, in relation to the surrounding topography, does not conform to the expected position of a glacial moraine at the toe of an ice body within the valley (Fig. 4.12a). The ridge is remarkably similar to the Fan Hir ridge in south Wales, which Shakesby & Matthews (1993) interpret as a moraine. Interpretation of the satellite imagery indicates that some geological control exists in the Killmore valley and adjacent valley to the east (Fig. 4.12b). The eastern flanks of both valleys are crescent-shaped and exhibit linear benches. These benches sit at the contact between the underlying sandstone and overlying basalt.

Originally, Lewis (1994) interpreted the Killmore ridge to be a pronival (protalus) rampart and indicates that several morphological and sedimentological attributes are similar to relict ramparts in Britain documented by Ballantyne & Kirkbride (1986). This evidence includes the overall height of the ridge, the arcuate nature of the ramparts/ridge, and the range of thickness of the ramparts/ridge. The ridge displays marked proximal slope, crest, and distal rectilinear slope facets similar to those recorded by Ballantyne (1987) from actively-accumulating ramparts in Norway (Lewis, 1994). Further, Lewis (1994) indicates that the sedimentology of the Killmore ridge is similar to ramparts in Norway (Ballantyne, 1987). Lewis (1994) also reports that the proximal slope angles of the Killmore ridge are comparable to the fossil ramparts in Great Britain but that the distal slope angles are appreciably less, possibly due to the underlying relief. The initial interpretation as a pronival rampart by Lewis (1994) was, however, challenged by Shakesby (1997) who highlighted that, although Lewis (1994) used the diagnostic criteria suggested by Ballantyne & Kirkbride (1986) to identify relict ramparts, the morphometric relationships between ridge thickness, width and crest to talus distance of the Killmore landform were very different to those identified in Britain.

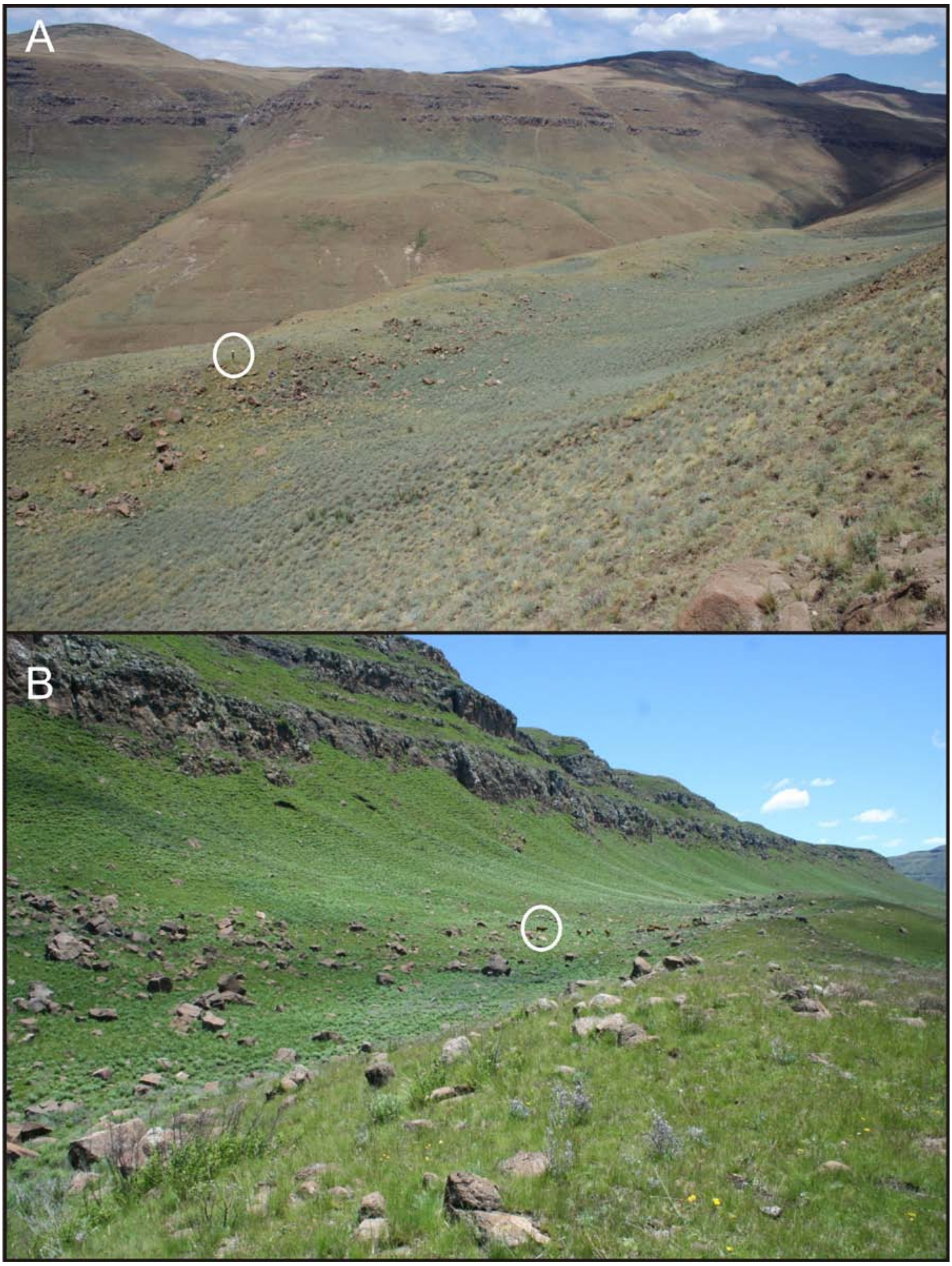

Figure 4.11: Photograph A: View of the Killmore ridge from the backwall. Note the ridge View looking south-west. Photograph B: View along the Killmore ridge. View looking north. Vegetation occurs in the trough and on the ridge. Cattle (circled) in the trough for scale.

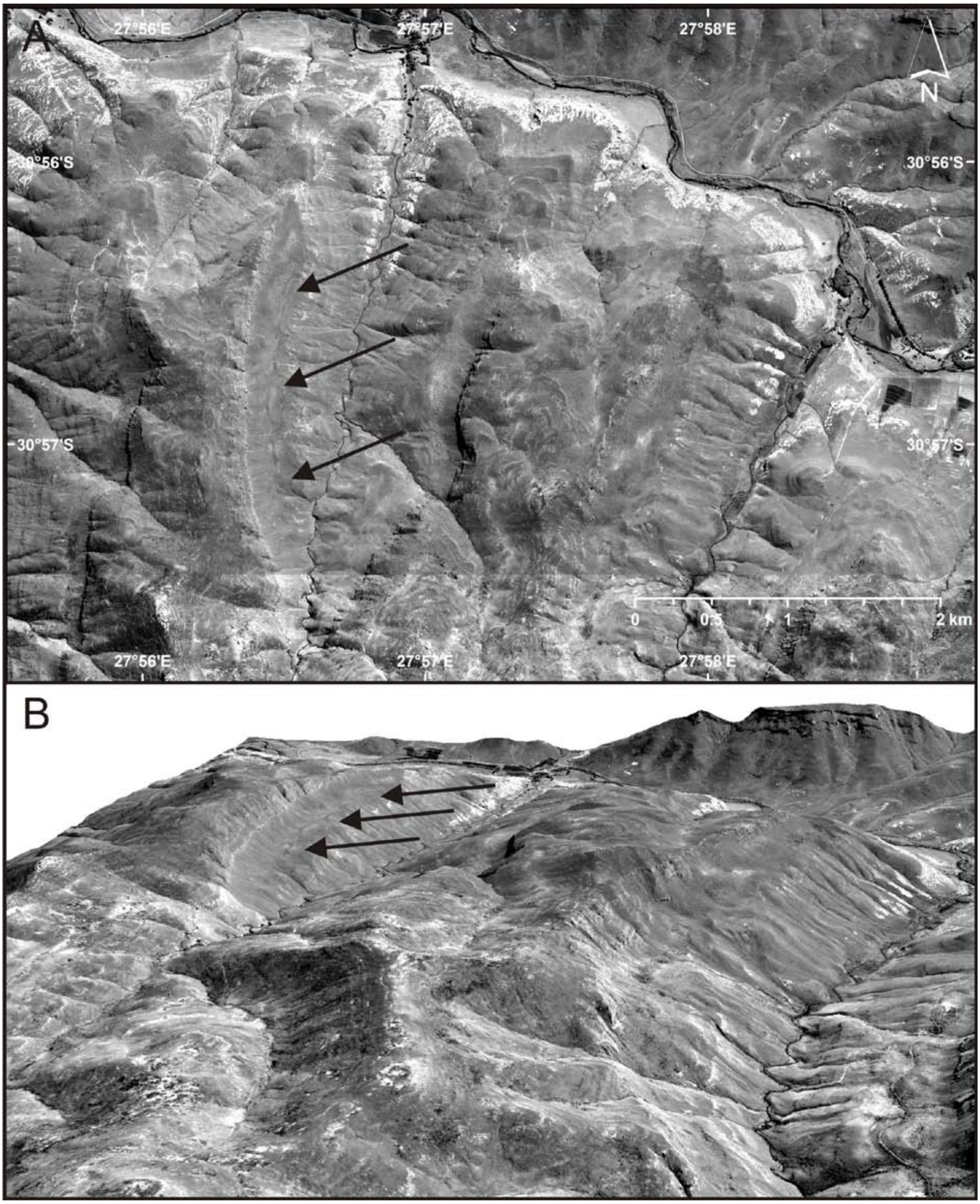

Figure 4.12: Image A: Worldview-2 satellite imagery of the Killmore ridge (resolution 0.6m). Image B: 3D visualisation of the Killmore ridge. Distinctive crescent-shaped valley flanks indicative of normal listric faulting can be discerned.

Shakesby (1997) identifies other flaws with the original interpretation of the Killmore ridge. In particular, he questioned whether the headwall above the talus slope over looks the rampart, but Figure 4.10b shows that the headwall is a cliff face which can provide rockfall debris. Most importantly, Shakesby (1997) indicates that the relationship of the Killmore rampart to the surrounding topography may be as, if not more, important than the characteristics of the landform itself in assessing the likelihood of a rampart origin. Lewis (1994) does not describe the size (depth and extent) of the proposed snowbed/firn field between the Killmore ridge and headwall but the observations presented here indicate that the Killmore ridge is between 150 and 200m from the headwall (Fig. 4.13). This exceeds the distance of 30 to 70m for the transition from stationary to dynamic ice proposed by Ballantyne & Benn (1987) and negates a rampart origin. In addition, the ridge documented by Lewis (1994) comprises consolidated material with a soil depth of up to 0.5m and rockfall material superimposed over it. Therefore, the ridge is not an openwork fabric with an absence of fines as is characteristic of pronival ramparts (see Table 3.2). Given the criticisms by Shakesby (1997), the subsequent reinterpretation by Lewis (2008a, 2011) and re-evaluation of characteristics using the diagnostic criteria for a rampart origin presented by Hedding & Sumner (2013), this landform cannot be considered a pronival rampart.

Lewis (2008b: 172) indicates that at the northern end of Killmore ridge “where the valley side above the bench is lower than elsewhere, so that there was less opportunity for snow accumulation, there is a clitter of boulders that form an ill-defined semi-circular ridge. This may have formed, as a protalus rampart, around the toe of a former snowbed that lay beyond the glacial limits”. This interpretation is also questioned. During the field visits to the site, boulders were identified between the ridge and source of debris (cliff) noted and, therefore, it is interpreted here as an accumulation of talus superimposed on the ridge and no snowbed is required for its formation.

