Quaternary periglacial and glacial geomorphology of southern Africa: review and synthesis

J.C. Boelhouwers[a*] **and K.I. Meiklejohn**[b]

The literature on southern African Quaternary periglacial and glacial studies is qualitative in nature with an apparent lack of scientific rigour. Landforms attributed to being of periglacial and glacial origin exist through a broad belt of high relief from the Western Cape mountains along the Great Escarpment to the Lesotho highlands. Present-day frost action is limited to the surficial action of needle-ice and segregation ice resulting from diurnal to mild seasonal freeze–thaw cycles. Environmental controls on current frost action are still poorly understood for the Lesotho highlands, where frost-induced processes are an important factor in accelerating land degradation. Relict periglacial landforms are most reliably identified in the form of large patterned ground, widespread solifluction mantles and blockstreams. These observations are supported by adjunct information, which together indicate somewhat drier conditions than present. Erosional forms, such as nivation hollows, cirques, and cryoplanation terraces, lack positive evidence and imply wetter conditions than at present. Interpretations suggesting rock glaciers, glacial cirques and former ice wedges at low relative altitudes are highly anomalous with respect to the other periglacial records and proxy data for the region. The limitations of the current research literature suggest that future emphasis should be directed towards sedimentary records by means of clay mineral, soil micro-structural and chemical analysis and dating to improve the reliability and accuracy of the interpretations and their temporal framework.

Introduction

The periglacial and glacial record of southern African mountains has been investigated for over 50 years, starting with a report on needle-ice activity in the Drakensberg by Carl Troll.[1] Since then, interest in periglacial research has grown apace.[2–4] Most work has focused on the identification and use of relict periglacial landforms as a basis for palaeoenvironmental reconstruction of the high mountain environments of southern Africa.[2,3,5,6] At first, such studies related primarily to the Natal Drakensberg and Lesotho highlands,[7–10] although Linton[11] also recognized what he termed 'niveo-gelifluction deposits' in the Western Cape mountains that extended down to the present sea level. Subsequently, relict periglacial and glacial landforms were reported for the Eastern Cape Drakensberg and Amatola Mountains.[12–14] Thus, geomorphological investigations have concentrated on a broad belt of high relief terrain from the southwestern Cape to the Lesotho highlands (Fig. 1). In addition to the identification and environmental interpretation of relict periglacial landforms, attention has been directed to the role of frost weathering in Quaternary debris production and potential glaciation during the Pleistocene. Recent fieldwork has characterized in greater detail the present-day frost processes and environmental controls in the Western Cape mountains and Lesotho highlands.[2,3,6,15–26]

Southern African periglacial studies have been subject to frequent review in the past.[2–7,10,11,27–34] This is largely a reflection of the degree of a perceived lack of rigour in methods used and the uncritical adoption of high-latitude, northern hemisphere concepts,[5,30,34,35] the perceived lack of significance of periglacial studies in southern Africa,[36,37] the complexities of the field evidence,[35,38] and the need for a regional assessment of available data records.[3,28,29] This review aims to assess and synthesize the current state of understanding of the southern African periglacial and glacial record, and to highlight foci for further attention. Emphasis is placed on research conducted in two regions, namely the mountains of the High Drakensberg and Lesotho (included in discussions on this region are the somewhat separate Eastern Cape mountains comprising the Amatolas), and the Western Cape mountains. While literature critical to the main focus of the debates is referred to, it has not been possible to include all material pertaining to glacial and periglacial research in southern Africa; a comprehensive bibliography on the topic has been published.[39]

Present-day frost action and frost environments

Located at relatively low latitudes in the southern hemisphere, present-day southern African frost activity is restricted to high altitude sites (Fig. 1). The two areas where frost action has been studied in most detail are the High Drakensberg and Lesotho mountains, and the Western Cape mountains. These areas have contrasting geological and climatic settings relevant to the assessment of the environmental controls on frost processes. Each is here outlined.

