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On the geomorphic evidence for a Late Quaternary periglaciation of the main escarpment region of eastern southern Africa

by

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Submitted in partial fulfilment of the requirements for the degree of
Doctor of Philosophy (Geography)

in the Faculty of Natural & Agricultural Science
University of Pretoria
Pretoria

March 2003

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ABSTRACT

Conflicting reports from geomorphic studies appear in the literature describing the environment of the southern African Main Escarpment region adjacent to the Lesotho Highlands during the cold phases of the Late Quaternary. Evidence cites limited glaciation and/or periglacial conditions with or without permafrost. The thesis emphasises debates and presents arguments for alternative interpretation of landforms previously described in the literature as indicative of specific cold environments. Field investigations into the distribution and characteristics of openwork accumulations in southern Africa show that blocky accumulations are found within a range of climatic conditions, including arid and semi-arid environments. Mode of emplacement is highlighted as the critical factor in association with a periglacial environment. Relict openwork block accumulations in the Lesotho highlands area around Thabana Ntlenyana, the highest summit in the escarpment range, supports the contention for a relatively arid periglacial environment during the Late Pleistocene. Findings militate against either deep snow cover or localised glaciation of insolation-protected south-facing slopes. The evidence for periglacial conditions is supported by the presence of relict sorted patterns that indicate deep seasonal freeze. Contemporary soil temperature monitoring indicates a near-surface current seasonal freeze of two and a half months which would have been prolonged and deepened under depressed temperature. No specific evidence for periglacial conditions is found for the escarpment region in the Amatola mountains.

ACKNOWLEDGEMENTS

Many thanks to my supervisor, Ian Meiklejohn, for his continued support, encouragement and advice while compiling this thesis; in the field, in discussions and working through manuscript drafts. Support and patience from the staff in our department is greatly appreciated. Thanks also to the company of many colleagues, friends and students in the field, particularly that of Werner Nel, Jan Boelhouwers and the encouragement received from Kevin Hall. Thanks to co-authors of papers; for your initiatives, contributions and general involvement. Many others were involved in small and large ways. Specific acknowledgements, including financial support where applicable, are given at the end of each of the papers that comprise the two sections of the thesis. You have not been forgotten!

My extended family provided enormous encouragement while undertaking this research. Special thanks to my father, Paris, Megan and Julia. To my wife, Julienne, for her love and belief in me, and to my "new" family for their support and tolerance - many thanks. Most importantly, I am forever appreciative of the blessings of our Creator; for making this beautiful world and hence this project possible.

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INTRODUCTION

The Quaternary glacial and periglacial history of southern Africa has been the focus of much attention in the geomorphic literature emanating from the sub-continent since the 1940's. Research into southern African cold-climate landforms and processes (subsumed under the auspices of "Climatic Geomorphology") totalled 22% of the papers published on the geomorphology of southern Africa pre-1985, and 28% between 1986-2000 (Beckedahl *et al.*, 2002 [Appendix 1]). A similar trend is apparent at local conference presentations. Of the ninety-nine articles appearing in the mainstream international geomorphology journals (up to the beginning of 2001), fourteen articles specifically focussed on the glacial and periglacial environment of southern Africa. In comparison, twenty articles were published on the geographically-vast arid and semi-arid environments and nine on the important fluvial components of the landscape (Table 1). To date, over one hundred publications in total have appeared in various forms locally and internationally on the topic (see de Villiers and Boelhouwers, 2000).

Notwithstanding this, there is still no consensus on the actual conditions around the Late Pleistocene glacial period; a deficiency that is best illustrated by the numerous review or discussion documents that have appeared over the past decade or so (Hall *et al.*, 1991; Boelhouwers, 1991, 1995; Hall, 1992; Lewis, 1996a, b; Grab, 1998, 2000; Sumner and Meiklejohn, 2000; Boelhouwers and Meiklejohn, 2002). Arguments for glaciation and for periglaciation of the mountainous regions of the Western Cape, and the Escarpment regions of the Eastern Cape and Lesotho/KwaZulu-Natal have been presented. The most controversial, and most studied, region is the Drakensberg and Lesotho Highlands. Problems appear to stem from, first, the qualitative nature and lack of rigour in studies (see Hall, 1991; 1992) and, second, the apparent contradictory evidence when spatially contextualised; such as the existence of low altitude relict ice-wedges and rock glaciers (Boelhouwers and Meiklejohn, 2002). The situation is compounded by the relatively poor knowledge of the cold-climate landforms with respect to their actual processes of formation and environmental controls. For example, the debates surrounding nivation processes and forms (Thorn, 1990), actual mechanisms driving sorted pattern formation (Kesler and Werner, 2003), the relative absence of detailed studies on active

protalus (pronival) ramparts (Shakesby, 1997), poor understanding of the mechanisms of apparently frost-shattered bedrock (Hall *et al.*, 2002), and the polygenetic origins of blockfields and blockstreams (Rea *et al.* 1996; van Steijn *et al.*, 2002; Boelhouwers and Sumner, 2003). All of these processes or landforms have been cited as geomorphic evidence for the palaeoenvironmental of the mountain areas in the Drakensberg and Lesotho Highlands.

Sub-discipline	1975-1980	1981-1985	1986-1990	1991-1995	1996-2000	TOTAL
Evaluation and mapping			1			1
Structural, neo- and morphotectonics		4			1	5
Macro-geomorphology	1			2	1	4
Theory and general review				1		1
Slopes		3	3	2	1	9
Soil erosion			2	3	2	7
Sediments and pedogenic materials					2	2
Cold climate landforms		1		7	6	14
Arid and semi-arid landforms	1	7	3	4	5	20
Quaternary and palaeo-landforms	1	1	1	1	1	5
Coastal			1		1	2
Karst			1		1	2
Weathering			3	3	2	8
Fluvial		1	2	1	5	9
Process			1	1		2
Landscape evolution	3		2	3		8
TOTAL	6	17	20	28	28	99

Table 1: Number of southern African published articles in mainstream geomorphology journals* for various sub-disciplines (see also Appendix 1).

*Journals: *Geomorphology*, *Geografiska Annaler (A)*, *Earth Surface Processes and Landforms*, *Progress in Physical Geography*, *Zeitschrift für Geomorphologie*, and *Permafrost and Periglacial Processes.*

Another, but fundamental, issue lies in the absence of contemporary climatic data from the southern African mountain areas upon which to base palaeoclimatic reconstructions. Basic climatic data, such as air temperature and precipitation, and crucial information such as ground temperature conditions, are virtually absent from the literature. Where actual field data are available they are either observations on frost penetration (eg. Grab, 2002) or short-term monitoring on specific landforms such as frost mounds (Grab, 1997a). Continuous records do not exist at the altitudes where relict and active landforms are recorded (mainly above ~2800m a.s.l.). Air temperatures and precipitation values are estimated or extrapolated from stations at lower altitudes (eg. Grab, 1997b). A perusal of the literature shows a variation in estimated mean annual air temperature (MAAT) in the Lesotho Highlands between 4°C and 7°C (Boelhouwers, 1994; Grab, 2002). Although the range may initially appear to be small, the implications under a 5.5° to 6°C drop in temperature at the Last Glacial Maximum (~18 000 B.P.) can be significant (Grab, 2002); for example with the prediction of permafrost. Precipitation at high altitudes remains entirely unknown; values extrapolated from lower altitudes by Shultze (1979) are still cited (eg. Grab, 2002) as these are the only estimates available. Contemporary snowfall conditions remain largely unknown or based on observation from the Drakensberg foothills.

Understanding the palaeoenvironmental conditions in the southern African mountains is of importance in a global context. A very strong bias exists towards understanding the Northern Hemisphere periglacial and permafrost environments while relatively little is known of contemporary and previous cold climate conditions in the Southern Hemisphere (Boelhouwers and Hall, 2002). Nonetheless, sites such as the Tasmanian blockstreams in Australia have stimulated a reconsideration of the origins of openwork accumulations (Caine, 1968; cf Boelhouwers and Hall, 2002). The mountains of southern Africa are distinct in that, unlike much of the Northern Hemisphere, the sub-continent was not glaciated in the Quaternary. As such, cold-climate landforms do not have the extensive depositional remnants from glaciation in which to form, and periglacial landforms may not be as well developed or as ubiquitous as in other environments due to material constraints. French (2000) suggests that the most convincing relict periglacial landscapes are probably the never-glaciated parts of north-western Arctic North America. An obvious question thus stemming from this is: what constitutes a true periglacial environment?

While answering the above question is not intended as a focus of the thesis, a working definition of what constitutes a periglacial environment is required. Both glacial and periglacial (with or without permafrost) conditions have been cited as elements of the Late Pleistocene environment of the mountains of southern Africa. While the concept of what constitutes, for example, a glacial environment or permafrost is relatively self-explanatory, the definition of a true periglacial environment is somewhat enigmatic. Originally introduced into the literature by Lozinski in 1909, the term has become accepted as defining an environment where frost action and/or permafrost impacts on landscape initiation or development (Thorn, 1992; French, 1996). It has been described as synonymous with a 'cold, non-glacial' environment (French, 2000). However, defining a 'cold environment' is not straightforward and probably depends on the discipline requirements (such as in engineering) or in specific studies such as 'frost weathering' (see Hall, 2001, p.6-12 for a discussion). Exact precipitation and temperature (usually air temperature) requirements vary (see for example Embleton and King, 1975); although these are unreliable as they may not reflect actual moisture availability or soil temperature conditions. Specific precipitation and temperature conditions receive less emphasis in more recent discussions (Thorn, 1992; French, 2000). Emphasis must thus lie in the processes associated with ground-ice phenomena when defining a periglacial environment, which by necessity then require moisture to be present and for ground temperatures to be amenable to water freezing. In the context of this thesis, the encompassing definition presented by French is applied where "the term 'periglacial' is regarded as synonymous with 'cold, non-glacial' ... environments in which frost-related processes and/or permafrost are either dominant or characteristic" (French, 2000, p. 35).

The aim of the thesis is to provide a contribution to an understanding of the Late Pleistocene palaeoenvironment of mountains in southern Africa using geomorphic landforms. As a geographical focus area, the region under consideration is the high altitude belt associated the eastern regions of the Main Escarpment of southern Africa (Figure 1) where evidence for previous glacial and periglacial conditions, including permafrost (see Sumner and Meiklejohn, 2002 [Section 1]; Boelhouwers and Meiklejohn, 2002) has been cited. Objectives include commenting on and re-evaluating existing literature, and the presentation of new evidence so as to assist in understanding of what characterised the geomorphic environment during this period. The specific landforms under scrutiny are relict openwork accumulations and sorted

patterned ground found at high altitude. Since numerous relict landforms exist (both in type and number), the intention in not to provide and exhaustive assessment of all landforms. However, the attributes of openworks and sorted ground appear to be such that they can provide a meaningful indication of the geomorphic and climatic environment under which they formed.

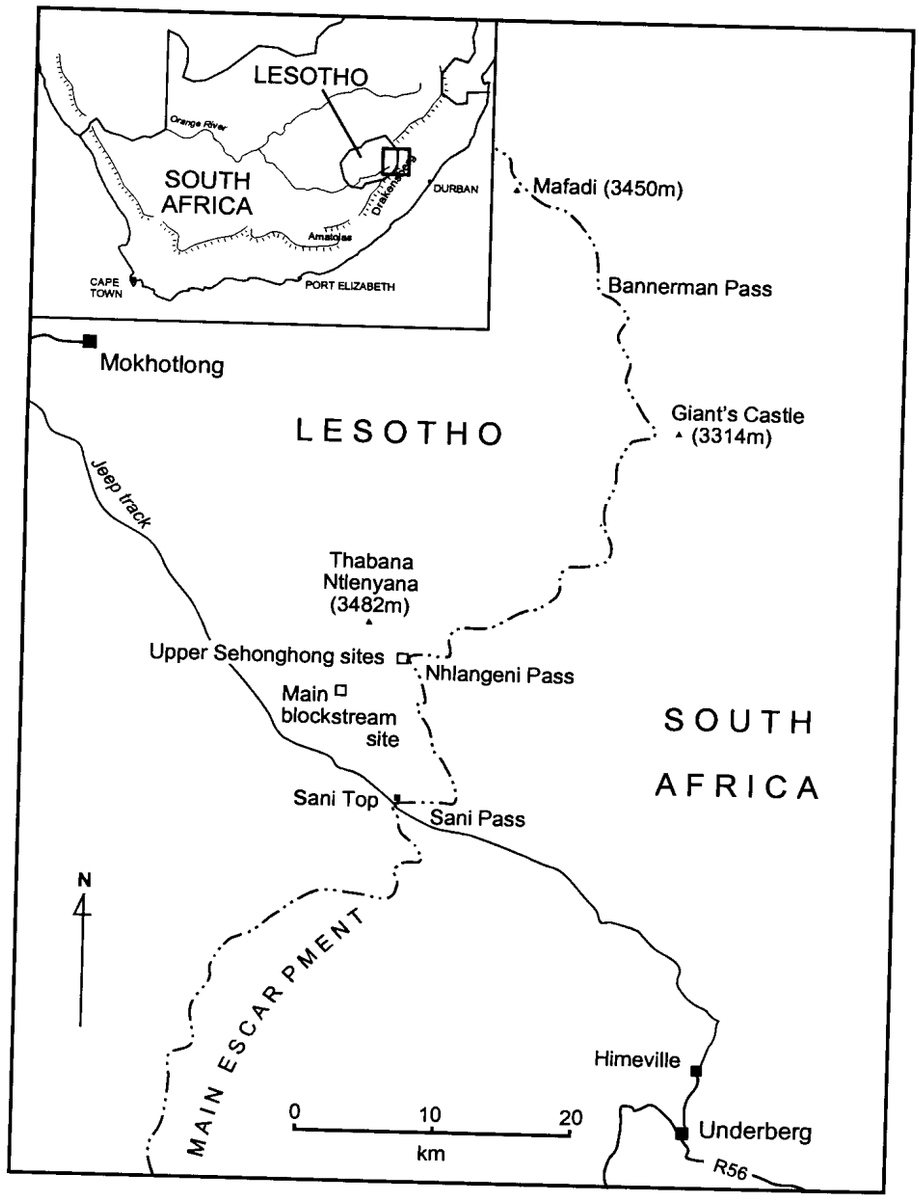

Figure 1: The Main Escarpment of southern Africa and locations of major study sites. In the enlarged area the Main Escarpment approximates the Lesotho - South Africa border. Topographic details are provided in site maps in the relevant sections.

The thesis is a compilation of documents produced by the author (some documents are co-authored), either already published or in various stages of submission and review for journals and comprises two main sections. Section 1 constitutes three Chapters: a book chapter from a South African geography text and two commentaries to journals on previously published articles. The three Chapters serve to introduce the reader to the study area and to some issues and debates prevalent in the southern African periglacial literature.

Section 2 comprises six Chapters, each originating from articles that present new field data and discussions on relict geomorphic phenomena, and their palaeoenvironmental significance. Both Sections are introduced with a Preface. The publication status of each article is noted on the Chapter title page and where papers are co-authored the relative contributions by the authors are noted in the Preface.

Some repetition occurs between Chapters, particularly in the introductions in the various documents. Unfortunately, this cannot be avoided since the documents are included as the text appears in the literature or in submission for publication. Relevant acknowledgements and references are included at the end of each Chapter. Where possible the style of graphical presentation is similar although published documents may show some variation due to external editorial requirements. Two documents by the author that are related to the thesis but not integral to the discussion are included in the Appendix. These are copied as they appeared in the original reprints and reference is made to them the relevant Chapters.

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SECTION 1: CONTEXT and COMMENTARIES

PREFACE

Section 1 comprises three Chapters as follows:

Sumner, P.D. and Meiklejohn, K.I. (2000). Landscape evolution in a changing environment. In Fox, R. and Rowntree, K. (Eds), *The Geography of South Africa in a Changing World*, Oxford: Cape Town, 304-325.

Sumner, P.D. (1995). Cutbacks in the Natal Drakensberg Escarpment: comments on an hypothesis on their origin. *South African Journal of Science*, 91, 285-286.

Sumner, P.D. (Forthcoming). Comment on "Characteristics and palaeoenvironmental significance of relict sorted patterned ground, Drakensberg plateau, southern Africa" by S.W. Grab. *Quaternary Science Reviews*.

The first Chapter of Section 1 is a chapter[1] co-authored with Ian Meiklejohn for a geography text book for undergraduate readership. The chapter focusses on geomorphic processes in mountain environments including the Drakensberg and Lesotho Highlands region. Readers are introduced to the contemporary geomorphic environment and to the relict Quaternary glacial and periglacial features. Issues regarding the interpretation of features and their spatial arrangement are also introduced. Glacial evidence is criticised and a periglacial landscape in the Late Pleistocene is supported. The theories behind rock weathering processes are summarised, their interdependence and interrelationships within mountain environments highlighted and the application of weathering to palaeoenvironmental interpretation is discussed. (The section on weathering was authored mainly by Meiklejohn.) Although the book[2] is aimed at undergraduate students in geography many of the issues discussed or highlighted in this chapter are intended as a post-graduate introduction to encourage further reading or research. On this basis it serves as an appropriate introduction and background to the thesis.

[1] One Table and one figure which appear in the book chapter are deleted as they are not directly relevant.

[2] Other chapters in the book are referred to as "Chapter xx" and do not apply to the thesis Sections

Sumner and Meiklejohn (2000) highlight an apparent lack of rigour in field studies of relict landforms and the absence of alternative mechanisms of formation being considered; a point that is further emphasised in the following two commentaries to journals; The first paper (Published in *South African Journal of Science* in 1995) criticises an hypothesis for niche glaciation within cutbacks on the KwaZulu Natal Drakensberg escarpment, notably the Bannerman Pass cutback (Figure 1, p.5). While no new field data are presented, the commentary serves to draw readers to possible palaeoenvironmental misconceptions that can arise from the hypothesis. (Additional comments derived from field data from the escarpment region and pertaining the glaciation of cutbacks are, however, included towards the end of Section 2.)

The second paper, submitted to *Quaternary Science Reviews* (*QSR*), is a commentary on an article published in *QSR* on relict sorted patterned ground near the Mafadi and Thabana Ntlenyana summits in the Lesotho highlands (Figure 1, p.5). Concerns are expressed on the interpretation of the landforms as true sorted patterns, the depth of freezing presented and specifically the implied presence of permafrost in the Late Pleistocene. Generalised palaeoenvironmental conditions stemming from the article regarding snow accumulation, glacier formation and permafrost distribution are criticised. Submitted to *QSR,* the commentary has been accepted but a shortening of the text has been requested by the Editor. It appears in this thesis in its original and most detailed form as submitted to the journal. As with the first commentary, no new evidence is provided in the paper. New evidence is presented and discussed in Section 2.

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LANDSCAPE EVOLUTION IN A CHANGING ENVIRONMENT

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Book chapter in: Fox, R. and Rowntree, K. (2000), *The Geography of South Africa in a Changing World*, Oxford: Cape Town, 304-325.

INTRODUCTION

Geomorphological processes are directly influenced by the environment within which they operate. Landforms and landscapes in turn reflect the environmental conditions that existed during the period of their formation. The concept of distinctive landscapes or landscape assemblages associated with specific climates has been a dominant philosophy within international geomorphology and has given rise to the field of 'climatic geomorphology' (Thorn, 1988). Central European geomorphologist have long been proponents of the idea that regional geomorphology is a response to climate.

In a time when predicting environmental changes is recognized as important for the well being of society (see Chapter xx), understanding the geomorphological response to environmental change is becoming increasingly relevant. Geomorphological features can be useful indicators of past environments. In order to predict possible future landscape changes it is first necessary to understand the geomorphological response to previous environmental change.

Understanding the past and present to predict the future is a difficult task. One of the greatest challenges facing geomorphologists is attempting to interpret the physical landscape is the development of an understanding of processes, particularly the identification of the type and rate of processes within both the present day conditions and those occurring during previous climatic fluctuations. One of the most important fields of international geomorphological research involves the use of relict landscape features to determine certain palaeoenvironmental variables such as temperature and moisture conditions. A serious problem hindering the interpretation of landscape features is that relict landforms may have been obliterated or their features reworked by other processes. An example would be evidence for marginal glaciation reworked by modern fluvial processes. Lithological and structural control, for example, contribute to the concept of strength equilibrium slopes. On rock-dominated slopes in southern Africa, such as the Drakensberg main escarpment, slope gradients are maintained in equilibrium with their underlying rock mass strength. The climatic influence appears to be less important (see Moon, 1990).

Notwithstanding this, certain landforms can be attributed to specific climatic conditions and can be used as environmental indicators. For example, glacial environments require specific temperature and precipitation conditions conducive to substantial ice mass build-up. Protalus (pronival) ramparts require lower snowfall conditions and the existence of snowbeds adjacent to cliff lines where weathered material from the cliff moves across the snow surface and deposits downslope (Shakesby, 1997). Ice wedge casts, deep vertical cracks in the soil caused by thermal contraction and filled with ice, occur in moist periglacial conditions with annual air temperatures below -6°C. Investigations of landforms have the potential to provide an indication of general climatic conditions. Some of these features found in southern Africa and used as palaeoenvironmental indicators are discussed below. Together with additional evidence from other disciplines, such as the palynological evidence found in sediments, geomorphological investigations can make a meaningful contribution to palaeoenvironmental reconstruction.

Meadows (1988, p.307) summarises the array of geomorphological features that have been used as evidence for different environmental conditions in the Quaternary. These include fluvial, alluvial and colluvial sediments, lake levels and lake sediments, pans, dunes, marine and estuarine sediments, archaeological evidence, palaeosols, duricrusts and periglacial and glacial features.

Due to the relative scarcity of continental land in the southern Hemisphere, South Africa is geographically strategically located to assist with worldwide interpreting of landscape evolution under different palaeoenvironmental conditions. While temperature and precipitation fluctuations and subsequent landscape response are reasonably well documented for the Northern Hemisphere (for example the extent of the Pleistocene ice sheets), few definitive geomorphic palaeoenvironmental data exist for southern Africa. Understanding geomorphic response in southern Africa, both past and present, is thus of international interest.

Geomorphic processes are generally more active in high altitude environments. This is due to the high slope gradients, generally higher precipitation, rapid changes in temperature, poorly developed soils and sensitive vegetation found in mountainous regions. As a consequence, any alteration of the climate or the environment will rapidly manifest itself in changing geomorphological processes. For example, a decrease in global temperatures and increased

precipitation could result in a lowering of the snow-line (and associated nival processes) in mountainous regions as well as alpine glacial advance. Mountainous areas thus offer ideal locations for interpreting geomorphic response to climatic change. This chapter will focus on both the current geomorphic landscaping processes and landscape evolution in the mountainous environments of southern Africa (Figure 1). This includes the Main Escarpment and Drakensberg mountains, the Lesotho highlands and the Eastern and Western Cape mountain regions.

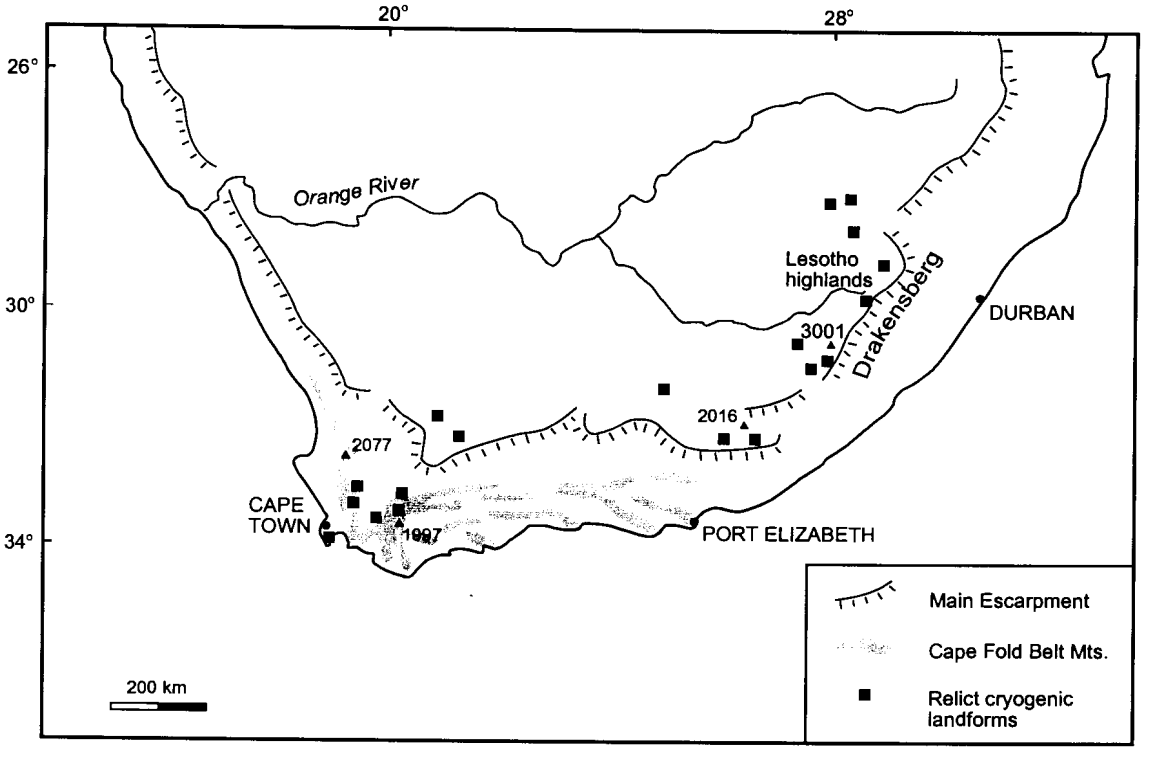

Figure 1: Locations of recorded relict cryogenic landforms (after Marker, 1995)

SOUTHERN AFRICAN QUATERNARY GEOMORPHOLOGY

Southern Africa has experienced at least seven glacial events in the past, the most significant being the Dwyka Glaciation (300 million years ago) of which tillite remnants are particularly conspicuous in southern Africa (Chapter xx). It is virtually impossible, however, to envisage geomorphological evolution over such large time scales. Consequently, much of the geomorphological evidence for climatic change has focussed on the Quaternary (the last two

million years) with greatest evidence coming from the Late Pleistocene and Holocene (the last 40 000 years) which fall within the range of carbon dating.

Southern Africa has undergone continuous climate changes throughout the Quaternary, ranging from alternating glacial and interglacial conditions (with a periodicity of about 100 000 years) through to shorter-term fluctuations in climate and weather conditions (see chapter 3; Partridge, 1997). These climatic changes have left their imprint on the landscape.

Southern African glacial and periglacial geomorphology

Under current climatic conditions, glacial and periglacial conditions worldwide are restricted to high latitude and high altitude regions. Evidence for glacial and periglacial conditions during the Quaternary has been found in the mountainous regions of southern Africa. A substantial proportion of geomorphological research in southern Africa, particularly over the past two decades, has focussed on past and present glacial and periglacial features (Boelhouwers, 1995). Although few problems are encountered in defining a "glacial" region, the definition of a "periglacial" region is more problematic. The term periglacial was originally used to denote the non-glaciated, but frost affected regions adjacent to the Pleistocene ice sheets. The regional definition was later refined through a combination of temperature and precipitation conditions; for example that periglacial activity occurs where mean annual temperatures are below 0°C and mean annual precipitation is in the region of 0 to 1500mm, regardless of the proximity to glacial activity (see Thorn, 1992). According to these and other suggestions as to what constitutes a periglacial environment (for example Thorn, 1992), no region in southern Africa is truly periglacial in nature today. Studies on current periglacial activities related to frost action are restricted to the Western Cape, Eastern Cape Drakensberg and the High Drakensberg/Lesotho Highlands suggesting current marginal periglacial conditions in the higher mountain areas of southern Africa (Lewis, 1996; Boelhouwers, 1998a; Grab, 1998).

Current (marginal) periglacial activity

Active periglacial features are recorded in the Lesotho Mountains and to a lesser extent the adjacent Escarpment, and in the Hex River Mountains of the Western Cape. In the Lesotho

Highlands these features include thufur (frost mounds), needle-ice, sorted patterned ground caused by soil freezing and thawing, and non-sorted patterned ground (circular plant growth forms) above 3000m (Boelhouwers, 1991; Grab, 1998). Sorted patterned ground is also found in the Eastern Cape Drakensberg at altitudes above 2900m (Lewis, 1996).

Other features include stepped micro-relief, which occurs both above and below the Escarpment in the form of cattle steps and terracettes, but they may not all be attributed to frost action. Stone- and turf-banked lobes and steps are described at high altitudes in the Drakensberg. Since, however, the nature of their formation is unclear, reservations are expressed as to their periglacial origin (Boelhouwers, 1991). Active stone- and turf-banked lobes are reported in the Hex River mountains where soil frost activity can give rise to micro-patterned ground (Boelhouwers, 1998a). Detailed investigations of frost related activity in the Western Cape mountains are provided by Boelhouwers (1998a) and for the high regions of the Drakensberg by Grab (1997). In general, the current periglacial activity in southern Africa can be described as limited, with the region exhibiting only marginal periglacial activity at high altitudes. The presence of these features does, however, provide the opportunity for process studies on active features. The marginal nature of periglacial activity and the susceptibility of landscape features to climatic change facilitates studies of landscape response to environmental change. Previous landforms, for example those resulting form an intensification of frost-related processes under a cold climate, may remain in the landscape as relicts and indicators of past climatic conditions.

Relict glacial and periglacial landforms in southern Africa

Numerous relict (or fossil) periglacial and glacial features formed under previous depressed temperature conditions are proposed to exist in the mountainous areas of southern Africa, including the Lesotho Highlands, Eastern Free State, KwaZulu-Natal and Eastern Cape Drakensberg, Amatola mountains and the Western Cape mountains (Figure 1). Relevant features include relict erosional and depositional landforms associated with cold climate geomorphic processes. The types of relict periglacial and glacial features found in southern Africa, with brief descriptions and locations, are listed in Table 1. A bibliography on current and relict periglacial activity in southern Africa is available (Boelhouwers, 1998b), while further descriptions of periglacial processes can be found in texts such as French (1996).

Relict feature	Definition	Location
Blockfield	Open work (no interstitial fines) block accumulations generally on low gradient slopes formed by *in situ* weathering (often suggested as freeze-thaw).	Lesotho highlands
Blockstream	Open work block accumulations that have a downslope stream-like appearance.	Drakensberg/ Lesotho highlands
Glacial striae	Scratches on a rock surface characteristic of glacial movement.	Eastern Cape Drakensberg
Nivation cirques	A hollow, open downstream but bounded upstream by a cliff or slope and formed by nival (snow related) processes.	Lesotho highlands, Eastern Free State
Niche glaciers	Small glaciers found in protected sites.	Drakensberg Main Escarpment
Rock glacier	Thick lobate mass of coarse material moving downslope through deformation of internal ice or frozen sediments.	Eastern Cape Drakensberg
Protalus ramparts	Ridge of predominantly coarse deposit formed parallel to the slope at the base of a snow patch.	Eastern Cape Drakensberg.
Stone-banked lobes (terraces)	Stone fronted lobes (terraces) formed though solifluction and/or sorting by freezing and thawing.	Drakensberg.
Screes	Open work block deposits (of cryogenic origin) on slopes below a cliff-line.	Amatola mountains, Eastern Cape
Valley Asymmetry	Valleys with different valley-side gradients caused by different (aspect related) slope processes.	Drakensberg Lesotho highlands

Table 1: Brief definitions, general location and main references for relict Quaternary periglacial and glacial features found in southern Africa (see Boelhouwers, 1995, 1998b).

An altitudinal distribution of periglacial features, where specific features are associated with specific altitudinal (and hence temperature) zones, has been proposed for southern Africa (Marker, 1995). The intention of proposing an altitudinal zonation for relict features is to

establish temperature and precipitation conditions and their altitudinal and latitudinal distribution across southern Africa during the period of their formation (the Quaternary), and thus contributing to palaeoenvironmental reconstruction. Marker (1995) correlates fossil Pleistocene periglacial and glacial evidence to altitude and latitude (Figure 2). Findings show minimum altitudes for relict cryogenic features to be in an inverse relationship to latitude, thus establishing minimum altitudes for cryogenic activity (and hence a snow-line) for southern Africa.

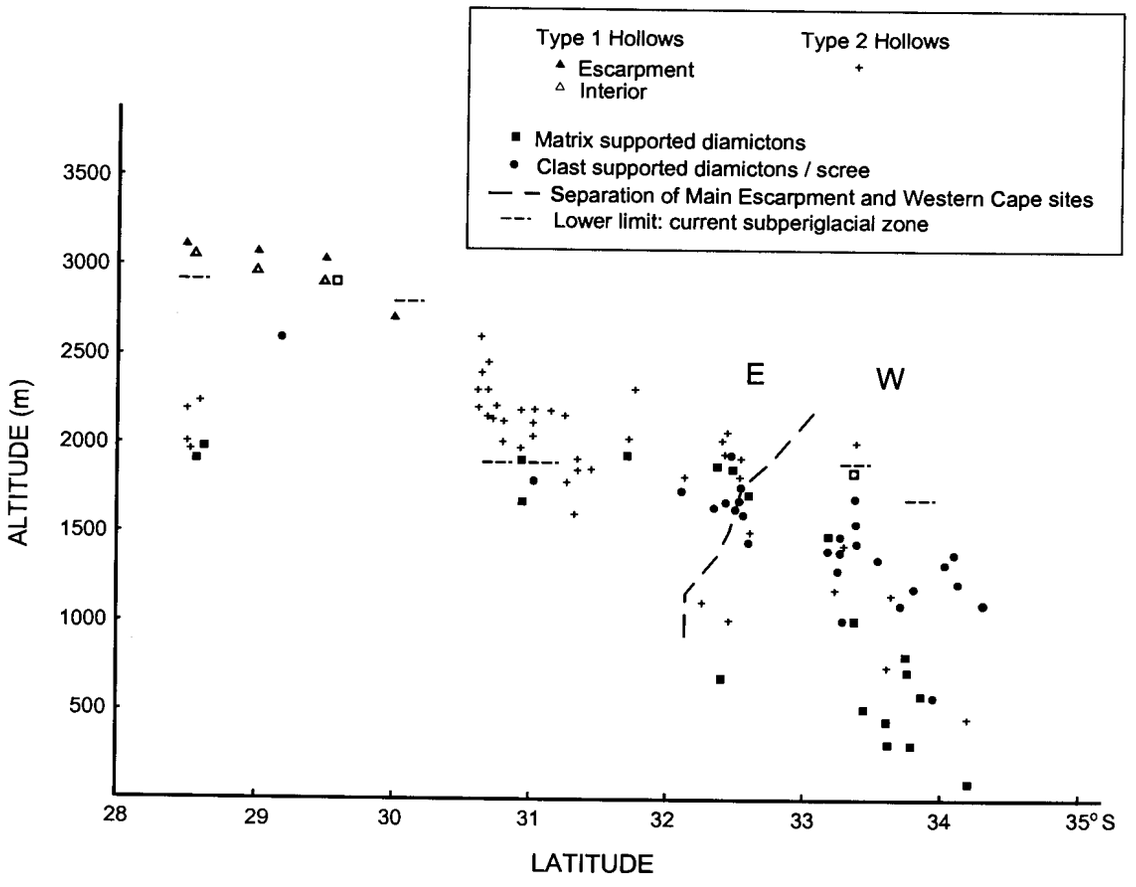

Figure 2: Altitudinal distribution of relict cryogenic landforms in southern Africa (after Marker, 1995).

This has important palaeoenvironmental implications. However, the rate of decrease in minimum altitude of cryogenic activity from in the region of 2000m at 28.5°S to sea level around

34°S is quite remarkable, given the lower rates of altitude-latitude temperature depressions for Colorado and New Mexico and Australia (Marker, 1992). Alternatively, it is possible that the altitudinal distribution of cryogenic features in southern Africa is predominantly dictated by lithological, altitudinal and relief distribution. Given that the subcontinent has experienced different phases and extremes of cold temperature conditions and precipitation in the Pleistocene (Partridge, 1997), exact correlation of cryogenic activity to landforms at specific time periods is difficult and constructing any general model will prove problematic.

Process (and climate) -form relationships are difficult to establish even under current conditions. It is not surprising that the exact nature of formation of the proposed relict periglacial and glacial features and their palaeoenvironmental implications in southern Africa has raised many debates. Of particular interest is the debate surrounding Quaternary glacial and marginal glaciation of the mountainous areas. Marker (1991) proposes marginal glaciation of the Lesotho highlands under arid conditions, while Hall (1994) and Grab (1996) present evidence that suggests localised (niche) glaciation in the Escarpment vicinity. In contrast to the proposed glacial evidence from the Lesotho highlands, Grab and Hall (1996) suggest possible formation of the Lesotho/Drakensberg hollows by "bog cirque" development under wet conditions, while Sumner (1995) criticises evidence presented for Escarpment niche glaciation on the lack of field data and possible alternative modes of formation. Similarly, Pleistocene glacial evidence for the Eastern Cape Drakensberg has been recently criticised and further investigations and alternative hypotheses require consideration. The presence of as yet undated blockfields and blockstreams in valleys in Lesotho indicates that glaciation could not have post dated their formation. The geomorphic activity of mountainous areas provides a further complication, as it is likely that evidence for any glacial activity may well have been removed. It appears unlikely that a generally accepted model for glaciation of southern Africa in the Quaternary will be reached at this stage.

The evidence presented for previous periglacial activity has not escaped scrutiny. Valley asymmetry has been attributed to aspect contrasts and hence different processes on different aspect slopes under periglacial conditions (for example Meiklejohn, 1994). Contrasting arguments suggest non-periglacial activity as contributing factors to the asymmetrical

development of valleys. The periglacial geomorphology of the Eastern Free State has raised similar comment based on the possibility for alternative non-periglacial explanations (le Roux, 1990). In the Eastern Cape Drakensberg, proposed relict rock glaciers generate considerable debate while the existence of protalus (pronival) ramparts and other possible ramparts in southern Africa have been questioned by Shakesby (1997). The attribution of angular material in sediments of cold-climate origin to freeze-thaw weathering processes, and hence specific climatic conditions, has also been criticised on the basis of a general poor overall understanding of the weathering process (see discussion below). The above debate can be highlighted further by the fact that most proxy data for the Quaternary indicate a 5°C to 10°C decrease in temperature for southern Africa during the Last Glacial Maximum (Partridge, 1997). It is also known that the environment during this period was more arid than at present and precipitation in the Drakensberg and Lesotho was approximately 70 per cent of current values. Apart from the fact that an 18°C to 24°C drop in temperature would be required for glaciers to have existed at the Last Glacial Maximum (18 000 BP), glacial environments require substantial amounts of precipitation in the form of snow (which changes over time to glacial ice). Given the existing estimate by most (interdisciplinary) research of a 5°C to 10°C drop in temperature and a drier climate, it is unlikely that glacial conditions could have existed. The indication, therefore, is that conditions around the Last Glacial Maximum were more likely to be periglacial than glacial. A dryer environment, moreover, could have resulted in a relatively inactive periglacial environment. It is thus possible that the most active landscape forming process occurred during the warmer interglacial periods under moist conditions, rather than during colder and dryer periods.

Additional problems can be considered. First, more than one process may lead to the same apparent landform or feature. Angular fragments moving in a debris flow may striate bedrock surfaces as fragments at the base of a glacier might, while fluvially incised debris deposits may have the same appearance as glacial moraines. Second, the duration and size of a geomorphic event and the intensity and duration of subsequent modifying processes will impact on the lifetime of the landform such that impressions of previous climatic conditions can be obliterated.

This discussion does not attempt to provide solutions to the above, but serves to highlight

contemporary debates where geomorphological evidence has been used for palaeoenvironmental reconstruction. The interpretation of relict features clearly requires a clear understanding both of the mechanism of formation of the relict feature and an understanding of the effects of subsequent processes operating in these mountain environments, including those at the present day. While international literature can focus on process studies in active periglacial and glacial environments, current southern African geomorphic process studies are limited to slope process investigations where periglacial activity, if any, is localised and seasonal. This is none the less an important contribution towards understanding the overall environment and provides insight into geomorphological response to environmental change. Since slope form and slope processes are integrated components of landscape development both slope development and slope surface processes are considered further.

SLOPE DEVELOPMENT AND PROCESS

Slope development

The earliest studies concerning landscape evolution emphasised macro-scale features and processes. Modern geomorphological studies have focussed more on the slope scale and smaller. The best known of the older models are those of Davis and King. An excellent comparative discussion of their models, as well as that of Penck, is provided by Thorn (1988).

Davision Geomorphology, as it became known, attempted to simplify the changing landscape into stages within a "geographical cycle" (Thorn, 1988). The ultimate landscape that resulted from the Davision stages is almost without relief and known as a peneplain. Davis's progressive stages of "youth" "maturity" and "old age" are often still used in many school text books, despite the fact that the science of geomorphology has progressed beyond these earlier models.

Lester King is recognised to be one of the last of an era of scientists that considered geomorphology on a global scale. In the southern African context, King is extremely important

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as his studies were largely based on work in this sub-continent; in fact, King is often credited with creating an awareness of southern African geomorphology. The model of King included uplift, cycles of erosion and the identification of associated landforms on a global scale (for example King, 1963). An essential component of King's model was the notion of parallel scarp retreat, and when observing the landscape of the South African interior, it is not difficult to see the origin of his thoughts.

Some more recent models for landscape development have been formulated that link process to slope and soil development (Dalrymple *et al.*, 1968). Other models illustrating slope form and development rather than regional development appear less problematic, attempting as they do to incorporate both lithological or structural control and geomorphic processes (see Moon, 1988 for a review). Scale extrapolation, from the individual moving soil particle to landscape morphology, is a problem inherent in any landscape development model. In many respects the regional approaches adopted by Davis and King have been abandoned and are now considered to be relevant by only a few researchers (Thorn, 1988). In order to describe landscape change, geomorphology has progressed towards a more quantitative, dynamic and process oriented approach focussing on processes operating at slope scales. Nonetheless, it is some of these earliest models of landscape evolution that have shaped the field of geomorphology.

Slope processes

Mass movement

Considering the diversity of mass movement phenomena in southern Africa, surprisingly few data are available on current processes or previous mass movement events. In the Drakensberg, current and relict mass wasting events include evidence for major relict landsliding and rotational slumping incorporating bedrock, active and inactive surficial landsliding on slopes and riverbanks, stepped micro-relief in the form of terracettes and the widespread occurrence of soil creep (see Sumner and Meiklejohn, 1998).