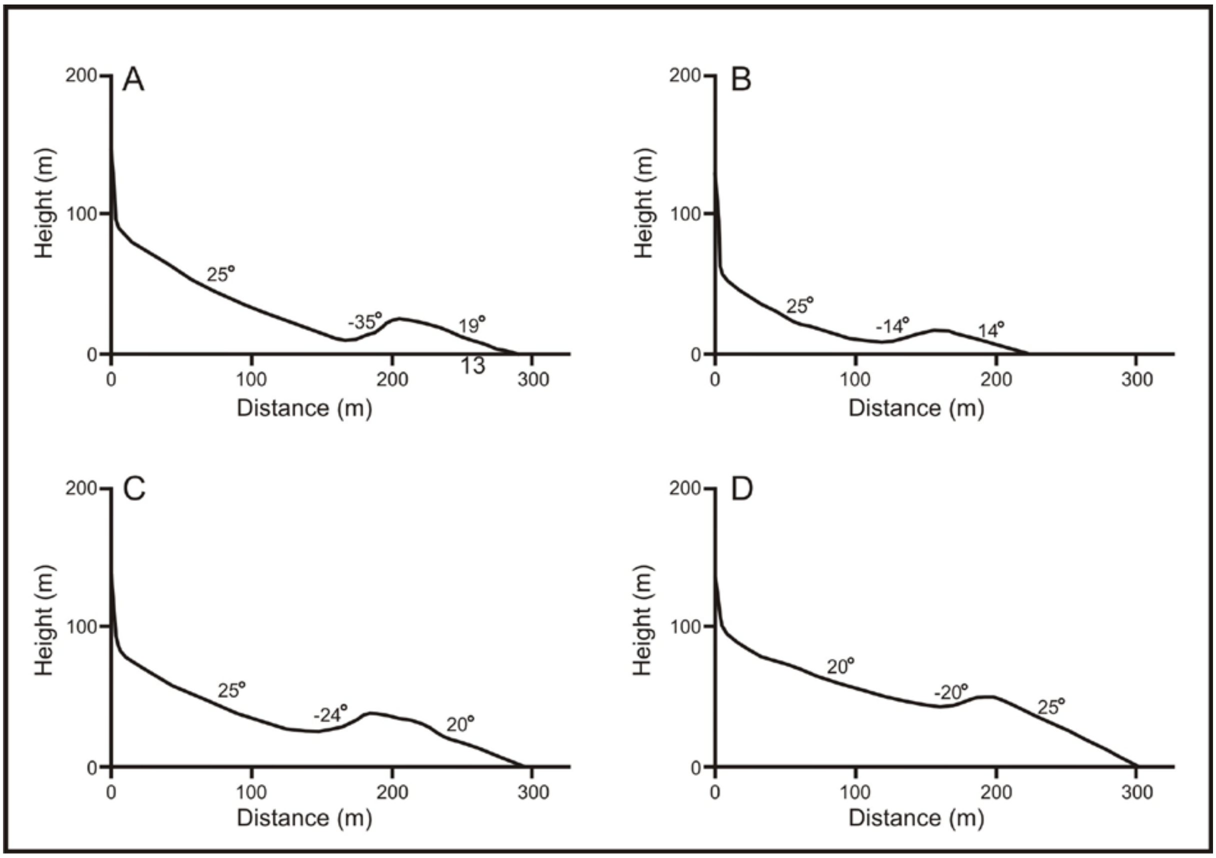

Figure 4.13: Cross profiles of the Killmore ridge originally identified as a pronival rampart and later as a glacial moraine (adapted from Lewis, 1994). Height and inclination of the near vertical backwall is not recorded. The ridge is approximately 150m from the backwall.

Following the criticisms of Shakesby (1997), Lewis (2008a, 2011) reinterpreted the main Killmore ridge as a cirque moraine but provides limited evidence. Lewis (2008a) only indicates that it appears that an ice body has pushed against the ridge (moraine), which has steep inner slopes suggestive of ice contact. However, site surveys indicate that the inner slope angles (13-27°) are well below the angle of repose. The interpretation of the Killmore ridge as a cirque moraine by Lewis (2008a) has a number of implications. First, the formative processes of the ridge moves away from debris accumulation at the foot of a snowbed (rampart) to a ridge that was formed due to the movement of ice (moraine). Second, and more important, a cirque moraine would imply the existence of glacial ice as well as the occurrence of at least discontinuous permafrost at and above an altitude of ~2100m a.s.l. in the Eastern Cape Drakensberg during the Last Glacial Maximum, an argument which is not supported elsewhere (*e.g*. Boelhouwers & Meiklejohn, 2002).

In the reinterpretation of the Killmore ridge as a cirque moraine, Lewis (2008a) provides limited evidence for this reclassification. When using the diagnostic criteria presented by Hedding & Sumner (2013) it becomes evident that this landform does not show the key characteristics of a cirque moraine. Site surveys reveal that the ridge does not comprise openwork fabrics with or without infilling fines but rather consolidated bedrock material in-filled with fines and covered in vegetation. Lewis (2008a) indicates that although the age of the Killmore ridge is unknown, the fresh morphology of the landform makes it likely that it is of Late Quaternary age. But this age estimation is questioned since ground proofing during field visits indicates a well-developed soil profile of approximately 0.5m can be found on the ridge. In addition, although a quantitative assessment was not done, visual inspection of the boulders embedded in the surface of the ridge display characteristics of chemically weathering expected of bedrock material, unlike the angular rockfall debris which has accumulated in the trough and is superimposed on the proximal slope of the ridge. It was observed that where the ridge is more pronounced, debris of rockfall origin appears to come to rest within the trough and on the proximal slope (Fig. 4.11b). Spot heights determined by Lewis (1994) indicate that the northern end of the ridge is 40m higher than the southern end. Although Lewis (1994) suggests that the trough represents a meltwater channel, it could just as easily be interpreted as a contemporary fluvial channel exploiting structural control.

The form of a cirque glacier is dictated by the armchair-shaped bedrock hollow, which acts as an accumulation basin, especially for wind-driven snow (Benn & Evans, 1998). This is not the case for the crescent-shaped backwall of the Killmore ridge and, more significantly, the ridge runs north-south down the length of the valley, not perpendicular to it. In addition, no striated clasts, were found anywhere on the ridge, nor were any glacial erosional forms noted between the Killmore ridge and the backwall or adjacent to the ridge during this investigation (see Hedding & Sumner, 2013; Table 3.2). The observations highlighted above indicate that the Killmore ridge cannot be classified as a cirque moraine either since the ridge is not composed of unconsolidated material and no striated clasts or glacial erosional forms were observed. In addition, the topographic location and linearity of the ridge on the side of the valley does not conform to that of a cirque moraine. An additional characteristic which points away from a cirque moraine origin is that the trough of the landform is orientated eastward and, therefore, does not correlate with the findings of Grab *et al*. (2009) who suggest substantial snow accumulation may have been limited to some high altitude south-facing sites during the last glacial cycle. Thus, even though the ridge is between 150 and 200m from the headwall (Fig. 4.13), which, according to Ballantyne & Benn (1987), is far enough for the transition from stationary to dynamic ice it is unlikely that enough snowfall would have accumulated into ice.

Based on the diagnostic criteria presented by Hedding & Sumner (2013), the Killmore ridge is not thought to be a pronival rampart, glacial moraine or protalus rock glacier. Use of the diagnostic criteria, point toward an origin through rock-slope failure. Following from this proposal, an alternative interpretation for the Killmore ridge which warrants investigation is that of a normal listric fault composed of consolidated bedrock material which has become further pronounced due to fluvial erosion of the trough between the ridge and the upper valley slope (Fig. 4.14). Interpretation of Worldview-2 satellite imagery of the study area also suggests localised (normal listric) faulting, both within the Killmore valley and the adjacent valley to the east (Fig 4.12b). Rockfall debris from the basalt cliffs above has subsequently been superimposed on top of this ridge, with a clear distinction between the deeply weathered bedrock material of the ridge and the fresh angular rockfall debris superimposed over it. The ridge comprises the same lithology (basalt) as the cliff face above the ridge and, using the classification for rock-slope failure by Jarman *et al*. (2013), the bench and ridge exceed the minimum size thresholds: 0.01km^2 in areal extent (source and deposit); 0.1Mm^3 in gross volume; and 5m depth of formerly intact bedrock. Such an origin should be investigated further in the context of landform development since the breakup of Gondwana (see Partridge, 1997).

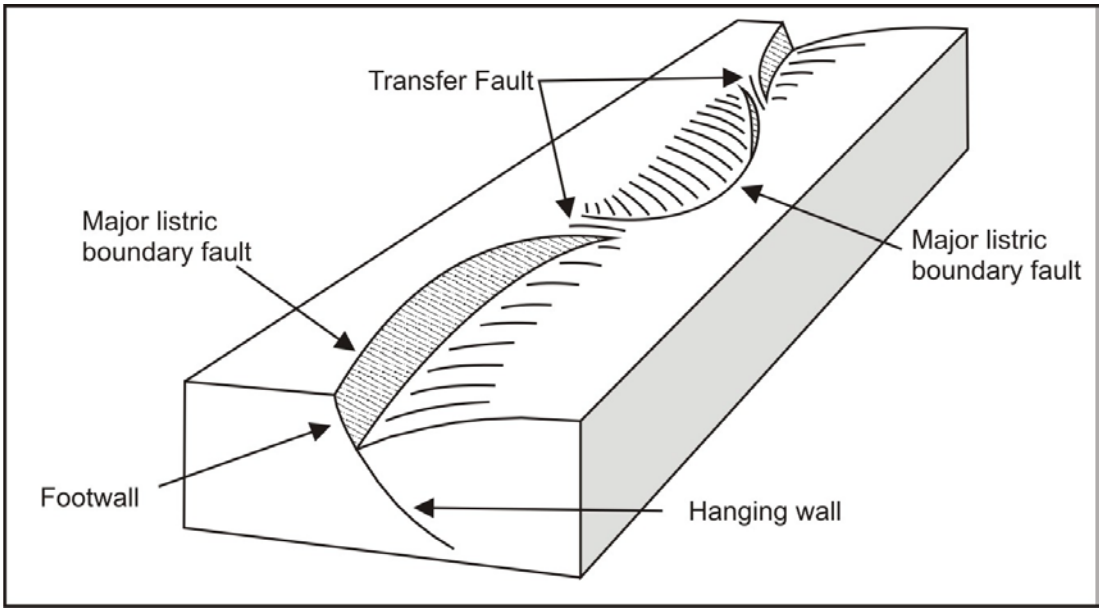

Figure 4.14: Diagram of normal listric faulting (adapted from Summerfield, 1991).

Mount Enterprise, Eastern Cape Province

Lewis & Illgner (2001) briefly describe two discrete east-facing pronival ramparts above and adjacent to a series of ridges which they consider to be a moraine below Mount Enterprise (Eastern Cape) at an altitude of 2000m a.s.l. The ramparts are found on a bench below an exposed cliff face at approximately 2160m a.s.l. (Lewis, 2008b). Lewis & Illgner (2001: 366) state that "Both ridges appear to be located too close to the backwall for sufficient snow to have accumulated in the backwall-ridge hollow to turn to glacial ice (Paterson, 1969) but are within the distance parameters associated with protalus ramparts by Ballantyne & Kirkbride (1986)". Lewis & Illgner (2001) also indicate that the pronival ramparts are outside of the lateral limits of the glacier responsible for the formation of the moraine downslope. Ground proofing of the site shows that the landforms are a single, but discontinuous, ridge which is located along the base of the cliff face (Fig. 4.15; 4.16). This ridge runs largely parallel to the cliff face in a north to south direction for approximately 700m and is dissected by fluvial erosion (seepage incision) in several places.