Drakensberg and Lesotho highlands

The Eastern Cape, High Drakensberg, Maluti and Lesotho mountains are the highest regions in southern Africa, with summits over 3000 m a.s.l., rising to 3482 m a.s.l. at the highest point (29°30′S, 29°30′E). These high mountains comprise horizontal sequences of plateau basalts that attain a total thickness of over 1500 m. The basalts weather to a loamy regolith with varying clast abundance, which supports an alpine vegetation of grass and heath communities. Precipitation is strongly seasonal with more than 80% of the mean annual total falling in the summer months between October and March.[40–43] Snowfalls are seen to occur two to eight times a year on average,[42,44] but this may be an underestimate as light, localized snowfalls of short duration have been observed even in summer (pers. obs.). Snow can remain on the ground in the High Drakensberg and Lesotho for several months during winter.[42]

The low latitude, high insolation, and clear skies promote strong diurnal heating and large diurnal temperature ranges leading to diurnal frost cycles in winter.[2,15,21] Diurnal, and sometimes more prolonged, freezing of the ground is a normal occurrence, but restricted to shaded sites above 3000 m.[19,21,42,45,46] No direct evidence of modern permafrost has been recorded.[22,44,47–51]

[a]Department of Earth Sciences, University of the Western Cape, Private Bag X17, Bellville, 7535 South Africa. Present address: Physical Geography, Department of Earth Sciences, Uppsala University, Villavägen 16, S 752 36 Uppsala, Sweden.
[b]Department of Geography and Geoinformatics, University of Pretoria, Pretoria, 0002 South Africa.
*Author for correspondence. E-mail: jan.boelhouwers@natgeog.uu.se

