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The palaeoenvironmental significance of southern African blockfields and blockstreams

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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.

1 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 Alexandre (1962) attention has focused on both potential indicators for glaciation and periglaciation associated with the Last Glacial. These have been 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 focused.

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.

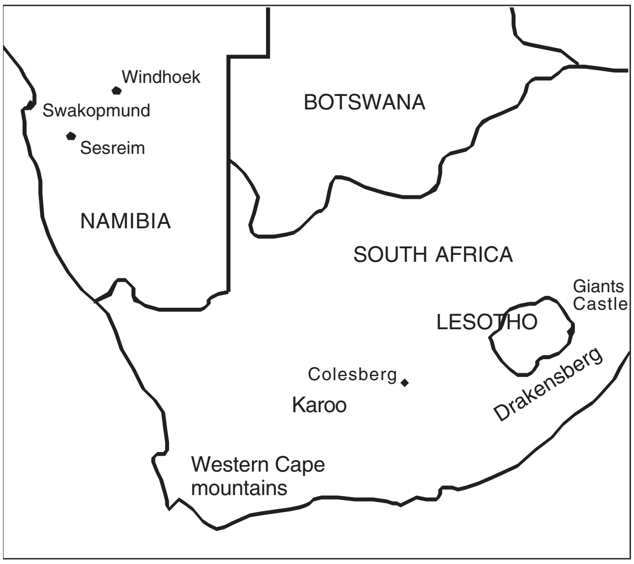

Figure 1. General locations in southern Africa.

2 LOCATIONS AND CHARACTERISTICS

2.1 *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 2800 m up to 3482 m, the highest point in southern Africa. Underlying lithology is a sequence of flood basalts with layers of varying mineral compositions and amygdaloidal content. These attain a total thickness of up to 1500 m and support alpine heath vegetation. Precipitation at the highest altitudes could exceed 1500 mm p.a. falling mainly as summer thunderstorms with occasional winter snow. Mean annual air temperature (MAAT) at 3000 m is estimated at 5–7°C. Soil frost can occur throughout the year typically to less than 0.2 m depth with possible frost penetration to 0.4 m within coarse materials (Grab 1997). The region has been called a marginal or sub-periglacial environment (Boelhouwers 1991).

In situ weathering on slopes and valley floors produces coarse granular loamy weathering mantles up to 2.5 m 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 1.0 m during the Late Pleistocene (Sumner, in prep.), would result in the concentration of blocks at the surface. This explains the ubiquitous near-surface (0.5–1.0 m) block concentration on slopes at altitudes above 3000 m a.s.l., 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 1.1 km long valley floor openwork accumulation comprising on average 0.6 m (a-axis) subrounded blocks. These exhibit 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. Cold 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 has been removed.

2.2 *Western Cape*

The Western Cape Mountains range between 1600 and 2200 m 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 1600 m a.s.l. 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 (2249 m), the highest summit of the Western Cape mountains. Surficial diurnal frost characterises the summit areas above 1900 m manifesting itself in micro-patterned ground no deeper than 3 cm.

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 blockstreams 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 3.0 m 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 1.5 m 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 (e.g. 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 resulted in an increased 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 throughout the world. Vertical sorting and weathering atterns 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 (e.g. 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 3 cm 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 BP) (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 1.5 m 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 7–8°C which corresponds well to other proxy data for the region (Talma and Vogel 1992).

2.3 *Karoo*

The semi-arid Karoo occupies most of the interior of South Africa (Figure 1) and is characterised 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 (1212 m 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 1.0 m 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 <1 mm), presumably aeolian in origin, may be present between blocks.

The 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 wildfires 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. Similar characteristics may be found to a greater or lesser extent however 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 active at present.

2.4 *Namibia*

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 (1728 m 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 20 mm, increasing to 370 mm 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 accumulations 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 1–2 m 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 actively forming under current desert conditions. Although further detail is 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.

3 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. Comparing the forms across the sub-continent however highlights the 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 (e.g. 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.

Notwithstanding difficulties in interpreting weathering modes and products, both the Western Cape and the highlands of Lesotho show a phase of increased

Table 1. Characteristics and palaeoenvironmental interpretation of blockstreams and 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 1500 mm est. Triassic-Jurassic basalts. ∼3000–3482 m a.s.l. Soil frost typically <0.2 m in depth.	*Autochthonous:* Rounded blocks, pitted surfaces, thin weathering rinds. Coarse granular loam matrix where present	*In situ* chemical weathering of bedrock. Upfreezing of rounded corestones and/or washing out of matrix.	Deep (Tertiary?) chemical weathering. Late Pleistocene deep seasonal freeze. Limited snow cover, no Late Pleistocene glaciation.
		Allochthonous: Lag-type valley floor block-streams. Subrounded, pitted blocks. Thin weathering rinds. Matrix removed by suffosion	Mechanical weathering of valley-side scarps. Upfreezing of corestones Solifluction and frost creep.	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 quarzite ∼1600–2249 m MAP 575 mm est. Soil frost to 0.03 m	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 1.5 m. 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 380 mm	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°) winter 12°C (12°) 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. 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.