The type and distribution of mass movement events in the Drakensberg appears to be regulated

by the underlying lithology. Larger landsliding events and rockfalls, although evident in the basalt, are primarily associated with the Clarens Formation sandstones and the transition to the Elliot Formation shales. Surficial mass movements predominate in the shales. Observations show that few large landslide events incorporating bedrock occur under current conditions and it is apparent that surficial events are the dominant mass movement processes under present climatic conditions. Trigger mechanisms for surficial mass movements probably include increased interflow at the bedrock-regolith interface and soil saturation during high rainfall events, or reactivation of relict landslide events. The larger relict mass movement events may have been associated with fluvial incision, and hence slope steepening, during the Pliocene uplift. No data are available on event frequency-magnitude relationships for the region and thus the overall significance of mass movements to landscape development, both past and present, is not known.

Frost creep caused by freezing and thawing of the ground and possible solifluction activity (slow flow of saturated slope material over an impermeable layer) is described for the marginal periglacial region of the Eastern Cape Drakensberg and the Lesotho highlands (Lewis, 1996; Boelhouwers, 1994). Turf- and stone-banked steps and possible evidence for solifluction, have been identified in the Lesotho highlands above 3000m. These may be inactive under current conditions (Boelhouwers, 1991). In general mass movements will contribute to landscape degradation and assist soil erosion through the disaggregation of soil and accelerating surface wash processes on disturbed surfaces.

Soil erosion

Southern Africa as a whole is susceptible to soil erosion while the mountainous regions are particularly vulnerable to degradation as illustrated by high erosivity indices and erodibility (susceptibility) potential (see Chapter xx). Both surface and subsurface erosion is prevalent in southern Africa. Surface erosion processes include rainsplash erosion caused by the impact of falling raindrops on the soil surface. Where rainfall intensity exceeds the infiltration capacity of the soil then runoff is initiated. Runoff has the potential to entrain and transport soil particles and, where wash is combined with rainsplash disaggregation, erosion is particularly effective. If wash processes are concentrated, soil erosion leads to the development of rills, which can

ultimately form gullies. Soil erosion assists in the reworking of slopes and surficial features such as mass movement events. As found elsewhere, soil erosion in the mountainous regions of southern Africa is enhanced by human activity. This includes grazing, for example in the Lesotho highlands, and management practices such as veld burning programmes as well as the use of footpaths and vehicle tracks in wilderness areas.

The development of soil pipes by subsurface erosion is also prevalent in the Drakensberg. Beckedahl (1998) describes subsurface erosion features associated with dispersive soil types and non-dispersive soil scree slopes in the foothills of the Drakensberg. Evidence for the onset of piping is not obvious in the landscape, but collapse of the pipe can lead to immediate gully development (Figure 3). Further explanations on soil erosion processes and features are provided in general texts while details on erosion features found in southern Africa are provided by Beckedahl *et al.* (1988).

Where moisture is present and temperatures are sufficiently cold for ground freezing to occur, small ice needle protrusions may grow near the soil surface lifting the surface layer of soil particles. Needle-ice growth results in soil and vegetation disruption (turf exfoliation), particularly in the Lesotho highlands and down to altitudes of 2300m in the Drakensberg in winter (Boelhouwers, 1991). Sites where vegetation is scarce, such as on footpaths or the banks of streams, are particularly prone to needle-ice disruption. Needle-ice growth in the risers of terracettes is thought to enhance their development, particularly in the Lesotho Highlands. While soil disrupted by needle-ice may either move downslope under gravity or be eroded by wind, it is likely that wash processes during the wetter summer periods are primarily responsible for the erosion of needle-ice disrupted soil.

Variables interacting to control the rate and type of soil erosion process include climatic conditions (erosivity), and erodibility factors such as soil properties, vegetation, geology and topography. In addition the human element plays a significant role in modifying the erodibility of soil. Changes in land management and land-use practices have the potential to influence soil erodibility, thus altering soil erosion process type and rate. A further discussion of human

induced soil degradation is provided in Chapter xx Similarly, changes in climate can influence temperature, precipitation and vegetation characteristics. For example, during a colder period the erosive influence of needle-ice may be enhanced and have a greater influence at lower altitudes. Wind erosion, while not considered a major factor at high altitude at present, can be accelerated during dryer phases. Evidence for these former intensified processes may not be maintained in the landscape as successive processes dominate.

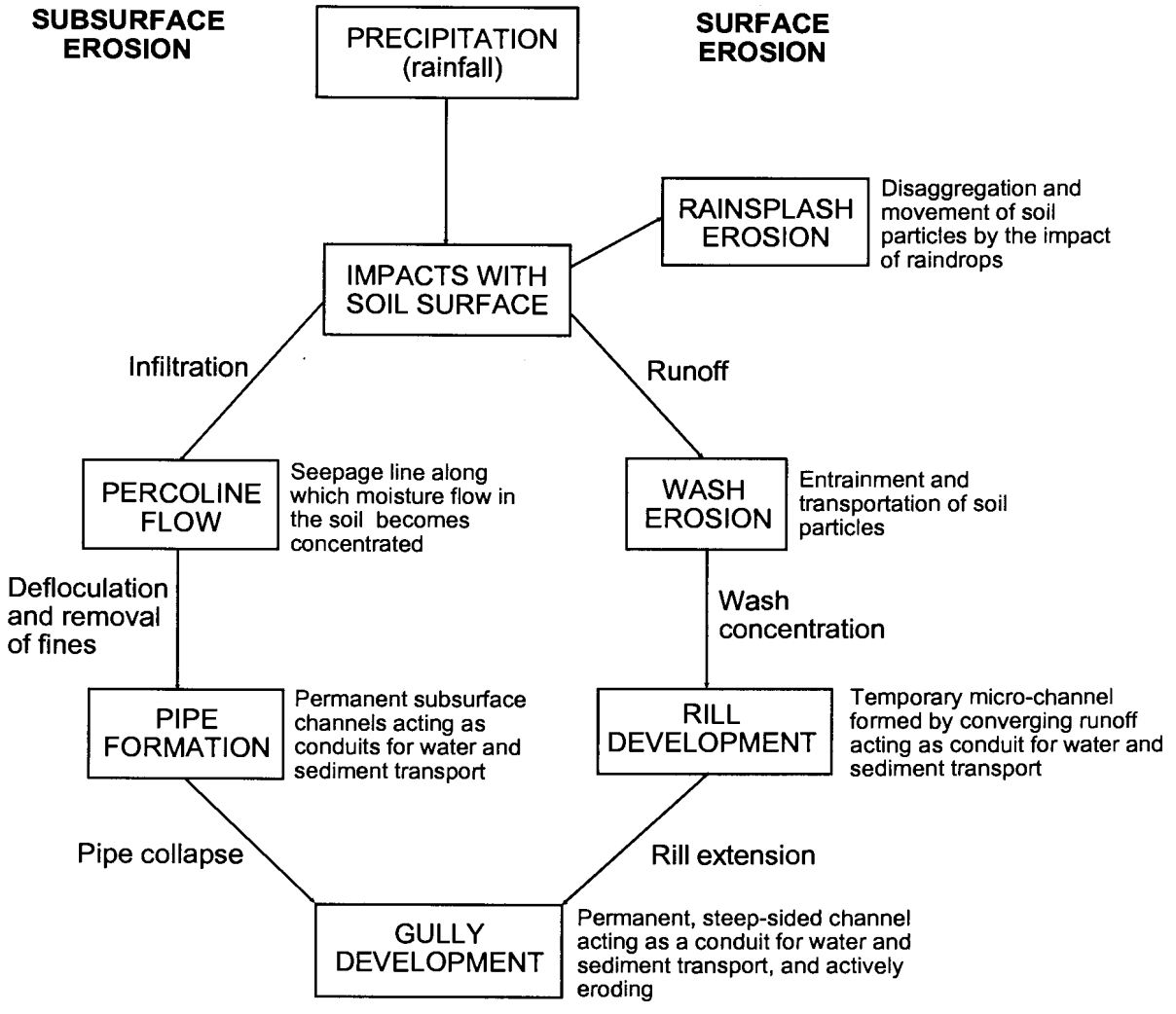

Figure 3: Gully development by surface and subsurface soil erosion.

Much of the material comprising relict glacial and periglacial features as well as the material within which current periglacial activity, mass movement and soil erosion process takes place originates from the weathering of bedrock. Palaeoenvironmental inferences in southern Africa and world-wide have also been drawn directly from the products of weathered bedrock. Weathering is, therefore, a fundamental geomorphic process and is particularly important in the context of palaeoenvironmental reconstruction and the understanding of landscape evolution. (Bibliographies for studies in southern Africa on weathering and slope processes (Sumner and Meiklejohn, 1998) and soil erosion (Watson, 1998) are available.)

WEATHERING

Despite the importance of weathering in landscape processes, there is a scarcity of published material on weathering processes active in southern Africa. In most cases weathering is considered as one component of other geomorphic processes. It is only relatively recently that research has been conducted into specific weathering processes by a small number of researchers (see Sumner and Meiklejohn, 1998). Very few of these studies (for example Meiklejohn, 1997) actually monitor field conditions and attempt to infer process. Recent process studies have concentrated on biological and cryogenic weathering as well as the deterioration of Drakensberg basalts and indigenous rock art through weathering processes. It is apparent that the contention of Hall (1988) that considerable research on southern African weathering is still required, still holds.

Notwithstanding the scarcity of weathering studies in southern Africa and the lack of field data worldwide, observations of weathered material have been utilised locally as an indication of palaeoenvironmental conditions. Angular "cryoclastic" material contained within deposits as well as sub-angular to angular material constituting screes and blockfields/streams have been considered the product of cold-climate weathering, notably the freeze-thaw process. Since the international literature indicates shortcomings in linking weathering products to field and laboratory observations, this approach has serious limitations. In order to highlight these

problems both the types of, and controls on, weathering processes are presented with a view to highlighting the complex interaction of process and hence the difficulties in relying on field observations.

Weathering processes and controlling factors

Weathering is defined as the *in situ* physical (that is mechanical), chemical or biological alteration of rock through a variety of processes (Table 2). As weathering takes place *in situ* no movement of material is implied and it is therefore apparent that it is a contributor to, but cannot result in, landform development (Hall, 1988). Landforms arise from the reworking of weathered material by processes such as soil erosion and mass movement.

Physical (Mechanical) Weathering	**Chemical and Bio-chemical Weathering**
Dilatation	
Thermal Shock	Solution
Thermal Fatigue	Hydration
Cryogenic Weathering	Acid-Base Interactions
Salt Crystallisation	Oxidation and Reduction
Hydration of Salts	Chelation
Expansion and Contraction of Salts	Hydrolysis
Hydration	Carbonation
Slaking	
Growth of Biological Organisms	

Table 2. Rock weathering processes commonly referred to in geomorphic literature.

Chemical weathering involves chemical alteration of rock minerals while physical weathering is the mechanical alteration of rock where no chemical change takes places. Without knowledge of the specific processes that take place at a small scale, it is not possible to determine how a landscape was formed. Therefore it is imperative that detailed information regarding the primary

alteration of bedrock is understood. Table 2 shows the weathering processes that are commonly referred to in relevant literature. In practice, individual weathering processes are impossible to separate, but for simplification are normally discussed as separate entities. Similarly, while biological weathering may be classified as mechanical or chemical, texts consider it as a separate issue.

Apart from some chemical processes, rock weathering does not take place in a constant environment. Changes in the environment, even on a very small scale, are required before any breakdown is possible. While the following discussion often refers to specific processes, it will be shown later that rock weathering is a series of interdependent processes with numerous variables interacting to control the rate and type of weathering process. These controls include the properties of the bedrock, climatic and micro-climatic conditions, the length of time available for weathering and the removal of the weathered product (Figure 4).

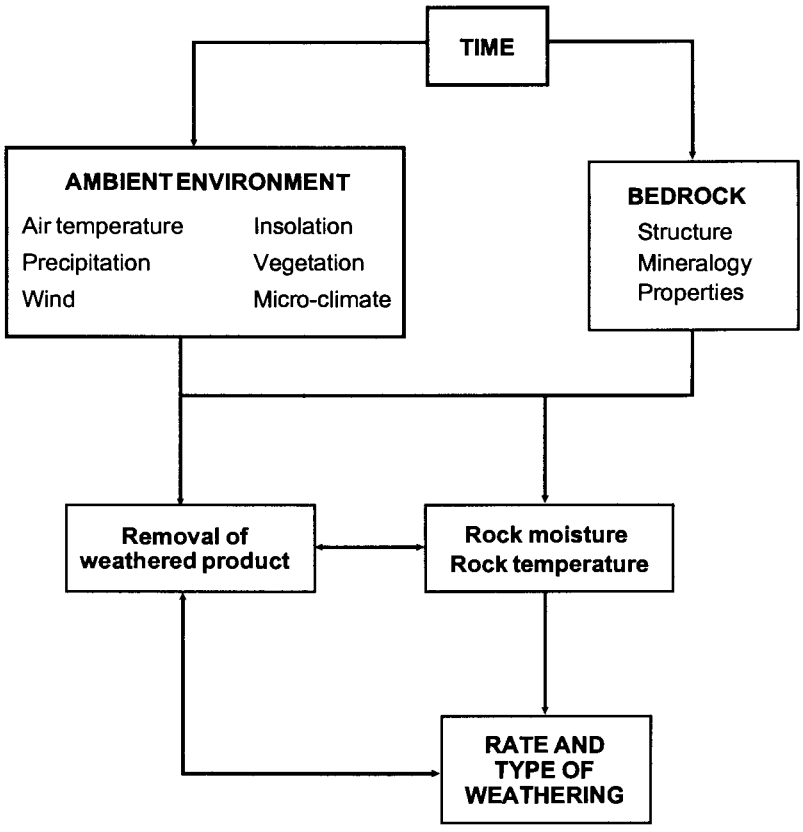

Figure 4: Variables interacting on rock weathering processes.

Bedrock properties determine the susceptibility to weathering processes and the ease with which weathered products can be removed. Rock mineralogy dictates the chemical composition, albedo, thermal properties and moisture absorption capacities of a rock. The chemical composition determines the susceptibility of a rock to undergo chemical alteration while minerals with a lower albedo (darker coloured minerals) absorb incoming solar radiation to a greater extent than do light coloured minerals and will therefore be more prone to thermal weathering processes.

Rock structure is important since discontinuities and other places of inherent weakness are the areas that will be most susceptible to breakdown. Bedding planes and joints are avenues for moisture and gaseous intrusion, making these locations for dynamic changes and thus enhanced weathering and weathered product removal. Further, structure influences both the rock tensile and compressive strength and thus its resistance to certain physical weathering processes. Important rock properties include porosity, micro-porosity, permeability, saturation co-efficient and water absorption capacity. These factors influence moisture movement and the ability of a rock to absorb moisture. This is especially the case with porosity and micro-porosity (micro-porosity being the percentage of rock pores with a diameter less than 1µm). Moisture absorption and movement increases with increasing porosity and decreasing micro-porosity.

General weathering models in the past have focussed on climatic conditions as controlling rate and type of weathering process. Weinert (1965) zoned southern Africa according to climatic conditions noting that chemical weathering will predominate in the eastern regions and physical in the west. Of greater importance in considering weathering processes, however, are the rock moisture and temperature conditions where the weathering is taking place: the weathering front (Pope *et al.*, 1995). The ambient conditions (micro-environment), although influenced by climate and vegetation, have a greater influence on the temperature and moisture conditions at the weathering front. General climate is thus not necessarily an indication of prevalent weathering processes or intensity. Rate and type of process will vary from site to site over short distances in the landscape. It is still generally accepted, however, that the most favourable conditions for rock weathering are moist, warm climates. On the other hand, cold dry climates are said to be less favourable for rock weathering. The relatively unfavourable weathering environment in cold,

dry areas is possibly the reason for angular material predominating; the relatively inactive environment may preserve angular fragments.

Given the perceived importance of thermal and cryogenic weathering processes, temperature is obviously an extremely important weathering control. While air temperature may have an influence on rock temperature, insolation has the primary influence. Care should be taken that the actual temperature of the rock is considered, as air temperature cannot be used as a surrogate for rock temperature. Absolute rock temperatures are important in determining rates of chemical reaction (rates of chemical reactions increase with temperature), and variations in rock temperature result in a variety of weathering processes discussed below. While moisture availability is normally associated with precipitation, the relationship is not always direct. Rate of slope surface drainage and infiltration influence moisture availability and groundwater quantities may not be directly related to precipitation. Snow may sublime rather than melt (evaporate directly from ice crystals) and therefore will not supply moisture directly for weathering processes. The actual rock moisture is of greater importance than the general precipitation conditions. A further influence is wind, which may cause dessication of rock surfaces and alter rock-surface temperatures.

Through time bedrock properties are altered by weathering processes and climatic change and variability influence rates and types of weathering processes. The rate of removal of weathered product is an important factor since weathering residues may offer protection from insolation while maintaining higher moisture contents. Weathering processes at a site are expected to change through time under different climatic conditions, but may also change though time even under constant climatic conditions due to the accumulation of weathered products.

Weathering process interdependence and interrelationships

In developing a hypothesis for rock weathering it is necessary to consider that no single process can be isolated. Rock breakdown is due to a complex interdependency and interrelationship between mechanical, chemical and biological mechanisms.

The major controls on weathering are rock temperature and rock moisture (Figure 4). Rock temperature has an important influence on all weathering mechanisms. It affects (amongst others) the rate of chemical reactions, chemical equilibria, as well as evaporation and condensation cycles (Ollier, 1984; Yatsu, 1988). The rock moisture regime may be influenced by temporal scales of variation ranging from seasonal variations to more rapid variations that occur within periods of a few minutes. A major influence on the moisture regime is atmospheric humidity, which controls weathering processes near the rock surface. Weathering processes likely to be active at this interface include salt crystallisation, hydration/dehydration of minerals and precipitates, solution processes, and hydrolysis (Figure 5).

Attempts to ascertain active weathering processes in the field are difficult and time consuming. In a long-term study on the deterioration of rock art by weathering of the Clarens Formation in the Drakensberg it was found that weathering of the sandstone is a complex set of interactions, rather than unrelated individual processes (Meiklejohn, 1997). While the rock moisture regime was identified as the major influence on weathering, other controls (for example thermal regime, differences in mineralogy and the depositional environment) cannot be ignored. The rock moisture regime itself is influenced by rock temperature, atmospheric moisture and ground water moving along rock discontinuities. To emphasise the interdependence and interrelationship of weathering mechanisms from this case study it is best to attempt to highlight the effect of changing rock moisture conditions.

Increasing rock moisture content due to precipitation, condensation from decreasing rock temperature or increasing atmospheric moisture will cause hydration of rock minerals, clay minerals and precipitated salts, solution of rock minerals and precipitates, hydrolysis and chemical alteration (Figure 5). Alternatively, a decrease in rock moisture content, which may be due to increasing rock temperatures, decreasing atmospheric moisture or a decrease in the amount of moisture moving along rock discontinuities, will cause dehydration of clay minerals, rock minerals and precipitated salts, and precipitation (crystallisation) of solutes.

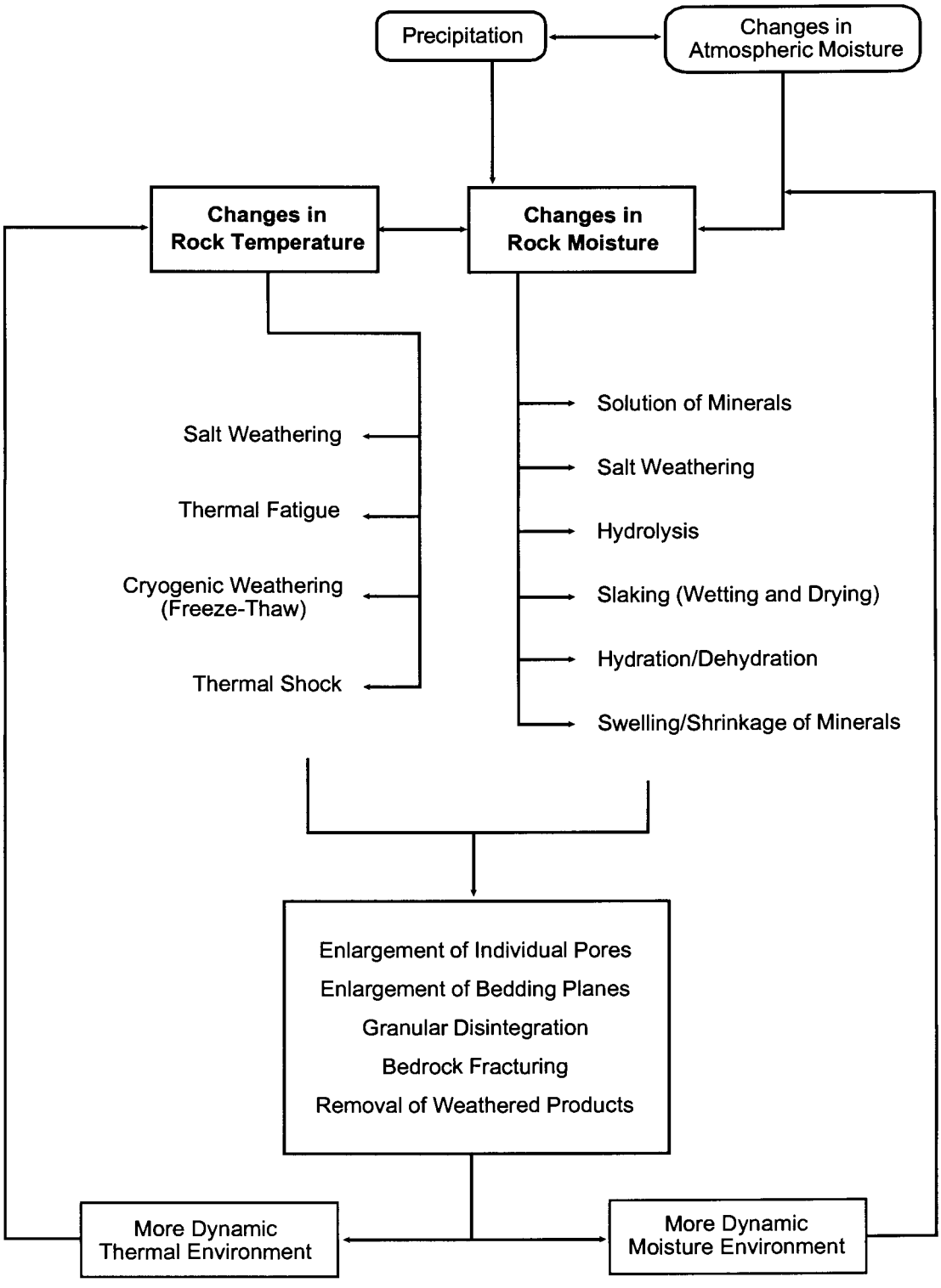

Figure 5: Effect of changing moisture and temperature conditions on weathering processes.

The above moisture controlled weathering processes and others related to changes in temperature, such as thermal fatigue, enlarge existing pores and cause granular disintegration. This increases the rock porosity and widens bedding planes. Enlargement of pores will cause a decrease in rock micro-porosity. Lower micro-porosity, higher porosity and wider bedding planes results in easier moisture infiltration, which in turn causes increased weathering. A further effect of moisture is that it has the ability to remove weathering products. Apart from those that take place along bedding planes, these processes will be most active at the rock surface and within the first few micrometers below it.

This is the very environment in which Bushman paintings are located, and as a result weathering processes cause the deterioration of rock art. While the above study was generalised with respect to weathering processes in the Clarens Formation, it was found that microclimatic and other environmental variables such as rock moisture, rock structure and rock chemistry not only differ from site to site, but also from one location to another within a single shelter. Adding to the difficulty of interpreting weathering, the processes are not only site specific, but also depend on the precise situation of a rock surface.

It follows that isolation of process operation based on field data is difficult, while an approach based only on field observations is virtually impossible. In addition to the complex integration of process, it can be seen that weathering, such as with the Clarens Formation sandstones, can be an "accelerating" process and that the intensity of process can alter with time as the physical properties of the material changes. To further highlight these process complexities within the context of using weathering products as palaeoenvironmental indicators, the freeze-thaw weathering process is considered further.

Weathered products as palaeoenvironmental indicators

Angular rock fragments attributed to cryogenic weathering (freeze-thaw) have been used in southern Africa to argue for previous and contemporary cold environmental conditions (Hall, 1991). While the inter-relationship of freeze-thaw with other weathering processes is as yet not

entirely resolved, the actual mechanism of freeze-thaw is also not clearly understood. Various theories have emerged which attempt to explain the mechanism of freeze-thaw based on the freezing of moisture outside an intact rock and moisture within the rock. These theories include (see McGreevy, 1981; Hall, 1995; Bland and Rolls, 1998 for further discussions):

- volumetric expansion of water freezing to form ice
- freezing of water within a closed system
- crystallisation pressure of ice
- capillary frost damage
- ordered (polar) water
- hydraulic pressure
- growth of salt crystals during depressed temperatures.

While a number of processes may be operative within a rock, the volumetric expansion on freezing of water external to the rock is the most cited freeze-thaw process. It is based on a 9% volumetric expansion when water in cracks freezes to form ice with the resultant stresses theoretically sufficient to cause the rock to break into angular fragments. However, the basic process is problematic. The idea of water freezing solely being able to cause angular debris is not possible as water can only enter pre-existing cracks and, in any event, the angularity of products will be caused by the bedrock structure. The possibility of moisture entering cracks and loosening blocks or extending cracks should also be considered. Again, a problem exists, in that when water freezes the expansion is likely to occur in the direction of least resistance, in other words towards open space and not towards the crack apex. Crack propagation must then be unlikely.

A further illustration of misconceptions relating to freeze-thaw weathering is seen in many texts where photographs and diagrams of open cracks are used to illustrate the activity of this weathering mechanism. Any water in these cracks is likely to flow out the side of the cracks before freezing. Further problems exist in the literature concerning the mechanism of freeze-thaw weathering. Air temperatures are often been used as a surrogate for rock temperatures

and 0°C is used as the freezing point for water. Measured rock temperature often shows little relationship to air temperature; for example, field data from Alexander Island, Antarctica, showed the air temperature to be –2°C, while that for rock was 31°C (Meiklejohn, 1994). In southern Africa air temperatures in the vicinity of the Clarens Formation of the Drakensberg were measured as low as –10°C; the minimum rock temperature recorded simultaneously was +4°C. The freezing point of water is also not necessarily 0°C; both dissolved salts and the ambient pressure will influence the freezing point of liquids.

In many instances freeze-thaw weathering may not be possible, simply because of the absence of sufficient quantities of moisture. It is unlikely that cryogenic weathering is active in most areas of the continental Antarctica, which is regarded as the driest place on earth. In a similar way, excluding the Western Cape mountains, freeze-thaw weathering is unlikely in the highlands of southern Africa; in summer it is too hot and in winter, apart from rock temperatures not being low enough, there is insufficient moisture.

There is thus little clarity regarding freeze-thaw weathering and logically its association with landform development in cold environments. Further, the interaction of cryogenic weathering and other types of weathering processes is poorly understood (Hall, 1992; 1995; Thorn, 1992). The presence of moisture required for freeze-thaw implies that a range of chemical weathering processes may take place even where air temperatures are low but insolation, and hence rock temperature, is high. Changing temperatures, a requirement for freeze-thaw weathering, and the associated moisture fluctuations give rise to a range of mechanical weathering processes that must be operating simultaneously to freeze-thaw. The isolation of one weathering system, freeze-thaw, or a single mechanism of freeze-thaw, is thus virtually impossible in the field and has also proved difficult in the laboratory. This problem is exacerbated by the scarcity of field data on rock moisture and temperature conditions in southern Africa and from regions beyond the sub-continent where cryogenic processes appear active.

The uncertainty with regard to actual processes that cause the weathering of bedrock, and hence the difficulty in understanding landscape evolution, extends beyond the freeze-thaw

weathering process. A further example is thermal shattering; extremely rapid changes in temperature have been noted to result in shattering of rocks, caused by the inability of the rock to adjust to rapid expansion and contraction. The result is angular fragments from breaks across existing discontinuities. Laboratory experiments have shown that a rock temperature change of 2°C.min^{-1} or more may be sufficient to cause cracks along grain boundaries (Yatsu, 1988). Despite such rapid temperature changes being recorded in the field in southern Africa, there is no evidence supporting this mechanism of weathering in the Drakensberg mountains (Meiklejohn, 1997).

The future of weathering studies in South Africa

It is apparent that there is a need for a thorough understanding of rock weathering processes and their role in the formation of the southern African landscape. Many of the misconceptions that arise concerning rock weathering result from that fact that few field data exist where weathering processes and the ambient environment are being monitored. Further, it is apparent that most laboratory simulations do not use field-based data as a basis for simulation. In this regard the current research emphasis should be on measuring actual environmental conditions and replicating these under laboratory conditions to determine active weathering mechanisms. With sufficient data regarding active weathering processes and their responses to changing environments, it may be possible to use weathering for palaeoenvironmental research. However, within the limits of our current understanding it is suggested that potential inferences from weathered material are highly problematic and should be treated with extreme caution.

CONCLUSION

By its very definition, geomorphology involves the study of landscape changes through time. Certain environments are particularly appropriate to research on evolving landscapes, no more so than mountain environments. The emphasis of this chapter is on landscapes in mountain environments where landscape evolution has been interpreted using relict features attributed to processes operative under previously different climatic conditions. Considering our knowledge

of current processes and the problems associated with interpreting process from relict forms, the understanding of geomorphic landscape evolution is problematic. Consequently, predicting future landscape response to environmental change is proving difficult.

Other important geomorphological areas in southern Africa exist which can contribute to the geomorphic understanding of our changing environment. This is particularly true for coastal and karst environments. Coastal areas respond dramatically to both environmental and human induced changes. Karst environments, where limestone dominates the local lithology, are particularly prone to subsidence through solution of bedrock. It is thus logical to assume that changing environmental conditions could result in these areas becoming more geomorphologically active and susceptible to subsidence. The gold mining areas of the western parts of Gauteng, eastern North West Province and Centurion in Gauteng are areas affected by this. Investigations into karst environments have also proved particularly useful for palaeoenvironmental reconstruction (Marker, 1998).

The changing environment and the impact of humans on it will manifest themselves in the processes that are active in the landscape. A better understanding of these processes will in turn make possible an understanding of how the landscape has responded to changes in the past and allow predictions to be made as to how processes, and therefore landscapes, will respond to environmental changes in the future.

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CUTBACKS IN THE NATAL DRAKENSBERG ESCARPMENT:

COMMENTS ON AN HYPOTHESIS ON THEIR ORIGIN

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Published in *South African Journal of Science*, 1995, vol. 91, 285-286

Hall has outlined an hypothesis for the origin of cutbacks along the Natal Drakensberg Escarpment (Hall, 1994). He postulates on the formation of debris in cutbacks and on the fluvial distribution systems within the debris. These are attributed to the rapid ablation of ice bodies (niche glaciers) within the cutbacks and the melting of snow and ice in Lesotho. While the understanding of the geomorphology of the Drakensberg is still in its infancy and the question of glaciation in the higher mountains in southern Africa is highly relevant, there are a number of points that need to be raised concerning the hypothesis. The purpose of this response in not to provide an alternative interpretation but simply to highlight the problems with the hypothesis in order to prevent misconceptions emerging from the related process interpretations and associated climatic implications.

The hypothesis is based on the presence of "fluvially derived, cobble to boulder size debris" of which the "origin ... appears obvious" and that "extreme, high energy events are necessary to produce such deposits and landforms". The high energy events are then attributed to meltwaters. Hall accredits the rounding of boulders as "evidently fluvial in nature, rather than due to weathering, as they are often juxtaposed against sub-angular blocks of comparable size." The petrology of basalt, however, as opposed to that of sandstone, is thought to be predisposed to rounded clasts (Hall, 1992) and will weather to rounded clasts (Sarracino and Prasad,1988) particularly in cold climates, where rock temperatures are high and conditions are wet (Hall, 1992). Basalt, prior to movement, can already be highly rounded *in situ* by weathering. Rounded basalt clasts are readily found on the escarpment where no fluvial action or clast movement could have taken place. The presence of rounded basalt in a deposit does not then necessarily imply high energy fluvial transportation. The juxtaposition of rounded and weathered material will militate against the *in situ* rounding of clasts in the deposit but not against rounding prior to transportation and deposition if there was any lateral or vertical spacial difference in debris source location. As a consequence the fluvial nature of the debris cannot be assumed by clast appearance alone, particularly since no quantitative data on the degree of rounding, and on the location of rounded and angular clasts in the deposits, were cited in support of the hypothesis. If the rounding of the boulders can be explained by some other mechanism then this immediately questions the basis for the hypothesis namely that "a rapidly ablating ice body could be responsible" for the "extreme high energy events".

In apparent contradiction to the fluvial-rounded hypothesis Hall then later attributes the debris to "nival processes, during which debris and debris flows would be produced". He states that the "subsequent meltwaters from ablating snow and ice would have then cut in to those deposits to produce the distribution systems we see today". The role of the meltwaters is thus not clearly defined. Are the deposits fluvially derived, or are they formed by debris and debris flows from outwash, with the subsequent incision to form the channels? If the deposits are from a mass movement event or events as suggested, how can "The whole" then be "the product of fluvial action"? Although the latter scenario presented appears to be more plausible it must be stressed that in the absence of quantitative data this is only a presumption, yet the associated climatic implications are considerable.

Some further comments on the contribution of meltwaters are appropriate. In negating the effects of precipitation (presumably rainfall) Hall states that "at the top of the escarpment the general downward slope is not towards the cutbacks but rather into Lesotho", yet later the author hypothesises that "the large volumes of water released by ablation of ice in Lesotho would pour down the incipient cutbacks". In explanation the author states that "the presence of ice on top of the escarpment would have helped negate the drainage of meltwater back into Lesotho". Gradients immediately beyond the escarpment above Bannerman Pass are in excess of 10° sloping into Lesotho. Thus meltwater contributions would have been negligible unless there was a substantial accumulation of snow/ice above the top of the Escarpment. Such accumulations would, for example, require ice thicknesses in excess of 80m a distance of 500m away from the escarpment for the surface of the ice/snow just to slope back into Natal. The ice/snow thicknesses would have to be well in excess of the escarpment height at the top of the cutback for "large volumes" of meltwaters to have contributed to processes in the cutback. In addition, the area immediately above Bannerman Pass is north facing. The volumes of snow/ice on the shaded, colder south facing slopes and in the valley floors must then have been considerable. Some clarification of the scenario is required since the large volumes of snow/ice envisaged would suggest glaciation of the higher regions of Lesotho. While such a situation is not impossible, the geomorphic-climatic implications are nonetheless considerable.

With reference to precipitation and events such as Cyclone Demoina, Hall is correct in stating

that "one cannot transfer the magnitude of impact of such events at low elevations to their possible effects at high locations." It is also apparent, however, that one cannot transfer the magnitude of events in recent history to those operating in the past. Indeed, based on personal observation of the features referred to in the hypothesis one may just as readily construct an hypothesis for a warmer, moister climate, with intensified weathering and high intensity rainfall events, which, in association with structural control of the basalt, have formed the cutback and the features in Bannerman Pass. Such an hypothesis would superficially be equally plausible, implying different processes and climatic conditions, but will be equally as flawed as the meltwaters hypothesis. The point again is that without quantitative data on the channel systems and the debris, process-form relationships cannot be established. Perhaps in recognition of this shortcoming the author refers to recent work by Grab (referenced as pers. comm.) on debris in the Drakensberg. This work will not, however, serve to contribute to explanations of these debris features since Grab concentrates on the high regions of a cutback in the southern region of the Drakensberg where the debris morphology differs vastly from those described in the hypothesis (Grab, pers. comm.).

In the hypothesis Hall attributes the development of the cutbacks to "nival processes". Nival processes cannot fully explain the origin of the cutbacks. If "niche glaciers" were present or "nival processes" operative in the "embayments along the edge of the escarpment" then these would have been in pre-existing cutbacks of some form. The hypothesis, contrary to what the paper title suggests, serves rather to explain the origin of the debris and channel systems within the cutbacks, rather than the origin of the cutbacks themselves since some form of embayment would have to exist for the accumulation of snow/ice.

Finally, analogies are drawn with observations of cutbacks on Alexander Island, Antarctica (lithology not specified). Although the author mentions "recent studies in the Antarctic Peninsular" no references to previous or current research are provided to substantiate the arguments. While both areas may have similar morphological features the process of development is disputable unless quantitative assessments are undertaken, and even then may still remain debatable. Although his recent publications show Hall to be very familiar with the geomorphology of high latitude areas, observation-supported hypotheses as "One possible way

forward" must be treated with caution. It appears that the situation described by Butzer (1973), 21 years ago on 'periglacial' phenomena in southern Africa, that "too much interpretation has been based on high latitude preconceptions" (p.9) still exists.

The intention of this discussion was not provide an alternative hypothesis for the formation of the features but to highlight problems with inferring process and related climatic conditions from qualitative judgements. Research on geomorphology in the Drakensberg may still be in its infancy but this does not preclude sound geomorphological assessment. The arguments presented here are best summarised by a number of recent comments pertaining to geomorphological research in southern Africa. Le Roux (1990) highlights the problem of "inferring causes from outcomes" (p.129) which Hall (1991) in support notes "has been a major problem with South African periglacial studies" (p.135). In reference to southern African cryogenic research Hall (1992) criticises that "qualitative presumptions have been made and deterministic hypotheses built upon them" (p.69) and continues by reminding researches: "Great care and rigour must be applied to *any situation* otherwise a completely misleading picture may result that could confuse and/or prejudice subsequent studies" (p.69, emphasis mine). Interpretation of these features has immense potential for unravelling past climatic conditions, providing avenues for geomorphologists to offer significant contributions to palaeo-climatic research. Hall (1992) states that "whilst glaciation of the higher southern African mountains is such a big question, with so many climatic-periglacial-botanical ramifications, great care must be taken in arriving at any judgements" (p.71). The closing comments must go to Butzer (1973): "southern Africa has experienced cold, glacial age climates, but there is a serious problem about many of the geomorphological observations and their interpretation" (p.1) and to Hall (1992): "A plea is made for more detailed work and greater exactitude in future studies" (p.69).

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COMMENT ON "CHARACTERISTICS AND PALAEOENVIRONMENTAL SIGNIFICANCE OF RELICT SORTED PATTERNED GROUND, DRAKENSBERG PLATEAU, SOUTHERN AFRICA" BY S.W. GRAB

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Forthcoming: *Quaternary Science Reviews*.

(Accepted pending shortening, full submission appears below).

Grab (2002) describes patterned ground in the high regions of the Drakensberg, southern Africa. The geomorphological features are interpreted as relict sorted circles and are ascribed to the colder conditions around the Last Glacial Maximum. The paper argues for ground sorting being indicative of the former existence of permafrost above 3400m and concludes that pronounced palaeoenvironmental variations existed over short distances in the area. These are significant findings, given the global importance of Quaternary glaciation and peri-glaciation of the southern hemisphere (eg. Boelhouwers and Hall, 2002), which can advance our understanding of the palaeoenvironment. However, on a number of points I find the evidence presented and subsequent interpretation problematic. Concerns pertain to the interpretations derived from the landform morphological descriptions and the mechanisms suggested for their origin. These are discussed below.

My first concern lies in the interpretation of the features as true periglacial sorted circles based on the morphological data provided. (Referring to information as "sedimentological data" on p. 1729 is inherently incorrect, as explained below). Sites 1 and 2 are the most problematic. At Site 1, it is unfortunate that the depth of sorting is largely "unknown" (Grab 2002, Table 1, p.1733) with only one sorted depth of 33 cm recorded. Although only one pattern at Site 1 was fully sectioned (p. 1732, Table 1, p. 1733), two different schematic sections are presented (Figures 9 and 11, p.1735 and 1736). While the horizontal dimension and the vertical exaggeration of approximately 2.5 times (although this applies only the axes scales, not to the material depicted) appear similar for the two diagrams, the schematic representations differ in that the fines' surface is elevated approximately 10cm above the clastic border in Figure 9, and is slightly depressed in the order of 5cm in Figure 11. In contrast, a mean "centre height above border" of 23.6 cm spanning a range of 12 to 42 cm is presented in Table 1 for the site, the dissected form having a 16cm deep border trough. The peripheral schematic representations of the features at Site 1 in Figures 9 and 11 also appear to be misleading as the clastic "border" (p.1732) visible in the photograph (Figure 2, p. 1732) is part of a blockfield (p. 1731). Unfortunately, no surface detail such as clast size or openwork surface topography are provided to distinguish the 'border' from the adjacent blocky material although size data are provided that distinguish the pattern centre from the surrounding area (Figure 8, p.1735). The border appears to be defined by a depression such as is illustrated in Figure 9, however, in Figure 11 the bordering clasts are

elevated above the centre. Perhaps as a distinction, the paper notes that "most of the larger rocks (on the borders) dip towards the centres" (p.1734). Such fabrics are not evident in the photograph (Figure 2, p.1732) and unfortunately no fabric data are provided in confirmation. Fabrics associated with the patterns at this site, whether observed or measured, will also need to be differentiated from the more obvious upright fabrics (as evident in the upper part of Figure 2) found in blockfields and blockstreams in Lesotho (eg. Grab *et al.*, 1999; Boelhouwers *et al.* 2002).

Very similar landforms to the one presented for the Mafadi Site 1 (Figure 2, p. 1732) are found within other low slope angle openwork accumulations in the region, such as in the upper Sehonghong valley above 3200m a.s.l a few kilometres south-east of Thabana Ntlenyana. A simple interpretation of such forms is that they are caused by the *in-situ* breakdown of an individual block within a blocky accumulation. Where the openwork accumulation is not substantially thick and the matrix lies near the block surface, such as that depicted in Figure 9 (Grab 2002, p. 1735) and Figure 11 (p.1736), the weathered product from a disintegrated block remains *in situ* at the openwork surface. This would explain the "significantly more rounded and less flat" (p.1734) character of the 'central' clasts which is noted by the author as apparently "a function of weathering over a long period" (p. 1738). The breakdown into a range of smaller particle sizes also accounts for the apparent 'vertical sorting' through the fall and wash of finer weathered products between the larger weathered pieces. The weathering product can account for the apparent elevation of fines in the "centre" of the feature in relation to the adjacent matrix and for the downslope elongation by wash. Similarly, *in-situ* breakdown of a block accounts for the pronounced increase in particle size at the boundary of the centre regions adjacent to the surrounding openwork blocks, as noted on p.1734, and depicted in the schematic diagrams. Unfortunately, the reason for isolated disintegration of individual boulders is not clear since, due to the absence of field data on rock moisture and temperature conditions, basalt weathering processes at these altitudes remains poorly understood. Differential weathering may be enhanced by the block being positioned higher than adjacent blocks (which would explain the elevated position of the disintegrated 'centres'), or be due to marginally different mineralogical composition varying over relatively short distances (see Mitchell *et al.*, 1996). The result of individual block breakdown, however, is a landform which is not attributable to ground freezing

but *appears* to have the attributes of vertical sorting and, when compared to immediately adjacent clasts, the characteristics of lateral sorting.