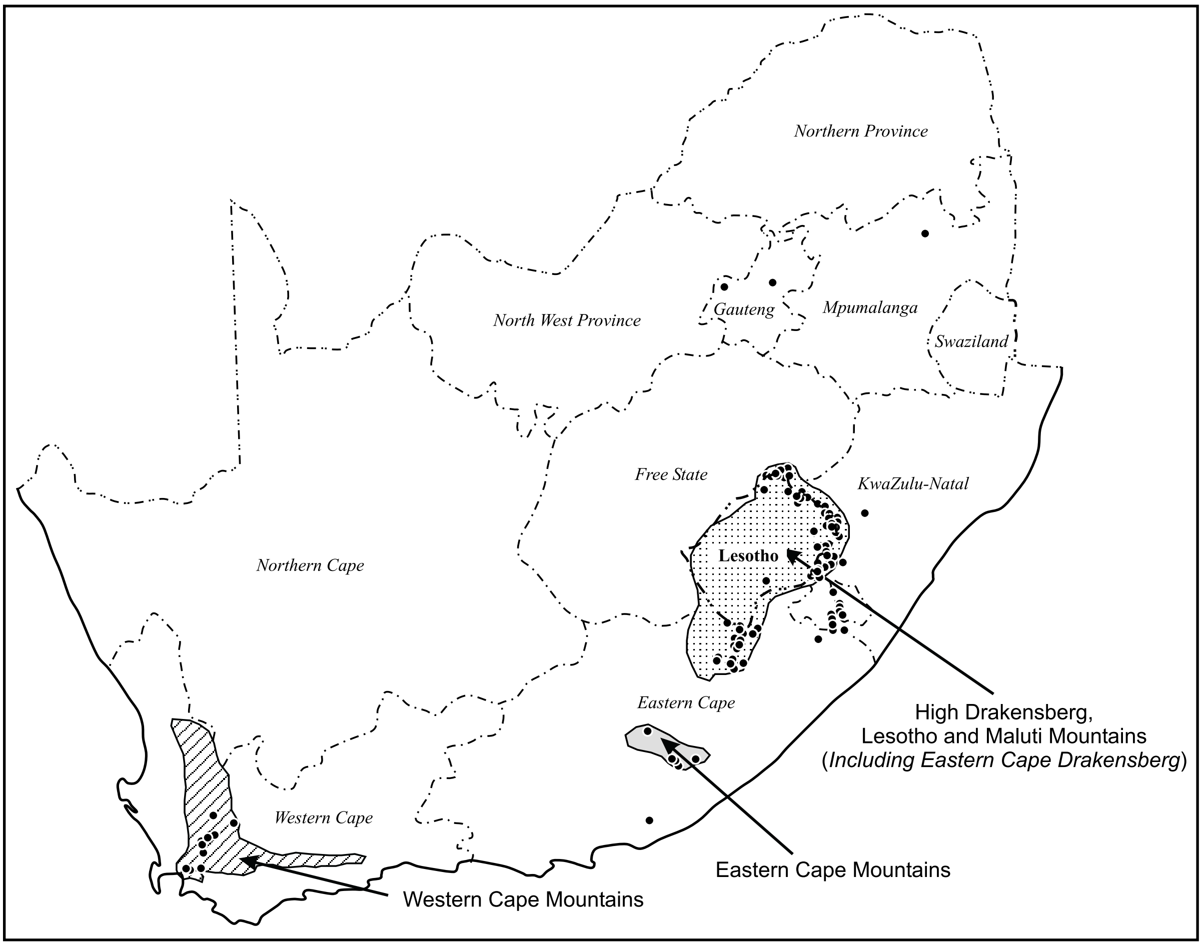

Fig. 1. Location of the high altitude terrain in southern Africa and sites with reported periglacial and/or glacial landforms or processes.[4] (No distinction is made between active and/or relict landforms.) Data processed in ARC View from de Villiers.[4] Albers Equal Area Projection; Cape Datum; central meridian: 24°; standard parallels: –18° and –32°.

In the Eastern Cape, High Drakensberg, Maluti and Lesotho mountains microforms of sorted and non-sorted patterned ground have been observed.[2–4,6,15,26,42,46,49–51] However, spatial information is limited due to the inaccessibility of the high altitude regions, so that the exact distribution of cryogenic activity is likely to be more widespread. The lower limit of present-day frost activity shows a decrease in altitude with increase in latitude,[46] but this distribution may be influenced by lithology and topography in addition to climate.[4,6,52]

Current cryogenic activity is dominated by needle-ice and the formation of sorted and non-sorted patterns, resulting from diurnal and seasonal freezing of the ground (Table 1). Turf-banked steps and small stone-banked lobes resulting from solifluction are also evidence for contemporary periglacial activity.[4,29,47]

Much of the literature regarding current periglacial activity is limited to descriptive inventories of features, their dimensions and qualitative observations; few process studies have been conducted,[1,2,16,19,22,25,53] and where present, they are isolated and cannot be used for general descriptions of the study area. Extreme caution needs to be exercised in the High Drakensberg and Lesotho mountains, where disturbance of study sites by grazing cattle and sheep sometimes prevents adequate interpretation of field results of movement rates (pers. obs.). Furthermore, during summer, when insolation is high and thunderstorms are regular,[40,44] the activity of other geomorphic processes (such as wash and fluvial action) should be considered before assigning the formation of landforms and features to periglacial activity (which mainly operates in winter); this has clearly not been done in most of the previous research.

Meteorological data are sparse because recording stations in the mountainous regions of southern Africa provide insufficient coverage. Climatic estimates from these data, for example from the use of four stations covering the whole of the extremely dissected Lesotho landscape for the interpolation of lapse rates,[21] must be used with caution. Only recently have ground and air temperature data been collected at the highest altitudes of the Drakensberg and Lesotho mountains.[2,22] Even then, while the data presented are all that are available, because of the remote location and the problem of theft of equipment, the methods used are inconsistent with accepted practice. These data may therefore not be relatable to proper meteorological records, and the record itself is not continuous.

Western Cape mountains

The Western Cape mountains form two distinct belts of folded strata parallel and adjacent to the west and south coast of the Western Cape Province. The coastal belt reaches altitudes up to about 1600 m a.s.l., while the interior belt attains a maximum altitude of 2249 m a.s.l. at Matroosberg (33°28′S, 19°40′E). The Palaeozoic quartzitic sandstones of the Table Mountain Group underlie over 90% of the Western Cape mountains, with the remaining lithologies consisting of thin bands of the Silurian Pakhuis tillite and Cederberg shale. The sandstone weathers to a sandy, acidic lithosol, which supports sclerophyllous shrub vegetation known as fynbos. The mountains are located in the winter rainfall zone of southern Africa. Annual rainfall totals vary from 900 mm to well over 2000 mm. High winter precipita-

Table 1. Published material on periglacial processes and landforms in the High Drakensberg and Lesotho mountains.[4] (Entries represent the best examples from references in the text and the table is, therefore, not a complete record of published material in the study area.)