The ridge crest lies approximately 55m from the backwall along its entire length (Fig. 4.17). This distance falls within the distance parameters for a rampart origin suggested by Benn & Ballantyne (1994). Lewis & Illgner (2001) note that the talus-rampart distance alone cannot be diagnostic of a rampart origin. This supports the viewpoint of Hedding & Sumner (2013) who highlight that the talus-rampart distance must be used in conjunction with other diagnostic criteria to differentiate a rampart from glacial moraines, rock-slope failures and various talus-derived landforms. Using the criteria proposed by Hedding & Sumner (2013), a moraine origin is discounted based on the lack of glacial erosional forms (*i.e.* glacially smoothed bedrock, *roche moutonnée*) and striated clasts in the vicinity of the feature. Lewis & Illgner (2001) present evidence of striated clasts on the lower reaches of Mount Enterprise but no striated clasts were found in the location of the rampart. Also, the ridge is too close to the backwall and the underlying gradient is too shallow (see Benn & Ballantyne, 1994) to facilitate the transformation of snow into dynamic ice movement. In addition, the feature is situated on an east-facing slope which does not correlate with the findings of Grab *et al*. (2009) who suggest that substantial snow accumulation would have been limited to some high altitude south-facing slopes. Classification of the landform as a protalus rock glacier is also discounted since the ridge is greater in width than it is in length, the distal slope is not convex, it does not terminate more than 70m from the talus slope, it does not exhibit lobate or crenulated outer margins and it does not comprise meandering and closed depressions, downslope ridges and furrows or transverse ridges and depressions (see Table 3.2).

Figure 4.15: Image A: Worldview-2 (Lewis & Illgner, 2001). Image B: 3D visualisation of the Mount Enterprise area (view looking north-east).

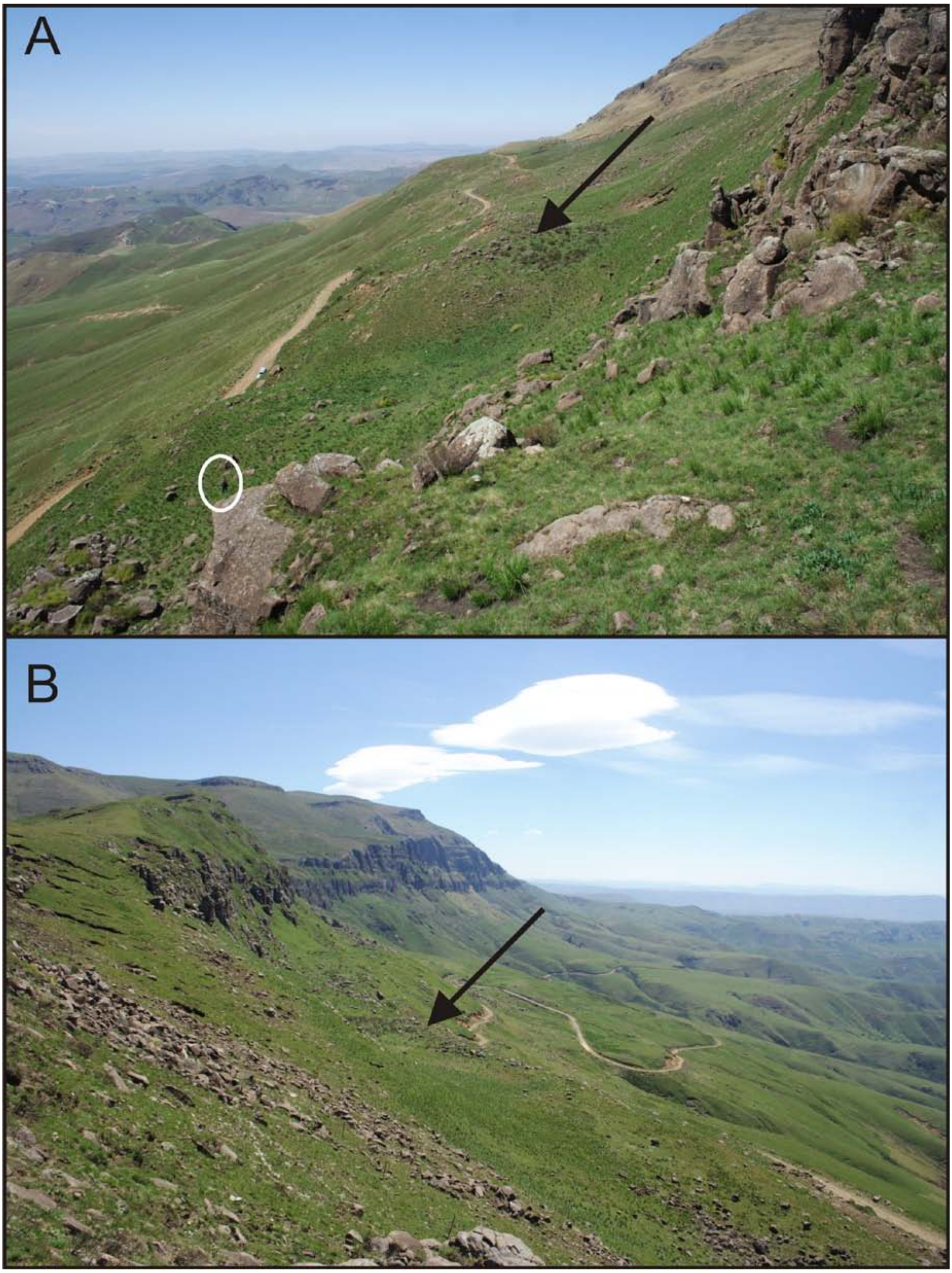

Figure 4.16: Photograph A: View south along the Mount Enterprise ridge. Note the rockfall material on the ridge. Person circled for scale. Photograph B: View looking north down along the Mount Enterprise ridge.

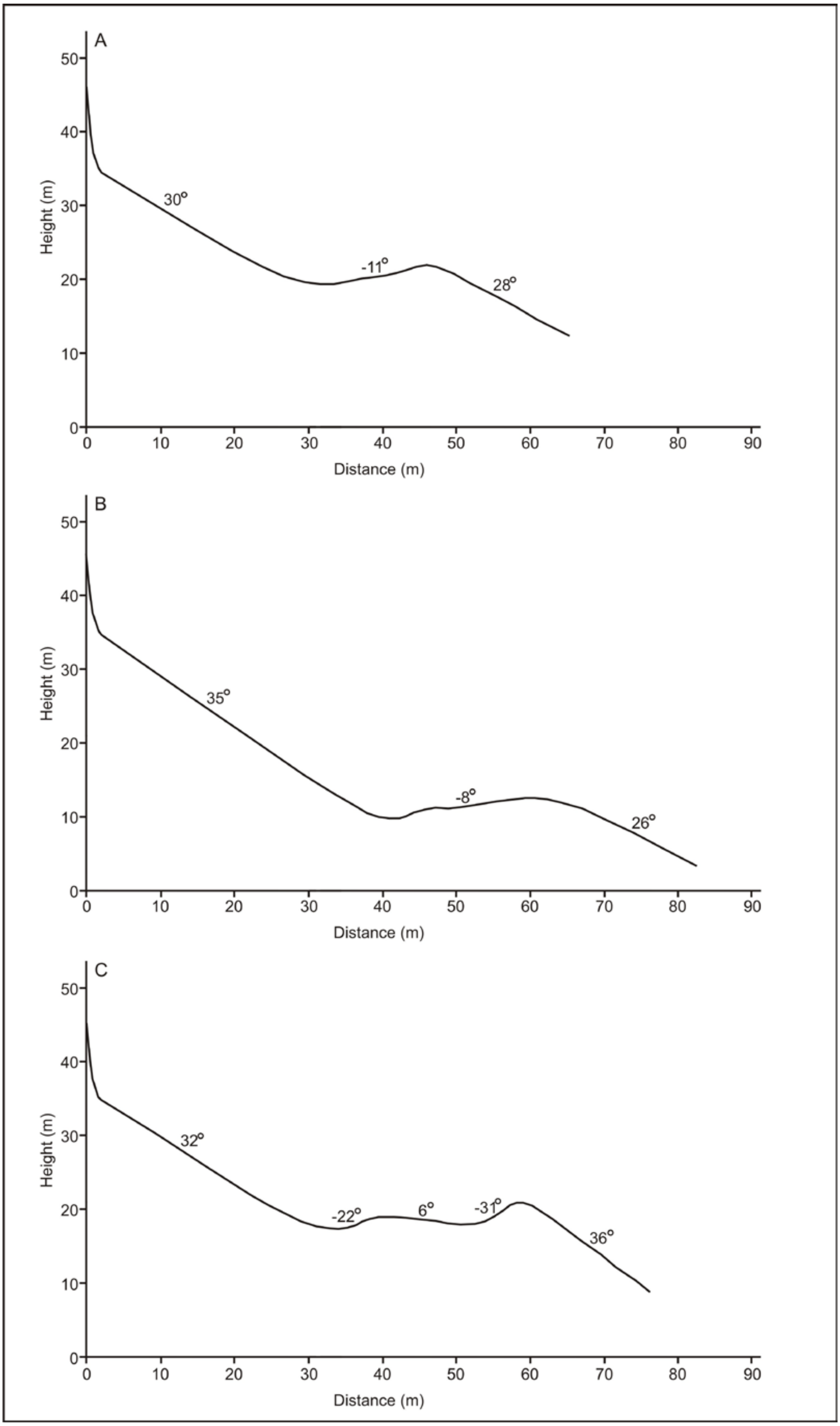

Figure 4.17: Cross profiles of the debris ridges identified as pronival ramparts by Lewis & Illgner (2001). The height of the near vertical backwall was not recorded.

The discontinuous ridge below Mount Enterprise is the most compelling morphological evidence for a pronival rampart origin. However, the ridge at Mount Enterprise is not unconsolidated openwork fabric, with an absence of fines. Rockfall material occupies the trough and in certain places sits on the proximal slope, the ridge crest and even surmounts the crest and has come to rest on the distal slope. The debris found above, on and below the Mount Enterprise ridge is much larger than adjacent talus accumulations. The feature is not a pronival rampart and an alternative should be considered. Origin through rock-slope failure with subsequent rockfall debris being superimposed on the ridge should be investigated further for the entire east-facing slope below Mount Enterprise, including the lower section of the east-facing slope below Mount Enterprise which has previously been described as a moraine (Lewis & Illgner, 2001).

The morphology of the Mount Enterprise ridge provides several similarities with evidence presented by Smith *et al*. (2009) for a ridge in the Inner Herbides, Scotland. Smith *et al*. (2009) demonstrate how localised faulting (neotectonics) through talus can mimic the morphology of a pronival rampart. A rampart-like feature documented by Selkirk *et al*. (2008) near Boulder Point on sub-Antarctic Macquarie Island is a similar feature to the one documented by Smith *et al*. (2009) and it, most likely, also owes its origin to localised faulting (neotectonics). These two examples illustrate that landforms with various origins may share morphological similarities to pronival ramparts when a ridge is viewed in isolation, resulting in so-called ‘equifinality’ or form-convergence (see Whalley, 2009).

Thabana Ntlenyana, Lesotho

Three relict pronival ramparts have been reported on the slopes of Thabana Ntlenyana in Lesotho, the highest summit in southern Africa at 3482m a.s.l., by Mills (2006) and Grab & Mills (2011). Figure 4.18, comprising a mosaic of a WorldView-2 satellite image (resolution: 0.6m), shows an aerial view of the landforms on Thabana Ntlenyana. Grab & Mills (2011) do not describe by what criteria these landforms have been identified but reference is made to Mills (2006). Mills (2006) discusses some characteristics of fossil pronival in the literature (*e.g*. Washburn, 1979; Harris, 1986; Pérez, 1988, Shakesby *et al*., 1999) but the criteria by which the landforms on Thabana Ntlenyana are identified as relict pronival ramparts are not explained explicitly.