At Site 2, a lateral sorting mechanism has undoubtably occurred in the landform depicted in the photograph (Figure 3, p. 1732) and represented in Figure 12 (p. 1736), although the consistency in clast size data in the centre is quite remarkable. The u-shaped form of the coarse 'boundary' and the distinctive riser and tread depicted in the photograph, however, appear to be classic attributes of a stone-banked lobe, examples of which are also found in the area (eg. Boelhouwers, 1994; Grab, 1997a). Although stone-banked lobes are typically found on steeper slopes, the slope segment angle of 3° for Site 2 (p.1735) approximates the lower limit for slopes where stone-banked lobes are known to occur (Van Steijn *et al.*, 1995 cited in Grab, 1997a). At the site, which appears to be slightly downslope of the Mafadi interfluve (Figure 1, p.1731), the formation of lobes will probably be enhanced by the proximity of the bedrock "rock bench" (p.1731) where a temporary water table could lie near the surface. Occasionally saturated conditions would enhance slope movement, as described for other stone-banked lobes on steeper gradients in the area (Grab, 1997a). A lobate form also accounts for the apparent lateral sorting and fabrics of the plate-like blocks as noted for active forms (eg. Hall, 1981), although no specific fabric data are presented from Site 2. Applying the interpretation of a mass movement form is probably the closest one could come to "sedimentological data" (p. 1729) from these sites; none of the sites actually constitute true sediments since they are "high summit interfluves" (p. 1729) while the apparent mechanics driving true sorted patterns processes cannot be envisaged as involving sedimentation processes. Once dissected, an *observed* depth of sorting to 65cm from one of the sectioned features, I believe, is not convincing evidence for assuming and generalising on the freezing depth within soil. Although the site provides interesting descriptions of three of these landforms the data and attributes are not convincing evidence for classical sorted circle formation. Apparently in recognition of this in an earlier unpublished version of the identical data, Grab (1997a) notes that insufficient analysis had been undertaken at the site and the evidence is omitted from further discussion on sorted circles in the thesis.

The most convincing evidence for relict deep sorting associated with the freezing of soil is

presented by Grab from Site 3, Thabana Ntlenyane, at an altitude of 3460m. Sorted features of this magnitude (up to 6m in diameter) on Thabana Ntlenyana were first noted by Harper (1969) although their location or existence remained elusive and open to scepticism, as noted by Grab (1997a). Grab (2002) describes the forms but provides no clast size data as evidence for lateral sorting at the site. The single vertical section through one of the patterns taken at three specific depths, namely the surface, at 15 cm and 60 cm (Figure 13, p.1736), clearly shows vertical sorting. Although no additional evidence for particle sizes are presented the depth of sorting is then given as 85 cm at the site (p.1736, Table 1, p.1733). In the paper this is the maximum (observed?) depth of sorting found for *one* excavated landform, although the Abstract indicates somewhat misleadingly that "Patterns are sorted to maximum depths of 85 cm or more" (p. 1729). This depth of sorting concurs with a site approximately 3km from Site 3 in the vicinty of Nhlangeni Pass on the Escarpment interfluve where relict vertical sorting has been found to a sampled depth of 85 cm at ~3280m a.s.l. (Sumner, 2000). Although soil saturation then prevented deeper excavation, sorting was later established to 98 cm (Sumner, forthcoming).

In comparison to Sites 1 and 2, the Thabana Ntlenyana landforms, which are mostly less than 4m in diameter (n=7) but which can exceed 6m in diameter (n=2) (Table 1, p.1733), do not contain significantly elevated centres. It is apparent from a photograph (Figure 14, p. 1737) that centres can actually be *depressed* below clastic material. Considering the micro-topography and vegetation evident in Figure 5 (p.1732), it is surprising that five of the nine patterns have 0 cm centre elevation above the clastic borders (Table 1). Using the given data, the statistical mode for elevation distinguishes the sampled population from those of Sites 1 and 2 as tabulated (p.1733). This suggests that a different mechanism of formation between the sites is probable.

The mechanism or origin of formation of the patterns is centred on soil convection under previous colder conditions, specifically the adoption of the Rayleigh free convection model in soils (p.1737). The convection theory assumes the presence of permafrost with convection cells forming in the active layer (Ray *et al.*, 1983). Grab thus uses the presence of the patterns as evidence for permafrost (eg. p.1739-1741). While a convective mechanism enhanced by warmer, less buoyant (more dense) water at 4°C at the surface mixing with cooler less dense water from the underlying permafrost-active layer boundary can be envisaged in the model (Ray

et al., 1983), Grab (p.1737) depicts a scenario of *cooler buoyant* surface water descending and exchanging with rising *warmer*, *less dense* (presumably also more buoyant?) water from beneath. Despite the contradictory buoyancy conditions, the temperature scenario presented by Grab applies to a surface freezing cycle, not "during thawing" (p.1737). In fact, the argument presented actually militates *against* the presence of permafrost. If permafrost *were* present, temperature conditions at the base of the active layer above the permafrost would approach the freezing point and be *cooler* and *less dense* than the upper layer where a *maximum density* would be reached in the slightly *warmer* water around 4° C during surface thawing (see Ray *et al.*, 1983, p.321).

Further problems exist in the adoption of the convection model. Based on the data depicted, the pattern width-to-depth (active layer) ratios for Sites 1 (152 cm / 33 cm = 4.61) and 2 (157 cm / 65 cm = 2.41) (data from Table 1, p. 1733) do not correspond to the theoretical value of 3.81 calculated by Ray *et al.* (1983). In a comparison of various theories on the mechanisms associated with ground patterning, Van Vliet-Lanoë (1991) notes that the required conditions for classical Rayleigh convection are rarely possible under periglacial conditions (p.134). In reviewing the problems associated with pattern formation, Van Vliet-Lanoë (1991) further highlights that apparently identical geomorphic sorted patterns can occur outside of the permafrost zone. Although permafrost *may* be associated with the development of sorted circles, permafrost has long been recognised as *not* being essential for sorted circle development. For example, in west Baffin Island, Iceland and Spitsbergen, circular patterns are associated with seasonal freeze; the latter location having a size range of 0.8 to 3m in diameter (Embleton and King, 1974, p.69) which is not dissimilar in size to those found in permafrost areas (eg. Table 2, p.1740) and approximates the size range measured by Grab (Table 1, p. 1733). Permafrost is thus not a requirement for vertical and lateral sorting evident in pattern formation and, as noted in the paper, "their inter-relationship with permanently frozen ground is still imperfectly understood" (p. 1730). If permafrost were present in the high Drakensberg and Lesotho, the depth of relict vertical sorting implies an active layer up to 1m deep on interfluves, underlain by permafrost. More intense freezing should be expected on the insolation-protected south-facing slopes. No other evidence in the area, such as ice-wedge casts or polygonal ground cracking, has been presented in the literature to convincingly support the presence of such a frozen layer

during the Quaternary. Although deep seasonal freeze can be envisaged, a conclusion proposing the existence of permafrost cannot be invoked from the data presented.

Central to any argument for vertical and lateral sorting, and hence pattern formation, are the depth of frost penetration and the moisture conditions. Unfortunately, contemporary data on ground thermal conditions in Lesotho and the Drakensberg are very scarce. Although thermal data from a thufa (frost mound) and adjacent trough are available (Grab, 1997b), no data are published on the thermal conditions for unsorted or non-patterned regolith in the region. In June 1994 at Site 1, Grab found ice "below 40cm depth at borders" (p.1734); presumably measured in relation to the centre surface (Figure 9, p.1735) and not the border surface, the position of which ranges from 12 to 42 cm below the centre surface (Table 1, p.1733). The ice front is "somewhat raised towards pattern centres" (p.1734) where ice is "encountered" at 37cm depth (p.1735). Unfortunately the actual depth limit of freezing is not provided although Figure 9 (p.1735) schematically depicts frozen ground from 40cm to at least 50cm depth. Later, the paper argues for contemporary freezing "to depths of 40cm" (p.1738) and, as with the moisture conditions presented, the one datum from "the exceptionally wet winter of 1994" (p.1738) is extrapolated to broadly imply "segregation ice at ~40cm during some winters" (p.1737). This is then assumed to be the depth of contemporary seasonal freeze.

Notwithstanding the confusion as to the actual depth limit of frozen ground at the site, a frost penetration through the centres, which constitute an "overwhelming predominance of gravels and cobbles... to a depth of 20cm" (p.1738), and through the clastic borders should exceed that found in adjacent unsorted regolith. Coarse surface material enhances the penetration of cold into the regolith and the thermal conditions can differ greatly from those of adjacent fine-grained mineral soils (Harris and Pedersen, 1998). A depth of freezing found at this site cannot, therefore, be presented as general contemporary conditions for the area. Neither can ice now found at these depths in an already sorted feature be used to support the mechanism of formation, as the frost penetration is a secondary effect enhanced by the landform characteristics. Similarly, comparing with the scenario where "coarse, dry materials overly saturated, frost susceptible material" (p.1737 citing French, 1976) as contributing to the *mechanism* which then assists to "provide suitable evidence for moisture-induced free

convection process during the time of pattern initiation" (p.1737) is an equally circular argument. In addition, moisture conditions in winter are generally low; as depicted by the data for the "exceptionally wet winter of 1994" (p. 1738) where a maximum moisture content of 17% in a 35% silt/clay matrix was measured at 37 cm depth. Even dryer conditions could be expected during the period envisaged for the pattern formation (p. 1739) when precipitation was in the region of 70% of present values (Partridge, 1997). Moisture conditions would thus be unlikely to be "favourable" (p.1737).

In summation of the evidence, Grab graphically reconstructs the palaeo-geomorphological/environmental conditions across the Escarpment (Figure 15, p.1741). Given that the profile is meant only as a schematic representation, a few elements are, however, misleading. An eastwards decrease in altitude from the Escarpment summit to approximately 2000m a.s.l. over a horizontal distance exceeding 20km is not typical, particularly adjacent to the sites investigated in the paper in the Central and Southern Drakensberg where gradients are steeper. Neither is the exaggerated mountain and valley profile depicted immediately to west of the Escarpment ("Plateau" region) typical of the area (see Boelhouwers, 1992, for multiple transects through the Central Drakensberg). A more serious error is the depiction of cold-frontal systems moving across the Escarpment from the eastern sector. Mid-latitude cyclones forming within the belt of westerlies drive cold fronts across the sub-continent from the south-western sector (Van Heerden and Hurry, 1982; Preston-Whyte and Tyson, 1988) and can bring snowfalls to the high altitude regions. The decrease in snowfall depicted from east to west in the direction of the approaching cold fronts from the south-west thus requires further explanation, particularly since the highest precipitation region depicted in Figure 15, where niche glaciers are proposed, appears effectively precipitation-shadowed by the evidently mountainous Plateau. As described in general texts, precipitation trends on the eastern escarpment region are related to on-shore airflow, the orographic effect and convective activity driven in part by offshore anti-cyclonic activity in summer (eg. Tyson and Preston-Whyte, 2000). The confusion with regards to precipitation distribution, however, is probably due to the absence of actual field data on precipitation regimes in the Escarpment region. Details on precipitation shown in Figure 15 should thus be viewed with caution, particularly when based on values extrapolated from lower altitudes (eg. Schulze, 1979).

Overall, I find that the paper does not present sufficient evidence for the important and far-reaching conclusion that the features described are sorted circles derived from a permafrost environment. The spatial depiction of palaeo-conditions showing a zone of permafrost above 3400m in Figure 15 is thus misleading and its connection with the palaeo-precipitation regime shown is tenuous, particularly where snowfall is concerned. Evidence for niche glaciation (Hall, 1994; Grab, 1996) depicted on the Escarpment and based on moraine-like features has also raised debate (Sumner and Hall, 1995) and remains only a possible hypothesis (Grab, 1996, p.389). In general I feel that the paper presents interesting sites but fails to rigorously describe their morphology and investigate alternative mechanisms of formation. Too many important generalisations are made from too few data/observations to derive more than "suggestive conclusions" (p.1730) and cannot provide "confirmation for Late Quaternary permafrost above 3400m" (Abstract, p.1729). I therefore find that the arguments and conclusions presented cannot be taken as significantly resolving the issue of previous glaciation or permafrost conditions (see Grab, 2000) and, on the geomorphological information provided, cannot present a reconstructed palaeoenvironment for the area.

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SECTION 2: FIELD STUDIES and DISCUSSIONS

PREFACE

Section 2 comprises six Chapters which present and discuss field data from the study area. They appear as follows:

Sumner, P.D. and de Villiers, S. (2002). On the palaeoenvironmental implications of the Amatola Screes. *South African Journal of Science*, 98, 598-601.

Boelhouwers, J., Holness, S., Meiklejohn, K.I. and Sumner, P.D. (2002). Observations on a blockstream in the vicinity of Sani Pass, Lesotho Highlands. *Permafrost and Periglacial Processes*, 13, 251-257.

Boelhouwers, J. and Sumner, P.D. (2003). The palaeoenvironmental significance of southern African blockfields and blockstreams. 8th International Conference on Permafrost, Zurich, July 2003, refereed conference proceedings, (in press).

Sumner, P.D. (Submitted). Relict sorted patterned ground in Lesotho. *Permafrost and Periglacial Processes*.

Sumner, P.D. (In press). A contemporary winter ground thermal profile in the Lesotho highlands and implications for active and relict soil frost phenomena. *Earth Surface Processes and Landforms*, 28.

Sumner, P.D. (For submission). Palaeo-geomorphic and -climatic implications of openwork block accumulations in the upper Sehonghong valley, Lesotho, southern Africa. *Geografiska Annaler*: A.

The first Chapter (Sumner and de Villiers; published in *South African Journal of Science* in 2002)[1] continues in the spirit of Section 1 by critically re-analysing geomorphic evidence for periglacial or cryogenic processes in the Eastern Cape region of the Main Escarpment (Amatolas, Figure 1, p.5). Understanding the origin of the relict landforms (openwork dolerite screes) is significant since the site serves as a vital linkage between the relict landforms of the Lesotho-Drakensberg and the Western Cape mountains. New data are presented on the screes,

[1] Stephanie de Villiers provided the data on the geographical distribution of the screes. The original idea for the paper was mine, and I undertook the text compilation, submission and revision.

from which a re-assessment of the accepted palaeoenvironmental conditions during their emplacement is made. The Chapter presents an alternative formative origin which highlights the role of depressed temperature conditions on block production, but excludes any dependance on snow or distinct periglacial phenomena on cooler south-facing slopes.

The second Chapter in this section (Boelhouwers, Holness, Meiklejohn and Sumner; published in *Permafrost and Periglacial Processes* in 2002)[2] presents new data from a relict openwork block accumulation site north of the Amatola Mountains near the escarpment in Lesotho (Figure 1, p.5). The high altitude site's basalt blockstream is the largest of its type found in the Lesotho highlands. Blockstream sedimentology is described and block origin and mobility are discussed. Interpretation of the geomorphic processes and conditions that gave rise to the blockstream and associated landforms lends itself more to the classical literature on cold-climate openwork accumulations. Origin is ascribed to block production under colder conditions and slope mobilisation though seasonal freeze and solifluction on the south-facing valley slopes during the Late Pleistocene cold period, although some blocks are suggested to have been upward frozen through the regolith. The presence of solifluction mantles, which must pre-date the phase of block production, provides an argument against the glaciation, or deep snow cover, of such valleys. This stands in contradiction to other geomorphic evidence found in the area which have been previously presented in favour of at least limited glaciation, or nivation.

Chapter three (Boelhouwers and Sumner, 2003)[3] of this section was written as a discussion paper for presentation at the International Conference on Permafrost in Zurich, July 2003, and will be published, as it appears here, in the refereed conference proceedings. The paper explores the characteristics of the various openwork accumulations which are found in distinctly

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[2] The paper was initiated and drafted by the first author, Jan Boelhouwers, who was also responsible for submission and revision. Other authors appear alphabetically. I was directly involved in field discussions, field measurements (notably the blockstream physical characteristics and relative-age dating), the final cartographic compilation and to a lesser extent on comments on drafts. I initiated the relative-age dating assessment by the rock surface roughness technique; the first occasion this was utilised in southern Africa.

[3] The idea for the paper was mine and the abstract for submission drafted by Jan Boelhouwers. I compiled the first draft of the paper and after various discussions and alterations submitted the paper, and revised it according to the referee's comments. Jan Boelhouwers presents the conference paper in my absence.

different climatic environments in southern Africa. The intention of the paper is to highlight the similarities and differences of openworks found under climatic conditions which match or differ vastly from the classical interpretation of blockfields and blockstreams - that they are derived under cold conditions. Openwork accumulations derived from *in situ* weathering in arid and semi-arid environments are found to challenge this view. An argument, however, is presented favouring a periglacial mode of emplacement for the blockfields and blockstreams of the Lesotho highlands and Western Cape mountains, and this allows for generalised palaeoenvironmental reconstruction.

The final three Chapters present data from sites near to the Boelhouwers *et al.* blockstream valley in the proximity of Thanbana Ntlenyana, the highest point in southern Africa at 3482m a.s.l. (Figure 1, p.5). Relict sorted patterns at the summit of Nhlangeni Pass (Figure 1, p.5), some two kilometres from the Thabana Ntlenyana massif, are presented in the first paper (submitted to *Permafrost and Periglacial Processes*). Horizontally and vertically sorted relict labyrinth patters (first described by the author in a conference presentation in 2000), an intermediate form between circles and strips, are presented as an indication of previous deep seasonal freeze. Since the current freezing depth is virtually unknown for the area, the following Chapter (in press in *Earth Surface Processes and Landforms*) determines the contemporary ground thermal conditions over a winter at 3220m in the vicinity of the sorted patterns. From sensors extending down to 2m in a valley floor colluvium, the first data on a contemporary "seasonal" freeze" and diurnal freeze-thaw of non-patterned ground for the area are presented. Projected freezing depths under depressed temperatures are correlated to the depth of relict vertically sorted landforms found at the nearby site and to those found at another site in the Thabana Ntlenyana vicinity. Findings are discussed in the context of Late Pleistocene deep seasonal freeze and the possibility of permafrost.

The final Chapter of the thesis (for submission to *Geografiska Annaler*: A) investigates the geographic distribution and characteristics of openwork units on the southern approach to Thabana Ntlenyana (Figure 1, p.5). The focus is on slope openwork accumulations extending from scarps on the interfluve down to the valley floor. Data are found to support the argument for a phase of block production and enhanced mobility on southern slopes. As noted above for

solifluction mantles, the data from openwork block distribution argue against the glaciation of southern slopes and valley-heads. Palaeoenvironmental significance of the findings, particularly those pertaining to localised glaciation of southern slopes and protected escarpment cutback environments, are discussed.

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ON THE PLEISTOCENE PALAEOENVIRONMENTAL EVIDENCE FROM THE AMATOLA SCREES

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Published in: *South African Journal of Science*, 2002, vol. 98, 598-601.

ABSTRACT

Relict openwork scree deposits in the Amatola Mountains in the Eastern Cape, South Africa, have previously been attributed to frost action and nival activity predominating on south-facing slopes. The data have been used as representing the minimum snow-line for the area and hence as supporting evidence for constructing a Pleistocene periglacial gradient for the sub-continent. A geomorphological re-examination of the deposits, however, does not support an origin specifically associated with enhanced periglacial activity above a minimum altitude on south-facing slopes. The spatial distribution is attributed to lithological and topographical control and the openwork block deposits are found to be remnants of screes slopes, formed irrespective of slope aspect orientation, which are subsequently infilled by fines. Although block production appears concurrent with that found at other high altitude sites in southern Africa during the colder Late Pleistocene, specific palaeoenvironmental conditions such as the presence of late-lying snow and enhanced frost action processes on south-facing slopes cannot be inferred.

INTRODUCTION

The origin of now relict openwork scree accumulations in the Amatola Mountains has been ascribed to Pleistocene frost action and the presence of late-lying snow, particularly for south-facing slopes above a minimum altitude (Marker, 1986). Upon this premise the screes are said to establish the minimum snow-line for the region and facilitate in the construction of a Pleistocene periglacial gradient for the sub-continent (Marker, 1986; 1995). More recent field data and spatial analysis from the slopes of the Amatolas indicate that the location and apparent distribution of the screes and hence the formative geomorphic processes may have been misinterpreted in the past and that a reappraisal of the palaeoenvironmental implications and associated processes is necessary.

LOCATION

The Amatola Mountains of the Eastern Cape form a part of the Great Escarpment of southern Africa. In the vicinity of the Hogsback village, the escarpment separates the upper post-Gondwana erosion surface (at altitudes of 1400-1500m.a.s.l.) from the lower altitude Africa surface extending from the base of the Escarpment (approximately 750m a.s.l.) eastwards towards the coast. The escarpment and the associated residuals are comprised of more resistant Karoo dolerites intruded through Beaufort Group sandstones and shales (Agnew, 1965). Doleritic outcrops above the post-Gondwana surface reach above 2000m a.s.l. (Figure 1) and support free-faces from which colluvial mantles extend to the lower gradients of the erosion surface. Contained within many of the colluvial mantles are openwork (no fines matrix) blocky accumulations; for example those found on the slopes of Elandsberg, Gaika's Kop, Rockford Ridge and The Hogsback (Figure 1). The openwork accumulations are derived as scree from the higher slope dolerite free-faces. With no evidence for contemporary accumulation of any substantial magnitude the screes are considered relicts of previous climatic conditions (Marker, 1986). Upon this basis they have been used as geomorphic indicators for the past climatic or environmental conditions under which they developed.

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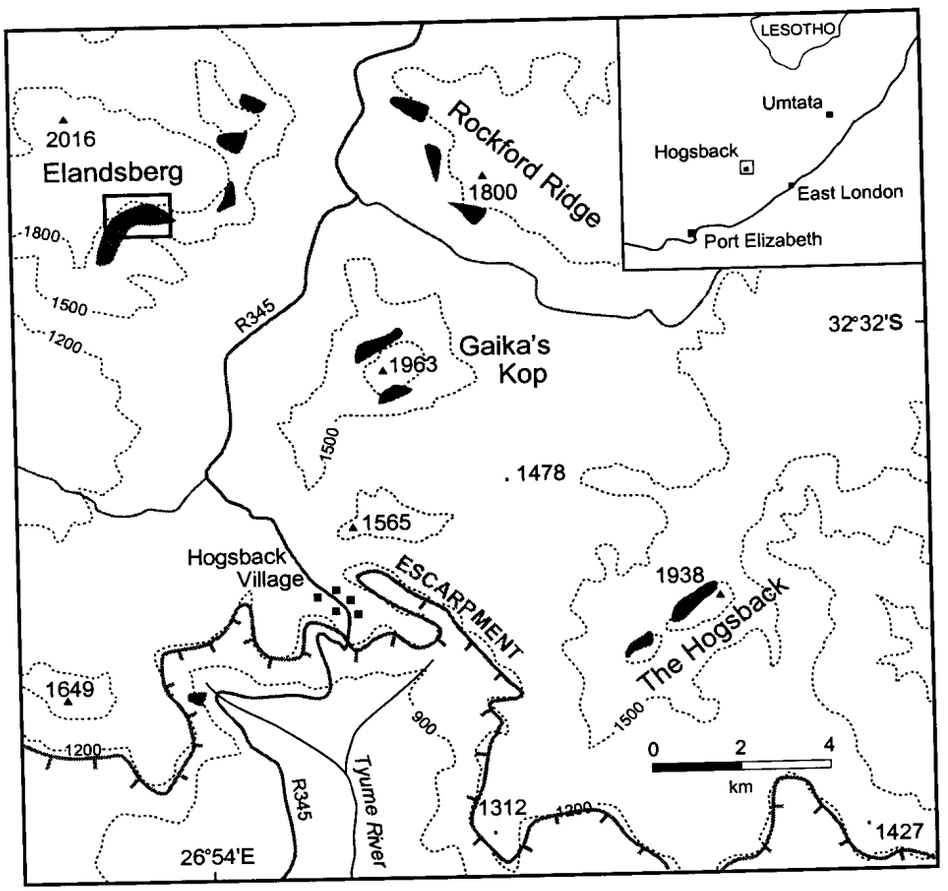


Figure 1: General location of openwork block accumulations (shaded) in the vicinity of Hogsback village in the Amatola Mountains.

EXISTING GEOMORPHIC AND PALAEOENVIRONMENTAL INTERPRETATION

Marker (1986) describes the screes on the slopes of Elandsberg, Rockford Ridge and Gaika's Kop noting the size and slope aspect distribution of 47 scree units. Several important points are noted: the screes are indicated to never abut directly onto free faces (see Figure 2), to lie dominantly on south-facing slopes (over 75% of screes recorded) and preferentially within former gullies and topographic hollows (or niches), and to extend down to a minimum altitude of 1550m. Scree physical characteristics are provided in more detail from the slopes of Elandsberg (Figure 2). They are noted as constituting angular to sub-angular blocks typically

measuring 0.5 to 2.0m (long axis) with some blocks weathered *in situ,* and as protruding or positive features in relation to the adjacent slopes with no evidence for derivation as a lag by fines removal. A cliff foot "flat" (p.905, 907) slope of 10° is noted at an Elandsberg site with screes extending down slopes typically in excess of 20° (F, Figure 2) (Marker, 1986).

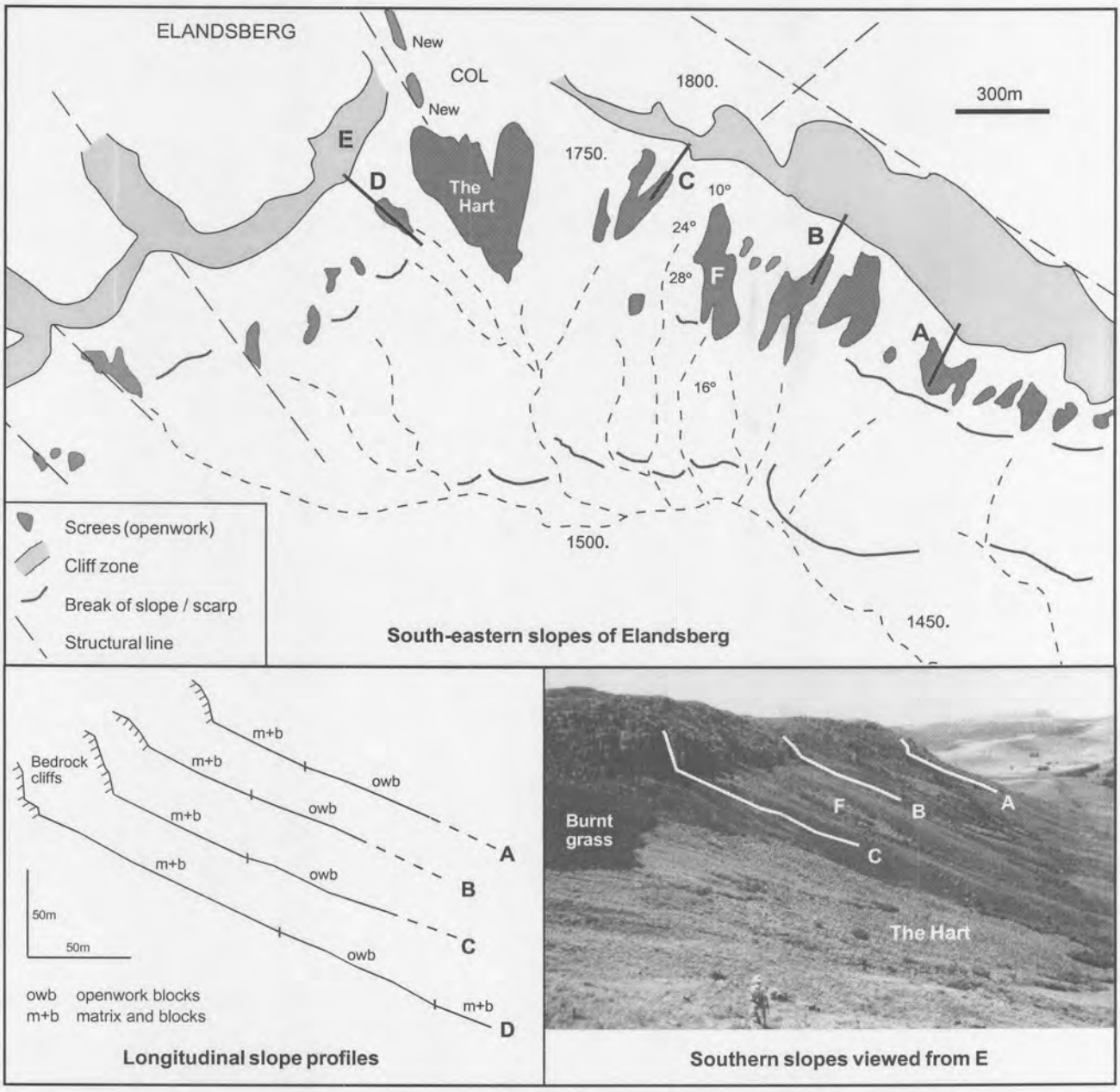


Figure 2: Openwork screes on the south-eastern slopes of Elandsberg enlarged from Figure 1 (modified after Marker, 1986). Slope angles from Marker (1986) indicated adjacent to previously measured unit F (see text for comment).

Marker (1986) interpreted the currently stable deposits as relicts from the colder periods of the Pleistocene. The larger scree tongues are described as associated with "nivation niches" (p. 908) with blocks derived from "frost action" (p.908) operating on the cliffs. Some of the screes are described as "protalus ramparts" (p.909) which implies a specific association with late-lying snow. A dominance of south-facing screes where slopes receive minimal insolation is given as supporting the argument for late-lying snow and depressed temperature conditions. The absence of screes directly beneath the cliffs is accounted for by the presence of snow at the base of free-faces, in the cliff foot "flat" (eg. p. 907), and within cliff-line hollow forms; blocks falling onto the snow from the cliff would slide across snow surfaces and accumulate downslope as a protalus rampart (Marker, 1986).

Based on being interpreted as Pleistocene cold phase phenomena the scree altitudes are used to set minimum altitudes for periglacial activity associated with the presence of snow in the area, and hence the palaeo snow-line. In a regional context the landforms are described as similar to other relict hollow and cirque-like forms described in the Eastern Cape and eastern Free State (Marker, 1986; 1998). In constructing a Pleistocene periglacial gradient for the sub-continent from geomorphic evidence (Marker, 1995) these data provide an important link between the eastern region, comprising the Drakensberg-Lesotho mountains, and the Western Cape.

NEW DATA AND OBSERVATIONS

Observations from several field undertakings in the area cast some doubt on the earlier interpretation of the deposits, particularly those derived from the apparent spatial distribution. For example, numerous openwork units are observed on the north-west facing slopes of the Hogsback ridges, a site not previously considered in the original research. Although generally smaller in size than the units described by Marker from other slopes, combined with Markers orientation data (derived from size-independent data) these units would alter the recorded overall aspect orientation for screes in the area. In addition, the scree units on Hogsback, and at other sites such as Gaika's Kop, appeared not to be confined to drainage lines or hollow forms. Such observations appeared to be contrary to the fundamental premise of the original

interpretation regarding nival conditions with enhanced frost action on the protected south-facing slopes.

Geographic and topographic (slope) locations of the openwork scree units were therefore mapped from ortho-photographs covering the area roughly corresponding to Figure 1, but also including the western extreme of Elandsberg. This included and extended beyond Marker's original areal coverage. A total of 157 openwork units were mapped and physical characteristics such as unit length, width, aspect orientation, distance from free-face recorded (de Villiers, 2000). Ground-proofing to verify the mapped units was undertaking on two subsequent field visits. Additional field data was obtained describing the openwork screes on the southern slopes of Elandsberg where the evidence for protalus rampart-type accumulation had previously been presented.

In the area, openwork block accumulations are found to occur on all slopes supporting free-faces, particularly where bedrock joint spacing is conducive to block production. The lower limit for scree accumulation is controlled by local topography. Slope gradients decrease from around 25 to 30° on the upper colluvial mantles off the dolerite summits down to angles less than 10° approaching the valley floors at approximately 1400 -1500m a.s.l.; the topographic lower limit for screes above the Escarpment. Below the Escarpment extending into the upper Tyume valley the dolerite exposures are typically massive with large joint spacing. Conversely, the sandstones and shales are highly jointed. Weathered products from these lithologies are thus not conducive to blocky scree accumulations and only one doleritic openwork block deposit resembling those at higher altitude was found beneath the Escarpment; in the upper Tyume catchment at an altitude of 900m a.s.l. on a north-east facing slope (Figure 1).

Topographic orientation and location of the 157 mapped openwork units on the slopes (de Villiers, 2000) are summarised in Table 1. As noted above, screes occur on all slopes that support free-faces. Rockford Ridge and ridges comprising The Hogsback (Figure 1) are inclined sills, dipping to the north-east and south-east respectively with typical free-faces on their respective south-east and north-west scarps. Consequently, screes on these ridges only accumulate below the free faces on the south-eastern slopes of Rockford and the north-western

slopes of Hogsback. Screes occur on all aspects of Gaika's Kop while a few openwork accumulations occur on the generally lower gradient northern slopes of Elandsberg. Therefore, although the largest units are associated with the south-eastern slopes of Elandsberg (Figure 2), which support the highest free-faces, geographic distribution is controlled primarily by lithological characteristics, geological structure and local topography and not directly by slope aspect or altitudinal-climatic gradients. In the area, relatively few screes are thus recorded for the aspect segment covering north- to east-facing slopes . In contrast to the dominant southerly orientation of screes (75%) noted by Marker, the mean topographic orientation of all scree units measured lies west of south-west (Table 1) which reflects the orientational nature of the free faces and underlying slopes of the area studied.

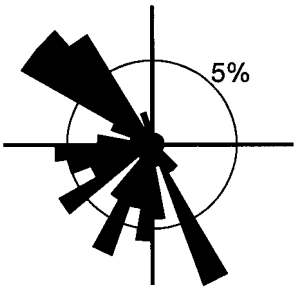
Topographic orientation of scree slopes (%)	**Location of openwork deposits on slopes**	**Number (%)**
	Spur	60 (38)
	Rectilinear slope	39 (25)
	Valley or drainage line	36 (23)
	Valley head	6 (4)
	Hollow	16 (10)
	TOTAL	157 (100)

Table 1: Topographic location of the openwork units.

As regards specific scree location on slopes; 63% of the openwork scree units are not associated with drainage or topographic hollow forms but lie on spurs (38%) and on rectilinear slopes (25%) where the units mostly protrude as positive features above the adjacent slope. The remaining 37% are found within hollows, valleys or valley heads and drainage lines (Table 1). Within all categories, 6% of the mapped units extend directly from the free-faces. Where openwork units do not abut directly on the cliff-zone, for example on Elandsberg (Figure 2),

blocks are contained within the fines matrix. On all slopes, the blocks are distributed continuously along the colluvial mantles although matrix dominates at the vegetated surface adjacent to the openwork units. Notwithstanding this, the apparent absence of openwork scree units extending from free faces, and verified by the above data, is attributed by Marker to the presence of snow. In support of this argument Marker (1986) notes a low gradient (10°) slope section at the base of the cliff-line on a south-facing slope of Elandsberg (Figure 2), ostensibly where the snow patch would lie and over which blocks falling from the cliffs above would move. However, no such decreases in slope angles on colluvium at the cliff bases were measured in the field on these slopes (Figure 2) or noted on other slopes where scree units are found. Neither do any scree units found in the area resemble the morphology of typical protalus ramparts found in other areas (Shakesby, 1997).

DISCUSSION

The underlying premise for formerly attributing the scree to periglacial conditions was the dominantly south-facing aspect where cold conditions and associated processes such as "frost action" are intensified and late-lying snow would exist (Marker, 1986). Scree would thus accumulate predominantly in topographic hollow forms where snow is most likely to accumulate and remain. However, a more extensive evaluation of the spatial distribution of screes indicates that the deposits occur on all aspect orientations and scree distribution is determined by geological and topographical factors. Implications for slope-scale climatic or micro-climatic conditions and possible related process implications can therefore not be derived from scree orientation. In addition, the openwork accumulations do not lie preferentially within topographic recessions as previously stated, but are predominantly on rectilinear slope segments or on spurs. Since no topographic evidence was found for protalus-type accumulations a formative mechanism which implicitly requires the presence of snow is, therefore, unlikely. Similarly, an argument for block production by enhanced frost action, a problematic weathering process to apply in itself (Hall, 1990; 1996), on south-facing slopes appears unlikely.

The openwork sections appear to simply be remnants of relatively continuous scree slopes,

portions of which have subsequently been infilled by matrix. This interpretation is based on the following: First, the ubiquitous distribution of the screes, apparent where dolerite free-faces of suitable joint spacing occur and extending from free-faces (although contained within a matrix) to the lower slopes of the erosion surface. Second, the preferential location of openwork scree units on slope spurs and the rectilinear slope segments and third, the positive protrusion of the scree units above the adjacent slope surface. Fines infill of the screes would have occurred through *in situ* weathering and mobilised weathered products from the higher slopes. The infill from above accounts for the relatively few remaining openwork remnants "abutting" onto the cliff-zone as matrix has gradually accumulated at the break of slope beneath the cliff. Infill would be least favourable on spurs due to slope drainage diversion, or where screes attain a greater thickness, and most favourable where drainage converges such as in hollow forms. In drainage lines or valley heads, topographically favourable sites for scree and infill accumulation, converged drainage may be sufficient to maintain an openwork structure.

No specific palaeoenvironmental conditions can, therefore, be drawn from the geographic and geomorphic characteristics of the scree units themselves. Scree formation was primarily a function of favourable lithological and topographical conditions and the openwork remnants observed in the landscape today are due to the gradual matrix infill and the vegetation of adjacent scree slopes. What is apparent, however, is that in the past the area was subject to a period where block production was dominant either due to a phase of enhanced mechanical weathering or due to limited chemical weathering. Phases of increased block production in the mountains of the Western Cape (Boelhouwers, 1999) and the Lesotho highlands (Boelhouwers *et al.*, 1999) have been recognised as indicative of enhanced periglacial activity with minimal snow cover and deep seasonal freeze. It appears most likely that the scree originated during this period, with subsequent Holocene infill. However, the data do not suggest enhanced periglacial activity in the form of frost action or late-lying snow.

CONCLUSION

Specific palaeoenvironmental conditions, such as the presence of late-lying snow, and the enhancement of frost weathering processes cannot be inferred from the residual screes units

found in the Amatola Mountains in the vicinity of Hogsback village. The scree units as they appear today are the openwork remnants of a gradual infill of the scree slopes. This infill is subsequent to a period of dominant block production from the free-faces, similar to that found for the colder Late Pleistocene in other mountain areas of southern Africa (Boelhouwers, 1999; Boelhouwers *et al.*, 1999). Although block origin is attributed to depressed temperature conditions no evidence at the site suggests full periglacial conditions or processes and as such caution should be exercised in including the screes in any regional assessment of true periglacial phenomena during this period.

ACKNOWLEDGEMENTS

Funding was supplied through a core grant from the National Research Foundation and from the University of Pretoria. Thanks extended to Ian Meiklejohn, Hermien Bijker and Werner Nel, and for comments in the field from Jan Boelhouwers, Paul Allen and Brian Whalley. Comments from two referees significantly improved the original manuscript.

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OBSERVATIONS ON A BLOCKSTREAM IN THE VICINITY OF SANI PASS, LESOTHO HIGHLANDS

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Published in: *Permafrost and Periglacial Processes*, 2002, vol. 13, 251-257.

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ABSTRACT

Coarse slope deposits, frequently grading into blockstreams, are common throughout the Lesotho highlands, southern Africa. This paper describes such a blockstream, which is interpreted as a typical lag deposit from valley-wide solifluction of colluvial mantles, which contains superimposed and incorporated Late Pleistocene blocky material. Blocks are largely derived from local scarps but may contain a component of corestones from mobilised regolith. The widespread solifluction mantles argue against landscape scale glaciation in the Lesotho highlands in the Late Pleistocene. Rather, the environment appears to have been highly conducive to deep seasonal frost during the period of block production. No unequivocal evidence for permafrost was found.

INTRODUCTION

The Quaternary geomorphology of the Lesotho highlands is the subject of controversy as regards the extent of Pleistocene glaciation and/or periglaciation (Boelhouwers and Meiklejohn, 2002). First reconnaissance studies commented on the presence of relict forms including distinct valley asymmetry (Alexandre, 1962), rock ledges interpreted as nivation sites (Harper, 1969), valleyheads resembling glacial cirques (Sparrow, 1967; Marker and Whittington, 1976; Dyer and Marker, 1979) and sedimentary deposits that included block mantles and blockstreams (Sparrow, 1967, Hastenrath and Wilkinson, 1973). Today, marginal soil frost results in small-scale patterned ground, thufur and needle-ice induced processes (Boelhouwers, 1991; Grab, 1997a, 2000). In this paper, one of the most well-developed blockstreams in the Lesotho highlands (Figure 1), originally visited by Hastenrath and Wilkinson (1973), was subjected to further analysis. It is located at relatively low latitude in an area with an uncertain Quaternary record.