Sedimentary forms/processes	
Blockfields and blockstreams	Linton (1969)[11]; Sparrow (1971[28], 1973[29]); Hastenrath and Wilkinson (1973)[101]; Hagedorn (1984)[80]; Marker (1992)[43]; Boelhouwers (1994)[50]; Grab (1996[92], 2000[6]); Lewis (1996)[48]; Grab *et al.* (1999)[26]; Sumner and Meiklejohn (2000)[95]
Cryoplanation	Hagedorn (1984)[80]; Grab *et al.* (1999)[26]
Cryoturbation	Lewis and Dardis (1985)[12]
Debris flows and fans	Hanvey *et al.* (1986)[13]; Hall (1994)[91]
Flarks	Backéus (1989)[41]
Gelifluction	Harper (1969)[10]; Linton (1969)[11]; Nicol (1973)[87]; Hagedorn (1984) [80]; Lewis and Dardis (1985)[12]; Dardis and Granger (1986)[31]; Lewis (1988[32], 1996[48]); Hanvey and Marker (1992)[42]; Boelhouwers (1994)[50]
Needle ice	Hastenrath (1972)[100]; Hastenrath and Wilkinson (1973)[101]; Lewis (1988[32], 1996[48]); Marker (1989)[64]; Boelhouwers (1991)[33]; Hanvey and Marker (1992)[42]; Grab (1996[19]; 1999[25]); Grab *et al.* (1999)[26]
Patterned ground (sorted)	Harper (1969)[10]; Hastenrath (1972)[100]; Hastenrath and Wilkinson (1973)[101]; Dardis and Granger (1986)[31]; Lewis (1988[32], 1996[48]); Boelhouwers (1991[33], 1994[50]); Hanvey and Marker (1992)[42]; Grab (1996[19]; 1996[92], 1997[23], 2000[6]); Grab *et al.* (1999)[26], Sumner (2000)[57]
Scree (cryoclastic)	Sparrow (1967)[9]; Marker (1986[14], 1992[43]); Lewis (1994)[99]
Segregation ice	Boelhouwers (1994)[50]; Grab (1996[19])
Solifluction	Sparrow (1967[9], 1971[28]); Harper (1969)[10]; Hastenrath (1972)[100]; Hastenrath and Wilkinson (1973)[101]; Nicol (1973)[87]; Marker (1989[64], 1992[43]); Meiklejohn (1992)[68]; Boelhouwers (1991[33], 1991[15], 1995[5]); Hanvey and Marker (1994)[63]; Grab (1997[2], 2000[6]); Grab *et al.* (1999)[26]
Terraces and terracettes	Harper (1969)[10]; Hastenrath (1972)[100]; Hastenrath and Wilkinson (1973)[101]; Dardis and Granger (1986)[31]; Marker (1989)[64]; Boelhouwers (1991[33], 1991[15] 1994[50]); Hanvey and Marker (1992)[42]
Thufur	Harper (1969)[10]; Marker and Whittington (1971)[60]; Sparrow (1971)[28]; Hastenrath (1972)[100]; Hastenrath and Wilkinson (1973)[101]; Lewis (1988[32], 1996[48]); Boelhouwers (1991)[33]; Hanvey and Marker (1992[42], 1994[63]); Grab (1994[16], 1997[2], 1997[23], 2000[6]); Grab *et al.* (1999)[26]
Erosional forms/processes	
Turf exfoliation	Hastenrath (1972)[100]; Boelhouwers (1991)[33]; Grab (1997)[2]
Nivation (processes and forms)	Sparrow (1967[8], 1967 [9], 1971[28], 1973[29]); Harper (1969)[10]; Marker and Whittington (1971)[60]; Hastenrath (1972) [100]; Hastenrath and Wilkinson (1973)[101]; Nicol (1973)[87]; Dyer and Marker (1979)[61]; Marker (1986[14], 1989[64], 1990[65], 1991[66]); Hall (1994)[91]; Hanvey and Marker (1994) [63]; Lewis (1994[99], 1996[48]); Grab *et al.* (1999)[26]
Valley asymmetry	Sparrow (1964[27], 1967[9]); Harper (1969)[10]; Marker (1989)[64]; Meiklejohn (1992[68], 1994[69]); Grab *et al.* (1999)[26]
Anomalous forms/processes	
Grèzes litées	Lewis and Dardis (1985)[12]
Ice wedges and casts	Harper (1969)[10]; Lewis and Dardis (1985)[12]; Lewis (1996[48])
Protalus rampart	Nicol (1973)[87]; Marker (1989 [64], 1990[65]); Lewis (1994[99], 1996[48])
Rockglacier	Lewis and Hanvey (1993)[72]; Lewis (1996)[48]
Other	
Freeze/thaw weathering and ice-shattering	Sparrow (1967[9], 1971[28]), Harper (1969)[10]; Marker and Whittington (1971)[60]; Fitzpatrick (1978)[47]; Hanvey and Marker (1992)[42]
Frost action and frozen ground	Sparrow (1967)[9]; Harper (1969)[10]; Hastenrath (1972)[100]; Hastenrath and Wilkinson (1973)[101]; Fitzpatrick (1978)[47]; Lewis and Dardis (1985)[12]; Dardis and Granger (1986)[31]; Hanvey *et al.* (1986)[13]; Marker (1986)[14]; Lewis (1988[32], 1996[48]); Boelhouwers (1991,[33] 1991,[15] 1994[50], 1995[5]); Hanvey and Marker (1992)[42]; Grab (1994[16], 1996[16], 1997[22], 1997[23], 1998[51], 1999 [25], 1999[53])
Permafrost	Fitzpatrick (1978)[47]; Boelhouwers (1994)[50]; Lewis (1996)[48]