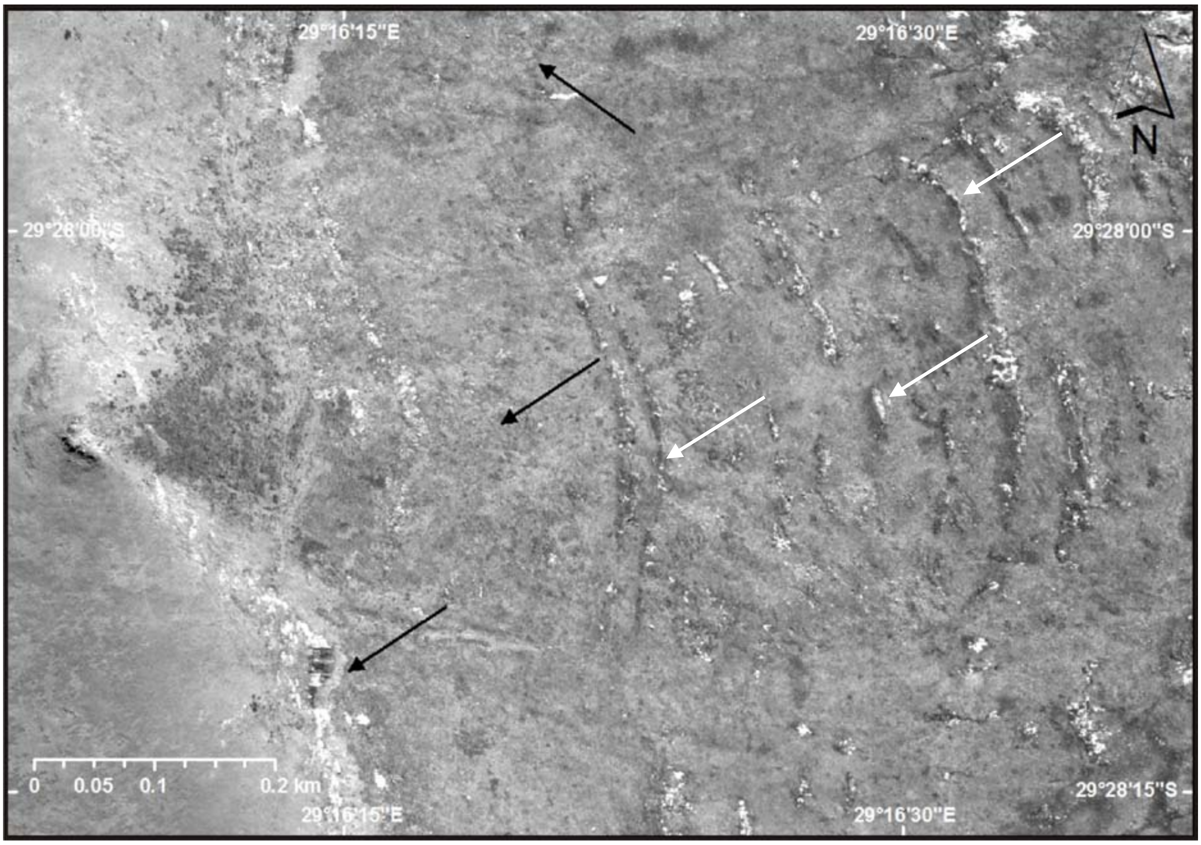

Figure 4.18: Worldview 2 satellite mosaic (resolution: 0.6m) of the Thabana Ntlenyana summit region, Lesotho (Grab & Mills, 2011). The black arrows identify the locations of the pronival ramparts documented on Thabana Ntlenyana. White arrows demarcate scarp faces contouring the summit region of Thabana Ntlenyana. These scarp faces produce a stepped topography.

Grab & Mills (2011: 179) indicate that the pronival ramparts are located on "southerly facing slopes" but all of the landforms occur on east to north-east facing sites, which are not preferential locations for snow accumulation in the high Drakensberg (see Grab *et al.*, 2009). More importantly, the features occur on modest relief and are not overlooked by exposed cliffs as typically envisioned for rampart genesis. Shakesby (1997) indicates that a rampart origin for the landforms described by Tinkler & Pengelly (1994) is unlikely because the modest relief above the Niagara escarpment ridges could not have supported a stable, perennial snowbed with a sufficiently steep snow surface across which rockfall debris could have been transported. The morphology, sedimentology and site characteristics do not appear to "fit" the typical characteristics of pronival ramparts and, thus, the classification of these landforms as pronival ramparts is re-evaluated using the diagnostic criteria proposed by Hedding & Sumner (2013) in the context of their surrounding topography.

Based on the criteria proposed by Hedding & Sumner (2013), the features on Thabana Ntlenyana should not be classified as pronival ramparts. Most importantly, the landforms are located on shallow slopes and not all of the features occur within the threshold value of 30-70m from the backwall (see Table 3.2). To account for "the small size of the scarps, short distances to the ridges and relatively low slope angle", Grab & Mills (2011: 185) propose that snowcreep and snow-push boulder movements are responsible for the development of the ramparts. Questions do not arise from the ploughing of boulders but rather the efficacy of snowcreep and snow-push as formative mechanisms for a rampart. Snow-push should not be considered plausible since the slope gradient is too shallow (*i.e*. not above 20°) and, more importantly, the a-axis of some clasts which constitute the landforms are too large (some are in excess of 2m) and would cause the interlocking of the clasts (Fig. 4.19a). The interlocking of clasts would arrest the movement of clasts downslope and negate snow-push as a formative mechanism.

The snow-push mechanism was originally proposed by Shakesby *et al*. (1999) for ramparts which comprised relatively small debris (b-axis < 0.2m). Grab & Mills (2011: 185) state that "the Thabana-Ntlenyana ramparts have a similar block size distribution to those reported elsewhere by Harris (1986), where some distal rampart slopes support the coarsest debris due to momentum carrying them farther downslope (Harris, 1986)". Harris (1986) indicates that material which has failed to lodge on the rampart crest, continues to slide or roll downslope to produce a wide apron of debris on the distal slope. This observation is limited to sections of the rampart on steeper ground which Harris (1986) proposes is linked to the asymmetry of the rampart in these sections. Harris (1986: 674) continues to state that "very large boulders (some reaching sizes of 5m or more) formed an apron downslope of the ridge, their momentum apparently carrying them further than smaller clasts". Thus, it is questioned if Harris (1986) was referring to lodgement on the distal slope of the ridge or deposition lower down on the distal slope. Harris (1986) also refers to Gray (1982) who describes a rampart consisting of large boulders (over 10m in diameter) along the crest-line with smaller boulders (0.15-0.50m) on the distal slope. But this observation is based on the Nant Ffrancon ridge which is now considered to be a rock-slide (see Curry *et al*., 2001).

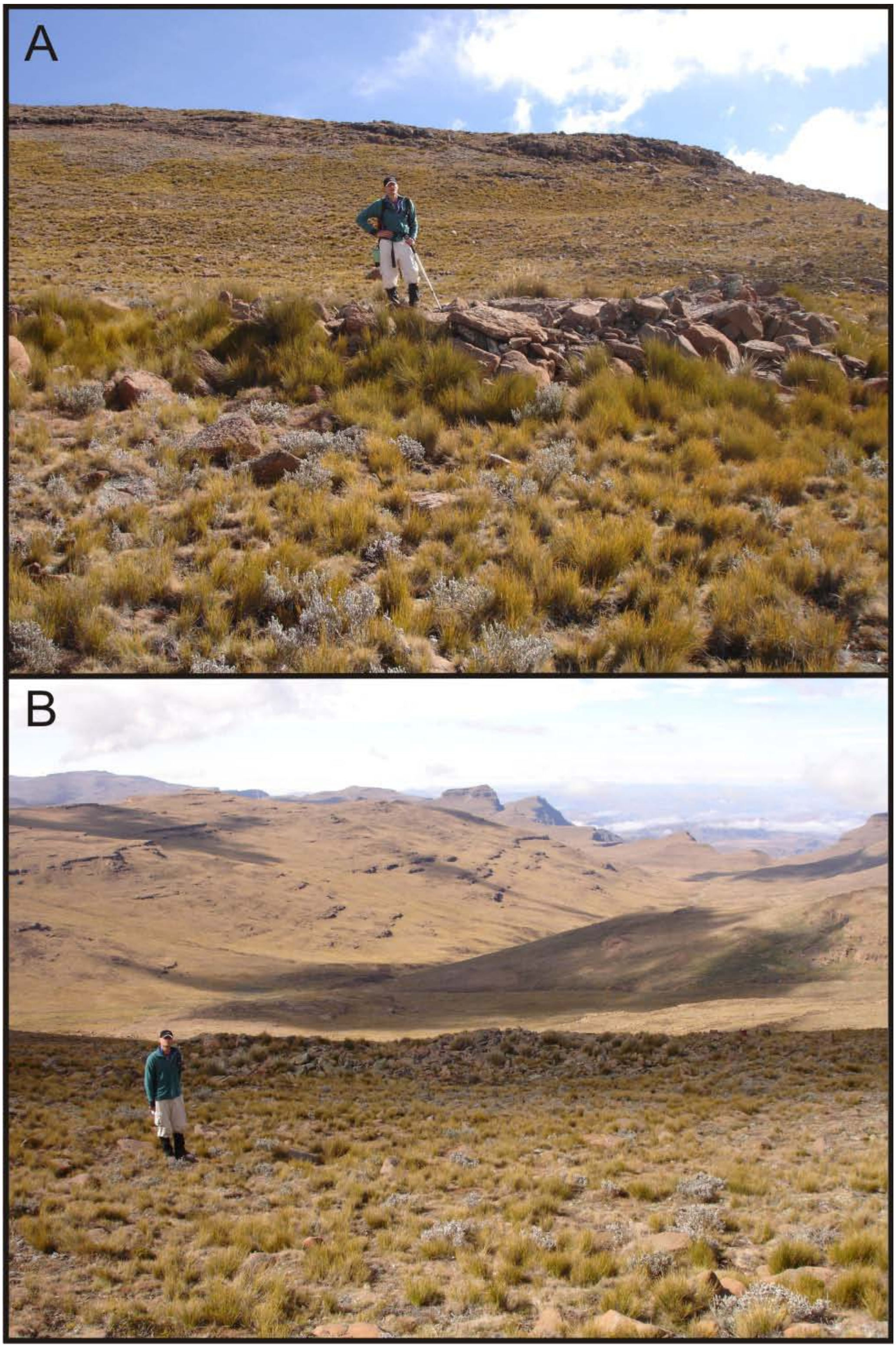

Figure 4.19: Photograph A is a view upslope (looking west) on Thabana Ntlenyana of the debris accumulation. Note the riser and tread of the accumulation, interlocking clasts and that the landform is not overlooked by a bedrock cliff but rather a 7m scarp face which is 163m upslope. Photograph B is a view downslope (looking east) on Thabana Ntlenyana, Lesotho. The debris accumulation mid-way in the photograph is the northernmost pronival rampart identified by Grab & Mills (2011; Figure 5).

For the southern-most feature identified by Grab & Mills (2011), the information provided indicates that the distance of the ridge from the backwall restricts the size of the snowbed and an underlying slope angle of 17° (based on Figure 5 in Grab & Mills, 2011) would limit snow-push as a mechanism of rampart formation. This landform is 41m from a scarp face which is 4m in height. For the remaining two, more northern, features identified as pronival ramparts, the distances from the backwall exceed 70m. The northernmost landform is over 150m from the nearest scarp face which is 7m in height (Fig. 4.20a) and the remaining feature is 78m from a scarp face which is 5.5m in height. Therefore, these distances preclude a rampart origin.