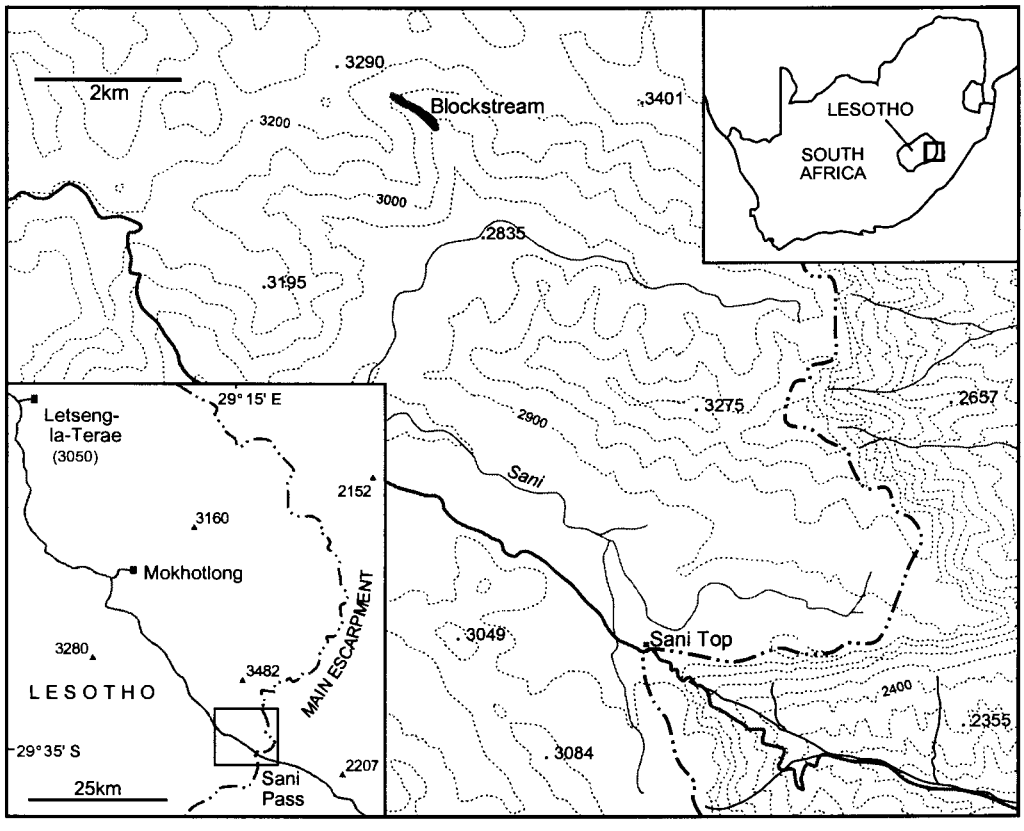

Figure 1. Location map of the Lesotho Highlands and blockstream site investigated. Altitudes in m a.s.l.

BACKGROUND

Much debate on the interpretation of the relict landforms in this region centres on the complexities of the field evidence (Hall, 1992; Hall *et al.*, 1991) and uncritical adoption of Northern Hemisphere concepts (Butzer, 1973; Hall, 1992; Boelhouwers, 1995, Boelhouwers and Meiklejohn, 2002). The glacial hypotheses rely assume a number of landforms as being due to glacial erosion (Dyer and Marker, 1976; Marker, 1991). In the absence of unequivocal glacial evidence, equifinality offers multiple alternative hypotheses. Sedimentological data by Lewis and Illgner (2001). do not show diagnostic evidence for glaciation and alternative interpretations remain.

The widespread relict blockfields and blockstreams appear most indicative of the periglacial conditions that the region probably experienced during the fluctuating climates of the Quaternary. Sparrow (1971) comments on the widespread block mantles above 1800m asl, presumably due to the presence of the resistant Drakensberg basalt at these altitudes (Boelhouwers, 1999a). Hastenrath and Wilkinson (1973) interpret a long, narrow blockstream over 1km long near Sani pass as indicative of solifluction, and Boelhouwers (1994) describes a sequence of coarse slope deposits in the same region that is interpreted within a context of deep seasonal frost environments and limited snow cover. Boelhouwers (1999a) also argues for the importance of non-periglacial autochthonous blockfield development in these highlands.

Several authors have argued for block generation in non-cryogenic weathering mantles that predate the onset of periglacial redistribution by frost heave and creep/solifluction. This hypothesis was originally put forward by Caine (1968). Similar arguments have been used subsequently to explain the Falkland stone runs (Clapperton, 1975), and blockfields in northern Norway (Rea et al, 1998). Because the preservation of pre-Pleistocene weathering surfaces has gained increasing recognition in northern countries (Lidmar-Bergström, 1995), the origin of blockfields in mid- and low-latitudes requires careful re-evaluation (Boelhouwers, 1999a). In addition to the possibility of their greater antiquity, their origin by frost weathering can no longer be assumed uncritically.

FIELD OBSERVATIONS

The blockstream under investigation is located in a valley about 5km west from the Main Escarpment, near Sani Pass, at an altitude of 3000-3200m asl (Figure 1). The surrounding slope materials are interpreted as Pleistocene solifluction deposits (Hastenrath and Wilkinson, 1973; Boelhouwers, 1994).

Figure 2 illustrates the catchment and its blockstream and Figure 3 is a geomorphological map of the area immediately adjacent to the blockstream. The valley is composed of four small catchments that converge in the central valley where the blockstream is located. The catchment is distinctly asymmetrical with tributaries B, C and D feeding into the main valley from the north. The upper slopes of the catchment comprise small rock scarps alternating with thin debris mantles. Rock scarps are less continuous on the south-facing slopes than on north-facing slopes and show mechanically-induced fractures.

By contrast, north-facing rock scarps are smooth, massive and convex shaped (Figure 4). Downslope from this upper scarp zone the north- and south-facing slopes develop notable differences. The north-facing slope continues as a rectilinear rock slope with a thin debris veneer less than 1 m thick and occasional rock ledges up to 2 m high. In contrast, the south-facing slope is concave in profile with a thicker debris mantle. Resistant basalt layers, although not necessarily exposed, create local breaks in slope above which wetlands are frequently present. Thufur are often well developed at such sites. Further downslope terraces with risers of 0.5 m - 1.5 m high are particularly well developed in catchment D. Clast content also increases in downslope direction resulting in occasional openwork block deposits. Where located along drainage lines, openwork deposits may be in a slightly depressed location. The south-facing slope is much longer and wider than the north-facing slope, thus providing a larger source area for debris and regolith production. Judged by the discontinuous rock scarps, block weathering appears more advanced on the south-facing slopes.

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Figure 2. View of the investigated blockstream near Sani Pass as indicated with the dotted line. Photo JB December 1998.

Sedimentology of the main blockstream

The long, narrow blockstream that occupies the central valley floor has a length of approximately 1.1 km and a maximum width of about 75 m. This openwork block deposit is aligned along the central drainage of the main valley and is positioned at the terminal end of the solifluction mantles from catchments A and B (see Figure 3). It extends downslope at a gradient of 8°. The block deposit has an irregular surface, with the highest parts slightly raised above the surrounding valley-floor (Figure 5). In contrast, the depressions and channels extend beneath the level of the surrounding slope. Today, a small stream emerges from beneath the terminal end of the blockstream in summer.

Block size (a-axis) data at various distances along the blockstream are summarized in Table 1. They indicate minimal variation in block size composition over the entire length of the blockstream. Fabrics of the a-b plane show well-developed bi- or trimodal clast orientation distributions (Figure 6). The primary alignment of clasts at all sites, except at 500 m, is parallel to the local maximum slope gradient. A secondary concentration of blocks with orientations at right angles to the primary mode is present at all sites reflecting imbricated and often steeply

dipping clasts. A third peak, indicating a preferred north-south alignment, is found on the northern margin of the blockstream at 500, 700 and 900 metres. These sites are located at the confluence with catchments B and C and have more complex (random) fabrics.

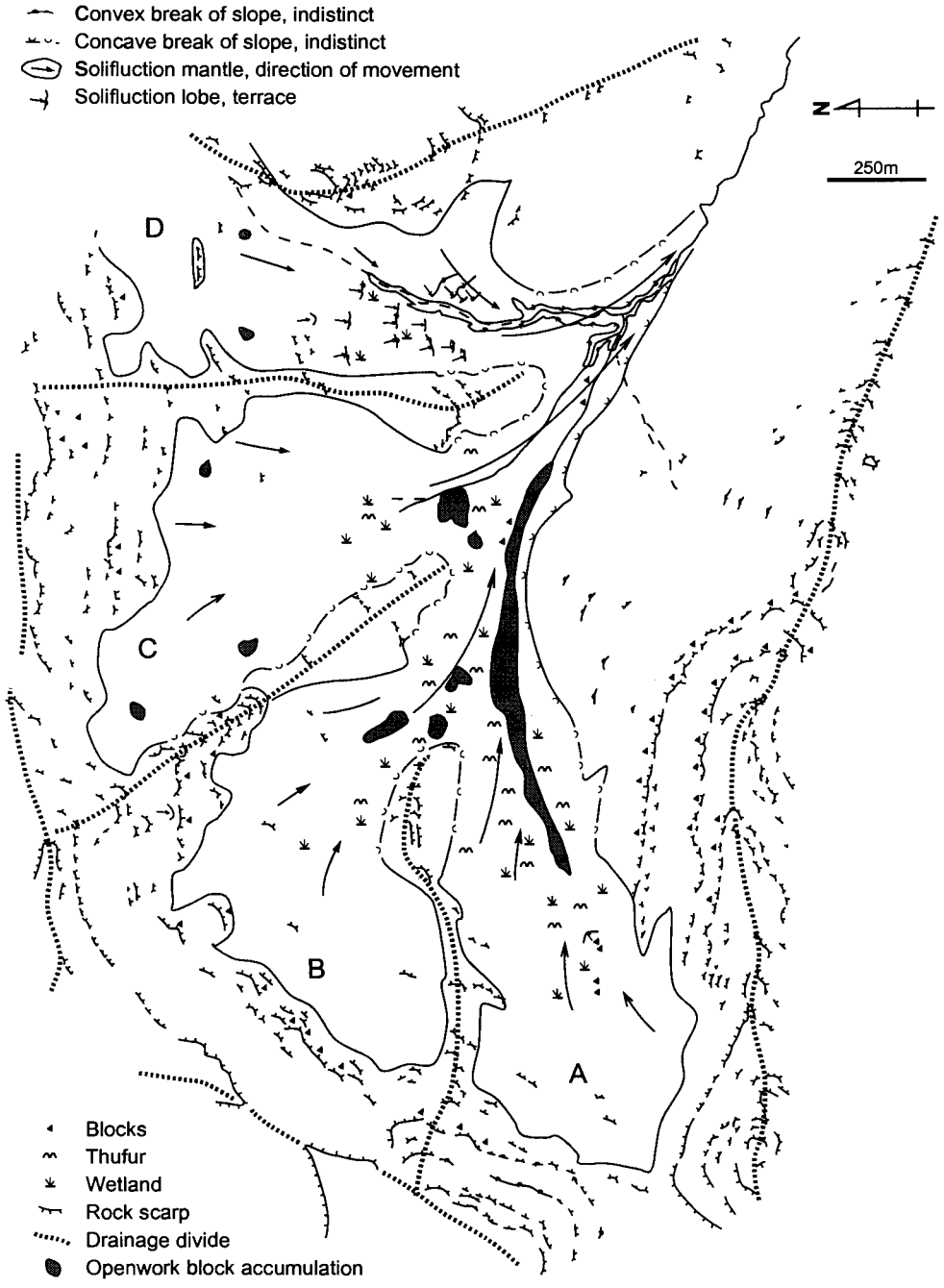

Figure 3. Geomorphological map of the blockstream valley. Based on 1:10.000 aerial photo interpretation and field mapping.

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Figure 4. Rock scarps in the upper catchment: a) discontinuous, mechanically fractured scarp facing southeast; b) continuous, massive and northeast-facing scarp at same altitude (3200m asl). Photo's JB.

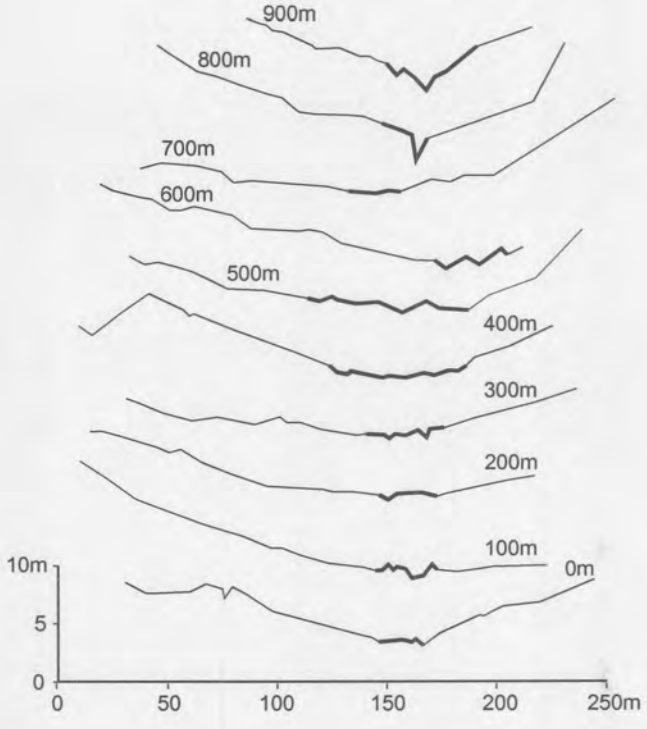

Figure 5. Cross profiles of the blockstream, viewed from its upper end (0m) in downslope direction. For location of the transects see Figure 6.

Distance (m)	n	Min (cm)	Max (cm)	Avg (cm)	St. Dev (cm)
100	75	28	143	63. 7	23. 1
300	75	26	141	62. 9	25. 6
500	75	24	158	69. 6	26. 9
700	50	21	104	58. 9	20. 2
900	50	25	112	60. 2	24. 0

Table 1: Summary statistics of block a-axis measurements along the blockstream in downslope direction. For location of sample sites see Figure 6.

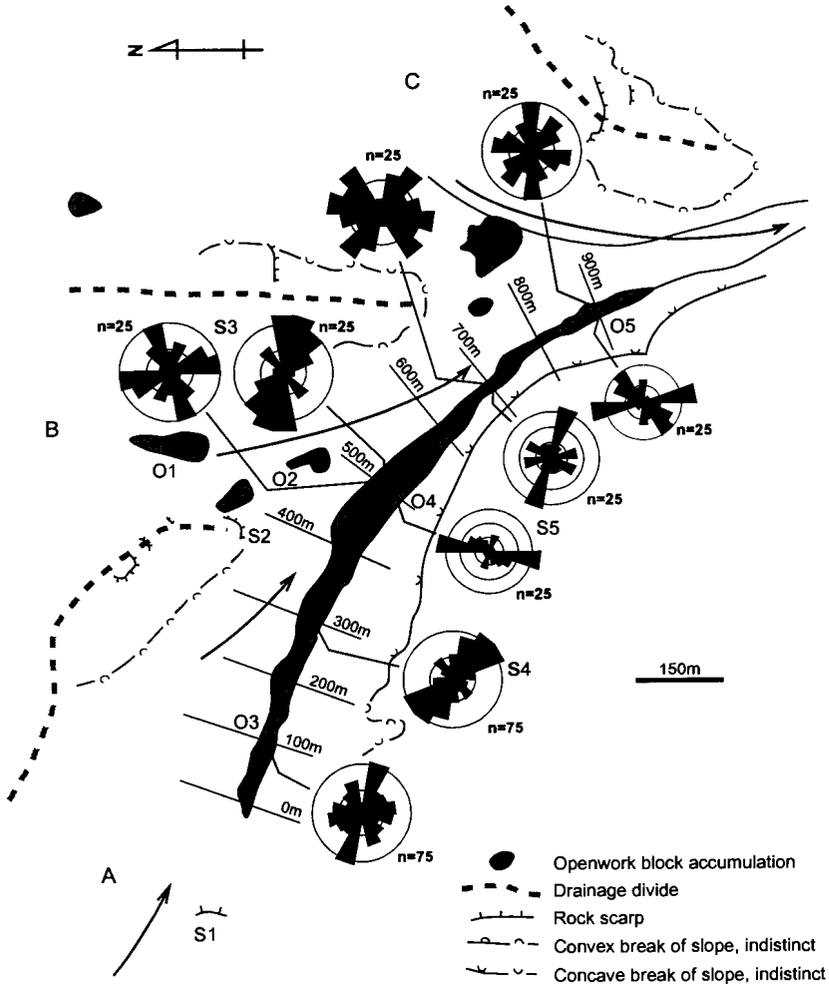

Figure 6. Fabric diagrams for surface clasts, location of transects and rock surface relative-age dating sites.

Evidence from exposures

No exposures occur in the central blockstream. However, stream incision has resulted in exposure of the terminal zone of the mass-wasting mantle from catchment C. This reveals a uniform, coarse, clast-supported diamict at least 4 m thick. Exposures in the slope materials from catchment D occur along its stream, which runs over bedrock. At its confluence the material is 15-20 m thick and is composed of a massive, unstratified, granular loam. Occasional thin layers contain a 10-30% abundance of small stones with a-axes up to 15 cm. Boulders, with a-axes up to 1.5 m, are restricted to the uppermost 0.4 m.

Three hundred metres upstream from the confluence the stream in catchment D exposes a 3 m thick deposit through a stone-banked terrace. A 1.6 m thick clast-supported diamicton is exposed along the 8 m wide front. Clasts have a-axes up to 80 cm and dip at 22° in upslope direction. Contact with the underlying material is near-horizontal on a 8° slope. The deposit rests on 1.5 m of uniform, granular loam.

ORIGIN OF THE BLOCKS

The boulders in the central blockstream are sub-rounded with pitted surfaces and weathering rinds less than 2 mm thick. In contrast, the blocks that comprise several smaller blockfields in the adjacent tributary valleys are distinctly angular and surface pits are absent. The rock scarps in the upper sections of the catchment have generally rounded surfaces, but highly fractured, angular rock scarps and tors dominate the south-facing slopes (Figure 4).

Relative-age dating of block and scarp surfaces was attempted by comparing values of Schmidt hammer rebound (eg. Mathews and Shakesby, 1984) and rock surface roughness (McCarroll and Nesje, 1996). Although the blockstream has marginally lower rebound values (Table 2) no definite trend was evident between sites. This is likely due to the absence of appreciable weathering rinds as a result of rapid removal by rainwash on the block surface. Rock surface roughness (Table 2), determined here for the purposes of site-to-site comparisons on three of

the index scales suggested by McCarroll and Nesje (1996), increases from scarp surfaces to the blockstream.

Site	Description	Schmidt hammer* Mean R (std)	Surface roughness index**		
			5mm	10mm	20mm
S1	Valley head scarp	-	1.04	1.72	2.64
S2	South-facing scarp	47 (3)	1.07	1.75	2.59
S3	South-facing scarp	49 (4)	0.94	1.56	2.47
S4	North-facing scarp	-	0.93	1.53	2.29
S5	North-facing scarp	-	1.11	1.81	2.83
O1	Openwork unit	46 (4)	1.21	1.92	2.89
O2	Openwork unit	44 (3)	1.21	1.90	2.84
O3	Blockstream upper	43 (4)	1.53	2.46	3.87
O4	Blockstream central	44 (4)	1.52	2.51	3.98
O5	Blockstream lower	-	1.38	2.22	3.37

* Values derived from 15 readings on 25 largest surfaces at each site.

** Site roughness indices (McCarroll and Nesje, 1996) on three scales obtained from six 150mm surface profiles on 15 largest block surfaces or scarp surfaces between joint structures.

Table 2: Schmidt hammer and rock surface roughness indices for relative-age dating of block and scarp surface sites indicated in Figure 6.

The blocks found in the valley-floor blockstream are more rounded and weathered than those in the tributaries and two possible sources for the blocky debris can be envisaged. Besides an origin from surrounding rock scarps, corestones derived from spheroidal weathering mantles in the valley-floor and surrounding slopes could provide significant volumes of rounded clasts.

Observations in nearby road cuttings, reveal in-situ weathering profiles of spheroidally weathered corestones, which show advanced decomposition and disintegrate readily. The advanced state of weathering of the corestones stands in contrast to the sub-rounded nature, thin weathering rind thickness and minimal loss of strength observed in blocks from the blockstream. In contrast, the blockstream material shows a distinct affinity with that found in the upper-catchment blockfields and rock scarps.

The origin of clasts seems best related to mechanical weathering and debris production on the south-facing scarps in catchments A-D. Based on angular fracturing along cooling joints, the size of the blocks and the aspect control, the extensive scarp disintegration is considered to result from frost wedging. The subsequent rounding and pitting is interpreted to result from subsurface weathering within the slope mantle. It must be emphasised that, although clast origin may be related to frost wedging, the mobilised regolith in the colluvial sheets is likely to significantly pre-date the blocks. Deeply weathered mantles with corestones can be observed in many road sections in the highlands. These saprolites may have provided the bulk of the matrix within the slope deposits.

BLOCKSTREAM DEVELOPMENT

The morphology of the openwork deposits, the clast fabrics and the low angled slopes on which they are found are typical of allochthonous blockstreams found in other mid-latitude environments, such as southeast Australia (Caine and Jennings, 1968), Tasmania (Caine, 1983) and the Appalachians (Potter and Moss, 1968). In all cases emplacement of the materials by slow mass wasting under periglacial conditions is proposed. In the Sani Pass area, the migration of blocks immediately downslope from the rockscarps, the presence of stone-banked terraces, the lobate morphology of the soil mantles emerging from each sub-catchment and the fabric in the central blockstream all suggest mass wasting into the central valley. The block accumulation probably took place within a diamict, with a matrix present between the blocks. This is inferred by the weathering status of the blocks and the recessed cross profiles of the blockstream.

Slow mass flow requires the build up of considerable pore pressure in the debris. In coarse materials an impervious layer at the base, here provided by bedrock, best explains this. However, coarse deposits drain readily even when a matrix is present between the blocks. Washburn (1980, p. 98) points out that sufficient hydrostatic head may be generated when a seasonally frozen surface layer impedes drainage. Such a mechanism has also been proposed by Caine (1983) for blockfield movement in northeastern Tasmania. These considerations indicate that ice must probably have been present for the mobilization of the regolith.

Frost creep also provides an additional mechanism of movement in the upper zone. Although no estimate of soil frost penetration can be given, Fahey (1974) measured 30 cm heave in the Colorado Rockies with seasonal frost penetration to 2 m depth in wet soil. Under such optimal conditions this results in 1.76 cm/a (potential) creep on a 10° slope. Based on this mechanism alone, a clast from the upper catchment in the study area investigated here would travel about 1 km in almost 57 ka. However, this is highly theoretical, and any quantification of movement amounts is complicated by the fact that the age of the deposit may well extend across multiple cold phases with mobilization of an even older regolith.

PALAEOEONVIRONMENTAL IMPLICATIONS

The thick debris mantles in the lower sections of the catchment suggest the mobilization of a pre-existing regolith, similar to the in-situ chemical weathering profiles found in near-by road sections. The blocky debris supply is considered to be contemporaneous to the mobilization of this regolith during a dominantly mechanical weathering phase. At that time the blocks became incorporated within the surficial mantles.

Although no evidence for permafrost is found, the blockstream and related deposits described here probably required an environment of seasonal frost. For ice segregation to occur moisture must be present at freeze up. Furthermore, abundant water is a necessity for thaw-failure under high pore water pressure conditions. On the other hand, to permit 1-2 m deep frost penetration, snow-cover must be largely absent. Sumner (in prep.) measured soil temperatures to 190cm

depth at 3200m a.s.l., 5km from the investigated blockstream. Recorded absolute minimum temperatures at 70cm, 125cm and 190cm depth were 1.6°C, 3.0°C and 4.0° C respectively. These values suggest that a 2m frost penetration would require a temperature depression of at least 4° C from present (Sumner, in prep.). Unfortunately the temperature record is insufficient to estimate the depth of freezing by means of the various equations described by Yershov (1998).

The regolith in which the blocks have developed may date back to the Late Tertiary. The uniform weathering status and angularity of the blocks points to emplacement of the, now- relict, openwork deposits in the Late Quaternary. Conditions for deep seasonal frost would have prevailed only during the Last Glacial, and particularly the Last Glacial Maximum. It is during this period that the main phase of solifluction and frost creep probably took place. The occurrence of coarse colluvial mantles throughout the highlands argues against any widespread glaciation of the region during the Late Quaternary. Slope materials became largely stabilised in the Early Holocene. At present, surficial frost generates creep and movement only in the upper 0.2m of the soil. However, low sediment yields due to increased vegetation cover in the Holocene would have resulted in washing out of fines and the current phase of stream incision within the colluvial mantles.

CONCLUSIONS

The Lesotho highlands boulderstream is typically of the lag boulderstream type (Harris et al., 1998). These may develop well outside permafrost environments. However, the conditions for mobilization of these coarse slope deposits remain poorly understood. Furthermore, their palaeoenvironmental significance is uncertain as these forms may develop over a wide range of temperatures. A further problem for Quaternary environmental reconstruction in the Lesotho highland blockstreams is the poor record from other proxies and the lack of chronological constraints within which to place the phases of slope activity

ACKNOWLEDGEMENTS

The boulder stream site discussed here was visited during the post-conference excursion B3 of the INQUA XV Congress, Durban, August 1999. Participants of the excursion are thanked for their contributions in discussion. Hermien Bijker, Werner Nel, Martelize Botha and Jay le Roux are thanked for their assistance in the field. Funding was provided though a National Research Foundation Core Grant.

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THE PALAEOENVIRONMENTAL SIGNIFICANCE OF SOUTHERN AFRICAN BLOCKFIELDS AND BLOCKSTREAMS

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In press: IPA International Conference on Permafrost (2003) refereed Conference Proceedings

ABSTRACT

Southern African high-altitude blockfields and blockstreams have been attributed to severe periglacial Pleistocene conditions. However, in this region coarse openwork slope materials are also found well outside the potential area of Pleistocene periglaciation. Thus, a reliable distinction needs to be found between periglacial and non-periglacial block deposits, considering both block origin and movement mechanisms. This paper describes the characteristics of openwork block deposits in the Western Cape mountains, the Lesotho highlands as well as the arid Karoo and Namibia. Various weathering mechanisms that may result in block production are explored and clearly show that blocky weathering products, angular or otherwise, cannot be assumed periglacial. The periglacial origin and thus paleoenvironmental interpretation of autochthonous blockfields is questioned. In contrast, the deformation in blockstream deposits in the Lesotho highlands and the Western Cape clearly requires periglacial conditions. While minimum environmental conditions for their formation can be offered it is clear that understanding of movement mechanisms in coarse block deposits is in its infancy, limiting reliable reconstruction of periglacial environments under which they formed.

INTRODUCTION

The Quaternary periglacial record of southern African mountains has been a source of debate for well over 50 years. From the early recognition of relict periglacial forms by Alexandré (1962) attention has focussed on both potential indicators for glaciation and periglaciation associated with the Last Glacial, as reviewed recently by Boelhouwers and Meiklejohn (2002). While discussion on glaciation relies on equivocal interpretation of erosional forms, sedimentary evidence centres on the interpretation of the widespread openwork block accumulations found throughout the southern African region. This paper aims to review the currently available data on southern African openwork block deposits, discuss their paleoenvironmental significance and outline where future attention could be focussed.

Observations to date on autochthonous (blocks derived in situ) and allochthonous (blocks emplaced) openwork accumulations focus on four regions. The Lesotho highlands and the Western Cape mountains, which fall within the region where glacial and periglacial activity has been proposed during the Quaternary (see Grab, 2000; Boelhouwers and Meiklejohn, 2002) and the semi-arid Karoo and arid to hyper-arid Namibia (Figure 1). Screes, residing at the angle of repose of the local material occur in all these areas and as the result of rockfall, will not further be considered in this discussion.

LOCATIONS AND CHARACTERISTICS

Lesotho highlands

The Lesotho highlands in the vicinity of the Drakensberg section of the Main Escarpment of eastern southern Africa (Figure 1) consist of rolling hills and occasional scarps dissected by incised valleys. Altitudes range from around 2800m up to 3482m a.s.l., the highest point in southern Africa. Underlying lithology is a sequence of flood basalts with layers of varying mineral compositions and amygdaloidal content attaining a total thickness of up to 1500m and supporting alpine heath vegetation. Precipitation at the highest altitudes could exceed 1500mm

p.a. falling mainly as summer thunderstorms with occasional winter snow. Mean annual air temperature (MAAT) at 3000m is estimated at 5° to 7°C. Soil frost can occur throughout the year typically to less than 0.2m depth with possible frost penetration to 0.4m within coarse materials (Grab, 1997). The region has been called a marginal or sub-periglacial environment (Boelhouwers, 1991).

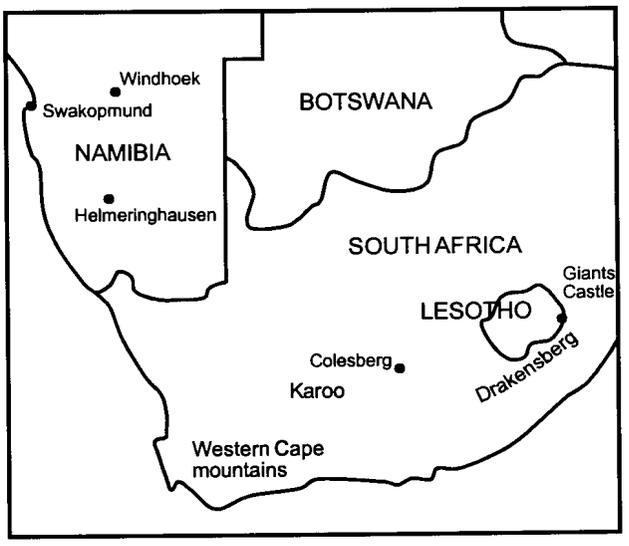

Figure 1: Locations within southern Africa.

In situ weathering on slopes and valley floors produces coarse granular loamy weathering mantles up to 2.5m thick with embedded spheroidal corestones (Boelhouwers, 1999a). This is due to moisture conditions and the high chemical weathering susceptibility of the basalts (Weinert, 1961). These mantles would have blanketed the slopes following enhanced chemical weathering during the warm periods in the Tertiary (Partridge and Maud, 1987) and provide a substrate of corestones within a frost-susceptible matrix. Upward freezing of corestones through seasonal frost penetration, which could have exceeded 1.0m during the Late Pleistocene (Sumner, in prep.), would result in concentration of blocks at the surface. This explains the ubiquitous near-surface (0.5-1.0m) block concentration on slopes at altitudes above 3000m a.s.l. and particularly on south-facing slopes where mantles attain their greatest thickness. Openwork block accumulations exist as lags where matrix is removed by surface or subsurface wash.

Thick colluvial slope mantles derived from slow mass wasting of the weathering mantles dominate the steeper valley sides. These are particularly noticeable on the south-facing slopes and extend as solifluction mantles onto valley floors (Boelhouwers *et al.*, 1999). Although contemporary mechanical block production on slopes is minimal, blocks concentrate within the mantles extending downslope from scarps and may exist as isolated openwork lags where matrix is removed by wash. The production of blocks is attributed to scarp recession by dominant mechanical weathering and mass wasting during colder Pleistocene periods and is probably the primary source of blocks in the upper mantle.

Blockstreams exist as valley floor accumulations of mobilised blocks which originate from the valley slopes, and may have matrix removed by wash. The most impressive of these is 1.1km long valley floor openwork accumulation comprising on average 0.6m (a-axis) subrounded blocks which exhibit a strong orientational fabric and imbrication (Boelhouwers *et al.*, 1999). Relative-age dating of rock surfaces shows an increase in age from valley scarps on the slopes to valley floor block surfaces, indicative of slope production and slow valley floor emplacement. Attrition during slope mobilization accounts for the subrounded block form and this militates against distinguishing upward frozen corestones from scarp derived blocks, particularly in the older and more extensive valley floor deposits. Fabrics and imbrication indicate the blockstream itself was mobile prior to the matrix removal. This is attributed to slow mass movement under periglacial conditions during the phase of boulder production in the valleys. Although weathering rinds are practically non-existent on the exposed blocks, the block surfaces are highly pitted. This is attributed to enhanced chemical weathering of block surfaces when buried and subsequent exposure to rainwash on removal of the matrix after emplacement.

Although blockfields in the highlands can be derived from upward freezing alone the allochthonous blockstreams are polygenetic in nature. The ubiquitous block distribution noted in the highlands and the concentration of blocks in the upper mantles is attributed to periglacial conditions in the Late Quaternary. Colder period mechanical block production, deep seasonal freeze and limited snow cover would have enhanced slope creep and solifluction both on the slopes and valley floors. A residual openwork structure remains on slopes where blocks are sufficiently concentrated and matrix is removed.

Western Cape

The Western Cape Mountains range between 1600 and 2200m a.s.l. and are located in the winter rainfall region of South Africa (Figure 1). The mountains are underlain by Paleozoic quartzite and support a sclerophyllous shrub vegetation. Beneath extensive rockwalls the footslopes consist of coarse debris mantles, with debris fans emerging from steep mountain gorges.

Openwork block deposits in this region exist as screes and rock avalanche deposits, openwork patches recessed in debris mantles due to suffosion, debris flow end-lobe and levee deposits on debris fans and as raised deposits on low-angle slopes (Boelhouwers, 1996, Boelhouwers *et al.*, 1998). Of these, only the latter are of interest in the light of this discussion and are easily distinguished from the other types.

Allochthonous openwork slope deposits are restricted to altitudes above 1600m. Those found in the Hex River Mountains have recently been described by Boelhouwers (1999b). A MAAT of 7°C is estimated for the summit of Matroosberg (2249m) the highest summit of the Western Cape mountains. Surficial diurnal frost characterises the summit areas above 1900m manifesting itself in micro-patterned ground no deeper than 3cm.

Openwork block accumulations are widespread in the summit area and vary in size from patches a few metres across to blockstreams measuring tens of metres in length and covering up to 6 ha. The block-streams originate from scarps, some of which have locally disintegrated. Blocks are typically angular to subangular although rounding and pitted surfaces indicate subsurface weathering in the presence of a matrix. Block form is typically platey or elongate measuring 0.2 to in excess of 3.0m and show distinct downslope fabrics in the blockstreams. Fabrics are transverse at lobate fronts and dip upslope in a well-developed imbrication. Downslope sorting from small to larger blocks is evident at sites, with vertical sorting to 1.5m depths.

The characteristics of the openwork block accumulations resemble those found in other deposits

in mid-latitude areas which are generally attributed to slow mass wasting processes under Late Quaternary periglacial conditions (eg. Caine, 1968; Caine and Jennings, 1968; Benedict, 1976). In addition to the morphological similarities, the periglacial origin of the Western Cape deposits is based on two arguments; block origin and movement mechanisms. Tertiary chemical solution has resulted in extensive pseudo-karst forms throughout the region and increased primary and fracture porosity. This has increased the frost susceptibility of the quartzites and rendered them more prone to frost wedging (Boelhouwers, 1996). Ubiquitous mechanical fracturing in the mountains of the Western Cape is superimposed over pseudo-karst weathering forms. Rock scarps in the summit region are completely mechanically broken down and the coarse blocky debris intrinsically associated with the blockstreams. Recognising that no diagnostic features exist to specifically identify frost-weathered debris (White, 1976) an origin post-dating the Tertiary favouring frost-induced mechanical weathering in the Late Quaternary is, nonetheless, likely.

Fabrics and lobate fronts indicate slow mass movement of blockstreams and are typical characteristics of blockstreams found in many parts of the world. Vertical sorting and weathering patterns indicate the presence of matrix at the time of emplacement and movement. Deformation by slow mass flow under increased pore water pressure may account for movement where bedrock is near the surface (eg. Caine, 1983) but would not account for vertical sorting in the deposits. Sorting is accounted for by ground freezing while relatively fast rates of clast movement in the order of 3cm p.a. can be achieved by frost creep on slopes of 20° (Benedict, 1976; Caine, 1983). Rates of movement applied to the blockstreams indicate that the emplacement could have occurred during the Last Glacial Maximum (21-15 ka B.P.) (Boelhouwers, 1999b).

Block production, movement and emplacement is suggested as associated with the colder period of the Late Pleistocene with subsequent Holocene washing out of matrix. Environmental conditions associated with frost penetration to at least 1.5m suggests little insulation by snow cover. No evidence for permafrost is found and is not required for the emplacement of the deposits. MAAT is estimated at 0°C for the summit regions; a reduction of 7° to 8°C which corresponds well to other proxy data for the region (Talma and Vogel, 1992).

Karoo

The semi-arid Karoo (Figure 1) occupies most of the interior of South Africa and is characterized by cool dry winters and hot summers with occasional thunderstorms. Extensive plains are interspersed with mesas and buttes formed by resistant sandstone and dolerite caprocks. The Jurassic dolerite intrusions are evident in the landscape as dikes and sills that cover extensive areas forming distinct ridges and plateaus. Blocky saprolitic mantles develop on these intrusions and form autochthonous blockfields which may extend into blockstreams on steeper slopes where matrix is removed.

Boelhouwers (1999a) describes doleritic autochthonous blockfields in the vicinity of Colesberg in the central Karoo (1212m a.s.l.). MAAT is approximately 16°C with winter and summer average temperatures 9°C and 25°C in the area. Vegetation is generally sparse although grasses establish themselves between blocks on the dolerite exposures and scattered acacia trees stand within blocky material where seedlings are protected from wildfires. Joint density varies and appears to be the main factor influencing the presence or absence of tors and the size of blocks. Block mantles are generally less than 1.0m thick and may consist of a single layer of blocks resting on tightly fitting, bedrock detached blocks. On summits, scattered blocks rest directly on intact bedrock. On lower slopes or level surfaces a silty sediment (particle size <1mm), presumably aeolian in origin, may be present between blocks.

Mode of weathering is predominantly spheroidal subsurface chemical weathering along joints, resulting in block separation and rounding with blocks remaining in situ. Weathered products are subsequently removed by wash or wind. Desert varnish on block surfaces indicates the considerable age of the blocks and the slow rate of weathering. Many blocks also have fresh angular surfaces with sharp-edged spalls broken off them. Some blocks are split in half. This fracturing is caused by infrequent wild-fires or lightening, which appears to be the dominant cause of further disintegration of the rounded blocks once exposed at the surface.

The openwork accumulations meet several of the criteria for autochthonous blockfields. Occurring on low gradient slopes they are the result of in situ weathering of block material of

sufficient thickness that any relationship with the underlying bedrock is lost (see White, 1976; Tyurin, 1983). Differences may lie in the degree of roundness of the blocks, the matrix infill which may be secondary, and the vegetation growth although similar characteristics may be found to a greater or lesser extent in block accumulations in true periglacial environments.

The extent to which blockfields develop in the Karoo depends on the presence of dolerite outcrops, topography, subsurface moisture availability joint density and vegetation cover. Effective removal of the weathered-product matrix is determined by local topography and vegetation characteristics which influence wash and aeolian processes. Joint density determines block size, the amount of matrix and the depth of the weathered zone. Secondary wind sediment may accumulate between blocks. A deep weathering zone allows for the generation of a sufficiently thick block cover that on removal of the interstitial matrix any link with the underlying bedrock is lost. Although formed over long periods of time through deep weathering and subsequent exposure, these blockfields do not specifically require cold conditions for their formation and fall outside of the region associated with Pleistocene periglacial and glacial activity. The process of formation can readily be perceived as continuous through various climatic regimes, perhaps even inhibited under colder conditions with reduced chemical activity, and as active at present.

Nambia

Arid to hyper-arid Namibia extends up the west coast of southern Africa (Figure 1). Mean air temperatures on the coast range between 12° and 18°, increasing to 12° and 26°C in the central interior at Windhoek (1728m a.s.l.), where winter temperatures may fall below zero and maxima increase to around 40°C. Mean annual precipitation at the coast is less than 20mm, increasing to 370mm in the central interior. Conditions in the Central Namib Desert, characterised by extensive dunefields, have remained hyper-arid for the past 5 million years (Ward *et al.*, 1983).

Although no detailed data exist on openwork ac-cumulations in the area, some observations can be made on accumulations which occur inland from the coastal dunefields. In the vicinity of Helmeringhausen, east of the dunefields, hill-summit blockfields extend downslope into

blockstreams on gradients which can exceed 20°. The openworks consist of a blocky mantle of exposed intrusive volcanics 1-2m thick overlying bedrock. Blocks are subrounded to subangular with no dominant preferred orientational fabric. Desert varnish attests to the age of the exposed surfaces and distinguishes the openworks from the adjacent matrix-dominated regolith which generally appears more mobile, extending into lobate forms on footslopes.

These slope deposits are remarkably similar to the slope deposits found in other arid areas such as those described by Whitney and Harrington (1993) in southern Nevada and Friend *et al.* (2000) in eastern California. Whitney and Harrington (1993) date the block deposits to the early to middle Pleistocene, note their present inactivity and attributed their formation to the colder periods of the early and middle Quaternary. In contrast, Friend *et al.* (2000) describe similar deposits which, although similar to true periglacial features, are forming actively under current desert conditions. Although further detail are required from this type of openwork accumulation in Namibia, given the environmental conditions the possibility of periglacial activity as a driving force behind their formation appears highly unlikely.

DISCUSSION

A summary of the attributes and palaeoenvironmental implication of openwork accumulations in southern Africa appears in Table 1. Used independently, the interpretation of blockfields and blockstreams may provide for specific environmental conditions and thus assist in palaeoenvironmental interpretation in the regions where few proxy data exist. However, contrasting the forms across the sub-continent highlights problems associated with the interpretation of these blocky features as periglacial in origin.

The blockfields and blockstreams described are the product of a variety of weathering mechanisms under contrasting climatic conditions. Deep chemical weathering contributes to autochthonous (blockfield) openwork development in mountainous and in arid environments. Blocks in these accumulations appear to be rounded to subrounded, although modified by subsequent weathering. Dominant mechanical weathering increases block production, particularly angular products, although directly attributing this to frost weathering is problematic

(White, 1976). Blocks will also be subject to secondary weathering processes on exposure at the surface or subject to attrition during emplacement. The development of blockfields may span millions of years during which numerous weathering regimes may have existed (eg. Rea *et al.*, 1996). Diagnosing openwork accumulations on the basis of weathering and resultant block form is, therefore, problematic and is manifest in the multiple origins of blockfields in southern Africa.

Location	Contemporary Environment	Description	Block origin and emplacement	Age and palaeoenvironmental interpretation
Lesotho highlands	Summer rainfall. MAAT 5-7°C est. Marginal periglacial MAP 1500mm est. Triassic-Jurassic basalts. ~3000-3482m a.s.l. Soil frost typically <0.2m depth.	<u>Autochthonous:</u> Rounded blocks, pitted surfaces, thin weathering rinds. Coarse granular loam matrix where present. <u>Allochthonous:</u> Lag-type valley floor blockstreams. Subrounded, pitted blocks. Thin weathering rinds. Matrix removed by suffosion.	*In situ* chemical weathering of bedrock. Upfreezing of rounded core-stones and/or washing out of matrix. Mechanical weathering of valley-side scarps. Upfreezing of corestones. Solifluction and frost creep.	Deep (Tertiary?) chemical weathering. Late Pleistocene deep seasonal freeze. Limited snow cover, no Late Pleistocene glaciation Late Pleistocene block production and emplacement. Wet, colder than present. Deep seasonal freeze without permafrost.
Western Cape mountains	Winter rainfall. MAAT 7°C est. Paleozoic quartzite ~1600-2249m a.s.l. MAP 575mm est. Soil frost to 0.03m.	Allochthonous blockstreams. Angular to subangular blocks. Pitted block surfaces. Vertically sorted. Matrix removed by wash.	Frost weathering and wedging of scarps. Slow mass movement by frost creep.	Late Pleistocene block production and emplacement. MAAT 0°C at summits. Similar winter precipitation. Frost penetration to 1.5m. No permafrost.
Karoo	Semi-arid (cool, dry winters, hot summers). Jurassic dolerites and older sediments. Central Karoo (approx): summer avg. 25°C winter avg. 9°C MAP 380mm	Blockfields extending less frequently into blockstreams. Rounded to angular blocks. Bedrock detached, joint-size determined. Varnished block surfaces. Aeolian sediment matrix or weathering product.	Rounding by *in situ* chemical weathering along joints. Angularity from fires and lightening. Weathering product (matrix) removed by wash or wind.	Quaternary (contemporary?). Non-periglacial origin.
Namibia	Arid to hyper-arid. Coastal [Interior]: summer 20° [26°] C winter 12° [12°] C MAP 20 [370] mm.	Openwork accumulations resembling blockfields and blockstreams. Sub-angular to sub-rounded. No orientational fabric. Varnished surfaces.	*In situ* weathering.	Largely unknown, probably polygenetic origin. Quaternary, perhaps older. Non-periglacial origin.