tion results in snow cover on an average of 31days a year, but this is highly variable between years. Diurnal frost is limited to 10–20 days a year at altitudes over 1600 m.[20] Sänger[54] was the first to report the occurrence of needle-ice growth and micro-patterned ground at 2000 m a.s.l. at Matroosberg. In a regional assessment, however, Boelhouwers[17] noted a general absence of active soil frost features in the sandstone-derived sediment, which covers over 90% of the mountains. Process monitoring in these lithologies revealed sites to be stable at present with no creep or solifluction detected over a period of five years.[20] By contrast, isolated shale exposures near summits reveal active sorted micro-patterned ground and turf- and stone-banked steps.[17] Here, needle-ice-induced frost creep occurs in the upper 6 cm of the sediment, which is characteristic of diurnal frost environments.[20,24]

Discussion

Important environmental contrasts between the Western Cape mountains and Lesotho highlands result in distinct differences in present-day frost activity. Despite their somewhat lower latitude, the greater altitudes and regional extent of the Lesotho highlands result in more severe, and more frequent, frost cycles. This is further aided by contrasts in seasonality of precipitation. The generally clear skies in winter, limited snow cover and low soil moisture conditions aid nocturnal radiation losses, limit thermal insulation, reduce thermal conductivity, and thereby enhance the occurrence of soil surface frost in Lesotho. Here, the absence of soil moisture is the main limiting factor to more widespread and effective frost-induced soil disturbance and mass wasting. Grab[3] suggests that the availability of moisture results in most soil frost activity during autumn and spring. However, a systematic approach to process monitoring, supported by detailed micro-climatic monitoring and analysis of soil physical properties is still largely absent for this region. Understanding of the mechanisms and their environmental controls involved in current frost action in the High Drakensberg and Lesotho highlands is, thus, still limited.