During a field visit to the site by the author, several morphological and site measurements were taken of the northernmost landform (Fig. 4.19b) (Figure 5 in Grab & Mills, 2011: 183). The distance of the feature from the nearest upslope scarp face is 163m, the average slope gradient is 19° and the scarp face is 7m high (Fig. 4.20a). The morphology indicates two separate crescent-shaped landforms. The smaller southern feature is 7.1m wide whereas the larger northern feature is 10.8m wide (across slope). Interpretation of site, morphological and sedimentological characteristics using the diagnostic criteria proposed by Hedding & Sumner (2013) indicates that these landforms are not moraines, protalus rock glaciers, rock-slides or pronival ramparts. Although Grab & Mills (2011) note that it is difficult to account for the ramparts in terms of rapid mass movements or slow mass movements, an alternative, which may explain these landforms and should be investigated, that they represent relict lobate solifluction lobes, where the fines have been washed out (Fig. 4.19a). Grab & Mills (2011) note that the distal slopes of these landforms support the coarsest debris which is characteristic of solifluction lobes and can be produced through solifluction and snowcreep. The view upslope (Fig. 4.19a) of the northernmost feature is particularly compelling where the riser and tread of the solifluction lobe can be seen. Lobate solifluction lobes are common at higher elevations in the KwaZulu-Natal Drakensberg (Fig. 4.20b).

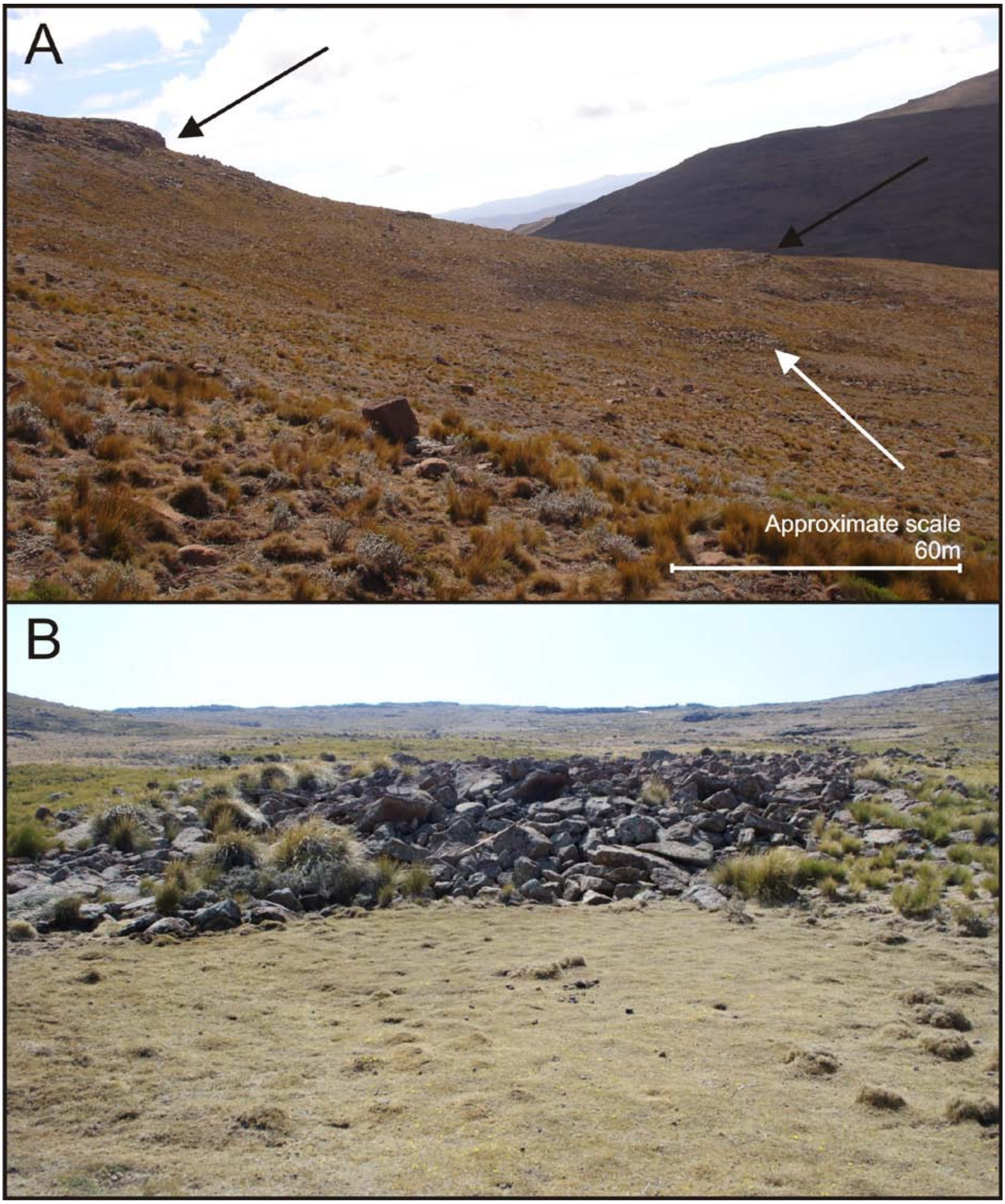

Figure 4.20: Photograph A: Black arrows identify the scarp faces to the north of the identified landform in the foreground. Scarp faces of 1-1.5m in height are common on Thabana Ntlenyana and contour around the summit (see Fig. 4.19). The landform in the foreground previously described as a 'rampart' by Grab & Mills (2011) is identified with a white arrow. Photograph B: A solifluction lobe on the south-facing slopes above the blockstream described by Boelhouwers *et al*. (2002). This solifluction lobe is 4.6km south of Thabana Ntlenyana at an approximate altitude of 3320m a.s.l. Staff length in centre is 1.2m.

Summary

Hall (2012) questions the correct identification of pronival ramparts in southern Africa within a broader debate on the possible glaciation of the Lesotho-Drakensberg region during the Late Quaternary. Re-evaluation of the previously identified pronival ramparts in southern Africa shows that only the ridge at Mount Enterprise (Lewis & Illgner, 2001) may possibly be relict pronival ramparts (Table 4.2). However, even though this ridge is the most compelling example of a relict pronival rampart in southern Africa, the sedimentological characteristics of the ridge and surrounding topography (site characteristics) cast doubt on its classification as such.

Application of the diagnostic criteria presented in Chapter 3 (Hedding & Sumner, 2013) to previously identified relict (fossil) pronival ramparts in southern Africa provides some interesting insights into their origin (Table 4.2). Many of the landforms identified as pronival ramparts in southern Africa are found at the contact between geological strata, namely underlying sandstone and overlying basalt. This coupled with the site, morphological and sedimentalogical characteristics indicate that several landforms are likely to be rock-slope failures. In contrast, an alternative interpretation which should be considered for the features identified as pronival ramparts on Thabana Ntlenyana is that of solifluction lobes which are common on the summit regions of the eastern Lesotho Highlands (*e.g*. Grab, 2000b). This is noteworthy in that it demonstrates that pronival ramparts can also be confused with landforms indicative of localised (small-scale) mass movements. Another observation from the application of the diagnostic criteria proposed by Hedding & Sumner (2013) is that although the criteria help to differentiate ramparts from landforms most commonly confused with ramparts, namely glacial moraines, protalus rock glaciers and rock-slope failures, ramparts can be also be confused with neotectonic faults, solifluction lobes and scree deposits. This observation highlights that a multiple-working hypothesis (Harris *et al*., 2004) should always be adopted when investigating discrete debris accumulations.

Table 4.2: Diagnostic criteria for pronival ramparts proposed by Hedding & Sumner (2013) applied to the pronival ramparts documented in southern Africa.

Criteria	**Elandsberg, Amatola Mtns**	**Killmore Ridge, Eastern Cape**	**Mt Enterprise, Eastern Cape**	**Melsetter, Golden Gate**	**Generaalskop, Golden Gate**	**Thabana Ntlenyana**
Pronival (Protalus) Rampart						
Ridge crest to cliff-foot distance <*c*.30-70m	**X**	**X**	✓	**X**	**X**	**X***
Insufficient cross-section depth for snow to glacier ice transformation	**X**	**X**	✓	**X**	**X**	**X***
Underlying slope gradient that will facilitate snow/firn bed angle >20°	✓	✓	✓	✓	✓	**X**
No glacial erosional forms or evidence of overdeepening of the associated backwall area through sapping and subglacial erosion	✓	✓	✓	✓	✓	✓
Openwork fabric; limited fines (<2mm)	✓	**X**	**X**	**X**	**X**	✓
Backwall and ridge same lithology (no erratics)	✓	✓	✓	**X**	✓	✓
Absence of striated clasts	✓	✓	✓	✓	✓	✓
Glacial Moraine						
Glacial erosional forms	**X**	**X**	**X**	**X**	**X**	**X**
Striated clasts	**X**	**X**	**X**	**X**	**X**	**X**
Broadly arcuate in plan-form but in detail are often irregular and winding	**X**	**X**	**X**	**X**	**X**	✓
Ridge crest to talus-foot distance >*c*.30-70m	✓	✓	**X**	✓	✓	**X**
Presence of fines (<2mm)	**X**	✓	✓	✓	✓	**X**

Criteria	Elandsberg, Amatola Mtns	Killmore Ridge, Eastern Cape	Mt Enterprise, Eastern Cape	Melsetter, Golden Gate	Generaalskop, Golden Gate	Thabana Ntlenyana
Rock-slope Failure						
Recognizable source cavity or distinct scar of comparable volume, linked to the deposit by a feasible trajectory	X	X	X	X	X	X
Debris aprons beyond the feature	X	X	✓	✓	✓	X
Debris much larger than adjacent talus accumulations	✓	X	✓	✓	✓	✓
Large masses of displaced hillside within or above the area of debris accumulation	X	✓	✓	✓	✓	X
Minimum size thresholds: $0.01km^2$ in areal extent (source and deposit); $0.1Mm^3$ in gross volume; and 5m depth of formerly intact bedrock	X	✓	✓	X	✓	X
Protalus Rock Glacier						
Greater in length (down-slope) than in width (across-slope)	X	X	X	X	X	X
Convex distal slope	X	X	X	X	X	X
Typically terminate >70m from the talus slope	X	X	X	X	X	X
Lobate or crenulated outer margins in plan form	X	X	X	X	X	✓
Meandering and closed depressions, downslope ridges and furrows, and transverse ridges and depressions	X	X	X	X	X	X

* not all documented features at this site exhibit this characteristic.

In many instances the palaeo-environmental inferences drawn from pronival ramparts in southern Africa also do not fit well with other palaeo-environmental reconstructions for the Late Quaternary (*e.g.* Meadows, 2001). For instance, Nicol (1973, 1976), Marker (1986, 1990), Lewis (1994), Lewis & Illgner (2001) and Grab & Mills (2011) use relict ramparts, typically in conjunction with the identification of relict glacial landforms or sedimentary sequences, to infer various scales of glaciation of the Lesotho-Drakensberg Mountains during the Late Quaternary whereas Meadows (2001: 39) indicates that "southern Africa was not subject to Quaternary glaciation". Thus, not only has there been a poor understanding of rampart genesis and the use of inappropriate diagnostic criteria but also a limited understanding of the palaeo-environmental significance of relict pronival ramparts. This aspect will receive attention in the following chapter.