* Climatic data and estimates for Giants Castle (Lesotho highlands), Matroosberg (Western Cape mountains), Colesberg (Karoo) and Windhoek, Luderitz and Swakopmund (Namibia). MAAT = mean annual air temperature, MAP = mean annual precipitation.

Table 1: Openwork characteristics and palaeoenvironmental interpretation.

Notwithstanding difficulties in interpreting weathering modes and products, both the Western Cape and the highlands of Lesotho show a phase of increased block production in the past. Weathering patterns and superimposition of blocks over and within the upper weathering mantles point to an environment where mechanical weathering was dominant. The most likely scenario is increased block production during the colder period of the Late Pleistocene where full periglacial conditions have been proposed for the mountains. Openwork development in the arid and semi-arid regions would have remained largely unaffected although chemical weathering rates may have declined and the rate of formation reduced accordingly.

Although few data exist worldwide on mobility and emplacement in actively forming blockstreams, block mobility and the subsequent development of blockstreams are the most critical diagnostic indicators for a periglacial origin. Blockstreams in the Lesotho highlands and the Western Cape mountains exhibit the characteristics pertaining to deep seasonal freeze. This provides for a stronger argument supporting increased frost weathering of scarps rather than the reverse of using block form as an indication of environmental conditions. In the light of the apparent dichotomy that exists between process-based weathering studies and interpretation of relict features in palaeoenvironmental reconstruction, further research needs to be attempted linking process and form, and in establishing scale linkages. In the absence of such data on weathering and the related products, use of block form alone in palaeoenvironmental interpretation a must be treated with caution.

CONCLUSION

Early recognition of the widespread occurrence of blockfields in periglacial environments and assumptions regarding their origin has led to a bias associating these forms with such. However, the presence of blockfields in the Karoo and Namibia indicates that a periglacial origin cannot be automatically assumed. Where detail are available on blockstream sedimentology and morphology in which a mode of emplacement or movement indicates ground freezing, such with as vertical sorting, a periglacial origin may be more obvious. The presence of both blockfields and blockstreams should be perceived as a function of multiple-stage development,

many of which require contemporary conditions for their maintenance or continued development.

Future research can be directed at: (1) establishing absolute dates for openwork accumulations from a variety of environments, (2) more detailed clay analysis (eg. Rea *et al.*, 1996) to reveal weathering environments, (3) debris production mechanisms associated with the origin of slope deposits, and (4) detailed process monitoring of actively forming blockstreams.

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RELICT SORTED PATTERNED GROUND IN LESOTHO

Paul Sumner

Submitted: Short communication to *Permafrost and Periglacial Processes*

ABSTRACT

Relict sorted patterned ground is described from an upland interfluve on the Lesotho-South Africa border at an elevation of 3280m a.s.l. The site occupies intermediate slope angles between the previously documented sorted circles and stripe forms. Pattern borders are laterally sorted in places and distinct vertical sorting has been measured. Frost penetration through the regolith is inferred to have been to 1m depth during pattern formation. Sorting was the result of deep seasonal freezing during the depressed temperatures of the Late Pleistocene Last Glacial period(maximum ~18 000 B.P.). No direct evidence for permafrost is documented.

INTRODUCTION

The Lesotho highlands reach a maximum altitude of 3482m a.s.l. in the vicinity of the eastern Main Escarpment of southern Africa. Altitudes along the escarpment typically exceed 3000m a.s.l. and the area currently experiences ground-ice activity in winter, the depth of which is limited to the upper 0.2m (Grab *et al.*, 1999; Sumner, in press). Estimates for mean annual air temperature (MAAT) are as low as 4°C for the summit areas (Grab, 2002) although no long-term climatic data are available. Temperature depressions, which could have been in the order of 6°C during the Last Glacial Maximum (21-15 ka B.P.), have been suggested (Grab, 2002) to account for numerous relict glacial and periglacial landforms in the highlands. However, the exact nature of the Late Pleistocene palaeoenvironment remains controversial (see Boelhouwers and Meiklejohn, 2002).

Sorted patterned ground has been documented in the highlands. For example, Boelhouwers (1994) reports upon sorted stripes at 3200m a.s.l. and attributes their formation to deep seasonal freezing. Grab (2002) describes laterally- and vertically-sorted circular forms above 3400m a.s.l. Although sorting to a depth of 0.6m at some sites can be accounted for by Holocene temperatures (Sumner, in press), the sorted circles described by Grab (2002) on a 2° slope on Thabana Ntlenyana appear associated with Late Pleistocene freezing. Grab (2002) considers the forms to be indicative of permafrost, from which a zone of permafrost above an elevation of approximately 3400m a.s.l. is proposed during this period.

Data are presented by Grab (2002) for the Thabana Ntlenyana sorted circles. However, details on surface geometry and lateral and vertical sorting of relict sorted landforms are scarce. Grab (2002) provides an observed maximum sorting depth to 0.85m for one of the patterns at the site. This corresponds with sorting measured to a depth of 0.85m at a nearby interfluve site excavated in the summer to watertable depth (Figure 1) (Sumner, 2000). The interfluve patterns, which are similar in magnitude to the circles but occupy a marginally steeper slope, were subsequently revisited during the dryer winter period and excavated more deeply to obtain the lower limit of sorting. These data are presented here.

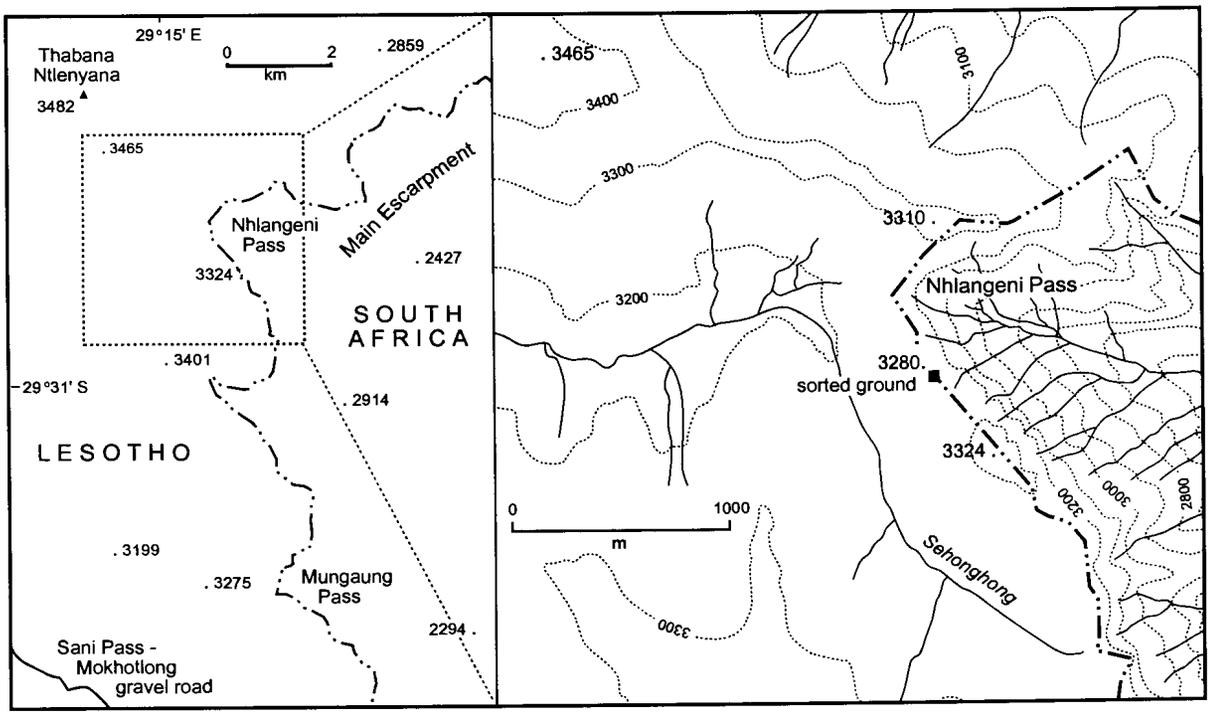

Figure 1: Location of sorted patterns on the Lesotho - South Africa border.

STUDY SITE

The patterned ground is located at 3280m a.s.l. on the watershed which delineates the international border between Lesotho and South Africa. Underlying lithology is Upper Triassic/Jurassic Drakensberg Group flood basalts which are deeply incised to the east of the watershed and less incised into Lesotho (Figure 1). The patterned ground lies approximately 3km from the Thabana Ntlenyana summit where Harper (1969) and Grab (2002) have earlier reported upon relict sorted circles.

The watershed interfluve has an uncharacteristically deep regolith. Typically, interfluve sites

support thin weathering mantles which are only a few centimetres deep. At this site, the patterned ground is found within a 1m thick regolith on the southern side of a basalt outcrop that lies on the watershed. Clast abundance is generally high adjacent to the outcrop, derived either directly from the outcrop scarps or as residuals from the weathering of underlying bedrock. Regolith is gravel-rich, although fines (silts and clays) can exceed 10% in the colluvial mantles that extend downslope (Sumner, in press). The clast enrichment and thick regolith matrix on the interfluve provides a suitable substrate for sorted patterns at a location which typically is relatively stable and thus assists landform preservation.

PATTERNED GROUND

The sorted patterns occupy a site where gradients are between 2° and 4° (Figure 2). Openwork clast-supported borders define the patterns, which resemble both circular and elongated circle-stripe forms at the surface. Clasts comprising the coarse borders are highly pitted and lichen-covered, indicative of a relatively long period of exposure and stability subsequent to emplacement (Grab, 1999; Boelhouwers *et al.*, 2002). Some of the stoney borders are sorted at the surface. Transects A and B (Figure 2) show coarse border boundaries where clasts can exceed 30cm (a-axis) and central zones where clasts may be smaller than 10cm. At the surface, the clastic openwork borders are not noticeably raised or depressed in relation to the adjacent matrix. The surface pattern of the openwork borders resemble the *labyrinth* transitional forms between lower gradient (0° to 2°) sorted circles and higher gradient (>6°) sorted stripes in frost active environments (Kessler and Werner, 2003; Mann, 2003).

The site was excavated at one point (D, Figure 2). In summer the water table was intercepted at 0.85m (Sumner, 2000) but excavation was completed to bedrock at 0.98m in the winter. Excavation revealed the openwork (i.e. no matrix) structure terminated at 0.62m depth. Beneath the openwork structure clasts are contained within a fines matrix. The final 2-3cm comprises a coarse, granular saprolite at the bedrock-regolith interface. The section shows not only distinct lateral but also vertical sorting (Figures 3 and 4). For example, in vertical section clasts are well-sorted and decrease in size from 15-20cm to 2-5cm at the bedrock surface (Figure 4b).

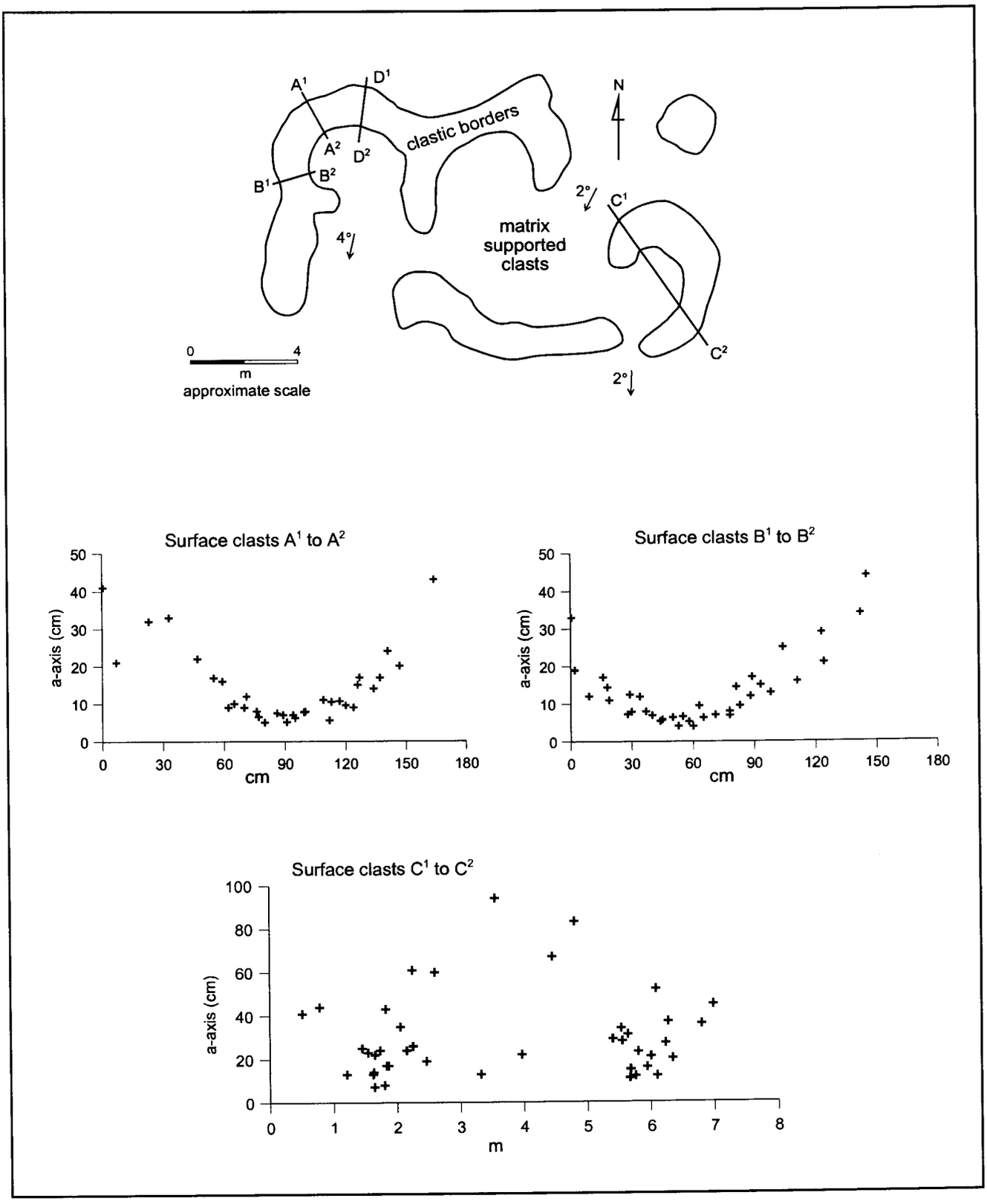

Figure 2. Plan view of patterns and surface transects of clastic borders showing clast size variations. Excavation along D shown in Figures 3 and 4.

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Figure 3. Excavated clastic border viewed towards the west.

Previous modelling of this type of sorting has centred on possible soil convection (see e.g. French, 1996, 140-147) usually in association with permafrost. Several problems exist with the application of convection theory to these landforms (e.g. Van Vliet-Lanoë, 1991). Recently, Kessler and Werner (2003) provide a numerical model which account for pattern formation through the displacement of soil to soil-rich domains and *vice-versa* for clasts, and the transportation of clasts along the axis of elongate-clast domains. The resulting surficial border-matrix patterns for these gradients are similar to those found at this site. The numerical model does not require permafrost and does not account directly for lateral sorting within a coarse border.

PALAEOENVIRONMENTAL IMPLICATIONS

Sorted patterns of this sze are often thought to be indicative of soil freezing. However, the contemporary diurnal frost environment cannot account for the depth of sorting found within the borders and the forms are currently inactive. The depth of sorting probably reflects a period of deep seasonal freeze to 1m depth (the bedrock surface), although deeper sorting may have occurred given a deeper regolith. The rarity of such landforms is most likely due to the absence of thick regolith on relatively stable interfluve sites.

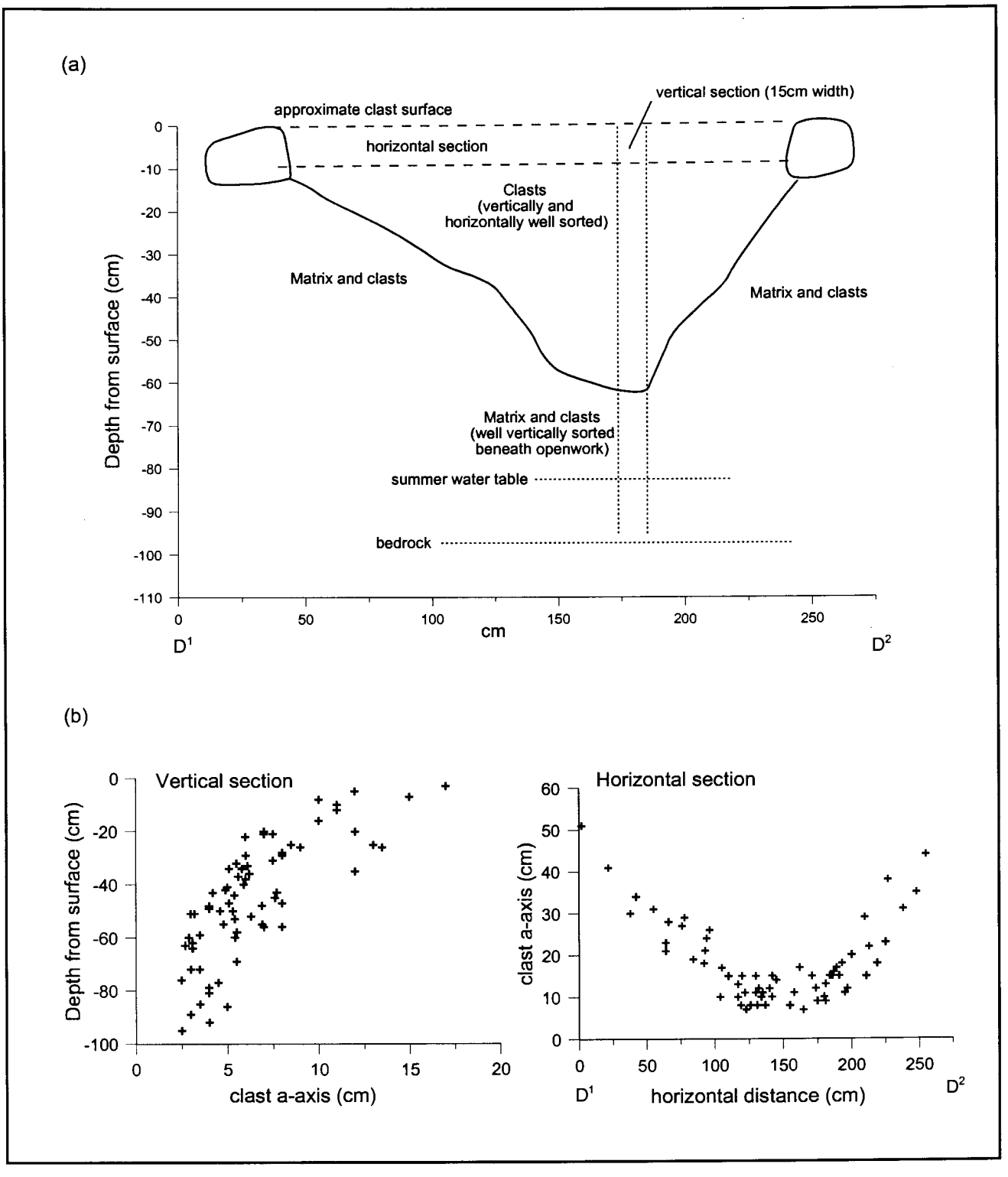

Figure 4. Vertical section representation (5a) of excavated border in Figure 3 indicating matrix-openwork clast interface and proximity to bedrock. Sampled clast a-axes in vertical and horizontal sections (5b).

These patterns are most likely associated with the Late Pleistocene Last Glacial. This concurs with the time placement of circular forms by Grab (2002) although the presence of permafrost during this period is not directly evident from these landforms and is not supported by ground thermal projections (Sumner, in press). It is also unlikely that extensive snow cover was present, as this would have had an insulating effect, which questions suggestions (eg. Grab, 1996) for summit glaciation during the same period.

CONCLUSION

Relict patterned ground occurs at 3280m a.s.l. near Thabana Ntlenyana on the Lesotho-South Africa border. The landforms are on a 2° to 4° angle slope, irregular in plan and resemble circle-stripe intermediate *labyrinth* (Kessler and Werner, 2003; Mann, 2003) surface forms. Vertical sorting is measured to bedrock at approximately 1m, the depth of which is limited by the regolith thickness and it is possible that frost penetration could have exceeded this depth during the period of formation. The borders show definite horizontal sorting in places which is not explained by numerical modelling (Kessler and Werner, 2003).

The sorted patterns are indicative of deep seasonal freeze most likely associated with the colder periods of the Late Pleistocene. This conforms with assessments by Grab (2002) and Boelhouwers (1994) for circle and stripe forms at similar altitudes where winter frost penetration would have exceeded 1m during this period.(Sumner, in press). No direct association can be made with the presence of permafrost, and the zone of permafrost depicted by Grab (2002, p.1741) for the summit regions is considered speculative.

ACKNOWLEDGEMENTS

The company of Stefan Grab and assistance of Jay le Roux the in the field is appreciated. Preliminary findings were presented at the Biennial conference of the Southern African Association of Geomorphologists at Hammanskraal in July 2000; participating delegates are thanked for their comments on the paper. Discussions with Ian Meiklejohn and Werner Nel, and helpful comments by Professor French on an earlier draft of the manuscript, are appreciated.

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A CONTEMPORARY WINTER GROUND THERMAL PROFILE IN THE LESOTHO HIGHLANDS AND IMPLICATIONS FOR ACTIVE AND RELICT SOIL FROST PHENOMENA

Paul Sumner

In Press: *Earth Surface Processes and Landforms*

ABSTRACT

A two metre deep ground thermal profile is constructed from temperature data collected over the winter and spring of 2000 at 3220m a.s.l. near the Thabana Ntlenyana summit (3482m) in Lesotho, southern Africa. The zero isotherm is found to have penetrated to 0.16m soil depth. Ground remained frozen at 0.05m for a total of 79 days and for shorter periods at 0.02m and 0.10m. Diurnal freezing and thawing is restricted to the upper 0.10m and conforms to the observed depth of active micro-patterned ground found in the region. Holocene temperature depressions projected along the thermal profile can account for freezing down to 0.45 to 0.65m. Deeper sorting to one metre, evident from relict patterned ground near the logger site, corresponds to at least a 2.5°C temperature depression and such landforms are evidently pre-Holocene. Projections indicate a seasonal freezing depth exceeding two metres during the Pleistocene Last Glacial Maximum although the existence of permafrost appears unlikely.

INTRODUCTION

The Lesotho highlands and adjacent Drakensberg mountain summits are classified as marginal periglacial or sub-periglacial (Boelhouwers, 1991; Hanvey and Marker, 1992). A range of ground ice-related landforms exist above 2800m a.s.l. and are geomorphologically active during surficial soil freezing in winter. These including thufa, stepped micro-relief, needle-ice, and sorted and non-sorted patterned ground (eg. Boelhouwers, 1991; Grab, 1997a). Very few contemporary climatic data are available for the region. Present-day air temperature and precipitation values are derived through lapse rate extrapolation from lower altitudes (eg. Grab, 1997b). Estimates of mean annual air temperature (MAAT) are as low as 3°C at 3450m and precipitation exceeding 1500mm at the high points on the eastern escarpment regions (Grab, 1997a; 2002).

Some contemporary ground surface temperature data and observations on freezing depth have been made (Grab, 1997a, c). The greatest depth of frost penetration on record is 40cm (Grab, 2002), although this occurred beneath the coarse section of relict sorted ground that would allow for deeper penetration of the freezing front (see Harris and Pedersen, 1998). The depth of sorting in micro-patterns is typically less than 0.10m (Grab, 1996a) above 2800m and is probably indicative of a diurnal freeze and thaw. Boelhouwers (1994) has reported on sorting depths to 0.20m at 3200m. A season freeze has been suggested (Boelhouwers *et al.*, 1999; Grab 2002) possibly to 0.20m depth, however, no complete winter soil thermal data to these depths are available to substantiate this.

Temperature depression for the highlands during Last Glacial Maximum (LGM) at approximately 18 000 B.P. is considered to be in the order of 4° to 6°C (Partridge *et al.*, 1990; Partridge, 1997) with precipitation in the highlands around 70-80% of present (Partridge, 1997). Geomorphic evidence has suggested full periglacial conditions (Boelhouwers, 1994; Boelhouwers *et al.*, 2002) or glaciation (Sparrow, 1967; Marker and Whittington, 1971; Dyer and Marker, 1979; Marker, 1991;Hall, 1994; Grab, 1996b) during this period. Evidence for former permafrost has been presented for elevations as low as 2280m a.s.l. (Fitzpatrick, 1978; Lewis, 1996) and may account for some relict features at higher altitudes (Boelhouwers, 1994; Grab 2002). Relict sorted patterned ground from this period are rarely found (Sumner, 2000, in prep.; Grab, 2002).

The exact Late Pleistocene palaeo-geomorphic and -climatic conditions are controversial and have raised much debate (Sumner and Meiklejohn, 2000; Grab, 2000; Boelhouwers and Meiklejohn, 2002), in part probably due to the absence of current climatic data upon which to base past reconstructions. As such, ground thermal conditions and extrapolations for freezing depth under depressed temperature conditions remain conjecture and the time placement of relict ground sorting speculative.

This paper presents the first data on contemporary winter ground thermal conditions at an undisturbed (non-patterned) site above 3000m a.s.l., extending from the ground surface to below the estimated current freezing depth. These data derive a thermal profile at high altitude and allow for determining the nature and depth of current freezing. From this a first approximation can be obtained for projected palaeo-freezing depths, and for estimation of temperature depression where freezing depth is known from relict sorted landforms.

STUDY SITE

The Lesotho highlands and high Drakensberg encompass the area along the eastern Escarpment of southern Africa (Figure 1). Upper Triassic and Jurassic Drakensberg Group flood basalts reach summit altitudes above 3400m a.s.l. Drainage is towards the east in South Africa and towards the west in Lesotho. In the southern high Drakensberg region around Sani Pass, regolith depth is typically only a few centimetres at summits and on valley interfluves. Colluvial mantles extending down to valley floors normally exceed 2m to 3m in depth but can reach 15-20m in thickness (eg. Boelhouwers *et al.*, 2002). These mantles may show organically darkened a/b-horizons but, constituting primarily slope material, do not extend through typical developed soil b- and e-horizons to weathered bedrock.

Both active and relict periglacial and glacial landforms have been studied near Thabana Ntlenyana, the highest point in southern Africa at 3482m (Grab, 1994, 1996b, 2002; Sumner, 2000; Boelhouwers *et al.*, 2002). MAAT at summit altitudes is estimated to be in the region of 3°C to 4°C, with a Late Pleistocene 6°C reduction in temperature (Grab, 2002). Snow is

common in the winter but typically melts within a few days. Soil frost is a regular occurrence in the colder months and gives rise to sorted patterns which degrade in summer, probably due to rainwash and livestock trampling. Given the estimates for air temperatures and the evidence from relict sorted ground on Thabana Ntlenyana, Grab (2002) suggests permafrost above approximately 3400m around the LGM.

The Sehonghong valley lies on the southern approach to Thabana Ntlenyana and heads onto the escarpment (Figure 1). Relict patterns sorted up to 1m deep are found on an uncharacteristically thick interfluve (Sumner, 2000, in prep.) (Figure 1). Colluvial mantles extend to the valley floors and are similar to those found a few valleys to the west (Boelhouwers *et al.*, 2002). The valley floor colluvium provided a substrate for installing temperature probes to monitor ground thermal conditions.

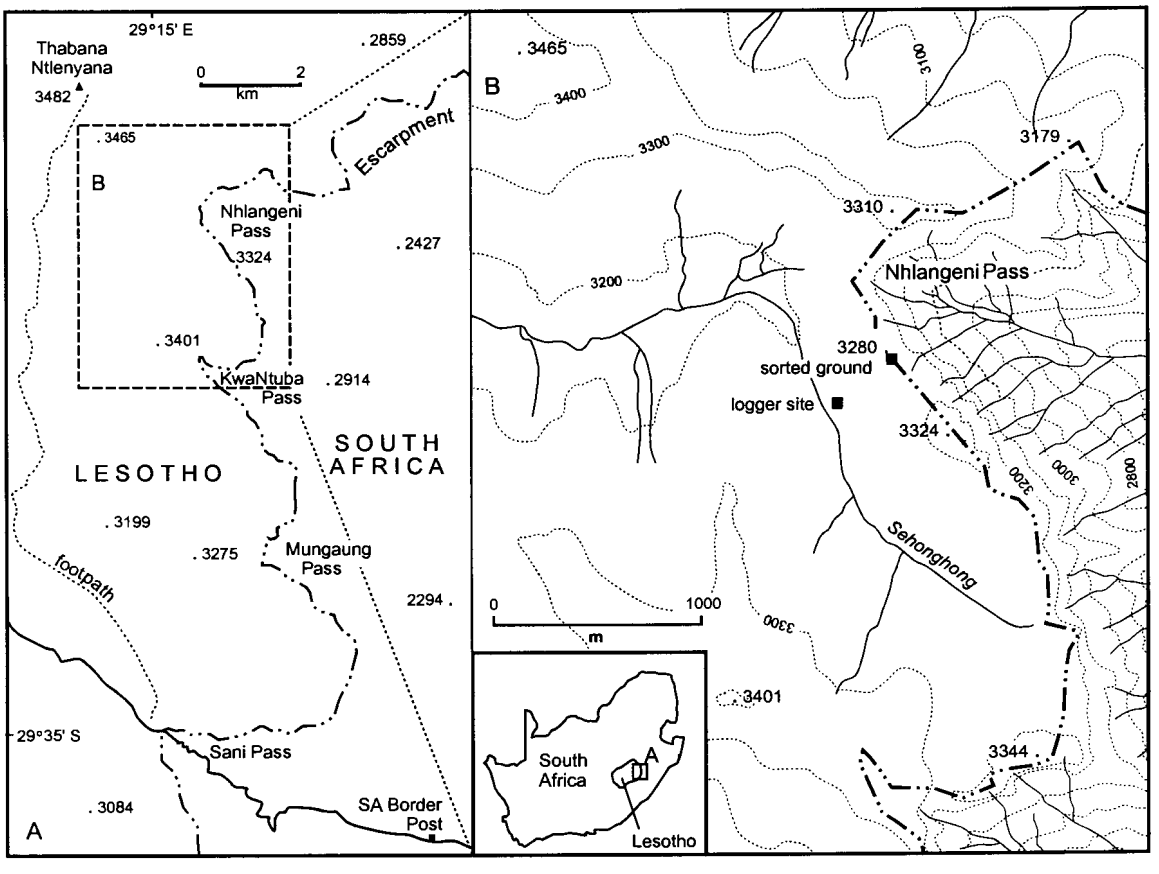

Figure 1: Location of logger monitoring site in Lesotho. (Relict sorted patterns are described by Sumner, 2000; in prep) .

METHODOLOGY

Ground temperatures were monitored at 3220m (Figure 1) using eight channels of a MCS (Mike Cotton Systems) 120-EX data logger. The logger was installed in May 2000 on a vegetation-free, 1° steep slope section adjacent to the river. A small hole was dug and five thermocouple sensors were installed 0.30m laterally from the side of the hole at depths of 0.02, 0.05, 0.10, 0.20 and 0.42m from the undisturbed surface. Three thermocouple sensors were attached to a fibreglass rod which was inserted adjacent to the other sensors through a dynamic cone penetrometer leader hole to a depth of 1.90m; sensors were located at 0.71, 1.26 and 1.90m (Figure 2). Since equipment theft is a problem in the area, the logger could not be recharged from solar power and thus the entire unit, powered by batteries, was sealed and buried in the hole. The setup precluded inspecting the logger during the year-long monitoring and was retrieved in May 2001. Daily minimum and maximum temperatures were recorded from 27 May 2000 until records showed battery failure in the beginning of summer on 06 November 2000.

Colluvium depth, as determined by dynamic cone penetrometer and auger at the logger site, was approximately two metres. After removal of the logger the adjacent colluvium was sampled with an auger to a depth of 1.85m (Figure 2). Soil layers shown in Figure 2 depict the sampled material from 0.00 to 0.20m (layer A), 0.20 to 0.40m (layer B) etc with the final layer (I) from 1.60 to 1.85m. The samples were analysed for primary particle size distribution (Briggs, 1977), moisture content and organic matter content.

RESULTS

Colluvium properties

Adjacent to the logger, silt and clay content (fines) are less than 10% (dry mass) for all samples and dominant composition is sand and gravel throughout the vertical colluvium profile (Figure 2). Coarse gravel (>4mm) content is at a maximum in layer A (upper 0.20m), considerably greater than the underlying layer B (0.20 to 0.40m). Coarse gravel content decreases to a

second minimum in layer E down to 1.00m, with higher gravel contents similar to the near-surface layer thereafter. Organic matter content is relatively low, even in the upper sections where it reaches a maximum of 5% in layer B and it is unlikely that any decreased biotic activity during colder phases would alter the thermal profile considerably. Moisture content reflects early winter conditions, with a partially desiccated upper layer in relation to the underlying regolith, and moisture decreasing with depth thereafter. Slope and regolith drainage after rainfall or snow melt could increase moisture content in the lower sampled layer (I) approaching the bedrock surface, thus assisting with heat transfer. Generally ground moisture conditions are low in mid-winter. A coarsening of particle size in sampled layers F to I could also assist with promoting heat transfer and steepen the thermal profile.

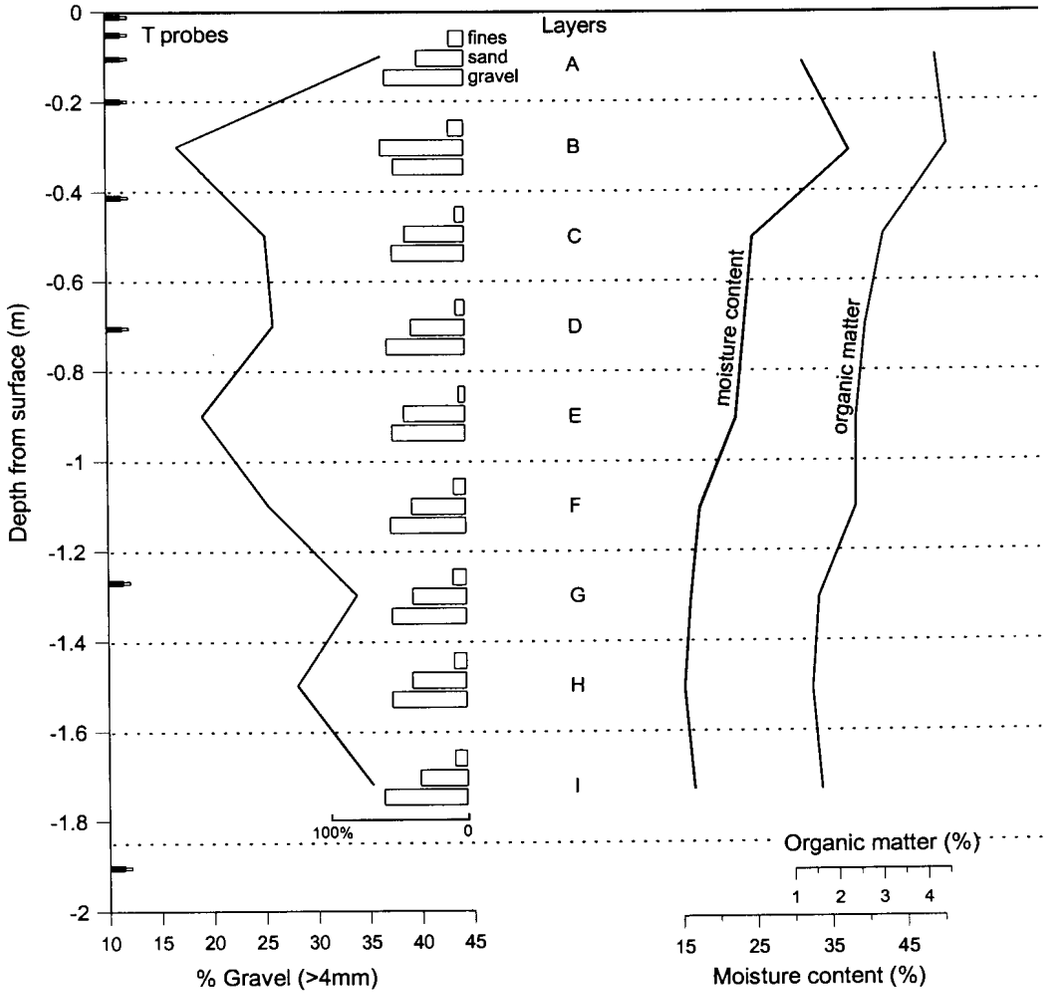

Figure 2: Colluvium characteristics adjacent to the logger temperature probes sampled in May 2001.

Temperature conditions

Daily minimum and maximum temperatures of all probes for the recording period are shown in Figure 3. As can be expected from surficial heat transfer, the near-surface (0.02m) probe shows the greatest diurnal temperature fluctuation. Range increases as maximum temperatures rise towards the end of winter. The minimum recorded temperature is -4.5°C on 10 July 2000 while temperatures were frequently above 15°C in October. Both maximum and minimum daily temperatures remained below zero at 0.02m from 30 May to 25 July, a total of 56 days which represents a period of "seasonal" freeze-up. Thereafter, diurnal oscillations around 0°C occurred on a total of 46 days up until 25 September.

At 0.05m depth, a minimum temperature of -2.3°C was recorded on 22 July, twelve days after the 0.02m probe minimum. Complete freeze-up commenced a few days after the upper sensor on 4 June and remained frozen a total of 79 days until 22 August. Diurnal fluctuation above and below zero occurred thereafter on only 9 days, ending on 31 August. At 0.10m, a minimum temperature of -0.7°C was recorded on 23 July and the daily temperatures remained below zero for 52 days from 9 July to 30 August. No diurnal fluctuations occurred at this depth. No temperatures below 0°C were recorded over the winter on the deeper probes. The daily temperature range decreased with depth from a maximum range of 10.8°C at 0.02m to 0.3°C at 1.90m.

A ground thermal profile (see for example French, 1996 p.53) is constructed from probe minimum and maximum values over the recording period (Figure 4). While minimum values are representative of the winter of 2000, the maximum temperature profile (depicted as a broken line in Figure 4) will be somewhat depressed since the recording period terminates in the beginning of summer. Higher maximum temperatures can be expected than those illustrated on Figure 4. Minimum temperatures occur at the surface and the minimum temperature increases with regolith depth. Projecting the zero isotherm along the profile indicates a potential freezing front at a maximum depth of 0.16m. Assuming similar ground thermal conductivity, the potential depth of freezing under depressed temperature conditions can be estimated from the temperature profile. For example, a 1°C overall drop in temperature corresponds with an

increase in maximum freezing depth to approximately 0.45m. Where evidence from ground sorting indicates the freezing depth, the decrease in overall temperatures can be derived. As indicated on Figure 4, a 2.5°C decrease in temperature would thus correspond to a zero isotherm at 1.0m depth.