In the Western Cape mountains frost is experienced only immediately after the passage of a cold front and the associated influx of cold maritime polar air. The associated precipitation ensures that soil moisture is not a factor limiting effective soil frost cycles. However, Boelhouwers[24] shows that in the sandstone-derived soils frost intensities are limited by the insulation provided by vegetation, the presence of snow and an efficient zero-curtain effect. By contrast, shale-derived loams are highly susceptible to frost. In these areas soil disturbance is effective enough to prohibit vegetation from establishing itself and soil frost features dominate the surface.

There is a contrast in the material properties of the mountain regions. The Western Cape mountains are largely blanketed by coarse-grained lithosols with a high clast content. Boelhouwers[24] reports on the (generally) non-frost-susceptible sediment in the summit regions under present-day conditions, but describes extensive relict solifluction mantles and allochthonous blockfields in these materials in the Hex River Mountains[55] and where shale-derived sediment is present.[17] The solifluction mantles at Matroosberg may point at the removal of fines from the debris mantles during the Holocene and/or regional facies variations in the sandstone strata. On the other hand, weathering of the Drakensberg basalt results in loam-rich soils, which are highly susceptible to frost. The basalt-derived regolith is well suited for slow mass wasting by frost and is an important contributing factor to the widespread occurrence of the, now relict, solifluction mantles (see below).

Given the limited frost activity, it is apparent that southern African mountains can be described as being only marginal with respect to active periglacial environments. In the Western Cape, pockets of diurnal soil frost activity occur at altitudes above 1600 m a.s.l, where frost-susceptible regolith is present. In these areas, soil frost processes dominate and control the surface morphology. In the Lesotho highlands and Drakensberg, the larger magnitude of frost-generated landforms points to a more severe, but as yet unquantified, frost environment. It is apparent that for a more complete evaluation of current periglacial activity in the escarpment and Lesotho regions of southern Africa, emphasis should be placed on more systematic surveying of morphology and relevant site parameters, supported by the collection of data relating to periglacial *processes* and accurate ground climate data. Improved understanding of the current environment is essential before the significance of relict features can be evaluated.

Understanding environmental controls on frost action in southern Africa not only provides an important datum for palaeoenvironmental interpretation of Quaternary periglacial landforms, but also has important applied aspects. Process studies on current soil frost activity can make important contributions to environmental management issues in the Lesotho highlands. Soil frost activity is an important soil disturbance factor in the high mountain catchments that are inhabited by a rural population dependent on grazing stock for their livelihood. In synergy with overgrazing and other biotic activity, frost action reduces the carrying capacity of the highlands for grazing animals. Frost action also contributes to stream bank erosion to increase sediment loads further in rivers.[53] Such factors may have significant, but as yet unquantified, effects on the high altitude regions of southern Africa,[56] especially that embracing the Lesotho highlands water diversion scheme (which aims to ensure water supply to millions of people in South Africa and Lesotho). A more comprehensive and systematic approach to land degradation issues in the Lesotho highlands, of which frost action is a contributing factor, is much needed to guarantee a sustainable livelihood for its impoverished population and for the management of the region's scarce water resources.

Impacts of global change also need to be considered. By approaching frost action dynamics as an integral part of regional development issues for southern African mountain communities, important new insights may be achieved in a far shorter time than has been possible to date.

Quaternary periglacial landforms and processes

Despite the marginal nature of current cryogenic activity, it is reasonable to consider that the climate was more severe during the colder periods of the Quaternary. Currently, few proxy data for Quaternary palaeoclimates exist in the higher altitudes of southern Africa. Consequently, a focus of geocryological research has been on the use of relict periglacial features as palaeoenvironmental indicators. However, interpretation of current research has resulted in contradictory evidence for Quaternary palaeoenvironments. For example, certain data suggest a moist periglacial environment, while others indicate an arid one; some data are even used to argue for the existence of marginal, niche, cirque or valley glaciation.