Chapter 5: Discussion and palaeo-environmental significance

Genesis of actively-accumulating pronival ramparts

Rampart genesis occurs at the foot, and/or lateral margins, of snowbeds which are situated on steep slopes that facilitate formative supra- and sub-nival processes (Shakesby *et al*., 1987). These snowbeds must be overlooked by sufficiently high cliffs of exposed bedrock that represent the zone of debris production for rampart genesis. Snowbeds typically occur in sheltered situations on mountainsides where snow survives the ablation season but where accumulation is insufficient to lead to the development of glacier ice (Lowe & Walker, 1997). Lowe & Walker (1997) indicate that snowbed survival is governed partly by local temperature regime, but the primary control of their development appears to be precipitation since the accumulation of too little snow will negate snowbed formation and too much snow would result in rapid snowbed growth and the transition to glacier ice, as calculated by Ballantyne & Benn (1994).

According to Sissons (1980), pronival ramparts are indicative of perennial snowbeds but evidence from Hedding *et al.* (2007) and Hedding *et al.* (2010) suggest that a snowbed may be stable, increasing, diminishing in extent and thickness and/or may not be permanent throughout the formation of a pronival rampart. This view is substantiated by Hall & Meiklejohn (1997) who indicate two phases of rampart development in the Canadian Rockies and, although Ballantyne & Harris (1994) have shown a rampart origin for the Baosbhein ridge complex to be erroneous, Sissons (1976: 187) suggested that “three phases of Lateglacial morphological activity, linked to … two distinct cold periods separated by a considerable time interval” resulting in the formation of the Baosbhein ridge complex. Although the positive identification of the pronival ramparts documented by Tinkler & Pengally (1994) has been questioned by Shakesby (1997) they suggest that the small localised inner ridges along sections of the main ridge might correspond to renewed cooling during the Younger Dryas. Harris (1986) also indicates that a minor ridge crest on the distal side of the rampart on the northern flanks of Oksskolten in the Okstindan Mountains, Norway may indicate an older rampart which developed when the snowpatch was larger. Thus, these studies demonstrate that the size and dimensions of associated snowbeds can fluctuate considerably during rampart genesis.

Initially, the outward (downslope) model was used to explain the development of ramparts (see Ballantyne & Kirkbride, 1986). This mode of rampart genesis was suggested to take place below snowbeds which increase in thickness and extent. Hedding *et al*. (2007) propose an alternative mode of formation whereby rampart development occurs below snowbeds which are fluctuating, and possibly declining, in thickness and extent. Hedding *et al*. (2010) demonstrate that the morphological characteristics of pronival ramparts traditionally attributed to outward (downslope) genesis below a snowbed which is increasing in thickness and extent can also be linked to a snowbed which is stable in size. The retrogressive (upslope) model proposed by Hedding *et al*. (2007) and the findings of Hedding *et al*. (2010) demonstrate that the environmental conditions governing rampart development are more varied than was considered previously. These findings also indicate that too little is, currently, known about the environmental conditions of actively-accumulating ramparts to link the morphology of ramparts to the specific environmental conditions under which they are forming.

Environmental characteristics of actively-accumulating pronival ramparts

Hedding *et al*. (2010) call for a comparison of the characteristics of actively-accumulating ramparts since it is necessary to ascertain their site and morphological attributes as well as determine the environmental characteristics under which they develop. Table 5.1 highlights that pronival ramparts have a wide geographic distribution and develop under a variety of environmental conditions. Curry *et al*. (2001) include the ramparts documented by Tinkler & Pengelly (1994) as actively-accumulating ramparts but these landforms have been questioned by Shakesby (1997) and are, on that basis, excluded here (see page 94 for discussion). Several actively-accumulating ramparts are found in Scandinavia, but there is a wide geographic and altitudinal distribution of pronival ramparts across the globe. No actively-accumulating ramparts have been documented in Africa but Grab (1996) reports a relict pronival rampart in the summit region of Mount Kenya. Pronival ramparts have been described in South America (*e.g*. Trombotto, 2000) but, to the author's knowledge, no detailed studies of actively-accumulating pronival ramparts have been published. Ramparts can be found in areas with mean annual air temperatures from -17°C (Hedding, *et al*., 2010) to 0.9°C (Hedding *et al*., 2007) and precipitation can vary greatly from almost no precipitation (Hedding *et al*., 2010) to levels of precipitation greater than 3000mm (water equivalent of snow) (Fukui, 2003). These wide ranges in temperature and precipitation at actively-accumulating pronival ramparts cast doubt on the use of pronival ramparts as specific palaeo-environmental indicators. Thus, researchers need to be cognisant of what precise palaeo-environmental or -climate information can be derived from relict pronival ramparts.

Palaeo-environmental significance

Regardless of changing snowbed dimensions, rampart genesis is dependent on the existence of a long-lasting snowbed. When the snowbeds disappear and ramparts become inactive, relict pronival ramparts are often conspicuous landforms in the landscape since the ridge or ramp of accumulated debris is disassociated from the backwall (zone of debris production). This characteristic may enable some useful inferences to be drawn from the absence or presence of pronival ramparts. The presence of relict pronival ramparts has been used in various palaeo-environmental reconstructions for Great Britain (*e.g.* Ballantyne & Kirkbride, 1986; Ballantyne & Harris, 1994) and southern Africa (*e.g.* Nicol, 1973, 1976; Marker, 1986; Lewis, 1994, 2008a; Lewis & Illgner, 2001; Grab & Mills, 2011). Ballantyne & Kirkbride (1986) used relict pronival ramparts to mark the positions of former snowbeds that accumulated under colder (more snowy) conditions and then, based on positions of these snowbeds, inferred palaeo-environmental (temperature and precipitation) estimates for the Late Quaternary. Since pronival ramparts were traditionally thought to develop at the foot of expanding (in both extent and thickness) snowbeds (Ballantyne & Kirkbride, 1986), pronival ramparts were typically used to infer environmental conditions that permitted progressively increasing snowbeds. However, recognition that pronival ramparts can develop at the foot of stable (*e.g.* Ballantyne, 1987; Hedding *et al*., 2010) or diminishing snowbeds (Hedding *et al*., 2007) dispels this traditionally held view that all ramparts extend downslope below snowbeds which are constantly increasing in extent and thickness – an observation which has noteworthy implications for palaeo-environmental interpretation.

The absence of relict pronival ramparts in areas which were/are dominated by glacial and periglacial conditions can also be particularly informative about the palaeo-environmental conditions. If debris production is sufficient and site and topographic characteristics are favourable for the development of pronival ramparts but none exist, this indicates that snow may not have persisted for sufficiently long periods for ramparts to develop on steep slopes below exposed cliffs. Thus, even if temperatures were cold enough to sustain snowbeds for extended periods, if no snow accumulated due to a lack of precipitation the landforms would have become masked by rockfall debris and not identifiable in the landscape.

Table 5.1: Environmental characteristics of actively-accumulating ramparts.

Location (latitude; longitude)	Author(s)	Altitude (a.s.l)	Mean annual air temperature (°C)	Precipitation (mm) / mean snow cover (days)	Notes
Okskolten, Norway (66°30'N; 14°20'E)	Harris (1986)	900m	-3°C (data cited from Worsley & Harris, 1974)	1032mm (data cited from Harris, 1974) / 210 (data cited from Harris, 1974)	Temperature data from Okstindsjøen (710m a.s.l.); Precipitation data from Hattfjelldal (380m a.s.l)
Kuranosake, Japan (36°36'N; 137°36'E)	Ono & Watanabe (1986); Fukui (2003)	~2500m	-2.8° C (data cited from Fukui & Iwata, 2000)	Summer precipitation > 1000mm; Winter precipitation > 3000mm (water equivalent of snow) (Fukui, 2003) / n.d.	Data from Muroda (2454m a.s.l.)
Lyngen, Norway (69°35'N; 20°15'E)	Ballantyne (1987)	760m	-1.8°C (Ballantyne, 1987)	600-850mm (Ballantyne, 1987) / n.d.	Temperature data from Tromsö and Skibotn (700m a.s.l.); Precipitation data from Jøvik and Lyngseidet (0m a.s.l)
Lassen Peak, USA (40°29'N; 121°30'W)	Pérez (1988)	2615m	<0°C (Winter: November to April) (Pérez, 1989)	1650-1700mm (Pérez, 1988) / n.d.	Data from Lessen Peak, California
British Columbia, Canada (54°14'N; 120°50'W)	Hall & Meiklejohn (1997)	1850m	High summer temperatures (≥ 20°C) (Hall & Meiklejohn, 1997)	n.d. / High winter snowfall (Hall & Meiklejohn, 1997)	Observations from Canadian Rockies (1850m a.s.l.)
Smørbotn and Romsdalsalpane, Norway (62°25'N; 27°35'E)	Shakesby *et al.* (1995); Shakesby *et al.* (1999)	800m	~1.5°C (Shakesby *et al.*, 1999)	1211mm (Shakesby *et al.*, 1999)	Data from Åndalsnes (20m a.s.l.)
James Ross Island, Antarctic (63°52'S; 57°48'W)	Strelin & Sone (1998)	100m	~-6.5°C (Strelin & Sone, 1998)	~200mm (water equivalent) / n.d.	Data from James Ross Island (0m a.s.l.)
Marion Island, South Africa (46°54'S; 37°45'E)	Hedding *et al.* (2007)	900m	0.9°C (Hedding, 2008)	~1000mm (data cited from Blake, 1996; Hedding,2006) / snow cover from May to October (data cited from Hedding, 2006)	Temperature data from Delta Kop (1000m a.s.l.); Precipitation data from Katedraalkrans (750m a.s.l.)
Grunehogna, Antarctica (72°03'S; 2°42'E)	Hedding *et al.* (2010)	1090m	-17°C (Hedding *et al.*, 2010)	n.d. / n.d.	Temperature data from Vesleskarvet (845m a.s.l.)
Krkonoše Mountains, Czech Republic (50°41'N; 15°39'E)	Margold *et al.* (2011)	1500m	0.3°C (data cited from Glowicki, 1997)	> 1500mm (data cited from Spusta *et al.*, 2003) / snow cover from November to April (data cited from Spusta *et al.*, 2003)	Temperature data from Snêžka (1602m a.s.l.); Precipitation data from Snêžka (1602m a.s.l.)
Smørbotn, Nystølsnovi and Alnesreset, Norway (62°29'N; 7°45'E)	Matthews *et al.* (2011)	800-900m; 400m; 850m	~1.5°C (Shakesby *et al.*, 1999)	1211mm (Shakesby *et al.*, 1999) / n.d.	Data from Åndalsnes (20m a.s.l.)

n.d. = no data

Lukas (2006: 725) notes that "extensive and 'mature' talus slopes would have been produced at non-glaciated sites" and "protalus ramparts would only have developed outside areas covered by glaciers" and thus the presence/absence of actively-accumulating pronival ramparts in conjunction with laterally terminating thick talus sheets along slopes could, potentially be used to reconstruct a distinct glacial limit. Sattler *et al*. (2011) indicate that the climatic conditions and the steep relief that is unsuitable for widespread glaciation favour the development and preservation of alpine permafrost, as indicated by the presence of numerous rock glaciers and protalus ramparts in valley head areas. Despite the fact that the existence of pronival ramparts is not strictly related to permafrost (*e.g*. White, 1981), Van Tatenhove & Dikau (1990) state that the existence of perennial or late-lying snow patches, a phenomenon typical of the alpine belt of discontinuous permafrost (Haeberli, 1975), in conjunction with actively-accumulating ramparts and the gradual geomorphological transition of these landforms into small rock glaciers make active pronival ramparts useful indicators of discontinuous permafrost in the alpine belt. Lewis (1994: 47) made a similar assertion when inferring "at least discontinuous permafrost" conditions at a supposed relict pronival rampart in southern Africa; referring in support to Haeberli (1985). These inferences stem from the incorrect translation of the term 'protalus rampart' used by Haeberli (1975, 1985) who used this term to denote proto-rock glaciers rather than landforms that form predominantly through the accumulation of debris at the foot of a snowbed (Shakesby, 1997). Therefore, any inferences that pronival ramparts are automatically indicative of permafrost are incorrect since, as Shakesby (1997: 413) stresses, "permafrost is not normally viewed as a requirement of rampart formation".