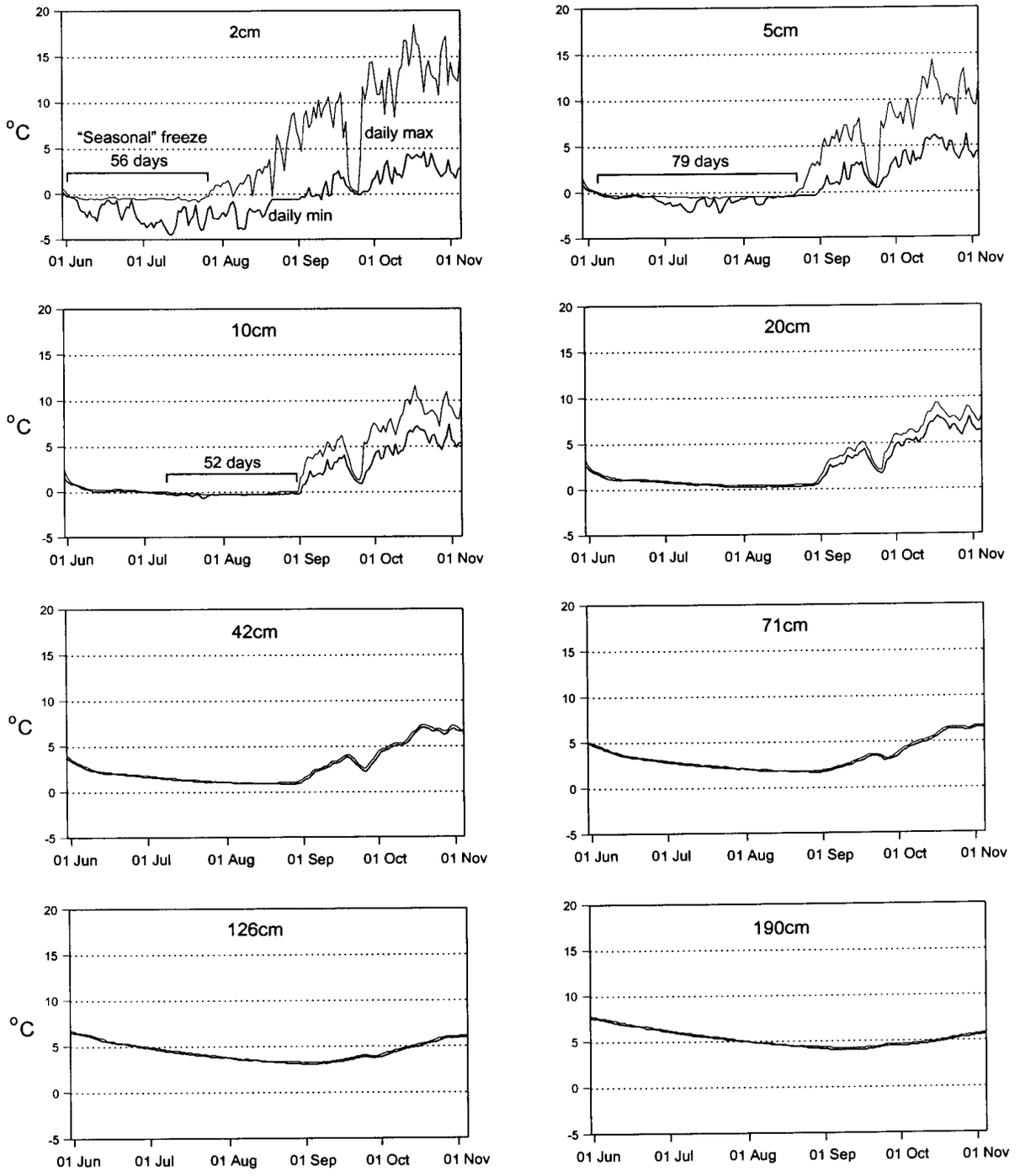

Figure 3: Daily minimum and maximum temperature records for all probes over the winter and spring of 2000. "Seasonal" freeze is indicated where both daily minimum and maximum temperatures remain below 0°C

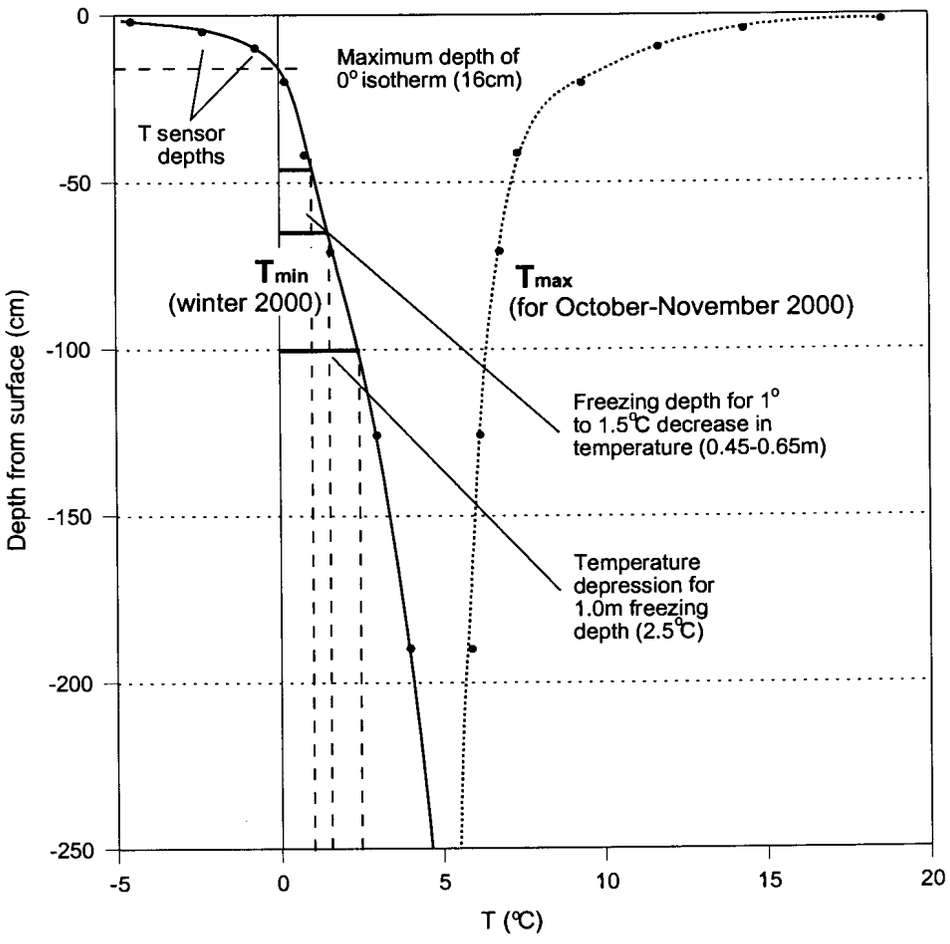

Figure 4: Thermal profile derived from the minimum and maximum temperatures recorded on probes between 17 May 2000 to 06 November 2000. T_{min} is representative of the 2000 winter, T_{max} underestimates summer maximum. Two scenarios for zero isotherm penetration under reduced temperatures are illustrated.

DISCUSSION

The penetration of the zero isotherm to approximately 0.16m conforms to assessments of freezing depth at this altitude (Boelhouwers, 1994; Grab, 1996a). The existence of a "seasonal freeze" is shown to occur in this upper layer, with the longest period of 79 days over June, July and August 2000 at 0.05m depth. The delay in the onset of freeze with depth can be expected due to the heat storage of the soil. Given that even the surface remained frozen for almost two

months (56 days over June-July) the geomorphic activity associated with ground freezing can be limited during mid-winter.

Diurnal freezing and thawing follows the complete freeze-up and is active only in the upper 0.10m, and most active within the first 0.05m. The potential for ground sorted is thus restricted to surficial material, which corresponds to the typical size of sorted stripes and circles found at these altitudes (eg. Grab, 1996a). Since the 0.02m probe shows the onset of diurnal freezing and thawing before the thaw at 0.05m, the moisture supply for ice formation and water migration to the freezing front, for example in the formation of needle-ice, may be limited until complete thaw of the underlying layer. The seasonal freeze may account for coarse enrichment in the upper layer of material, although freezing below 0.20m would be necessary to explain the relative coarse fraction enrichment of layer A (0 - 0.20m) at the apparent expense of B (0.20 - 0.40m) (Figure 2).

Projections along the minimum and maximum temperature profile allow for the first approximations of freezing depth under cooler conditions at these altitudes. Holocene fluctuation of around 1° to 1.5°C would potentially account for vertical sorted down 0.45 to 0.65m depths (Figure 4). (Freezing may not actually correspond to the zero isotherm due to a freezing point depression; see French, 1996.) This correlates to much of the relict sorting described by Grab (2002) at similar altitudes. Temperature depression of at least 2.5°C would be required for freezing to penetrate to 1.0m depth (Figure 4). Relict sorted patterns to approximately this depth have been found for in the vicinity of the logger site. Grab (2002) reports on an observed sorting depth of 0.85m near the Thabana Ntlenyana summit at 3460m and Sumner (2000, in prep) measured relict vertical sorting to 0.98m near the Nhlangeni Pass summit (Figure 1) at 3280m. Relict sorted patterns of this magnitude are thus probably pre-Holocene and formed under the cooler conditions of the Late Pleistocene.

Mean annual soil temperatures could not be derived from the data due to the absence of summer peak recordings. Nonetheless, it is apparent from the data collected, which underestimates summer maxima, that mean soil temperatures are unlikely to be below 5°C at any depth at present. Although proxy data indicate a 4° to 6°C decrease in temperature around

the LGM (Partridge *et al.*, 1990; Partridge, 1997) for this area, Grab and Simpson (2000) and Grab (2002) argue for a 6°C decrease from present values. Given the maximum predicted decrease of 6°C, frost penetration could have exceeded 2m although permafrost is unlikely due to maximum ground temperatures remaining above 0°C. Permafrost underlying the vertically sorted patterns at 3460m from a depth of 0.85m (Grab, 2002) would require a temperature reduction greater than 6°C. The existence of permafrost at high altitude must thus remain speculative, particularly since the relict landforms do not directly require permafrost for their formation.

SUMMARY

Ground temperature conditions monitored over the winter of 2000 within valley floor colluvium at 3220m in Lesotho indicate that the zero isotherm has a maximum penetration to 0.16m. Ground remained frozen for a maximum of 79 days at 0.05m depth, representing a seasonal freeze. A diurnal freeze-thaw is restricted to the upper 0.10m, and is most active in the upper 0.05m which corresponds to the depth of sorting found in actively forming sorted patterns at these altitudes.

Projections along a minimum (and maximum) ground thermal profile indicate that ground sorting to around 1m depth requires a temperature reduction of at least 2.5°C. Inactive landforms sorted to these depths and found in the area are thus probably pre-Holocene, while shallower relict landforms were probably active under cooler conditions in the Holocene. Assuming the maximum estimated temperature depression of 6°C for the area (Grab, 2002) it appears improbable that permafrost would have been present, and unlikely to have underlain the sorted forms. The contemporary short and shallow winter seasonal freeze would have been prolonged under depressed temperatures and seasonal freezing could have exceeded 2m in the Late Pleistocene without the presence of permafrost.

ACKNOWLEDGEMENTS

Ian Meiklejohn and Jan Boelhouwers are thanked for discussions related to this study. Field assistance from Jay le Roux, Werner Nel and Hermien Bijker is acknowledged. Comments from anonymous referees significantly improved the original manuscript. Equipment was provided by the University of Pretoria.

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PALAEO-GEOMORPHIC AND -CLIMATIC IMPLICATIONS OF RELICT OPENWORK BLOCK ACCUMULATIONS NEAR THABANA-NTLENYANA, LESOTHO.

Paul Sumner

For submission to: *Geografiska Annaler:* A

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ABSTRACT

Conflicting reports from geomorphic studies appear in the literature describing the Late Pleistocene environmental conditions of the southern African Main Escarpment region adjacent to the Lesotho Highlands. Evidence cites limited glaciation and/or periglacial conditions with or without permafrost. An investigation of relict openwork block accumulations in the area around Thabana Ntlenyana, the highest summit in the range, supports the contention for a relatively arid periglacial environment during this period, without either deep snow cover or localised glaciation of insolation-protected south-facing slopes. Enhanced block production and slope mobility on south-facing slopes is attributed to depressed temperature conditions and seasonal freeze. Colluvial mantles, within which blocks have been superimposed, indicate that slope colluvium predates the onset of the colder period. Findings show that evidence supporting valley asymmetry development under periglacial conditions and the glaciation of other sites such as pass summits, some of which contain relict openworks, should be reconsidered.

INTRODUCTION

Geomorphic evidence for the Quaternary palaeoenvironmental conditions of the Lesotho highlands and Drakensberg Escarpment (Figure 1) has raised much debate and been subject to frequent review (see Boelhouwers and Meiklejohn, 2002). Arguments have been presented in favour of glaciation, periglaciation and the presence of permafrost during the period spanning the Last Glacial Maximum (LGM, 21-15 ka B.P.). Limited glaciation of the Lesotho plateau region has been suggested by Sparrow (1967), Marker and Whittington (1971), Dyer and Marker (1979), Marker (1991) and Grab, (1996), and proposed for protected sites along the Escarpment (Hall, 1994; Grab, 1996). Relict periglacial landforms, which are found predominantly on the cooler south- and southwest-facing slopes, have also been described in the region and their formation attributed to the same Late Pleistocene colder period (eg. Lewis, 1988; Boelhouwers, 1994; Grab, 1999, 2002). Grab (2002) suggests a zone of permafrost above 3400m a.s.l. based on the presence of relict sorted circles at high altitudes. Although it is possible for marginal glaciation, periglacial and permafrost conditions to have co-existed at these attitudes in the past, no consensus has been reached that either reconciles all three proposed palaeoenvironmental conditions.

Several references to relict openwork blocky accumulations and their palaeoenvironmental significance to the mountains of southern Africa have appeared in the literature in the past decade. Boelhouwers (1999) describes blockstreams in the Western Cape mountains and attributes the block production to bedrock shattering and the subsequent mobilisation to seasonal frost during the LGM. Relict scree deposits in the Eastern Cape escarpment region, first described by Marker (1986) and later re-evaluated (Sumner and de Villiers, 2002), are attributed to enhanced block production under colder conditions. Openwork block accumulations are widespread above 3000m a.s.l. in the Lesotho mountains adjacent to the Main Escarpment of southern Africa. Boelhouwers (1994) and Grab (1999) have reported on relict slope openwork units above 3100m immediately west of the escarpment in the central Drakensberg region (Figure 1). Both ascribe to an origin by enhanced periglacial activity in the Late Pleistocene on south-facing slopes. Grab (1999) incorporates blockslopes and blockstreams found in the central Drakensberg region (Figure 1) above 3100m in a palaeo-geomorphic model for high altitude

south-facing slopes in the Drakensberg under depressed temperature conditions. Further south near Sani Pass, relict block accumulations are noted within Nhlangeni Pass at 3100-3200m and attributed to glacial activity (Grab, 1996).

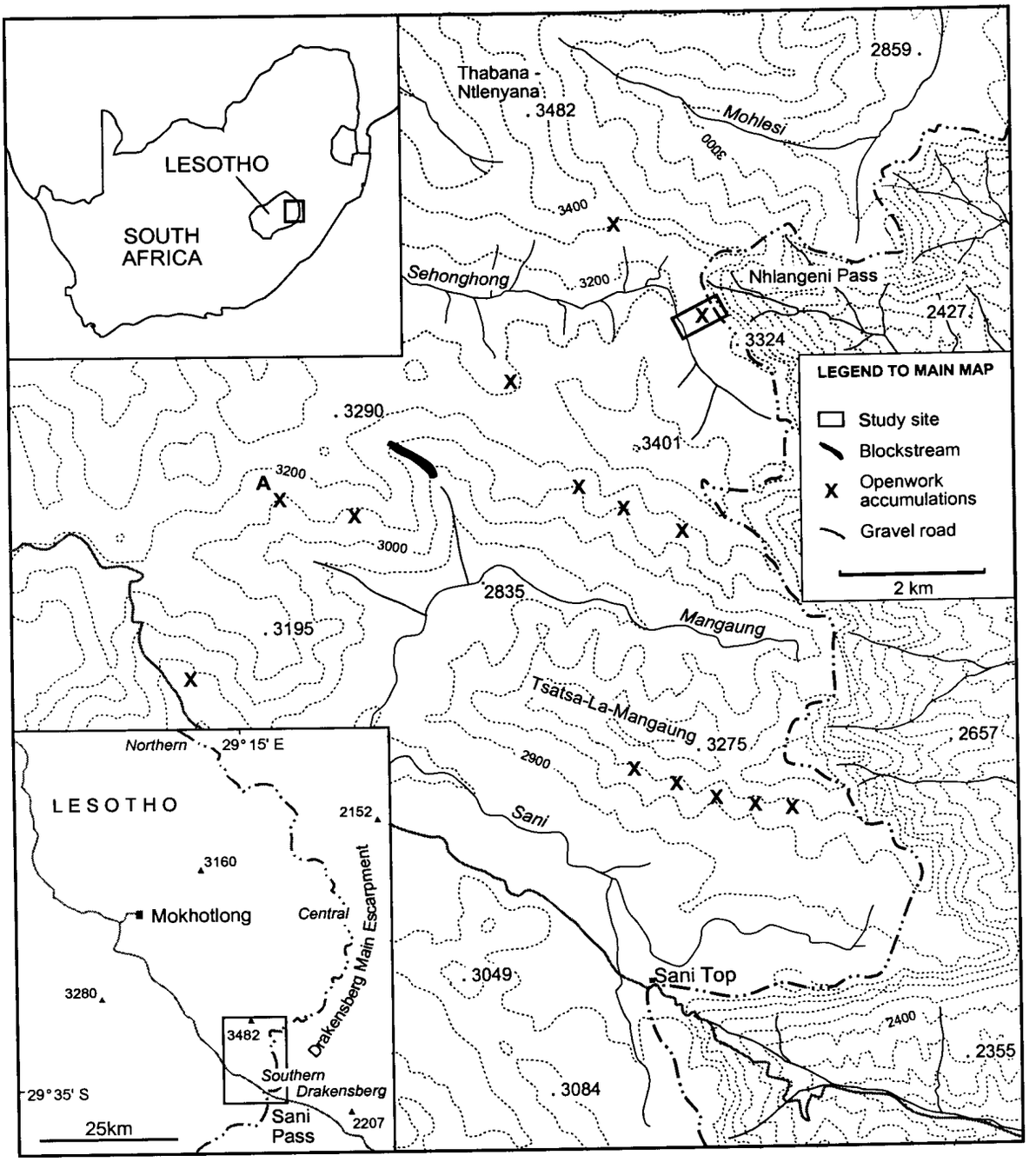

Figure 1. Location of study site in upper Sehonghong valley, valley floor blockfield (Boelhouwers *et al.*, 2002) and openwork units in the area.

A 1km long valley floor blockstream (3000-3200m) a.s.l. in the vicinity of Sani Top (Figure 1) was recently investigated in detail (Boelhouwers *et al.*, 2002). The blockstream is described as a lag deposit derived from mobilised colluvial mantles which contain blocks originating primarily from slope scarp disintegration. Slope mobility and block origin is attributed to colder conditions in the Late Pleistocene with deep seasonal freeze and dominant mechanical weathering on south-facing slopes. Boelhouwers *et al.* (2002) suggest that the blockstream presence militates against valley glaciation and/or deep snow cover during this period. The intention of this study is to provide further evidence for the widespread existence of openwork accumulations in the Sani Top region, to provide additional detail on the characteristics and hence formative mechanisms of openwork slope deposits and to consider the palaeo-environmental or -climatic implications.

STUDY AREA

The study incorporates the area west of the Main or Great Escarpment of southern Africa, extending from Thabana-Ntlenyana (3482m) to Sani Top (Figure 1). Drainage at the escarpment is divided towards the east into the KwaZulu Natal Province of South Africa and towards the west into Lesotho. The escarpment and highlands comprise Upper Triassic to Lower Jurassic amygdaloidal flood basalts. Stream incision into the basalts on the east has created numerous steep cutbacks or passes up the escarpment such as Nhlangeni Pass and Sani Pass. West of the watershed, the topography constituting the Lesotho Highlands is more undulating.

Few contemporary climatic data exist for the area adjacent to the escarpment. By extrapolating from lower altitudes mean annual air temperature (MAAT) is estimated to be as low as 4°C at 3450m in the central escarpment region (Grab, 1999) and precipitation exceeding 1500mm p.a. at the escarpment edge (Schulze, 1979). Recent and ongoing climatic monitoring, however, has shown a mean air temperature of 7°C at 3200m on the escarpment in the northern Drakensberg and a total precipitation of 770mm at Sani Top during 2002 (Nel, pers. comm.). The climate has a marked seasonality with only approximately 10% of the precipitation falling in winter, occasionally as snow. Frost can occur throughout the year although ground-ice phenomena such as needle-ice, freezing of thufur mounds and small scale soil sorting is primarily limited to the

winter period. The upper 5cm of soil appears to be the most active for frost sorting and this corresponding to the diurnal freeze-thaw in winter (Sumner, in press). Frost penetration has been noted to 40cm beneath coarse, sorted ground (Grab, 2002). However, soil freezing to 16cm recorded over the winter of 2000 on a valley floor at 3200m near Thabana-Ntlenyana seems more representative of general conditions (Sumner, in press) and corresponds to the observed size of frost-sorted micro-patterns in the Highlands.

West of the escarpment a marked valley asymmetry characterises the east-west valleys with steeper south-facing than north-facing slopes (Meiklejohn, 1992; Meiklejohn *et al.*, 1999). The soils are generally thin silty loams at interfluves although colluvial mantles exceeding 10m in thickness can extend down to valley floors, particularly on south-facing slopes (eg. Meiklejohn *et al.*, 1999; Boelhouwers *et al.*, 2002). Valley sides are characterised by a stepped topography due to variation in strength of individual basalt layers which are visible as horizontal scarps across slopes. Mechanical fracturing of bedrock and scarps has resulted in blocks distributed on the slopes, often concentrating sufficiently to form openwork structures (no matrix present at the block surface)

FIELD METHODOLOGY

Numerous openwork accumulations characterise the slopes of the area between Thabana-Ntlenyana and Sani Top . General locations of openworks units (eg. Figure 2) were mapped within the study area. The exercise was not intended to be completely exhaustive and aimed to provide an overall indication of the spatial distribution of openworks on the valley slopes. Numerous small accumulations of blocks occur on the slopes but slope locations where openwork units exceeding approximately 10m x 10m were noted.

A detailed study of the attributes of openwork block accumulations was undertaken on a southwest-facing slope in the upper reaches of the Sehonghong river (Figure 1). The site was selected since it appeared to typify blocky openworks found in the area, and due to its location immediately west of the Nhlangeni Pass summit where the bedrock outcrops have been cited as indicative of previous glaciation (Grab, 1996). Three openwork sites on a transect from valley floor to interfluve were studied (Figure 3). The sites comprised a valley floor blockfield, a

midslope scarp with associated openworks and, at the interfluve, an outcrop resembling a weathering tor from which openwork accumulations extend.

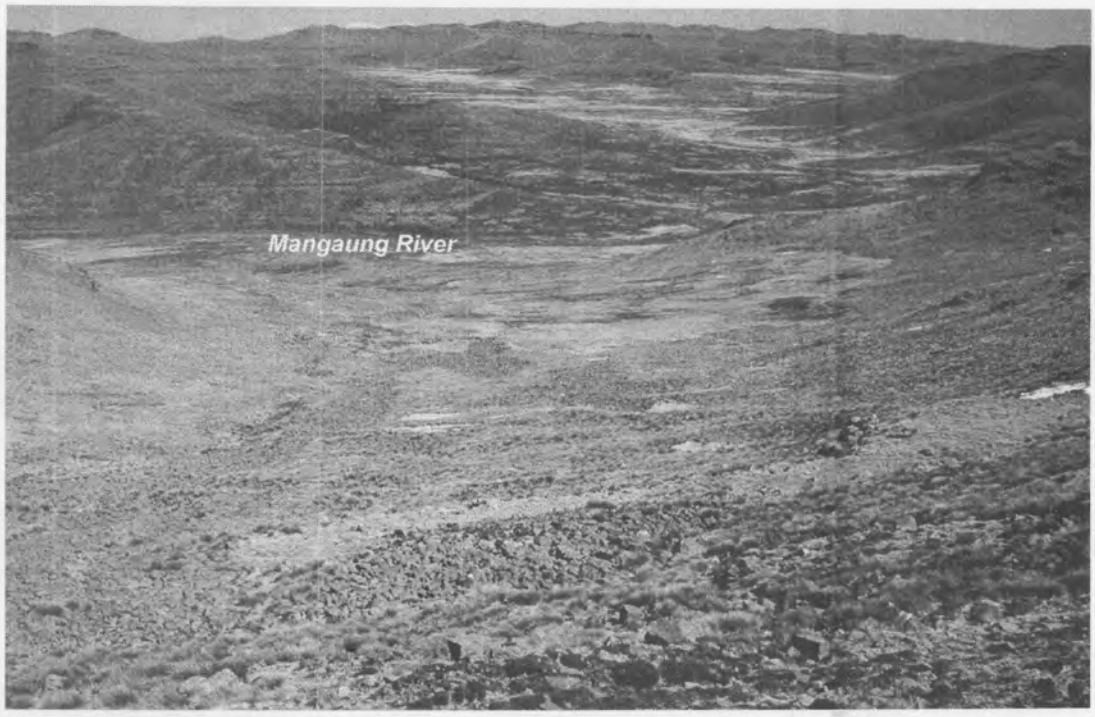

Figure 2: Slope and valley-floor openwork block accumulations on a southeast-facing valley tributary to the Mangaung River (viewed towards the southeast from A, Figure 1)

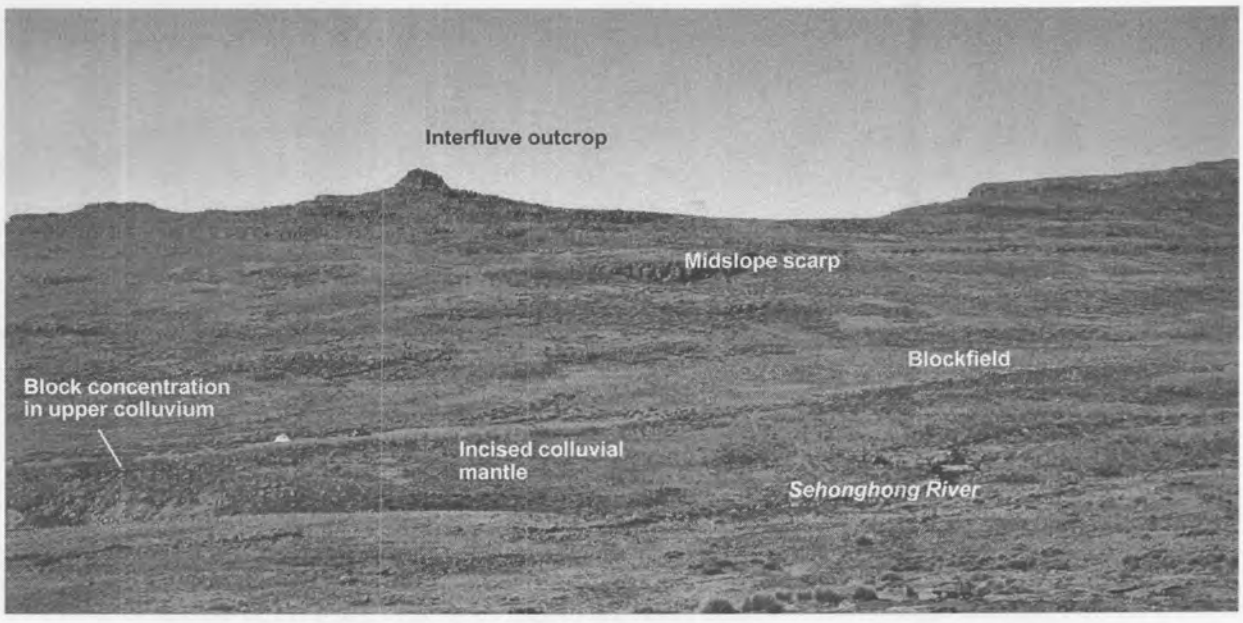

Figure 3: Study location on a southwest-facing slope of the upper Sehonghong valley showing the three sites. Hiking tents in centre left for scale.

Each site was mapped and surface topographic profiles measured with an Abney level. Clast size (a-axis) and orientational fabrics (a-b plane) were determined at selected sample points using the largest blocks nearest the sample point (n=50 for most sites). Relative-age dating of the upper block surfaces was undertaken. Rock surface roughness (Williams and Robinson, 1983) and potential differences in rock moisture (Sumner and Nel, 2002 [Appendix 2]) precluded the use of a Schmidt hammer at this site, as did very thin weathering rinds (see also Boelhouwers, *et al.*, 2002). However, an increase in roughness of exposed rock surfaces can be attributed to duration of exposure and has been successfully applied elsewhere as a relative-age dating indicator (McCarroll, 1992; McCarroll and Nesje, 1996). Roughness indices for rock surfaces (McCarroll and Nesje, 1996) were thus derived for sample site positions following the method used by Boelhouwers *et al.* (2002) (see also Table 1).

RESULTS

The distribution of openwork accumulations in the area is shown in Figure 1 and will be discussed further below. The following descriptions and measurements are from the Sehonghong river valley study site.

General characteristics

Numerous openwork accumulations are found on the southwest-facing slope of the Sehonghong valley but are virtually absent from the northeastern slopes. On the southwest-facing valley slopes, blocky accumulations extend from basalt scarps and overlie, or are incorporated into, colluvium slope mantles. Scarps are typically less than 6m in height but can exceed 10m in places. A colluvium thickness of 1m on the interfluve and 2-4m in the valley floors has been measured (Sumner, in press). Slope mantels cover outcrops in the lower regions of the slopes. Similar valley-slope colluvium has been described as gelifluction sheets (Boelhouwers, 1994) and solifluction mantels (Boelhouwers *et al.*, 2002) at these altitudes on south-facing slopes. Very few scarps on the slopes show contemporary mechanical fracturing or scree production. In places, scarps are overridden by creeping colluvium which are manifest as lobate deposits incorporating blocks. On the valley floor, a blockfield exists adjacent to the Sehonghong river

(Figure 3).

Blocks comprising the openwork units are sub-angular to sub-rounded. Surfaces are rough and solution pits are found in places indicating a period of stability after emplacement. Weathering rinds are thin, typically less than 1mm, probably due to rainwash removing any surface weathering product (cf. Boelhouwers *et al.*, 2002). Some blocks within the openworks are weathered *in situ* to smaller fragments. In the lower reaches of the slopes, where gradients decline from around 8° to 3° in the vicinity of the valley floor blockfield, blocks within the openwork and those protruding from the adjacent areas often show near-vertically orientated a-axes.

Site-specific attributes

Interfluve site

The interfluve site comprises a basalt outcrop which lies on the drainage divide between the Sehonghong valley and Nhlangeni Pass (Figure 4). The outcrop resembles the tors noted by Grab (1996) in a description of the summit area adjacent to Nhlangeni Pass. Scarp height varies between 5 and 8m and joint spacing is typically in the order of 0.3 to 1.0m. Openwork block accumulations cover an extensive area on the southern and south-western slopes beneath the outcrop (Figure 5). Fewer blocks and openwork units exist on the northern side, although up to 50% (by surface area) is blocks within matrix at some sites beneath the tor scarp (Figure 4). There is very little evidence for contemporary mechanical fracturing of bedrock or dislocation of blocks from the scarp.

On the south-western side of the tor, openwork accumulations extend directly downslope from the scarp. Surface gradients are at a maximum (21°) where the blocks override a 2m high scarp (at U2, Figure 3) and extend into a blockfield on the lower gradient area above the next scarp, where gradients are between 4° and 6° (U3, Figure 4). Clast size sampled downslope from the tor scarp remains relatively uniform with a mean a-axis length of approximately 0.5m (sites U1 to U4, Figure 4). Bimodal fabrics are evident in the blocky accumulations in the downslope direction and transverse to the slope (Figure 4).

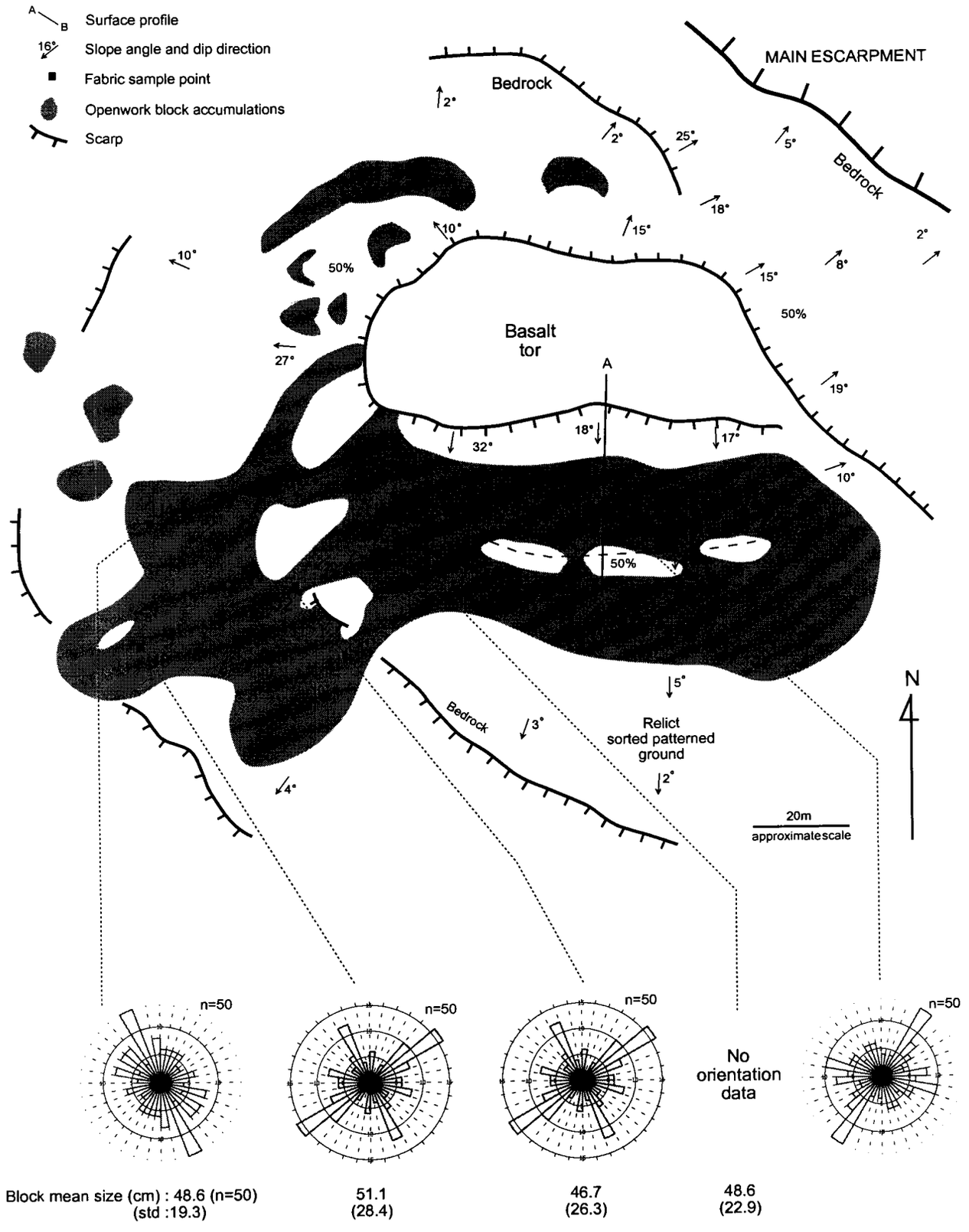

Figure 4: Characteristics of the openwork accumulations at the interfluve site.

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Figure 5: Openwork blocks extending from the interfluve outcrop towards the southwest.

The southern side of the tor is characterised by a steep, vegetated section at the base of the scarp extending into an openwork accumulation (Figures 4 and 6). In the vegetated section the blocks comprise 50-70% of the surface area. The openwork surface is marginally elevated in relation to the scarp base (Profile A-B, Figure 4) and terminates at a break of slope (CD, Figure 4) 20m from the scarp where gradients increase to 10-13°. Surface block size (a-axis) varies from 0.15m to 1.50m but show no overall trend in size along the surface transect (Figure 6). A bimodal fabric at U5 on the transect corresponds roughly to, and transverse to, the general slope direction. Below the openwork block surface the block concentration is 40-60% by surface area on the profile although the openwork is continuous in places adjacent to the measured profile (Figure 4). Openwork units continue below point B (Figure 4) but terminate as slope gradients decrease to around 5°. Relict sorted patterned ground is found on the lower gradient area above the next scarp (Figure 4), comprising labyrinth (elongated circular-stripe) surface forms and sorting to bedrock at 1.0m (Sumner, 2000, in prep).

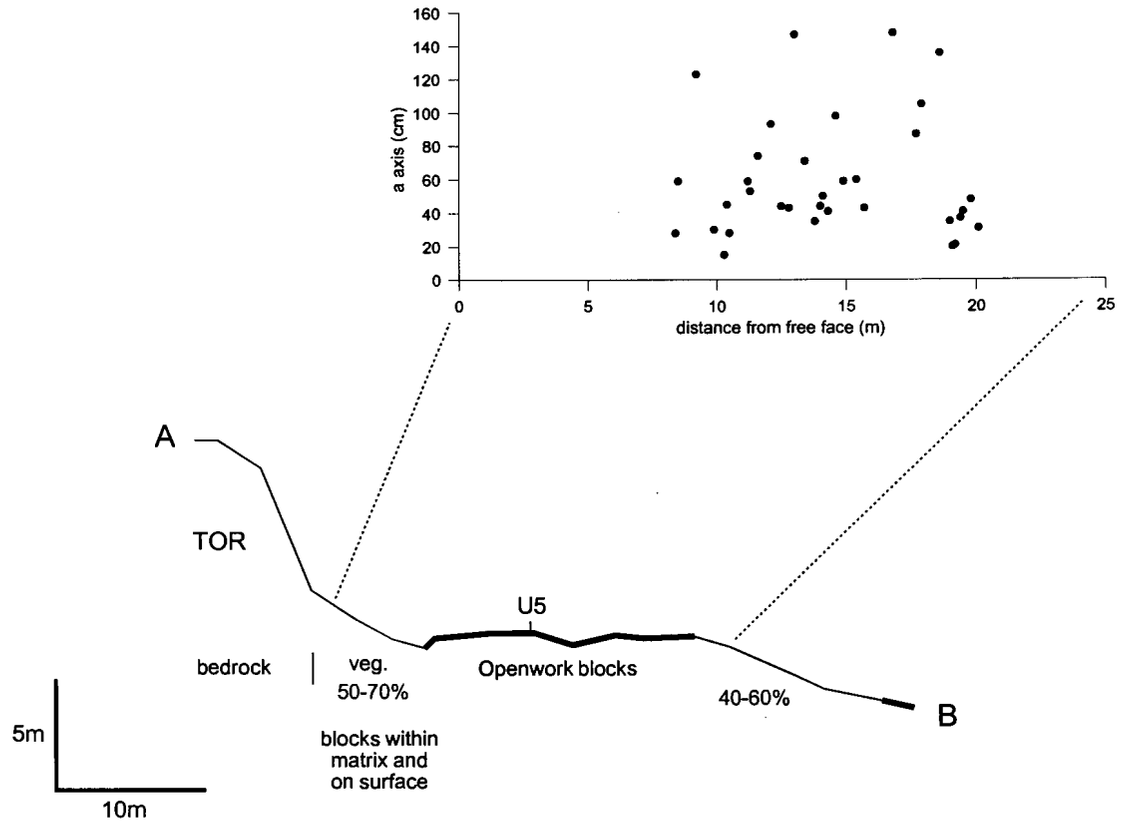
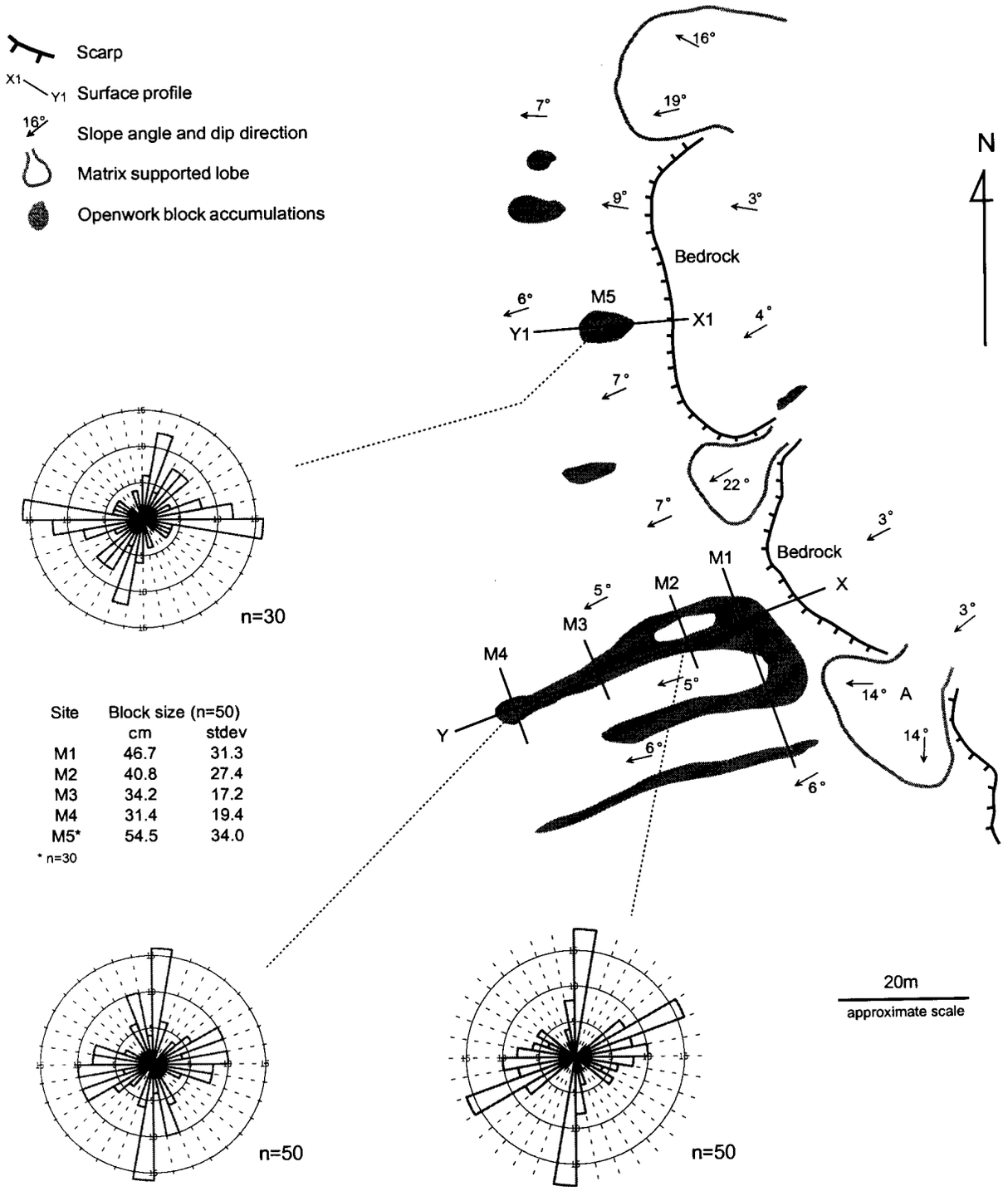


Figure 6: Surface transect (A-B, Figure 4) on the southern scarp of the interfluve site.

Midlsope site

This site comprises one of the typical horizontal basalt outcrops that characterise the midlsope regions on the southwestern-facing slopes of the valley. The scarp outcrop runs from north northwest to south southeast reaching a maximum height of 7m. Joint spacing is similar to the tor site, but can be exceed 2m. Overall slope gradient is 8° although slope gradients decrease to less than 3° above the scarps and near horizontal at the bedrock exposures behind scarp crests. Immediately below the scarp where openwork accumulations are found, gradients are 5° to 7° (Figure 7). As with the tor, the scarps appear to be mostly inactive with regard to mechanical weathering and block production, although some small clasts can be found that appear to be recently fractured or dislodged from the scarps.



Site	Block size (n=50)	
	cm	stdev
M1	46.7	31.3
M2	40.8	27.4
M3	34.2	17.2
M4	31.4	19.4
M5*	54.5	34.0

* n=30

Figure 7: Midslope site characteristics.