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 when 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 exists 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 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 must be treated with caution.

4 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 environments. 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 contem porary 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 (e.g. 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.

REFERENCES

Alexandre, J. 1962. Phenomenes periglaciaires dans le Basutoland et le Drakensberg du Natal. *Builetin Periglac* 11: 11–13.

Benedict, J.B. 1976. Frost creep and gelifluction features: a review. *Quaternary Research* 6: 55–76.

Boelhouwers, J.C. 1991. Present-day periglacial activity in the Natal Drakensberg: a short review. *Permafrost and Periglacial Processes* 2: 5–12.

Boelhouwers, J.C. 1996. The present-day frost action environment and its geomorphological significance in the Western Cape Mountains, South Africa. Belleville South Africa: University of the Western Cape, School of Environmental Sciences, Occasional Publication Series no. 2.

Boelhouwers, J.C. 1999a. Block deposits in southern Africa and their significance to periglacial autochthonous blockfield development. *Polar Geography* 23: 12–22.

Boelhouwers, J.C. 1999b. Relict periglacial slope deposits in the Hex River Mountains, South Africa: observations and palaeoenvironmental implications. *Geomorphology* 30: 245–258.

Boelhouwers, J.C., Duiker, J.M.C. & van Duffelen, E.A. 1998. Spatial, morphological and sedimentological aspects of recent debris flow activity in the Du Toitskloof Valley, Western Cape mountains. *South Africa Journal of Geology* 101: 73–89.

Boelhouwers, J.C., Holness, S., Meiklejohn, K.I. & Sumner, P.D. 1999. A blockstream in the vicinity of Sani Pass, Lesotho highlands, and its palaeoenvironmental implications. In Grab, S., Boelhouwers, J., Hall, K.J., Meiklejohn, K.I. & Sumner, P.D. (eds), *Quaternary Periglacial Phenomena in the Sani Pass Area, Southern Africa*, Field Guide to the INQUA XV Congress, Durban.

Boelhouwers, J.C. & Meiklejohn, K.I. 2002. Quaternary periglacial and glacial geomorphology of southern Africa: review and synthesis, *South African Journal of Science* 98: 47–55.

Caine, N. 1968. *The Blockfields of Northeastern Tasmania*. Canberra: Australian National University, Department of Geography, Publication G/6.

Caine, N. & Jennings, J.N. 1968. Some blockstreams of the Toolong Range, Kosciusko State Park, New South Wales. *Journal and Proceedings, Royal Society of New South Wales* 101: 93–103.

Caine, N. 1983. The mountains of Northeastern Tasmania. Rotterdam: Balkems, 200p.

Grab, S. 1997. Thermal regime for a thufa apex and its adjoining depression, Mashai Valley, Lesotho. *Permafrost and Periglacial Processes* 8: 211–217.

Grab, S. 2000. Periglacial phenomena. In Partridge T.C. & Maud R.R. (eds), *The Cenozoic of Southern Africa.* Cape Town: Oxford, 207–216.

Friend, D.D., Phillips, F.M., Campbell, S.W., Liu, T. & Sharma, P. 2000. Evolution of desert colluvial boulder slopes. *Geomorphology* 36: 19–45.

Partridge, T.C. & Maud, R.R. 1987. Geomorphic evolution of southern Africa since the Mesozoic. *South African Journal of Geology* 90: 179–208.

Rea, B.R., Whalley, W.B., Rainey, M.M. & Gordon, J.E. 1996. Blockfields, old or new? Evidence and implications from some plateaus in northern Norway. *Geomorphology* 15: 109–121.

Talma, A.S. & Vogel, J.C. 1992. Late Quaternary paleotemperatures derived from a spleothem from the Cango Caves, Cape Province, South Africa. *Quaternary Research* 37: 203–213.

Tyurin, A.I. 1983. Classification of rock streams. *Permafrost: Fourth International Conference Proceedings*. Washington DC: National Academy Press, 1283–1285.

Ward, J.D., Seely, M.K. & Lancaster, N. 1983. On the antiquity of the Namib. *South African Journal of Science* 79: 175–183.

White, S.E. 1976. Rock glaciers and block fields: Review and new data. *Quaternary Research* 6: 77–97.

Whitney, J.W. & Harrington, C.D. 1993. Relict colluvial boulder deposits as palaeoenvironmental indicators in the Yucca Mountain region, southern Nevada. *Geological Society of America Bulletin* 105: 108–1018.

Weinert, H.H. 1961. Climate and weathered Karoo dolerites. *Nature* 4786: 32–39.