In the past, the difficulty of positively identifying pronival ramparts and a poor understanding of the topographic and climatic thresholds governing rampart genesis has limited the potential for palaeo-environmental inferences. This led Shakesby (1997: 410) to state that, "for many workers, fossil ramparts provide little useful palaeo-environmental information other than indicating the obvious; that climatic conditions were formerly cooler and/or more snowy". The wide range of temperature and precipitation characteristics at actively-accumulating pronival ramparts, presented in Table 5.1, substantiates this view. In contrast, White (1981: 135) suggests 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). However, it is critical that researchers are aware of the limitations of using pronival ramparts in palaeo-environmental reconstructions. Hedding *et al*. (2007) assessed rampart morphology coupled with relative-age dating, in the form of weathering rind thickness, percentage moss cover and rock hardness of the constituent material of ramparts to determine the mode of rampart genesis and then employed this evidence to infer the palaeo-environmental conditions under which the rampart formed. This showed that the pronival rampart, formed under fluctuating and possibly declining snowfall. Later, Hedding *et al*. (2010) combined a field experiment of debris transport and locality of accumulation with an assessment or rampart morphology to infer snowbed conditions during the formation of the rampart. 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 vary 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 can also be useful for palaeo-environmental inferences. Site characteristics, rampart ridge morphology, namely a proximal slope at repose and relative-age dating (Hedding *et al*., 2007), can indicate retrogressive (upslope) development whereas a distal slope at repose (Ballantyne & Kirkbride, 1986) may indicate outward (downslope) development. These contrasting modes of rampart development imply fluctuating snowbed conditions in terms of thickness and extent through time. Retrogressive development of pronival ramparts occurs under fluctuating, possibly declining snowfall, whereas outward rampart extension occurs below stable snowbeds or snowbeds which are increasing in extent and thickness. This enables ridge morphology, in the context of site characteristics, coupled with relative-age dating of the constituent material of the rampart to infer the direction of rampart genesis and associated snowbed conditions during rampart genesis (*e.g.* Hedding *et al*., 2007; Hedding *et al*., 2010). This information can be used in palaeo-environmental reconstructions but cognisance of the limitations inherent in this information should be taken into consideration.

Relict pronival ramparts as palaeo-environmental indicators in southern Africa

Based on geomorphological studies, two stables of thought have emerged with regard to palaeo-environmental conditions in southern Africa during the Late Quaternary. Initially it was suggested that high-lying areas in southern Africa (*i.e.* Eastern Cape Drakensburg, Lesotho-Drakensberg escarpment and Golden Gate National Highlands Park) were glaciated during the Late Quaternary (*e.g*. Alexandré, 1962; Sparrow, 1967; Harper, 1969; Nicol, 1973, 1976; Marker, 1986, 1990; Lewis, 2008a). This proposal has recently been revised to the notion of niche glaciations in preferential locations above 3000m a.s.l. (Grab *et al*., 2012). The other stable of thought questions the glacial evidence presented thus far (*e.g*. Boelhouwers & Meiklejohn, 2002; Sumner, 2003; Osmaston & Harrison, 2005; Hall, 2010) and uses geomorphological evidence to infer arid periglacial conditions across the high-lying areas of southern Africa during the Late Quaternary. Mark & Osmaston (2008: 604) indicate that "the most convincing sedimentary details have supported only very limited cirque glaciers at the highest elevations", presumably above 3000m a.s.l. The major question with regard to palaeo-environmental reconstructions in the Lesotho-Drakensberg and other high-lying areas of southern Africa has been that of palaeo-precipitation and not palaeo-temperatures. Even if the temperatures permitted snow to persist during the Late Quaternary, Hall (2012) questions whether enough precipitation was present during this period to form snow and accumulate into glacial ice; even in the summit regions above the escarpment of the Lesotho-Drakensberg mountains. Given the periglacial versus niche glaciation debate for high-lying areas in southern Africa, the absence/presence of relict pronival ramparts may be particularly useful in palaeo-environmental reconstructions for southern Africa during the Late Quaternary. Pronival ramparts would be expected in marginal glacial regions with persistent snowbeds and, therefore, the presence of pronival ramparts above 3000m a.s.l. would help resolve the on-going debate.

Shakesby (1997) and, more recently, Hall (2012) question the correct identification of pronival ramparts in southern Africa. Placed within a broader debate surrounding the glaciation of the Lesotho-Drakensberg region during the Late Quaternary a critical evaluation of pronival ramparts may help shed some more light on this matter. Using the diagnostic criteria suggested by Hedding & Sumner (2013), Chapter 4 of this thesis demonstrates that none of the landforms previously identified as pronival ramparts in southern Africa are clear examples. This finding also applies to the "ramparts" documented on Thabana Ntlenyana, which Grab & Mills (20110 date development to ~AD 300-1000 and not the Late Quaternary. The question then arises where would one expect to find pronival ramparts in southern Africa? The first criterion for rampart development would be below zones of debris production in the form of exposed bedrock. Second, locations where late-lying snow could prevail and, third, sufficiently steep slopes on which snowbeds could form to deliver debris would be needed for rampart genesis. In southern Africa, the cutbacks (indentations) along the Lesotho-Drakensberg escarpment (Hall, 1994, 1995; Sumner, 1994) become the prime locations for rampart development. These sheltered areas could facilitate accumulation of snow fall and persistence of snowbeds, high cliff faces of exposed bedrock could produce debris for entrapment and accumulation and sufficiently steep slopes could facilitate debris transport. The cutbacks along the Lesotho-Drakensberg escarpment, where steep slopes are overlooked by precipitous cliffs of exposed bedrock and, in preferential locations, shaded from the sun, are the most likely locality for pronival ramparts. However, no relict pronival ramparts have been found in the cutbacks thus far. It is, thus, likely that snowfall (precipitation) was too limited to enable snowbeds to persist for extended periods to facilitate rampart development during the Late Quaternary.

Ramparts as part of a continuum of talus-derived landforms

Pronival ramparts have been assessed in terms of a continuum of talus-derived landforms and as separate, independently produced landforms (Shakesby, 1997). It is plausible that pronival ramparts can, under certain climatic conditions, transform into protalus rock glaciers (*e.g*. Corte, 1976, 1987; Ballantyne & Kirkbride, 1986) and even moraines (Van Tatenhove & Dikau, 1990) but this is not a ubiquitous occurrence. Hedding *et al*. (2007) show that pronival ramparts can also develop under fluctuating, possibly declining, snowfall. Therefore, climatic amelioration resulting in diminishing snow cover can also lead the incorporation of pronival ramparts in the formation of scree deposits. This transformation could occur as the snowbed disappears and rockfall debris fills the proximal trough to create a continuous apron of debris extending from the foot of the rockwall. Thus, the view expressed by Shakesby *et al*. (1987) and Shakesby (1997) that ramparts are a part of a non-developmental morphological continuum is supported here. This could be viewed, by some, as diminishing the value of pronival ramparts as indicators of palaeo-environmental conditions but the opposite is argued: with positive identification and assessment of rampart genesis in terms of site and morphological characteristics coupled with relative-age dating, relict pronival ramparts can be useful palaeo-environmental indicators, particularly in areas which experienced marginal glaciation. The absence of pronival ramparts, such as in southern Africa, can also be particularly revealing about palaeo-environmental conditions. The morphology and relative-age dating of the pronival rampart in the context of the surrounding topography may allow researchers to infer increasing, stable or diminishing snowbed which can add considerable value to the use of pronival ramparts as indicators of palaeo-environmental conditions. However, few authors recognise the significance of post-depositional modification of pronival ramparts (*e.g.* masked by rockfall debris, solifluction) and this aspect should be considered further.

Summary

Some authors (*e.g.* Rapp & Nyberg, 1988; Shakesby, 1997) have expressed reservations with regard to the palaeo-environmental significance of pronival ramparts. Recent studies of actively-accumulating features (*e.g.* Hedding *et al.*, 2007; Hedding *et al.*, 2010) have provided a better understanding of rampart genesis and the topographic and environmental controls for their development. This enables the use of rampart morphology in the context of site characteristics coupled with relative-age dating of the constituent material to infer the general environmental conditions prevalent during the genesis of actively-accumulating pronival ramparts. However, it is stressed that the limitations of using relict pronival ramparts in palaeo-environmental reconstructions should be recognised. Furthermore, post-depositional modification should receive attention when using relict ramparts to infer palaeo-environmental conditions.

Chapter 6: Conclusions and avenues for future research

Conclusions

The overarching aim of this thesis is to improve our understanding of the genesis, identification and palaeo-environmental significance of pronival ramparts. To accomplish this aim, the history of research on pronival ramparts, which is largely focussed on relict features, has been reviewed. Research on actively-accumulating features was then addressed to provide a complete review of research on pronival ramparts which provided the necessary background to present a synthesis of how the term 'pronival rampart' has evolved and is currently used in English and several other languages. It expands on the work of Hedding (2011; Appendix A) and illustrates that the term is used in different languages with the potential to create much confusion. The term currently used to define a pronival rampart is a ridge, series of ridges or ramp of unconsolidated debris formed at the downslope margin of a perennial or semi-permanent snowbed that is overlooked by an exposed bedrock cliff. Thorn & Hall (2002: 540) succinctly note that definitional issues are "not trivial nor mere semantics, (for) our field research is ultimately steered, knowingly or unknowingly, by our conceptual or theoretical expectations. A large portion of our expectations are embedded in terminological definitions, the sharpness of these definitions reflects the sharpness of our thinking; the sharper our thinking the greater our ability to extract information from what are clearly complex landscapes". Although Thorn & Hall (2002) refer to nivation, the quote is equally applicable to pronival ramparts and many other periglacial landforms and geomorphological processes.

Shakesby (1997: 394) states that since "most of the literature on pronival (protalus) ramparts deals with supposed fossil examples with very few studies devoted to active features and/or observed processes … this has led to circular reasoning and assumptions about typical rampart form, constituent material and genesis". Thus, the focus of this thesis has been placed on actively-accumulating features. The genesis, identification and palaeo-environmental significance of pronival ramparts has been addressed, primarily based on the evidence derived from actively-accumulating features. Contributions of the thesis include the proposal of a retrogressive (upslope) mode of rampart genesis (Hedding *et al*., 2007), mode that contrasts with the conventionally envisaged outward (downslope) rampart genesis. Retrogressive development implies that ramparts can develop under fluctuating, and possibly declining, snowfall. Another contribution of the thesis is the evidence presented by Hedding *et al*.

(2010) that outward (downslope) rampart development can also occur below stable (in extent and thickness) snowbeds. This finding, coupled with the work of Hedding *et al*. (2007), indicates that the mode of rampart genesis can occur under specific environmental conditions not previously considered.

Chapter 3 integrates and synthesises existing criteria for pronival ramparts and presents a revised set of diagnostics (Hedding & Sumner, 2013). Field parameters, based on rampart morphology and site characteristics, are also suggested to help distinguish pronival ramparts from morphologically similar glacial moraines, rock-slope failures and talus-derived landforms. In chapter 4 the origin of all documented pronival ramparts in southern Africa (Nicol, 1973, 1976; Marker, 1986, 1990; Lewis, 1994; Lewis & Illgner, 2001; Mills, 2006, Grab & Mills, 2011) is assessed. Rampart origin is evaluated using a multiple-working hypothesis and the diagnostic criteria presented by Hedding & Sumner (2013). This re-evaluation reveals that none of these landforms should be regarded as pronival ramparts. Alternative origins which could be considered range from scree deposits and rock-slope failures to stone-banked lobes. Future studies must evaluate the origins of discrete debris accumulations using a multiple-working hypothesis and must assess the landform in terms of the surrounding topography, developmental history and potential post-depositional change.