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The scarp at the site is bisected in places by colluvial lobes that extend downslope between scarp recessions (Figure 7, 8A). These lobate forms appear to override the slope colluvium at the scarp base. Blocks are entrained in the matrix (approximately 10-30% by surface area) which militates against an origin by surface wash; the lobes appear to be formed by slow mass movement. Below the scarps the block concentration is high in the colluvium and a number of openwork accumulations exist as isolated units or as downslope elongations (Figure 8B). No openwork units abut directly against the scarp although some blocks can be found within the matrix at the scarp base (Figure 7 and 9). On the two measured downslope profiles, a small depression is evident between the base of the scarp and the openwork units.

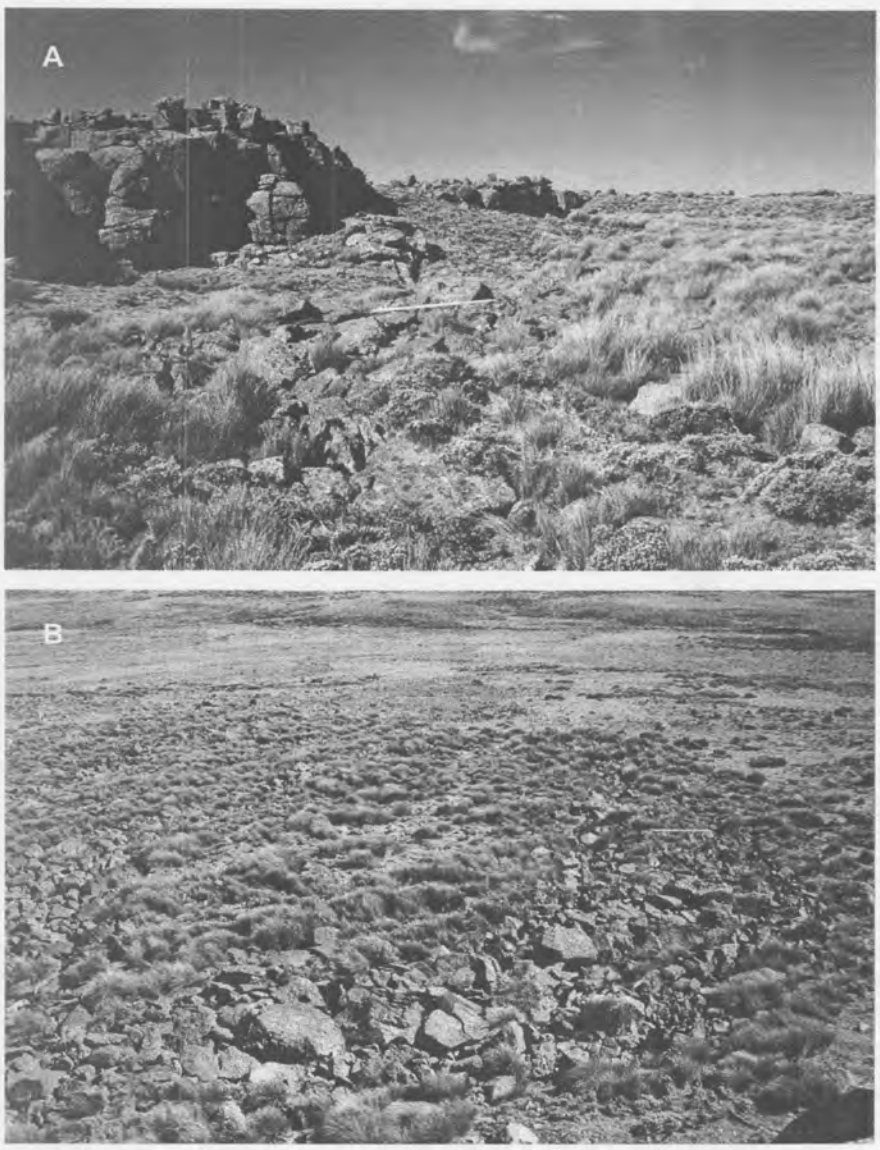

Figure 8: (A) Midslope scarp with lobate forms (A, Figure 7) and (B) openworks elongated downslope below the scarp. Scale bar 2m on both photographs.

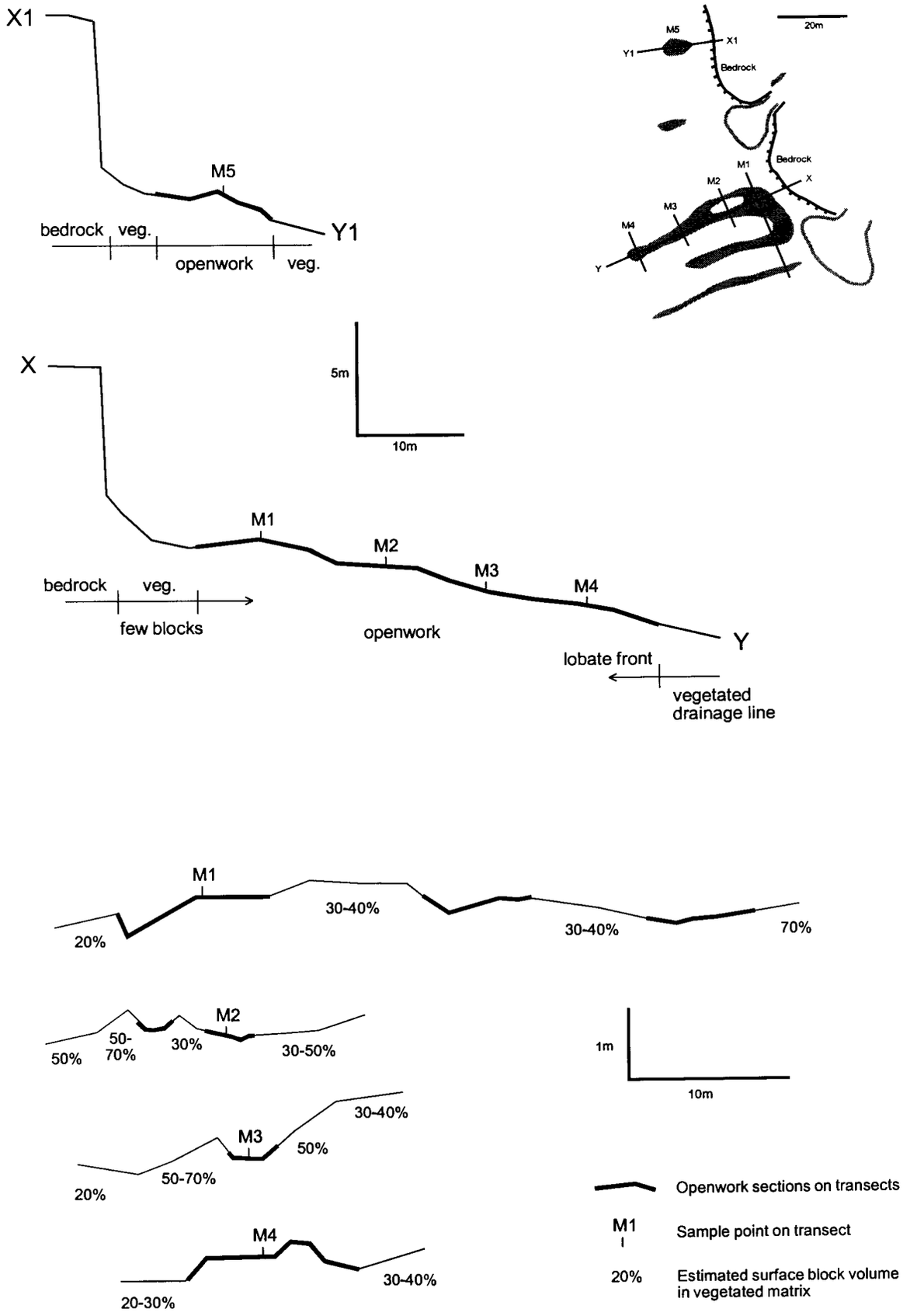

Figure 9: Midlsope site surface transects through the openwork units.

Fabrics sampled from the openwork units show a bimodal orientation suggesting downslope mobility subsequent to block production. Block size on the XY profile (Figure 9) decreases marginally downslope. The openwork structure at this site appears to be maintained by wash that is evident from the depressed surface of the openwork unit on the slope transects (Figure 9). A small fan-type lobate deposit extends from the terminal end of the openwork below sample site M4. Other openwork lineations immediately south of XY appear to be maintained in a similar manner. As with the upper site, blocks are sub-angular and highly pitted although some blocks have evidently been further broken-down into smaller fragments after emplacement.

Valley floor blockfield

A blockfield occupies the lowest region of the slope below the midslope site adjacent to the Sehonghong river (Figure 10). Slope gradients immediately east of the blockfield decrease to 3° to 4° and the slope gradient over the blockfield is approximately 4° orientated along the valley drainage to the north northwest. In general the colluvial mantle adjacent to the river measures 2-4m in depth and comprises predominantly sands and gravel with the fines (silts and clays) component less than 10% by mass (Sumner, in press) interspersed with basalt blocks. Exposures from river incision reveal a block concentration in the upper 1m of the mantles.

The blockfield measures approximately 70m in length and 25m wide at its widest point. Drainage lines emerge from the downslope (northern) extent of the openwork (Figure 11). The surface of the openwork unit approximates to the adjacent slope surface although subsidence, probably related to drainage through the blockfield, is evident from the transects. Block primary orientational fabric follows valley direction. Orientation may, however, have been disturbed subsequent to emplacement due to washout and the subsidence of blocks, particularly at L2 (Figure 11). Many of the blocks within the blockfield show steeply dipping axis, some approaching vertical. Blocks with vertically dipping a-axis also protrude occasionally from the matrix-dominated slope directly adjacent to the blockfield (Figure 10).

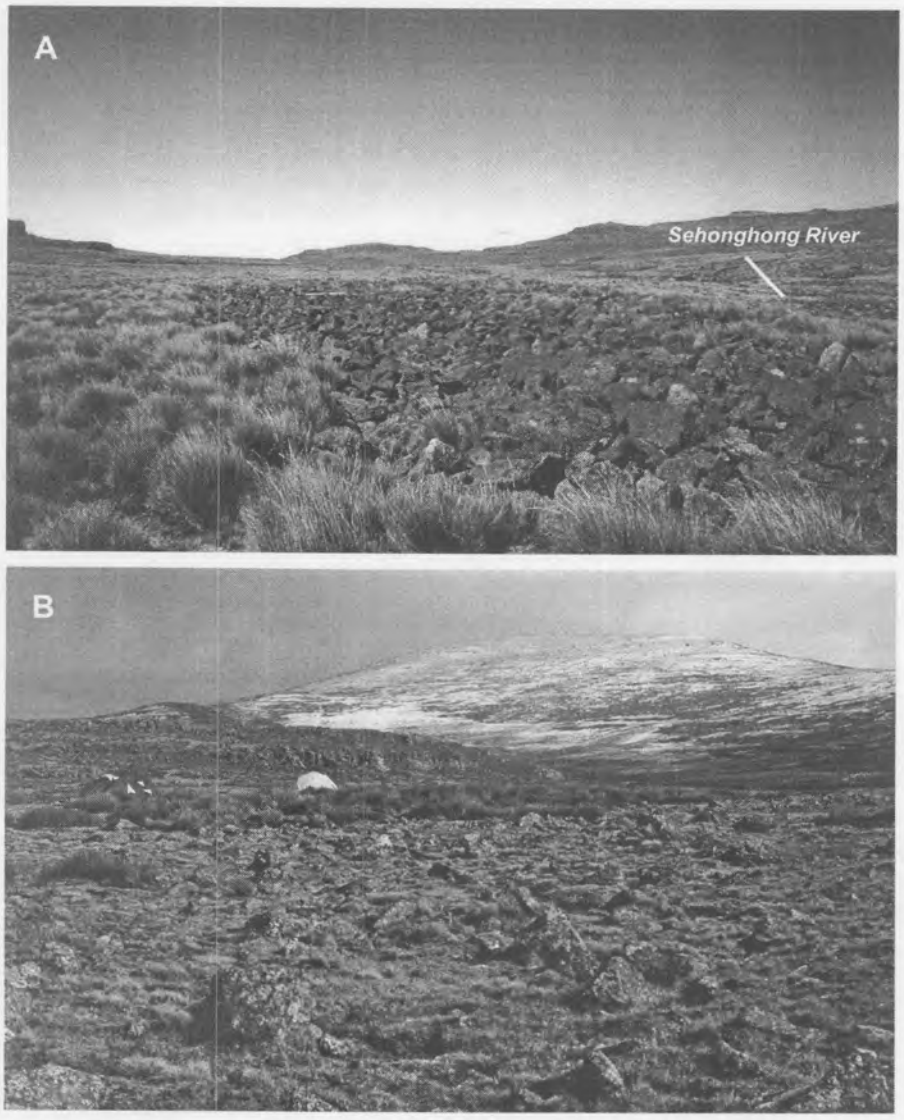

Figure 10: Valley-floor blockfield (A) viewed south with 2m scale bar. Upright block fabrics (B) adjacent to blockfield (viewed down valley of the blockfield); Thabana Ntlenyana massif in background and hiking tents for scale left of centre.

A vertical profile excavated through the blockfield at L3 shows a marginal decrease in block size with depth, and a measured a-axis size range of 0.10m to 1.35m (Figure 12). Smaller material at depth can be accounted for by the fall of the smaller blocks through the voids between the larger blocks. The matrix base underlying the openwork accumulation measured 0.86m from the approximate upper surface of the openwork. At L3 this would lie below the matrix-dominant surface adjacent to the blockfield.

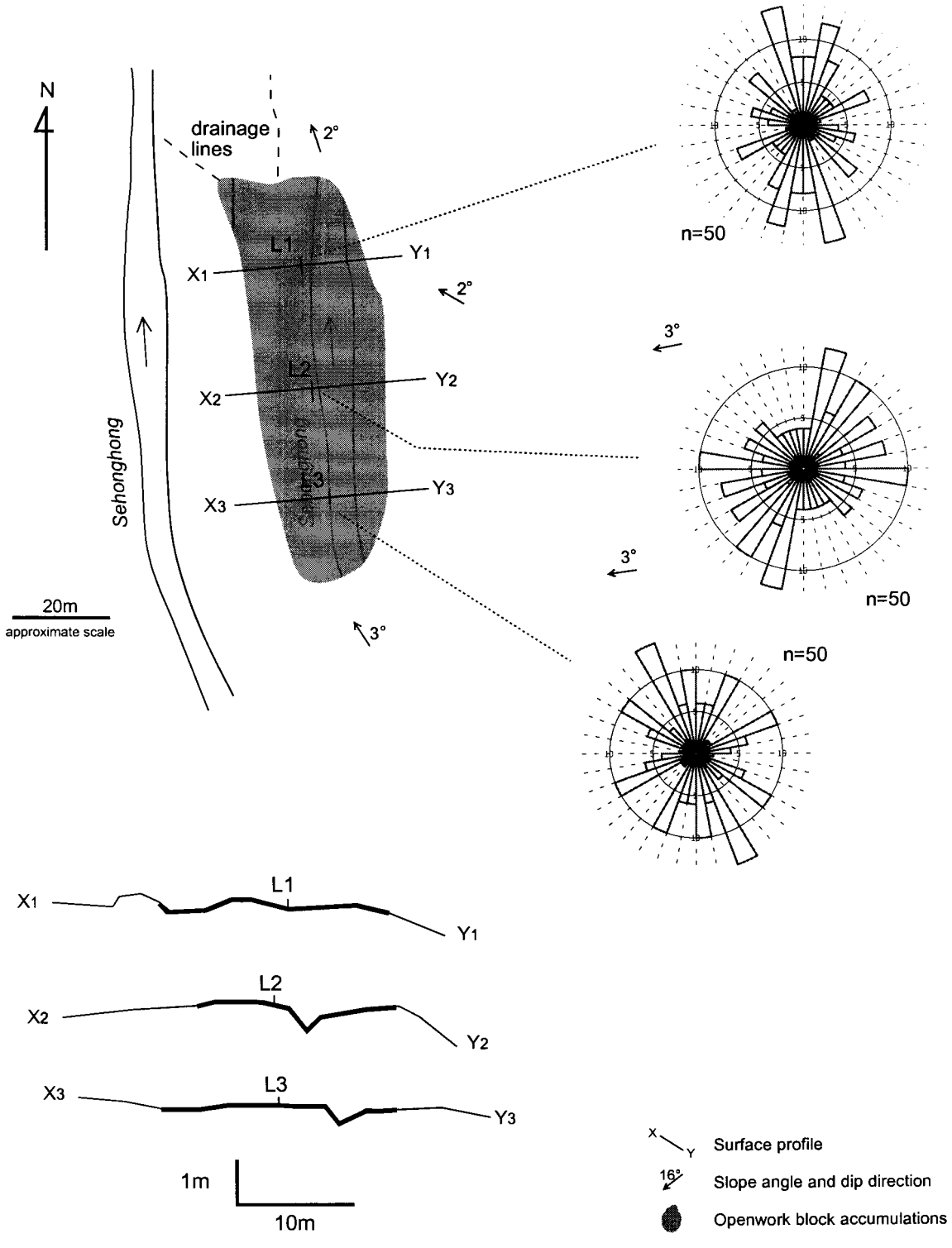

Figure 11: Valley-floor blockfield characteristics.

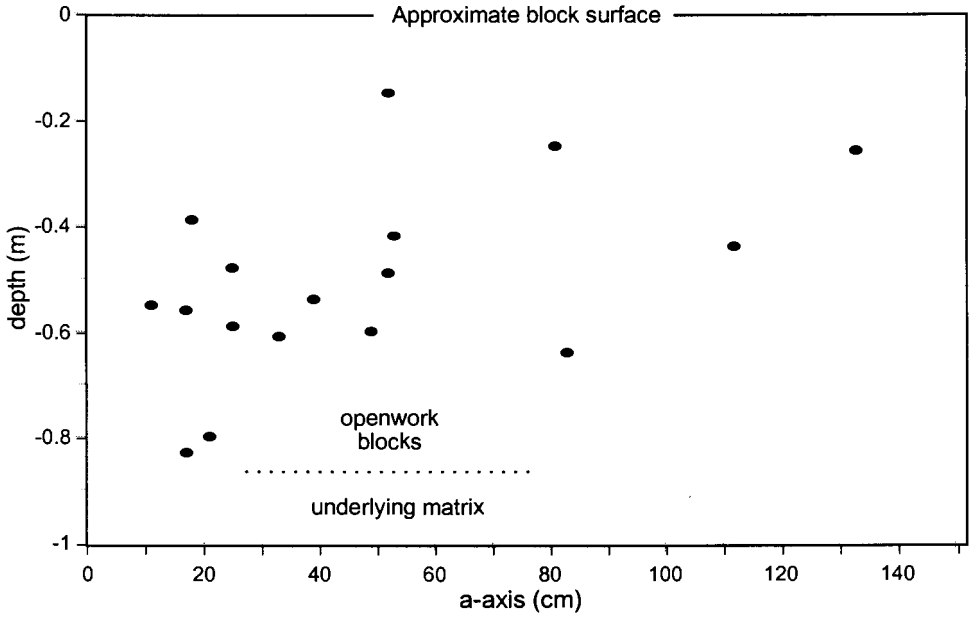

Figure 12: Clast-size variation from blockstream surface to underlying matrix (L3, Figure 11).

Surface roughness measurements

Roughness indices for upper block surfaces at various sample points on the openwork units are shown in Table 1. At the interfluve site, the openwork accumulation surfaces are all rougher than those found for the southern scarp. In the openworks, similar values at 5mm and 10mm intervals are found for the two sample sites closest to the scarp (U1 and U5, Table 1, Figure 4) although the U5 surfaces were rougher at the 20mm interval. Further away from the scarp and within the blockfield (at U3) surfaces are marginally rougher than the other two openwork sites at the 5mm and 10mm intervals but similar to U1 at 20mm intervals. No clear distinction between roughness at the three openwork sampling positions is thus apparent.

At the midslope site the scarp roughness values are lower than the two openwork samples sites that extend away from the scarp (M1 and M4, Table 1, Figure 7). Exposed block surfaces on the lobate material extending between scarps (A, Figure 7) are of a similar roughness to the scarp surface at all three intervals. Roughness at 5mm and 10mm intervals is sightly greater at M1 than M2, however, 20mm roughness is greater at M2. As with the upper slope site no difference

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is apparent at the sample sites on the openwork accumulations although the values are greater than those found for the openworks at the upper interfluve site.

Sample site		N	Roughness Indices		
			5mm	10mm	20mm
Interfluve tor	scarp (south)	15	1.07	1.70	2.54
	U1	15	1.22	2.07	3.30
	U3	10	1.44	2.34	3.31
	U5	15	1.22	2.01	3.01
Midslope	scarp (on XY)	10	0.94	1.46	2.17
	lobe (A)	15	0.88	1.40	2.15
	M1	15	1.52	2.46	3.70
	M4	10	1.41	2.44	3.96
Blockfield	L1	10	1.89	3.06	4.52
	L3	10	1.91	3.11	4.57

Table 1: Mean roughness indices for selected intervals of 5mm, 10mm and 20mm at sample sites on the openwork block accumulations (see Figures 4, 7 and 11). N = number of block upper surfaces measured, comprising six 150mm profiles on each block surface (following McCarroll and Nesje, 1996).

Very similar roughness values are recorded at the two sample sites on the valley floor blockfield. The roughness values from the valley floor openwork block surfaces are the highest recorded on the slope and, overall, the roughness at all three measured intervals increases in the downslope direction from the interfluve to the valley floor. The scarp surface at the upper site is rougher than the midslope site but both scarp sites are notably smoother than the blocks in the openwork units. These are the lowest values recorded for roughness on the slope and

correspond well to the values found for other scarps in the area (Boelhouwers *et al.*, 2002).

DISCUSSION

Block origin and distribution

The dominant distribution of openwork block units in the area around Sani Pass is on the southern-facing slopes (Figure 1). Block accumulations occupy valley floor positions, such as the large blockstream northwest of Sani Top (Boelhouwers *et al.*, 2002) (Figure 1), the valley immediately to the west of the blockstream (Figure 1, 2) and the blockstream site in the upper Sehonghong valley. Numerous openwork units are found in south-facing valley heads as evident in the upper Sani and Mangaung river valleys (Figure 1) although block concentration is very low on the north-facing slopes. This is best illustrated on the east-west Tsatsa-La-Mangaung ridge between the two rivers where openworks are found only on the south-facing slopes within the first order valley heads.

Openwork units in the area are also associated with bedrock scarp outcrops on valley sides. Boelhouwers *et al.* (2002) note that on the south-facing slopes of the blockstream valley (Figure 1) the south-facing scarps are discontinuous and mechanically fractured. These scarps are the source of blocks for the blockstream after incorporation into the mantle and movement downslope under solifluction and seasonal creep. On the south-facing slopes of the blockstream valley, blocks are concentrated within the upper 1m of colluvium (Boelhouwers *et al.*, 2002). This concentration of blocks is ubiquitous on the south-facing slopes in the area, and particularly evident in the Sehonghong valley, and in the Mangaung and Sani river valleys.

Mechanical fracturing of bedrock appears to be largely absent today. Weathering and mass wasting under contemporary conditions cannot account for block production on the scale required for the formation of the openwork units. As for the blockstream site (Boelhouwers *et al.*, 2002), block origin is accounted for by an increase in mechanical weathering on the south-facing slopes during the colder period of the last glacial.

Surface roughness and relative-age dating

At the Sehonghong site, two separate groups of data emerge from the assessment of rock surface data. The two scarp sites and the exposed block surfaces on the lobate material overriding a scarp comprise the first group. Block surfaces within the openwork units which show distinctly rougher characteristics comprise the second group. A difference between scarp and openwork sites can be accounted for by scarp micro-environmental conditions which will differ from those of the exposed blocks. Vertical faces allow for rapid runoff of rainfall and will reduce the erosive impact of rain. Southerly aspect orientation accounts for reduced rock temperatures and a relative decrease in surface chemical weathering in comparison to more horizontal surfaces. Insolation-protected sites at the base of the scarp are also the sites where contemporary late-lying snow exists in winter. Any effect on surface characteristics and the weathering regime is unknown. Therefore, a direct comparison of the scarp and openwork surfaces in terms of relative-age dating is not possible. Similar relative roughness findings were also measured at the valley blockstream site (Figure 1) (Boelhouwers *et al.*, 2002).

No discernable difference is measured in roughness within each of the three slope sites. However, an overall trend of increasing roughness is recorded in the downslope direction. The implication is for an increase in the age of the material extending from the scarps in the upper to mid-slope regions, extending onto the valley floor. Apparent age could be somewhat exaggerated due to sub-surface chemical weathering once a block has been incorporated into the matrix and then re-exposed to rainwash. Nonetheless, the implications are that blocks are produced from scarp mechanical breakdown and once incorporated on or within the matrix, are mobilised in the downslope direction to accumulate in the valley floors.

Slope mobility

Some contemporary slope mobility is evident in the slow creep of colluvium over bedrock outcrops, such as observed at the midslope site. Movement at these sites is probably enhanced by the buildup of moisture at the bedrock-colluvium contact. Fabrics in the relict openworks at all three sites in the valley indicate slope mobility subsequent to block production and emplacement. In order for a clast-supported diamict to be mobile an interstitial matrix is required,

or an ice enrichment at the block base. No direct evidence is found for ice enrichment. The removal of matrix by wash, evident from the transverse profiles and the emergence of drainage on the downslope ends of the midslope and valley floor openwork units, supports the contention for mobilisation and subsequent relative stabilisation such as found at other slope (Boelhouwers, 1994; Grab, 1999) and valley floor sites (Boelhouwers *et al.*, 2002) at similar altitudes.

Palaeo-geomorphic and -climatic implications

Evidence from the area indicates a phase of widespread block production on southern-facing slopes from basalt scarp outcrops. In contrast, fewer blocks are noticeable on the northern-facing slopes. Blocks are concentrated in the upper mantles, typically within the upper 1m, which indicates a superimposition and incorporation of the blocks within pre-existing slope material, possibly enhanced by up-freezing of blocks through the matrix. Slope colluvial mantles therefore pre-date block production. This concurs with findings in the large blockstream valley (Figure 1) (Boelhouwers *et al.*, 2002). A similar scenario should be considered in the Nhlangeni Pass cutback (Figure 1). Blocky material in the upper regions of the pass overrides and is incorporated into a pre-existing mantle (Grab, 1996, p.395) while ridge-like structures lower down in the pass, considered previously to be due to glacial action (Grab, 1996), appear to be incised colluvial mantles. Reworking of these types of colluvial mantles, which evidently pre-date the colder period, are most likely the source material for the lower cutback deposits (Hall, 1994; Sumner, 1995; Grab 1996). In addition, no evidence for *roches moutonnée*-shaped tors, which were used as supporting evidence for the glaciation of the pass summit region (Grab 1996), were found on the slopes adjacent to the pass summit.

Widespread distribution of blocks on cooler southern-facing slopes in the area supports the contention for block production during a phase of dominant mechanical weathering during the colder Late Pleistocene period. Notwithstanding the problems inherent in trying to ascribe a specific cold-temperature weathering process, such as freeze-thaw, to the weathering product (see Hall *et al.*, 2002), evidence exists for a phase of block production in the mountainous regions of southern Africa. Several reports on openwork blocky accumulations appear in the literature for the Drakensberg-Lesotho escarpment region (Boelhouwers, 1994; Grab, 1996, 1999; Boelhouwers *et al.*, 2002), the Western Cape (Boelhouwers, 1999) and the Eastern Cape

(Marker, 1986; Sumner and de Villiers, 2002) where block production is associated with this period. Concurrent with block production in the Lesotho Highlands is enhanced slope mobility that manifests itself in solifluction sheets on the lower reaches of the slopes (Boelhouwers *et al.*, 2002) and in the fabrics of the slope openworks. This is supported by an increase in relative-age of block surfaces in a downslope direction. Slope mobility was probably enhanced by deep seasonal freeze on the southern slopes, which also accounts for the upright fabrics which are particularly characteristic of the valley-floor deposits. In contrast to the openworks found in other areas (for example the Amatolas in the Eastern Cape), it is this emplacement that identifies the periglacial component of the environment (see Boelhouwers and Sumner, 2003).

Openwork accumulations are described to the north of the study area in the central Drakensberg (see Figure 1) escarpment region (Boelhouwers, 1994; Grab, 1999). Grab's (1999, p.12 and 13) model proposes snow melt and seasonal ice thaw with intensified weathering on the convex-slope interfluve region on south-facing valley slopes during the Late Pleistocene and Holocene. Below this the development of stone-banked lobes, blockfields and blockstreams, and debris flow depositional zones extending to the valley floors. Evidence from the Sehonghong site does not fit into the model; block material is produced throughout the slope and no evidence for debris flow-type deposits are found. Similarities can, however, be drawn with the relict openworks described on the southern slope of Giant's Castle (Boelhouwers, 1994) that are attributed to mechanical bedrock fracturing and mass wasting processes under periglacial conditions. Boelhouwers suggests "significant temperature fluctuations" (1994, p. 134) which implies limited snow cover with moisture supply from snow at the base of scarps.

Several comments can thus be made on the palaeo-climate of the study area during this colder period. Glaciation of the summit areas, for which no irrefutable erosional or depositional evidence has been found, could not have taken places since the openworks dominate on the south-facing slopes and would have been reworked by glacial action. It is unlikely that the time-period for the development of the colluvial mantles along the slopes in the Holocene would be sufficient for the development of the mantles and these pre-date the phase of block production. Extensive snow accumulation on southern slopes and particularly on southern slope valley heads also appears to be unlikely as this would inhibit deep seasonal freeze, slope mobility and active mechanical breakdown of scarps. Although Grab (2002) suggests permafrost above

3400m in the area, no direct evidence for permafrost was found. Permafrost would actually inhibit the mobility of the slopes during the colder phase as seasonal freeze would be restricted to the frost-active upper layer. Since the sorted patterned ground in the upper 1m at interfluve sites in the area (Sumner, 2000, in prep; Grab 2002) does not require permafrost for its development no data directly imply permanently frozen ground, even on the more insolation-protected southern slopes.

From the evidence available, the overriding perception of the Late Pleistocene environment in the study area is for a periglacial environment with limited snow cover and a deep seasonal freeze on south-facing slopes. The scarcity of classical periglacial landforms, such as widespread sorted patters, can be attributed to the absence of previous glaciation to provide the clastic range of material (such as found in tillite), the absence of permafrost and the relative mobility of the slopes. True sorted patterns near the escarpment are restricted to interfluve site where regolith is usually very thin and slopes are relatively stable. The periglacial environment would have been characterised by block production and slope mobility under depressed temperature conditions and seasonal freeze, followed by relative stability during temperature amelioration leading into the Holocene and washing out of fines from the blocky accumulations.

CONCLUSIONS

The characteristics and distribution of slope and valley floor relict openwork block accumulations in the escarpment region near Sani Pass were investigated. Relict openwork units are found to lie predominantly on south-facing slopes and in valley heads where valleys are incised. Blocks are concentrated within the upper slope colluvium implying a phase of block production over pre-existing mantles, supporting previous findings for a blockstream valley in the area (Boelhouwers *et al.*, 2002). Block production is attributed to phase of increased mechanical weathering and mass wasting from slope scarps, which conforms to sites of relict block in these mountains (Boelhouwers, 1994; Grab, 1999) and other high altitude areas in southern Africa (Boelhouwers, 1999; Sumner and de Villiers, 2002).

The findings support arguments against active glaciation of the Lesotho Highlands in the Late

Pleistocene. Scarp forms immediately west of Nhlangeni Pass summit bear no resemblance to *roche moutonées* as described by Grab (1996). No evidence for permafrost was found in the study area and need not be invoked to justify the formation of any of the observed landforms. Findings suggest that periglacial conditions dominated the south-facing slopes, characterised by deep seasonal freezing that would have been inhibited if deep snow cover were present. New climatic data suggest that temperature and precipitation conditions may have been exaggerated in previous studies. Given a decrease in precipitation to the order of 70% of present values (Partridge, 1997) and a fall in MAAT of 5.5° to 6°C (see Grab, 2002), a cold, relatively arid highlands environment can be envisaged during the LGM. In contrast, the north-facing slopes were probably subjected to a diurnal freeze and could have been geomorphologically more active. The basic bedrock slope structure and colluvial mantles of the south-facing valley sides, however, would predate the colder period. Valley asymmetry development (Meiklejohn, 1992, 1994) thus largely precedes the Late-Pleistocene colder period.

Other sites where relict block accumulations exist within colluvium should be re-evaluated since the colluvial mantels which contain the blocks probably predate the period of block emplacement. Evidence for the glaciation of the Nhlangeni Pass site (Grab, 1996), should be reconsidered since relict openwork block accumulations are found in colluvium near the pass summit; colluvium which appears to be fluvially incised at lower altitudes in the pass (pers. obs.; Meiklejohn, 2001). On this basis, the palaeo-geomorphic and -environmental model for the escarpment region at the LGM (Grab, 2002), upon which much evidence from Nhlangeni Pass is based (Grab, 1996), should also be reassessed.

ACKNOWLEDGEMENTS

The author is indebted to field assistance from and discussions with Ian Meiklejohn, Stefan Grab, Hermien Bijker, Jay le Roux and Werner Nel. Comments from Ian Meiklejohn on a first draft of the paper are appreciated. Funding was provided through a National Research Foundation Core Grant.

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CONCLUSIONS

Numerous publications and several dissertations and theses have appeared in the local and international literature on the periglacial and glacial landscape of southern Africa in the Quaternary. Many of these have raised conflicting issues regarding the interpretation of the palaeoenvironment, and hence the operative geomorphic processes, around the colder phase of the Late Pleistocene. Boelhouwers and Meiklejohn (2002) interpret the problem as originating from qualitative field assessments, complexities in field data, a lack of scientific rigour and an absence of regional assessments. Focussing specifically on the eastern regions of the southern African escarpment, such inadequacies are highlighted in this thesis (Section 1) using two examples where reinterpretation can be undertaken. The Bannerman Pass cutback (Hall, 1994; Sumner and Hall, 1995) still requires additional field data to resolve arguments; which highlights the inability for larger scale assessments at this stage. Problems pertaining to misinterpretation of field data are also highlighted in the commentary on sorted patterned ground in Section 1 (Sumner, forthcoming). Findings criticised in both papers by Hall (1994) and Grab (2002) have important palaeoenvironmental significance which can be re-interpreted.

Similarly, the book chapter in Section 1 (Sumner and Meiklejohn, 2000) highlights (p. 18-19) a need for re-assessing the proposed periglacial gradient for southern Africa (Marker, 1995) by reconsidering the controlling factors of lithology and relief distribution across the sub-continent. One of the sets of data used in deriving the periglacial gradient are the the Amatola screes, interpreted previously as indicative of late-lying snow and enhanced periglacial conditions on south-facing slopes (Marker, 1986). When re-evaluated in Section 2 (Sumner and de Villiers, 2002), the Amatola screes are found to show no evidence for the existence of snow or enhanced frost action on south-facing slopes. While a phase of enhanced block production during the colder Late Pleistocene accounts for scree formation, and appears to fit in with assessments for relict openwork accumulations in the Western Cape mountains (Boelhouwers, 1999), no specific criteria for a periglacial environment are illustrated from the Amatola mountains. Given the alternative evidence presented in the thesis that can be derived from sites previously attributed to a former glacial or periglacial environment, additional detailed re-evaluation should be

undertaken. Sites of significance are the insolation-protected escarpment zone (eg. Grab, 1996) and sites where erosional and depositional features may be re-interpreted, such as topographic hollow forms (eg. Marker and Wittington, 1971; Dyer and Marker, 1979; Marker, 1991).

In Section 2 of the thesis, palaeoenvironmental evidence for the Late Pleistocene is presented from relict openwork accumulations and relict sorted patterned ground. Two criteria are found to be important when investigating openwork accumulations; block production and mode of emplacement. Openworks are found to exist through a wide range of climatic conditions in southern Africa (Boelhouwers and Sumner, 2003), including the Karoo and Namibia. Mode of emplacement is found to be the diagnostic criteria for periglacial conditions, although block production appears to also be enhanced under colder conditions. Such conditions account for openwork units found in the Western Cape and in Lesotho.

Detailed investigations of openwork sites were undertaken near Sani Pass and Thabana Ntlenyana (Figure 1, p.5) in Lesotho highlands (Boelhouwers *et al.*, 2002; Sumner, submission 1). Findings show a phase of block production from scarps on south-facing slopes and the downslope transportation of material by solifluction attributed to the depressed temperature conditions of the Late Pleistocene. Openwork units are superimposed onto, or incorporated into, the upper part of colluvial mantles. A contribution by upwards freezing of blocks through a deep seasonal freeze is suggested.

Relict sorted patterned ground (Sumner, submission 2) found near Thabana Ntlenyana indicates freeze penetration to at least one metre depth and supports the contention for a period of deep seasonal freeze. Ground thermal conditions at a nearby site (Sumner, submission 3) show contemporary seasonal freeze at 0.05m for 2.5 months and project a freezing depth possible to 2m depth during the height of the Last Glacial. In contrast to suggestions by Grab (2002), no evidence for permafrost is derived from the presence of such patterns. These data support the contention for a seasonal freeze enhancing slope mobility, particularly on south-facing slopes.

Several major findings on the Late Pleistocene palaeoenvironment and geomorphic activity can thus be made from the assessments in Section 2:

- A phase of block production characterised the mountain environments in Late Pleistocene. Relict block accumulations characterise the eastern escarpment region in Lesotho and the Amatola mountains, as found in the Western Cape mountains (Boelhouwers, 1999). In the Lesotho highlands block production coincided with a period of enhanced slope mobility.

- The colluvium mantles in Lesotho must have pre-existed the phase of block production. This is evident from the incorporation of the blocks within the upper mantles. Although some contribution may come from upwards freezing of bedrock-derived corestones , this would also occur through a pre-existing mantle.

- An absence of glaciation above the escarpment. The existence of the colluvium and block accumulations on the slopes, valley heads and valley floors militates against previous active glaciation (eg. Marker, 1991; Grab, 1996) as the openwork landforms would have been severely altered. No other convincing erosional or depositional features are evident in the area.

- Deep seasonal freeze characterised the southern-facing slopes. This is evident from the enhanced slope mobility, the orientational character of slope openwork blocks and is supported by the evidence for deep seasonal freeze in sorted patterned ground and projected temperature profiles under cooler conditions. Deep seasonal freeze on south-facing slopes concurs with the suggestion by Boelhouwers (1994) for a site in the central Drakensberg escarprment region.

- Deep snow cover would have been absent. Extensive snow cover, even on insolation-protected south-facing slopes, is unlikely as it would have restricted temperature variations and inhibited block production. A low precipitation regime concurs with the estimates for a precipitation reduction to 70% of present (Partridge, 1997) while it is possible that extrapolations from lower altitudes (eg. Schulze, 1979) overestimate contemporary precipitation totals.

- No evidence is found for permafrost. No direct evidence for the existence of permafrost on the cooler south-facing slopes was found in Lesotho. Permafrost on interfluve sites, even at slightly higher altitudes where sorted ground is found (eg. Grab 2002), is also unproven. Seasonal freeze can account for the landforms found in the area.

In summation, conditions in the Lesotho highlands in the vicinity of the escarpment during the Late Pleistocene were probably more arid than present and characterised by an active frost environment. An overall predominance of blocks on the south-facing slopes indicates severer temperature conditions in relation to the north-facing slopes. It is likely that the south-facing slope environments probably resembled the "periglacial" regime (eg. French, 2000) more closely than the northern slopes. Active processes included enhanced slope mobility, block production and possible upward freezing of weathered bedrock corestones through the mantles. Soilifluction mantles predominate on the souther-facing slopes. In contrast, little periglacial evidence is evident on the north-facing slopes. Here the environment may have experienced a less intense seasonal-freeze and was probably dominated by a diurnal freeze-thaw.

Some comments can be made regarding the modelling of palaeo-slope processes and modelling. Since the solifluction mantles and block incorporations occur in a largely pre-existing valley form, valley asymmetry development (Meiklejohn, 1992, 1994) must pre-date the colder period and not be directly associated with it. Asymmetry development should thus be considered as a continuum as opposed to being associated with a specific time period. Grab's (1999) model for Late Pleistocene south-facing slope processes in the central Drakensberg region is not directly applicable to the Thabana Ntlenyana area. Insufficient information exists for palaeoenvironmental conditions to be fully modelled (eg. Grab, 1999, 2002) at this stage, and the relative (in?)activity of the north-facing still needs to be investigated.

Findings for the region above the escarpment have implications for the interpretation of relict landforms in the cutback regions. Niche glaciation of the cutbacks at Bannermans Pass (Hall, 1994) and Nhlangeni Pass (Grab, 1996) have been proposed, and these insolation-protected sites appear to be the most likely sites for snow accumulation. Colluvium mantles evident within the cutbacks appear to duplicate those immediately above the escarpment, such as those found

in the Sehonghong valley immediately west of Nhlangeni Pass. Evidence presented for glaciation should be reconsidered as the mechanism for fluvial reworking of the colluvial mantles, not as deriving the material for their formation (eg. Grab, 1996). Such reworking by meltout would then account for the large alluvial deposits (eg. Hall, 1994) which characterise the lower cutbacks extending down to altitudes below 2000m a.s.l. in KwaZulu Natal.

Some problematic issues are highlighted from the thesis. A full understanding of rock weathering and block production under depressed temperatures remains enigmatic (eg. Hall *et al.*, 2002). Exact linkages of weathering processes with coarse blocky slope material (van Steijn *et al.*, 2002) is thus problematic. Notwithstanding this, evidence for blocky material characterising cold environments is ubiquitous and result from either an enhanced mechanical weathering environment, a restricted chemical weathering environment, or the protection/preservation of coarse (sometimes angular) material. Although the association of block production with a cooler climate is inherent in this thesis the direct linkages between process and form are not fully resolved.

Another problem stems directly from the poor understanding of the contemporary climatic conditions of the studied area. The absence of climatic data for the high altitude region of Lesotho seriously hampers the starting point for palaeoenvironmental reconstruction. Although some data are available from direct monitoring, these are few and are normally not continuous. Long term, detailed monitoring of current air temperature and precipitation are required, and more importantly, details on soil temperature and moisture conditions. Such research can also be directed at ascertaining aspect contrasts in micro-environments.

In addition to detailed climatic and soil-climate monitoring, additional research directions can include:

- A more widespread analysis of relict landforms.
- A search for more relict sorted patterns on interfluve sites.
- Detailed clay analysis (Rea *et al.*, 1996) of matrix in association with landforms such as the blockfield.
- Reviewing existing sites where features can be open to plausible alternatives.