Chapter 5 discusses the palaeo-environmental significance of relict pronival ramparts and highlights that they can be useful indicators in palaeo-environmental reconstructions, particularly in marginal glacial environments. However, researchers must also be cognisant of the limitations of using pronival ramparts in palaeo-environmental reconstructions. The chapter then uses the information conveyed to assess the re-interpretation of the supposed pronival ramparts in the high-lying areas of southern Africa within the context of the debate surrounding the palaeo-environmental reconstruction during the Late Quaternary for this region. The site and topographic characteristics required for rampart development stipulate that landforms must be situated on steep slopes (> 20°) below exposed bedrock cliffs of sufficient area for debris production. Steep slopes are seen as a requirement to facilitate debris transport under the influence of gravity. The cutbacks along the Lesotho-Drakensberg escarpment, straddling the border between Lesotho and South Africa, are the most likely locations for rampart genesis but no ramparts have been identified in them which raises the question about palaeo-precipitation in the form of snow during the Late Quaternary. This observation lends credence to the view held by Hall (2012) who questions whether enough precipitation was present in this region during the Quaternary to form snow accumulations that could be modified into glacial ice; even in the summit regions above the escarpment of the Lesotho-Drakensberg Mountains.

Avenues for future research

Ballantyne & Kirkbride (1986) suggested morphometric regularity among nine relict pronival ramparts across Great Britain. Ballantyne & Harris (1994) indicate that two of the landforms used by Ballantyne & Kirkbride (1986) had subsequently been reinterpreted as having alternative origins; this casts doubt on the morphometric characteristics of pronival ramparts that they suggested. Nevertheless, Lewis (1994) used the morphometric regularity suggested by Ballantyne & Kirkbride (1994) to evaluate a rampart-like feature in South Africa. Shakesby (1997) highlights that Lewis's (1994) comparison with the morphometric regularity suggested by Ballantyne & Kirkbride (1986) demonstrates more differences than similarities. More importantly, however, Shakesby (1997) notes that the use of relict ramparts to assess morphometric regularity is inappropriate and that more emphasis should be placed on the characteristics of actively-accumulating landforms. At the time, not many actively-accumulating ramparts had been documented, but over the past decade some progress has been made in this respect. In addition, progress has been made in terms of improving our understanding of the genesis and characteristics of ramparts. Thus, the opportunity now exists to reassess further the morphometric characteristics of ramparts in the context of debris production and surrounding topography. Mathematical modelling of field parameters (referred to in chapter 3) may hold the key in this regard. Its use could help elucidate what landforms should not be considered pronival ramparts rather than using morphometric regularity to positively identify ramparts.

Mathematical modelling

Mathematical modeling could provide an interesting avenue with which to positively identify pronival ramparts in the field. Based on measurements of actively-accumulating pronival ramparts certain morphometric and site characteristics could be used to develop a threshold value to help identify them as pronival ramparts. Various ratios, based on morphometric criteria have in the past been used but they have largely been unsuccessful (Ballantyne & Kirkbride, 1986) and arguably applied incorectly (*e.g.* Lewis, 1994). The problem with the morphometric ratios proposed by Ballantyne & Kirkbride (1986) is that they were (1) used in isolation, and (2) based on supposed relict examples.

Topographic controls of rampart genesis include the height of the backwall of exposed bedrock, the underlying slope on which the snowbed rests and the distance between the rampart and the backwall. These three aspects determine rampart genesis. Often ignored in research on pronival ramparts, the height (source area) of the exposed backwall should be evaluated in terms of debris production. Cognisance of factors (*i.e.* jointing, palaeo-environmental conditions) controlling debris production through time will be significant and enable researchers to place the debris accumulation in an appropriate context to then investigate the remaining two topographic controls. Research can then focus on the gradient of the underlying slope as it determines supranival debris transport across the surface of the snowbed. The last topographic control is the distance between the rampart and the source of debris (*i.e.* the backwall). According to Ballantyne & Benn (1994), the maximum distance of the rampart crest from the source of debris (backwall) is 30-70m depending on slope angle. The shallower the slope angle the further the distance can be.

Surveying, mapping and relative-age dating

Greater accuracy in surveying and mapping techniques will improve the manner in which pronival ramparts and other landforms are mapped and possibly depicted in three-dimensional models. Use of small unmanned aerial vehicles could be particularly useful to map discrete debris accumulations in relation to their surroundings. This information could then be used to create accurate three-dimensional models which could then be used to help calculate the volume of landforms to assess rampart development in relation to debris production. Finally, relative-age dating of the constituent material of ramparts would be crucial in determining the mode of rampart genesis which, in turn, will be extremely important in terms of using pronival ramparts in palaeo-environmental reconstructions. Relative-age dating of the constituent material of previously documented pronival ramparts may also help resolve some of the existing questions surrounding their development in space and time.

Owing to their 'distinct' nature many periglacial landforms are used as palaeo-environmental indicators. The significance of pronival ramparts, like cryoplanation terraces, can be useful in palaeo-environmental reconstructions when genesis and formative processes are explained. Shakesby (2014: 880) indicates that if relict ramparts are identified correctly, "they can have a limited though useful role in palaeoenvironmental reconstruction, not only by indicating the former presence of long-lived snowbeds and palaeowind direction but also, where there are sufficient (features) in an area, in reflecting any gradient in the snow line". This study has presented that in contexts where marginal glacial conditions are suggested to have prevailed in the past, the absence or presence of pronival ramparts can add considerable information to the palaeo-environmental reconstruction of the region, particularly if the mode of rampart genesis and formative processes are determined. Thus this study presents some answers on the genesis, identification and palaeo-environmental significance of pronival ramparts but it also highlights further questions for these conspicuous landforms which, to paraphrase J. Keats, illustrates that the poetry of the earth will never die …

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Appendix 1

Pronival rampart and protalus rampart: a review of terminology

D.W. Hedding

Footnote

The article appears as it did in print but it has been formatted to conform to the formatting guidelines of the thesis. Permission for inclusion has been obtained from the Journal of Glaciology under the auspices of the International Glaciological Society.

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Sir,

In the late 1980s, a series of letters in this journal (*e.g*. Butler, 1986, 1987; Ballantyne, 1987; Porter, 1987; Butler, 1987; Unwin, 1988; Wilson, 1988) described the history of the early work on 'pro-talus ramparts'. These letters also highlighted that many different terms, such as winter-talus ridge (Daly, 1912), nivation ridge (Behre, 1933) and protalus rampart (Bryan, 1934), have been used to denote these discrete debris accumulations found at the foot of firn fields. The most common of these terms was 'protalus rampart' and it became entrenched in the literature (Ballantyne, 1987) until it evolved yet again when Shakesby *et al*. (1995) proposed replacing the descriptor 'protalus' with 'pronival' since they concluded that the latter term provided a universally appropriate term to describe firn-foot debris accumulations; regardless of their position on the slope. The descriptor 'pronival' has largely gained acceptance in literature (*e.g*. Hedding, 2008), while some studies (*e.g*. Hedding *et al*., 2010) use 'pronival (protalus)' so as to avoid any ambiguities. Several recent studies (*e.g*. Lewis, 2011) continue to use the descriptor 'protalus' since interchanging the descriptor 'protalus' with 'pronival' has not been very problematic in the literature thus far. Scapozza *et al*. (2011) have, however, recently proposed that the term 'protalus rampart' be used to define small permafrost creep phenomena (embryonic rock glaciers) in contrast to the former usage of the term to describe pronival ramparts. This may lead to some confusion in the literature because the differentiation of embryonic rock glaciers from pronival ramparts may prove difficult, particularly in relict features, since these features are morphologically similar. To further compound the difficulty in differentiating these features is that many of the existing 'diagnostic criteria' used in the identification of pronival ramparts are plagued by circular arguments and assumptions about typical form, constituent material and genesis (Shakesby, 1997). Therefore, this paper aims to determine if the terms 'protalus rampart' and 'pronival rampart' can co-exist in literature by investigating the applicability of existing 'diagnostic criteria' that may be used to differentiate embryonic rock glaciers from pronival ramparts.

A pronival rampart, formerly referred to as a protalus rampart, is defined as a ridge, series of ridges or ramp of debris formed at the downslope margin of a perennial or semi-permanent snowbed, which is typically located near the base of a steep bedrock slope in a periglacial environment (Shakesby, 2004). Shakesby (1997) highlights that pronival ramparts are mostly viewed as separate, independently produced forms of modified talus occurring in a nondevelopmental morphological continuum of unmodified talus but other researchers (*e.g*. Haeberli, 1985) argue that ramparts represent part of a linear developmental continuum of rock glacier and moraine formation. Stemming from the work of Haeberli (1985), Scapozza *et al*. (2011) have recently proposed that the term 'protalus rampart' be used to define small permafrost creep phenomena (embryonic rock glaciers). The alternative usage of the term 'protalus rampart' by Scapozza *et al*. (2011) within the new genetic definition of active rock glaciers as the visible expression of cumulative deformation by long-term creep of ice/debris mixtures under periglacial conditions (Berthling, 2011) may, in theory, allow the term 'protalus rampart' to co-exist with 'pronival rampart'. However, the morphological similarities of pronival ramparts and incipient or immature rock glaciers make it difficult to distinguish between these features in the field. Pronival ramparts are typically differentiated from embryonic rock glaciers through the identification of specific morphological and sedimentological characteristics (Hedding *et al*., 2010) but use of these 'diagnostic criteria' may prove inappropriate when differentiating embryonic rock glaciers from pronival ramparts.

Curry *et al*. (2001) indicate that well-developed protalus rock glaciers can be differentiated from pronival ramparts since these features are typically lobate in plan form, greater in length (down-slope) than in width (across-slope), exhibit a convex distal slope, terminate >70m from the talus slope and most distinctively they comprise meandering and closed depressions, downslope ridges and furrows, and transverse ridges and depressions. Many of these 'diagnostic criteria' are, however, inappropriate for the positive identification of embryonic rock glaciers since these features would lack many of the characteristics of well-developed protalus rock glaciers; making it extremely difficult to differentiate these features from pronival ramparts in the field. To further complicate the differentiation of pronival ramparts from embryonic rock glaciers Shakesby (1997) highlights that, although rampart development is the result of supranival and subnival processes, pronival ramparts may also comprise permafrost and exhibit associated permafrost creep. Therefore, the identification of permafrost creep cannot be used to positively differentiate embryonic rock glaciers from pronival ramparts. In addition, Shakesby *et al*. (1999) have identified snow creep as a subnival process responsible for pronival rampart formation and snow creep may generate various morphological characteristics that may be exhibited by an embryonic rock glaciers derived from permafrost creep. Thus this paper rejects the alternative usage of the term 'protalus rampart' to denote embryonic rock glaciers until such time that diagnostic criteria are identified by which pronival ramparts can be differentiated from other talus-derived landforms. Instead, it is suggested that protalus rock glacier be used to denote embryonic rock glaciers. This is critical to avoid the incorrect identification and associated palaeoenvironmental inferences that have plagued research on pronival ramparts in the past; particularly since relict protalus rock glaciers could be used to infer former permafrost conditions whereas pronival ramparts do not require permafrost for their formation.

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"…Would that the pencilled outlines in the pocket diaries have been written out elsewhere more at length; and yet how short would have been their endurance as the centuries roll by, even had they been engraved on tablets of stone with an iron quill."

W.M. Davis (1922)

Biographical Memoir of Grove Carl Gilbert 1843-1918