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APPENDIX 1

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South African Geographical Journal (2002) 84 (1), 145-152

SOUTH AFRICAN GEOMORPHOLOGY: CRITICAL CHOICES FOR THE FUTURE

H.R. BECKEDAHL, P.D. SUMNER AND G. GARLAND

The paper traces the major themes in southern African geomorphology from its early roots in both geography and geology at the start of the twentieth century through to the present. The development of the sub-discipline is considered on the basis of four epochs, namely: the early period up to the 1940's, the 1940's and 1950's, the period from the 1960's through to 1985, and the period since the First International Geomorphology Congress in Manchester (1985) and the first international conference on the geomorphology of southern Africa in Umtata (1988) through to the present. The trends in southern African geomorphology, based on a review of some one thousand five hundred journal articles and eleven conference proceedings from both the local Geomorphology Association and the Geographical Society are reviewed. These trends are then contrasted with developments within the discipline as a whole as represented by the more than three thousand abstracts contained in the proceedings of the international congresses on geomorphology between 1985 and 2000. Finally, the extent to which modern geomorphology is of significance in South Africa at present is considered.

Introduction

Geomorphology has its roots as firmly grounded in Geology as in Geography, with many of its concepts originally having been defined by geologists. A review of the philosophical writings of early Eastern, north African and Greek scientists highlights the fact that several concepts which are now clearly identifiable as being geomorphological in nature were already in existence over two thousand years ago, as aptly outlined by the work of Tinkler (1985). The field of geomorphology has thus been evolving over a considerable period of time, even though the term itself only came into common usage towards the end of the nineteenth century. The value of hindsight is further emphasized by Hart (1986), who argues that paradigm shifts by their very nature are most easily recognisable in retrospect. Increasingly, the recognition and pursuit of what becomes a significant paradigm within any given scientific discipline is influenced in part (and sometimes largely) by trends and modes of enquiry outside its immediate domain. A perusal of the works of Chorley *et al.* (1964), Tinkler (1985) and Hart (1986) shows the same to be true for Geomorphology.

At the start of the 20th Century, Geomorphology was dominated by the *inductive* approach to science (Goudie, 1990), as is evident from the many attempts at describing and classifying landscapes; *inter alia* the well known debates of Lester King and William Morris Davis. This approach gradually gave way to greater adherence to the *deductive* scientific school of Popper (1972), based on the testing of theories - a paradigm which was in part driven and in part facilitated by measurement techniques and advances in other branches of science such as precision engineering fuelled the 'quantitative revolution'. The deductive-positivist approach was (and still is) greatly facilitated by a broad range of statistical techniques initiated by the original benchmark work of Strahler (1952). The greater precision in measurement and the drive for quantification led to a revival of interest in the processes shaping the landscape; concepts which were subsequently modified by the paradigm of systems theory (Chorley, 1962). This was in turn followed by analyses of 'process-response' mechanisms and the inclusion of the concept of thresholds (Schumm and Lichty, 1965). More recently, geomorphological explanation has been sought through mathematical modelling (Kirkby, 1971; 1976), random change and chaos theory (Ergenzinger, 1987; Malanson *et al.*, 1990 and Phillips, 1994).

Clearly, with the aim of geomorphological research being principally to explain the physical, non-biotic landscape (presumably so as ultimately to facilitate sustainable management and predictive capabilities (cf. Chorley *et al.*, 1984)), the overall focus is on fieldwork and field observation rather than theory *per se*. It is therefore not surprising that southern African geomorphology does not necessarily reflect each (or all) of the dominant paradigms outlined above. The argument made by Thorn (1988) must, however, be emphasized, namely that fieldwork must of necessity take place within a particular theoretical framework - that is to say theory must precede fieldwork.

The first forays into the geomorphology of southern Africa stem from contributions made by both early geologists (see for example the works of Rogers, 1911; Dixey, 1938 and King, 1942, 1944) and geographers such as Wellington (1929) and Fair (1947). However Bauer's (1996) point that the roots of geomorphology stem from contributions from considerably more than these two disciplines, is well taken. The origins and nature of geomorphology in southern Africa have been reviewed previously by Moon (1989) and Moon and Partridge (1993), who have argued for a three-fold classification into: the period up to the 1940's, the 1940's and 1950's, and the period post 1960. This paper recognises essentially four epochs. Broadly similar time frames to those of Moon (1989) and Moon and Partridge (1993) have been adopted for the sake of consistency, but with the addition that the post 1960 period of Moon is subdivided in this review into the two periods of the 1960s through to 1985 and from 1985 through to 2000. The benchmark of 1985 was chosen as it represents the start of the then fledgling International Association of Geomorphologists (IAG) as a consequence of the first International Congress on Geomorphology (ICG) in Manchester that year. However, the first inaugural meeting of the formalised IAG took place in Hamilton, Canada, only some eight years later. The establishment of the IAG necessitated the formation of national groups of geomorphologists, and hence laid the foundations for the establishment of the Southern African Association of Geomorphologists (SAAG) as a direct consequence of the first conference on the geomorphology of southern Africa in Umtata in 1988. The date of 1985 is perhaps of further significance too in that it also represents the first slow beginnings of political change in South Africa, which culminated in the democratic elections of 1994. In reviewing the state of the Geomorphology in southern Africa, it is necessary to:

- highlight the geomorphologically relevant scientific themes which have existed in southern Africa, and examine how these have changed over time,

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- compare these observed trends with those for the discipline in its global context, and
- analyse the extent to which modern Geomorphology is of significance in southern Africa at present. The question needs to be asked that whether it serves a purpose in contemporary South African society beyond the 'novelty' and appeal of its academic enquiry.

Early southern African geomorphology

The pre-1940s period was as one dominated by exploration and the description of the southern African landscape by both geologists (in particular Rodgers, Hall and du Toit) and geographers, most notably John Wellington, although many of his benchmark publications only appeared in the second epoch - that of the 1940s and 1950s. (Moon, 1989; Moon and Partridge, 1993).

This second period was dominated by the work of King and Dixey with some seminal work from Wellington in terms of his physiographic classification of the subcontinent as part of his volume *'Southern Africa'* (1955). In essence, the epoch is characterised by debates concerning the macro-geomorphic evolution of landscapes in general and of the sub-continent in particular, as illustrated by the formulation of King's theories on pediplanation, epitomised in his '*Canons of Landscape Evolution*' (1953). Moon (1989) and Moon and Partridge (1993) emphasise the dominance of the contributions made by King to South African geomorphology, yet one might argue that the situation is not too dissimilar from that described by Rhoads and Thorn (1996) concerning the role of Davis' theories of landscape cycles on North American geomorphology. They argue that Davis based his theories largely on 'personal examination' of landscapes around the world, and used maps 'primarily to supplement visual information on landscape form, rather than as a source of quantitative data' (Rhoads and Thorn, 1996, p38). Thus they concur with the view expressed by Hart (1986), that the macro-scale landscape models of Davis and King have retarded the development of the discipline by their dominance and to the exclusion of the process studies being undertaken at the time by *inter alia* J.W. Powell (1875) and G.K. Gilbert (1877; 1914).

It could be argued that evidence supporting this view from a southern African perspective emerged from the quantitative work of Fair (1947; 1948), concerned with slope development in relation to structure and process. Although largely ignored, hindsight has assessed Fair's work as the single most important contribution to slope studies (Young,1972). As will become evident in later discussion, King's work on denudation chronology arguably still directs research on macro-scale landscape development within the region even today. Certainly it is still the core of geomorphology in many South African school text books, whereas process studies are still not mentioned.

Trends in southern African geomorphology over the past four decades

A review of geomorphological research in the region over the past four decades as reflected in more than one thousand five hundred journal articles as well as the bibliographic series published by SAAG (covering the sub-disciplines of weathering and slope studies; fluvial research; erosion and sediment transport; coastal geomorphology, and periglacial research, all with specific reference to southern Africa; see Table 1), and in eleven conference proceedings of the Society of South African Geographers (SSAG), the South African Geographical Society (SAGS) before that and the Southern African Association of Geomorphology (SAAG) (Table 2), is contrasted here with developments within the discipline as a whole as represented *inter alia* by the more than three thousand abstracts contained in the proceedings of the international congresses on geomorphology between 1985 and 2000. Notwithstanding the large body of literature perused for this review, the authors emphasize that the trends discussed here should be viewed in their broad context rather than in absolute terms, as there is still a large body of relevant literature in the journals of the closely allied disciplines (e.g. pedology, hydrology and geology) which, for purely logistical reasons, could not be incorporated in this analysis. The ten dominant sub-disciplines of Geomorphology were used for comparative purposes to determine trends within the discipline, as illustrated in Table 1. An eleventh category, that of Process Studies, was used as an overarching category in that research which was process-based was considered here, but would also have been included in the analysis of, say, slope or coastal geomorphology. Where research dealt with more than one of the categories used in the Tables, the dominant category was used to avoid distortion of the data. All figures quoted are presented as a percentage of the total data set.

The percentage of applied geomorphic work in the pre 1966 era averages out at 10% of the publications, as shown in Table 1. The trend shows a steady, slow increase to 13% by 1985. This trend is sustained such that the pre '85 era averages at 11% as compared to 14% for the era of 1985 to 2000. This trend is also evident from Table 2 showing an analysis of the abstracts of papers presented at Geomorphology and Geography conferences in South Africa from 1988 to 2000. The applied work presented at conferences has increased from 0% in 1988 to 11% in 2000, with an average at 6%. It is interesting to note that the average of applied contributions presented at Geography conferences over the same period is 9% of the geomorphology papers. (Due to the small number of geomorphology presentations at Geography conferences, it was not statistically feasible to track applied geomorphic work for individual conferences). By contrast, tectonic and macro-geomorphic research has shown a steady decline in support from a maximum of 22% pre '65 to 10% by '85. This decline has continued to a value of only 4% in the period of 1996 to 2000. These figures may be summarised as representing an overall value of 15% in the pre '85 era to 4% in the post '85 era, broadly reflecting the international trends reflected in Tables 2 and 3. Although conference contributions fluctuate to some degree, a similar decreasing trend is evident.

What is disturbing is that purely theoretical work in any form or branch of Geomorphology has declined from a maximum of 6% in the pre 1966 epoch (where it largely concerned itself with theories relating to the macro-scale evolution of the landscape) to a minimum of 3% during the 1986 to 1995 decade. Overall, the contribution of publications to theoretical research has decreased steadily from the 6% mentioned, to 5% in the pre '85 era, down to 4% in the post '85 era. The low level of support is even more noticeable when the conference presentations are reviewed (Table 2). Although the nature of the theoretical research has clearly undergone significant change, it is generally accepted that the extent and vibrancy of theoretical research is a measure of the academic 'health' of a discipline; it is therefore clearly important to identify reasons for the low pursuit of extending the boundaries of the body of theoretical knowledge in southern Africa. This will be explored further in later discussion.

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In contrast to other themes, process studies have increased from constituting only 1% of the pre 1966 publications to as much as 11% during the 1986 to 1995 decade, before decreasing slightly to 9% by the end of the millennium. This trend is very clear when comparing the average values of 3% for the pre '85 era compared to 10% post '85. While there has been an increase in the process based conference contributions, these average out at 7% with a peak value of 10% during the '94 Conference held in Pietermaritzburg in association with GERTEC (the IGU Commission on Geomorphological Research To Environmental Change). The number of contributions at Geography conferences is even less, averaging 5%. These values do, however, highlight a different aspect of the data presented here. The data are skewed by a phase of high productivity from one region, driven by a relatively small group of researchers dealing with erosion, land degradation and climato-geomorphic (principally periglacially aligned) research. However, interest in what Gregory (1978) terms 'hydro-geomorphology' (geomorphology related to the action of fresh water on and within the earth's surface) has been broadly consistent above the 10% level, as is to be expected from a primarily semi-arid region. The nature of such research has changed over the decades. While the pre-'85 published research (12%) concerned itself overwhelmingly with the qualitative description of river systems and their possible morpho-genetic evolution, the post '85 publications are highly quantitative and often either process-based or focused on considerations of water chemistry and water quality. A recently emerging theme is that of mathematical modelling and prediction of change in the fluvial system. Conference contributions fluctuate between a maximum of 25% (1990) and a minimum of 17% (1988; '94 and '96), the average for the period '88 to 2000 being 19%. Geography conferences have significantly fewer contributions, at only 9%, reflecting the research of hydrologists presented at SAAG conferences.

Work pertaining to erosion and land degradation has (not surprisingly) experienced broadly similar trends to those of hydro-geomorphology. It has moved from 14% pre '85 to 19% in the post '85 era, but has changed significantly in the approach adopted from a principally subjective description of the *status quo* to being strongly process based, predictive and highly quantitative, arguably to the extent where periodically it may be pertinent to consider whether our current level of understanding warrants the degree of prediction made possible by several of the mathematical models *in vogue*. The trends for conference papers (Table 2) oscillate between 45% in 1992 and 13% in 1996 and 1998. It is interesting to note that the level of research contributions at Geography conferences does not differ markedly from that of geomorphology (23% *vs.* 25% respectively), reflecting that this is a topic of concern to both human and physical geographers alike. Karst geomorphology, weathering studies and coastal research are not well represented in southern African geomorphology but have generally retained their share of the attention from researchers, principally due to the active research of small 'core' groups of researchers who are actively (and passionately) promoting their sub-disciplines.

Slope geomorphology has declined in prominence from 11% in the pre 1966 era (arguably the hey-day of the pediplanation and denudation chronology school of Lester King) to only 4% during the '96 to '00 era, although the average for the two periods is the same. Such decline may well be seen in the context of the fundamental change in importance attached to macro-scale geomorphic interpretation of the landscape to quantitative, semi-process based, mathematical predictive models of slope stability. As was noted earlier, although less frequent, there are still regular, often semi-quantitative publications presenting re-evaluations of the denudation chronology of southern Africa. Most notable among these was the work of Partridge and Maud (1987) which, while using a thoroughly scientific approach to the re-interpretation and genesis of erosion surfaces in southern Africa, has failed to address several of the key issues concerning denudation chronology highlighted in the international literature (see for example Young, 1972; Ollier, 1985 and Ollier and Marker, 1985). The number of conference papers varies quite considerably from a minimum of 5% in 1992, to a maximum of 17% in 1994 and 1996, with an average of 11% compared to 14% at Geography conferences over the same period.

An important, ongoing theme in the southern African geomorphological literature has been that which is best described as '*climatic geomorphology*' (cf. Büdel, 1982 and Tricart and Cailleux, 1972). This topic covers the spectrum of diverse themes from environmental change; arid and semi-arid geomorphology, Afro-Alpine research and allied studies of periglacial geomorphology, to questions of climatic change (principally Plio-Pleistocene and Quaternary, but to a limited extent also Holocene). This is a sub-field which is gaining in popularity (one suspects at least in part due to its obvious relevance to the debates concerning global climate change and Global Warming with the associated lure of potentially greater access to research funds). It was unfortunately necessary to group these themes together as there is a broad commonality of approach which has facilitated the comparison with international trends. Such analysis would have been impossible had individual topics been used. As is evident from Table 1, it has gained steadily in importance from 22% pre 1985 to 28% in the post '85 era. Table 2 indicates a similar measure of interest among geomorphologists specifically despite some fluctuation, as well as among geographers.

South African geomorphology in the international context

A review of geomorphological research in the region over the past four decades as reflected in conference abstracts and more than fifteen hundred journal articles has been reviewed in the discussion thus far. It is now necessary that this be contrasted with developments within the discipline as a whole. The comparison is achieved by using the abstracts of the International Conferences on Geomorphology (ICGs) from 1985 through to 2000, (now held under the auspices of the International Association of Geomorphology), and six commonly used tertiary geomorphology texts published outside southern Africa (see Table 3).

Such comparison shows that although there is a fair degree of commonality between trends for the southern African region and for the discipline as a whole, there is a distinct under-emphasis at the regional level on process studies (particularly medium to long-term process studies), applied research and human-environment interactions. A relatively greater emphasis is placed on macro-geomorphology (although journal publications are roughly on par with those internationally), to a limited extent climatic geomorphology (encompassing the sub-fields of arid and semi-arid environments and Afro-Alpine research) and studies of palaeo-geomorphic landforms at the regional level. Output in karst, hydro-geomorphology, coastal and slope - related

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research is approximately on par with what is produced proportionally in the international arena, although the southern African publications are broadly still less orientated towards process (including detailed chemistry and physics) than the international literature. Notably greater emphasis is in research placed on land degradation and erosion in southern Africa than internationally - the percentage of publications and conference abstracts is between twice and three times that of the international arena, and reflects the semi-arid conditions in southern Africa and the relative paucity of suitable arable land.

Perhaps most significant is the relative paucity and continuing decline of theoretical work in southern Africa whereas, by contrast, Thorn (1988) argues that theoretical geomorphology is growing rapidly in the international literature, albeit in an 'inefficient' manner in that it is not as yet having a notable influence on current geomorphic paradigms. This trend is all the more disturbing in the context of the long geomorphic history evident in the southern African landforms when compared to those of the northern hemisphere. Southern African landforms arguably represent a palimpsest of processes since at least the mid Miocene some 20 Ma ago, while most northern hemisphere landforms post-date the last Pleistocene glaciation less than 100 Ka ago.

The future

It is necessary for the opportunities afforded by the geomorphological history of southern Africa to be utilised to a far greater extent in the future than has been the case to date. Many of these landforms represent the ideal laboratory for testing much of the theory and many of the philosophical principles being debated in the current literature (see for example Richards, 1990; Baker and Twidale, 1991; Rhoads, 1994; Rhoads and Thorn, 1994). Not only do the landscapes themselves present great opportunities, but also the close proximity of a range of morpho-climatic regions facilitates investigations to be carried out under a range of climatic conditions. Such analysis and the consequent insights *must* feed back into a greater understanding of the controls affecting geomorphic process, hence facilitating feedback to applications in prediction and environmental management; the latter already being one of the important growth areas of the discipline regionally. This is all the more important in the context of the assertion that theory informs methodology (Thorn, 1988; Goudie, 1990). However, the tendency of the public and the employers alike is to require that geomorphological input under such conditions is generally expressly qualitative in nature.

If the sub-discipline is to thrive in southern Africa in the future, it is imperative that the perception that geomorphology is a 'soft science' (and thus inherently second rate to the likes of civil engineering) be dispelled. The simplest and most effective manner of achieving this is to show the capabilities that the discipline has as an applied, quantitative science, offering solutions to real world problems. This has shown that the inclination and capability exist within the region already; it now remains to be put into practice. This is not to say that all effort should be 'relevance driven', for without the existence of a strong theoretical framework there is nothing to apply and little insight with which to solve the problems. Rather, it is the contention of the authors that the positive feedback which can be gained from the development of theory, at least in part in an applied context, will challenge the frontiers of present knowledge and in so doing open new avenues for research funding and support. A recurrent theme in the existing international literature (which is also emerging in the context of erosion and land degradation in local research), is that of humans as agents of geomorphological change, needs to be brought to the fore again strongly within the regional context.

A serious constraint affecting much of the southern African geomorphological literature is the questions surrounding long term data series; the general difficulties with regard to which have been succinctly reviewed by Harrison (1999). Broadly, the longer the time frame for a data series, the more reliable the prognostication based thereon *but,* the more costly such data are to obtain, both in real terms and in terms of the obstacles confronting the researcher(s) in terms of lack of publication output. These two impediments result in the general duration of most quantitative southern African studies averaging less than five years, with many lasting as little as three. The consequence is that there is a general dearth of reliable field data which can be used in the validation of mathematical process-response models for the region, and the necessity for data from often vastly disparate studies to be 'cobbled' together in an attempt to extend the length of data trends.

A further challenge exists; although not evident from the data presented here, there is a perceptual, logistical and, to some extent still philosophical, impediment to collaborative research and multi-authored papers. A subjective perusal of the international conference abstracts *versus* those for regional conferences shows that while the norm for international research papers appears to be three co-authors, the norm for southern Africa still tends to be single authorship. This practice clearly has implications, not only in terms of research output, but also with respect to the scope and scale of the individual projects themselves. This trend may, however, change in the near future in response to funding initiatives driven by the South African National Research Foundation (NRF) which is emphasising collaborative research.

It is difficult to imply future trends in South African geomorphology without at least some reference to the training of geomorphologists. Although the most recent information on this dates from eight years ago (Garland, 1994), the training situation has not changed significantly over this period. At that point, no South African undergraduate degree included more than 35% of geomorphology in its total content, (as a consequence of the country-wide restructuring of higher education initiated in 2000, only one university has an optional undergraduate programme with 45% geomorphology content), and the average for degrees at all South African Universities was closer to 10%. This compared poorly with other natural science disciplines such as biology and geology, where undergraduate students typically spent around 60% or more of their time in their main disciplines. It is clear that specialist geomorphologists are not being produced at the undergraduate level, and this has certain implications for post-graduate study and research, as well as employment. In particular, those students embarking on Masters or Ph.D. research programmes must inevitably spend a considerable amount of time catching up with basic theory, principles and techniques before they can produce useful work. It also implies that a post-graduate research degree becomes a pre-requisite for almost any form of geomorphological employment.

It is argued that the challenges facing southern African geomorphology as a discipline are not in general terms vastly different from those identified in Europe and North

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America during the nineteen seventies and early eighties. It is concluded that, notwithstanding the value of abstract theoretical research, unless the problems within our discipline are acknowledged and addressed by a constructively aggressive approach with, where possible, some clearly defined applicability to real-world problems as suggested by Richards (1994), the work of physical geographers will increasingly be undertaken by non-geographers to the detriment of our discipline.

Table1: Changing trends in published Southern African Geomorphological research over time.

TIME PERIOD / Discipline	PRE 1966 %	1966 - 1975 %	1976 - 1985 %	1986 - 1995 %	1996 - 2000 %	PRE 1985 %	POST 1985 %
Applied Geomorphology	10	10	13	12	15	11	14
Tectonic & Macro-Geomorphology	22	12	10	4	4	15	4
Geomorphic Theory	6	4	5	3	5	5	4
Process Studies*	1	2	6	11	9	3	10
Hydro-Geomorphology	12	14	9	11	14	12	13
Erosion; Degradation	14	10	17	18	20	14	19
Coastal	7	11	8	10	5	9	8
Karst	1	6	3	2	1	3	2
Slopes	11	5	6	8	4	7	7
Weathering	2	2	3	5	3	2	4
Climatic Geomorphology	15	26	26	27	28	22	28

* The values cited for 'Process Studies' are a duplicate count, as the research papers deal with the respective sub-disciplines but are process based.

(Data for this table have been abstracted from some 1500 articles, primarily in SA Journal of Science; South African Geographical Journal; South African Journal of Geology; South African Geographer; Palaeoecology of Africa; Water SA.; Earth Surface Processes and Landforms, Geomorphology and Zeitschrift für Geomorphologie)

Table2: Representation of the sub-disipline of Geomorphology in percentages ad depicted by papers presented at SAAG and SSAG conferences between 1988 and 2000.

TIME PERIOD / Sub-Discipline	SAAG 1988	SAAG 1990	SAAG 1992	SAAG 1994	SAAG 1996	SAAG 1998	SAAG 2000	SAAG AVG '88 - '00	SSAG AVG '87 - '00	ICG AVG '85 - '00
Applied Geomorphology	0	5	5	7	6	11	11	6	9	14
Tectonic & Macro-Geomorphology	14	0	5	0	0	3	0	3	7	11
Geomorphic Theory	3	0	8	3	2	0	2	3	5	7
Process Studies*	5	4	6	10	8	9	8	7	5	12
Hydro-Geomorphology	17	25	18	17	17	21	18	19	9	15
Erosion; Degradation	20	35	45	27	13	13	20	25	23	7
Coastal	6	0	5	0	2	8	4	4	2	8
Karst	0	0	0	0	2	0	0	0	5	3
Slopes	11	10	5	17	17	11	7	11	14	7
Weathering	6	0	2	7	13	3	5	5	2	4
Climatic Geomorphology	25	25	7	23	27	32	33	25	23	20

* As with Table 1, the values cited for 'Process Studies' are a duplicate count, as the research papers deal with the respective sub-disciplines but are process based.

Table3: Trends in South African Geomorphologic ext

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(mean values in percent) Sub-discipline	International Geomorphology Conferences ICG '85 - '00	Mean of Six Commonly Used Geomorphology Texts [1] (Tertiary)	Journal Publications '60 - '00	National Conferences '88 - '00	Pre 1985 % in South Africa	Post 1985 % in South Africa
Applied Geomorphology	14	5	10	2	11	14
Tectonic & Macro-Geomorphology	11	17	11	7	15	4
Geomorphic Theory	7	7	4	4	5	4
Process Studies*	12	15	5	6	3	10
Hydro-Geomorphology	15	15	15	21	12	13
Erosion; Degradation	7	7	14	30	14	19
Coastal	8	11	8	3	9	8
Karst	3	3	2	1	3	2
Slopes	7	7	5	9	7	7
Weathering	4	5	2	2	2	4
Climatic Geomorphology	20	21	23	20	22	28

*As with Table 1, the values cited for process studies are a duplicate count, as the research papers deal with the respective sub-disciplines but are process based.

1 Pitty (1971); Chorley et al.,(1984); White et al.,(1984); Summerfield (1991); Selby (1992); and Ahnert (1996).

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APPENDIX 2

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Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **27**, 1137–1142 (2002)
Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/esp.402

THE EFFECT OF ROCK MOISTURE ON SCHMIDT HAMMER REBOUND: TESTS ON ROCK SAMPLES FROM MARION ISLAND AND SOUTH AFRICA

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Received 2 October 2001; Revised 4 April 2002; Accepted 29 April 2002

ABSTRACT

In an assessment of the influence of internal rock moisture content on Schmidt hammer readings, rebound (R) values are found to decrease with increasing moisture content. For samples of basalt, sandstone and dolerite the maximum decrease in R-values is found between oven dry values and saturated rock rebound values, the magnitude of which varies from 2 to 10 points on the R-scale. A quartzite block has the greatest decline of 6 points at 60 per cent saturation. For certain rock types under differing site-to-site field moisture conditions the moisture effect can be a significant factor in the interpretation of the relative state of weathering from rebound values. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS: Schmidt hammer; rock moisture content; weathering

INTRODUCTION

The Schmidt hammer (sclerometer) was originally developed to measure the surface hardness of concrete and is commonly used in geomorphological investigations to determine rock hardness in the field (McCarroll, 1991). Rock hardness, as reflected by hammer rebound (R) values, is a function of the inherent intact rock strength. Weathering generally decreases rock strength and this is reflected in the measured surface R-values. Geomorphic applications of the tool have included the assessment of intact strength in classifying overall rock mass strength on bedrock-dominated slopes (Selby, 1980), measurement of the state of weathering in relative-age dating of inorganic deposits (e.g. Matthews and Shakesby, 1984; McCarroll, 1989a, b; Boelhouwers *et al.*, 1999; Sumner *et al.*, in press) and in spatial comparisons of the degree of weathering (e.g. Ballantyne *et al.*, 1990; Nyberg, 1991; Sjöberg and Broadbent, 1991; Hall, 1993; Meiklejohn, 1994).

The limiting effect of lithological and surface characteristics on the accuracy of the Schmidt hammer has been well documented (Day, 1980; Williams and Robinson, 1983; McCarroll, 1987, 1989a, b, 1991). These assessments, however, do not consider any potential effect of internal rock moisture on R-values. McCarroll (1990) commented that internal moisture content could explain the spatial variations between snowpatch and snow-free site rebound values found by Ballantyne *et al.* (1990). Ballantyne *et al.* (1990) surmised that 'the presence of imcompressible (sic) water in subsurface voids might actually *increase* the R-values' (p. 473, their emphasis) and identify the influence of internal moisture content as a topic for further study. Later, Hall (1993) used the tool under similar conditions to those described by Ballantyne *et al.* and compared rebound values with cone indenter penetration and weathering rind thickness and still found it useful. In an unrelated study, Broch (1979) found that point load strength values for a variety of rock types varied with moisture content: a decrease when saturated while a few fine-grained rocks increased in strength. Similarly, using ultrasonics on laboratory samples, Hall (1988) found a decrease in rock strength of quartz-micaschist and sandstone with increasing moisture content. These findings suggest that rock moisture content may influence

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hammer rebound values which would in turn affect field results where moisture varies from site to site. As yet, however, no assessment of the effect of rock moisture on Schmidt hammer readings has been undertaken.

METHODOLOGY

Rebound testing of bedrock surfaces poses fewer problems than the testing of loose blocks, which can move under impact or are too small to return hammer impact energy. However, the use of blocks is necessary to enable the determination of actual rock moisture content and rock moisture content fluctuation. These measurements are achieved by ascertaining the difference in rock mass from the dry weight, as typically measured for soils, and indicated as percentage dry rock mass or the percentage of total water saturation.

When measuring rebound in the field, Sjöberg and Broadbent (1991) note that intact blocks or boulders should be sufficiently large and placed in a stable position such that hammer impact energy is returned to the hammer. However, no specific minimum rock mass is suggested in the study, or in other investigations using the hammer. This is not surprising since usually the largest blocks are used at a site and there are practical and instrumental difficulties in weighing such blocks. Operators of the Schmidt hammer in the field do, nonetheless, realize by the sound of the hammer on impact, block movement and inconsistent results if the size (mass) of a specific block is too small for accurate results. Experience of the authors with the hammer has shown that block size should exceed approximately 25 kg for accurate and consistent rebound. This presented problems in the initial stages of the study as, after overcoming the challenge of transportation from field sites to the laboratory, the block must be oven dried in a suitably large desiccation oven and weighed on a balance capable of measuring moisture content fluctuations.

Initial testing for a possible effect of moisture content on R-values was conducted on sub-Antarctic Marion Island (46°54'S, 37° 45'E) where a (type L) Schmidt hammer was used for relative-age dating glacial and post-glacial surfaces and deposits (Sumner *et al.*, in press). Although data collection on the island was limited due to access only to a 0·1 kg resolution (100 kg) gymnasium beam balance, the general trend was worth noting. A 35·2 kg basalt boulder (grey lava) from Transvaal Cove was dried for three months in the Meteorological Station drying room at approximately 35–40 °C. Rebound values were taken on the upper surface corresponding roughly to the centre of the a–b plane. At this point the surface was ground smooth with the hammer carborundum over an area measuring approximately 0·1 × 0·1 m to remove the outer weathering rind and any roughness inconsistencies which could influence results. Surface preparation was undertaken only at the beginning of the test. Fifteen rebound readings at different points on this area were taken on the dry boulder following the methodology utilized by Boelhouwers *et al.* (1999) and Sumner *et al.* (in press) where the five greatest outliers are discarded and the measurement mean R-value calculated from the remaining ten values. Hammer values on the prepared surface were sufficiently reproducible and the risk of surface deterioration through additional impacts was not warranted. The rock was then submerged under water and removed every 12 hours, with 15 readings taken as above on the dried surface, extending with larger time intervals to a total of 185 hours (Figure 1) at which stage readings had stabilized. Thereafter the boulder was air dried and rebound readings taken during the drying cycle. Total moisture uptake at saturation was approximately 0·3 kg (0·9 per cent of dry mass) (Table I). Determination of moisture content between the extremes of dryness and saturation was not possible due to the resolution of the balance. As a surrogate for saturation rate, three smaller clasts which could be weighed on a smaller, higher resolution balance were later monitored for moisture uptake and the trend shown for general comparison on Figure 1.

R-values after moisture uptake were found to differ from the dry value. Values decrease from 64 when dry to a value of 60 near saturation (approximately 90–95 per cent saturation as estimated from the smaller clasts); a decrease of 4 on the R-scale (Figure 1, Table I). This represents a maximum decrease of 5 per cent in rebound values. R-values then increase from saturation and show a trend towards the original dry values during the drying cycle, although the boulder was not heat-dried again. With moisture shown to have a measurable effect on hammer rebound, additional rocks were tested in South Africa using a modified procedure.

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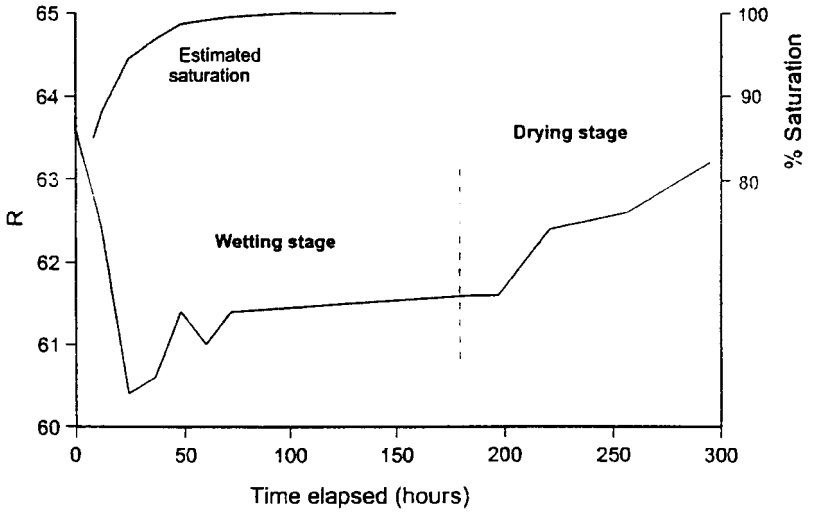

Figure 1. Trend in Schmidt hammer rebound values (R, mean of $n = 15$ at each time interval) for a 35 kg Marion Island basalt boulder during wetting and drying stages. Estimated saturation (percentage of maximum moisture uptake) obtained from monitoring moisture uptake of smaller clasts (see text)

Table I. Schmidt hammer (R) readings for different rock types from Marion Island (sub-Antarctic) and South Africa showing decrease in measured R-values due to internal rock moisture

Rock type	Dry mass (kg)	Rock sat. (% dry)	Initial dry (R)	Final dry (R)	Min. R (% sat.)	Max. decrease (R-units)	Max. decrease (%)
Marion Island basalt	35·2	0·9	64	not taken	60 (est. 90–95)	4	5·0
Drakensberg basalt	43·10	0·23	62	63	58 (100)	5	7·3
Quartzite	27·78	0·72	62	60	57 (60)	6	7·1
Dolerite	36·46	0·24	64	63	62 (50, 100)	2	3·1
Clarens sandstone	34·00	3·41	55	55	45 (100)	10	17·6
Elliot sandstone	33·92	1·59	54	discarded	45 (100)	9	17·7

Rock sat., moisture uptake (kg) after extended immersion in water as a percentage of rock dry mass (kg). Initial dry and final dry, mean R-values ($n = 15$, see text) at the beginning and end of the tests [A]. Min. R, lowest R-values ($n = 15$, see text) measured [B] (percentage saturation at min. R). Max. R decrease, (maximum value for [A]) − [B] = [C] Max per cent decrease: [C]/[B] as a percentage.

Rock types originating from South Africa were tested using a 60 kg, 0·02 kg resolution balance. This permitted the measurement of actual moisture content of the tested blocks at the time of hammer readings. Suitably large (>25 kg) blocks or boulders of Drakensberg basalt, Karoo dolerite, Magaliesberg Series quartzite and Clarens and Elliot Formation sandstone were dried in a desiccation oven at 60 °C for 1 week, the surface prepared and 15 rebound values taken as for the Marion Island boulder. Thereafter, the rocks were saturated by submerging under water for 1 week and then progressively air dried with readings taken from complete saturation to 20–30 per cent of saturation (Figure 2). Where possible, readings were taken at regular moisture increments. The relatively small moisture uptake of the Drakensberg basalt and dolerite made measurements at these increments difficult and mid-point rebound readings between saturation and dry were taken. Some rocks required fan drying at room temperature or were placed briefly in a fan desiccation oven at 30 °C to assist drying and allowed to stabilize for 2 hours at room temperature before readings were taken. A final set of oven dry readings (1 week at 60 °C) were taken so as to assess the effect of repeated surface hammering by comparing hammer results with the dry readings at the beginning of the test (Table I).

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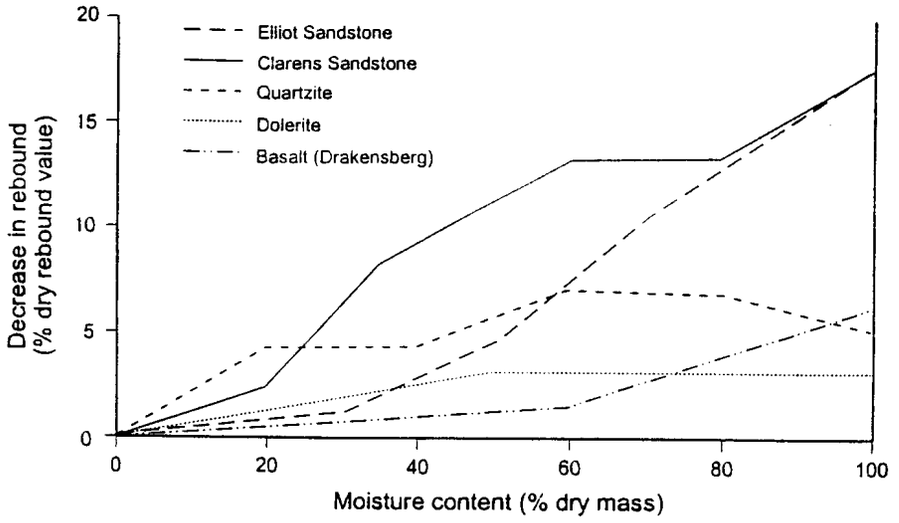

Figure 2. Decrease in rebound values for different rock types at different rock moisture contents shown as a percentage of the initial dry reading or the mean of the initial and final dry rebound measurements where available

RESULTS AND DISCUSSION

As with the results for Marion Island basalt, all five South African samples show a decrease in R-units with increasing moisture content (Table I). Whilst the maximum decrease of only 2 units on the R-scale for the dolerite is small, and only 1 R-unit below the initial dry readings, the other rocks show a decrease in the range of 5 to 10 R-units from dry to saturation. The two sandstones have the greatest moisture uptake (by dry mass) and show the maximum decrease in R-values almost 18 per cent below dry rebound values. Although Day (1980) suggests a possible increase in rebound if a site is used repeatedly, initial and final dry R-values differ only marginally. The maximum difference between initial and final dry readings was 2 R-units for the quartzite whilst a small increase of 1 unit was found for the Drakensberg basalt (Table I). Repeated testing would ultimately affect measured values and the procedure should, therefore, be minimized where possible and the samples not subjected to repeated oven drying, saturation and unnecessary hammer impacts. For example, a set of readings after the final oven drying at the end of the testing was not obtained for the Elliot sandstone which showed crack extension through the centre of the block and some surface crumbling at the impact site. However, the trend for the sandstone before final placement in the oven showed increasing R-values with the 30 per cent saturation rebound reading approaching the initial dry value (Figure 2) and the measurements seemed valid to that point.

The relationship between moisture content and R-values is not linear (Figure 2). The magnitude of the influence of rock moisture varies for rock type, possibly related to physical properties such as porosity and permeability as reflected in the moisture uptake of the sandstones. For the quartzite block, the maximum decrease in measured R-values is at 60 per cent saturation while the range within the 20–80 per cent saturation intervals is 2 R-units. For practical purposes the effects on the basalt, dolerite and quartzite are small and may not have a significant effect on relative rebound values between sites in the field. More significant are the ranges in R-values amongst the sandstone samples. For example, the Clarens sandstone has an R-value difference of 6 units between 20 and 80 per cent saturation while the two sandstones show a total decrease in rebound values between dry and saturated exceeding 17 per cent (9 and 10 units respectively). Of the samples tested the greatest variation in R-values over any 20 per cent moisture range, which is probably more representative of field moisture ranges, is 6 per cent for the Elliot sandstone between 60 and 80 per cent of full saturation.

Overall, rock moisture content, which has been found to affect rock strength (Broch, 1979; Hall, 1988), shows a measurable influence on Schmidt hammer rebound values and could therefore influence field results.

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The magnitude of the moisture effect varies according to rock type and may also be a function of rock properties. Where differences in moisture from site to site in the field are small, or where rock strength is mostly unaffected by moisture content, the results may not be significantly influenced. For example, although basalt moisture content typically ranges from 35 to 75 per cent on Marion Island (Boelhouwers *et al.*, 2001) the magnitude of site rebound readings in the relative-age dating of surfaces varied between 50 and 64 (Sumner *et al.*, in press). A maximum difference of 4 R-units between dry and near saturation was found. The influence of rock moisture content on rebound values is therefore small whilst the trend in weathering and hence relative age of rock surfaces was also confirmed with other techniques, such as weathering rind thickness and angularity.

Sandstones, however, show a greater variability in rebound values over smaller rock moisture content fluctuations and field readings may be considerably affected for this rock type and for other rock types as yet not tested. Previous studies utilizing the Schmidt hammer in the field may have been to a greater or lesser extent affected by the rock moisture content, particularly where rock surface exposure to moisture, insolation or wind desiccation varies between tested sites. In the absence of data which quantify the moisture effect for a rock type, field studies can test for rock moisture content variations between sites by subsampling smaller clasts, or more rapidly obtain moisture data with an infrared optical moisture meter (Matsukura and Takahashi, 1999). Schmidt hammer readings from locations where rock moisture content exceeds 20 per cent variation between sites should be treated with caution, although the effect may still not influence results. Other rock types as yet untested may show a greater variation in hammer readings over a smaller moisture range. Alternatively, blocks may be allowed to equilibrate after, for example, extraction from beneath snow (e.g. Ballantyne *et al.*, 1990). However, the physical effort required in moving a sample set of sufficiently large blocks (those weighing less than 25 kg appear to give unreliable rebound values) would be prohibitive and the time period required for equilibration unknown. Ideally, the effect of rock moisture should be quantified for a specific rock type before R-values are acceptable and the collection of Schmidt hammer data in combination with other techniques or measurements (e.g. Hall, 1993) is recommended.

CONCLUSION

For all six rock types tested, moisture content decreases Schmidt hammer rebound values. The magnitude of the effect varies between rock types and is most pronounced in the sandstones which have the greatest moisture uptake. Variations in R-values in the field due to site-to-site differences in moisture content can therefore affect Schmidt hammer results depending on rock type and the magnitude of the differences in moisture content. Where the hammer is used for comparisons of the state of weathering, the internal moisture needs to be taken into consideration if the site moisture environments differ, such as on different slope aspects, across a ridge or where late-lying snow is present. Ideally, the influence should be tested for rock types where the Schmidt hammer is used. Alternatively, measurement with the hammer should be undertaken in combination with other techniques suitable to the objective of the study.

ACKNOWLEDGEMENTS

Research on Marion Island was conducted under the auspices of the South African National Antarctic Programme (SANAP). Suggestions by Jan Boelhouwers and comments from Ian Meiklejohn during the course of the research are appreciated. Comments by two referees considerably improved the original text.

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