Drakensberg and Lesotho highlands

Evidence for a periglacial environment during colder phases of the Quaternary may be usefully separated into sedimentary or depositional forms, erosional features, and regionally anomalous forms. Sedimentary evidence for periglacial activity generally provides the most significant diagnostic criteria that will allow quantitative analysis and reliable interpretation. In addition, in the Lesotho highlands and Drakensberg such sedimentary forms have a wide distribution and include features that have been identified as patterned ground, solifluction lobes, gelifluction sheets and lobes, frost-shattered debris, and blockstreams and blockfields (Table 1). Erosional forms provide inconclusive evidence as the principle of equifinality generally applies. Invariably, erosional landform information results in disputed and unverifiable interpretations, such as is the case for cryoplanation terraces across structural benches, asymmetrical valleys and nival cirques (Table 1). Anomalous landforms that have been interpreted on inconclusive datasets, and have led to disputed interpretations, include ice-wedge casts, protalus ramparts and rock glaciers (Table 1).

The evidence for sedimentary landforms above 2900 m a.s.l. indicates that where sufficient regolith is present, large patterned ground forms with widths up to 2 m and vertical sorting down to over 80 cm exist on the interfluves.[49,57] The valley sides display evidence of slow mass flow and creep in the form of solifluction lobes and sheets, which in many cases mantle the entire valley.[6,26,58] Downslope concentration of blocks, derived from cliffs and weathering mantles, results in blockstreams up to 1.6 km long on gradients of less than 10°, displaying distinct fabrics and imbrication (Boelhouwers *et al.*, in prep.).[26] None of this evidence is diagnostic for permafrost and is interpreted as associated with deep seasonal frost.[26] The occurrence of these widespread valleyfills is considered to be indicative of limited and seasonal snow cover, which is substantiated by most of the published proxy data[59] concerning the Last Glacial.

By contrast, southerly valleys with concave backwalls are considered to indicate former periglacial conditions under enhanced snow cover and are referred to as 'nivation hollows' or 'cirques'.[43,60–66] While it has been proposed that the hollow forms are 'bog-cirques',[67] the absence of significant saprolite at the contact between sediments and bedrock largely discounts this argument.[26] Meiklejohn[68–71](in prep.), however, points out that the orientation of the hollows is structurally controlled. As with the widespread valley asymmetry observed in the highlands, the valley forms are most likely the result of longer slope evolution than that associated with the period of Pleistocene glacials, and are in fact not diagnostic of a periglacial origin.

From the distribution of fossil features in southern Africa, it is apparent that certain anomalies, or outliers, exist with regard to the interpretation of what have been referred to as relict periglacial landforms. This is particularly the case with several features identified by Linton[11] that appear to be misinterpreted.[4] In addition, the deposits interpreted as rock glaciers by Lewis and Hanvey[72] lack any diagnostic features of such forms and are most likely debris flow deposits (Shakesby, pers. comm.). Similarly, so-called ice-wedge casts[12] lack the diagnostics of such forms and occur alongside shear planes in neotectonically affected colluvium. In all these cases the interpretations suggest temperature and precipitation conditions in contrast to the sedimentary periglacial records found at higher altitudes and other proxy evidence from the region.

Western Cape

Cryoclastic debris production

The rock slopes in the Western Cape are typically strength equilibrium slopes with steep cliffs and thick, coarse debris mantles at their footslopes.[73] The origins of such coarse clastic materials near sea level at Cape Town were first attributed to frost shattering by Linton.[11] Butzer and Helgren[74] and Butzer[26] reiterated such a hypothesis, based on the angularity of spalls in a cave at sea level on the Cape south coast and were later supported by Lewis.[32]

Hall[34] cautioned against the use of clast angularity as evidence for frost weathering, a point already admitted to by Butzer and Helgren.[73] Boelhouwers[75] considered alternative modes of mechanical weathering, including salt weathering, thermal stress, hydration, dilatation and the role of seismic activity in triggering rockfalls. Supported by further field observations, Boelhouwers[55] concludes that i) fire-induced spalling appears the most important mode of mechanical weathering at present, ii) sporadic seismic activity results in localized rockfall, and iii) sporadic frost wedging may occur at favourable sites on pre-weathered rock at mountain summits.

Boelhouwers[55] still argues in favour of frost wedging as the main cause of the high rates of mechanical weathering throughout the region in the Pleistocene. This is based on the circumstantial evidence that large volumes of angular rock fall material are produced throughout the region, superimposed on Tertiary pseudokarst weathering forms. At high altitudes such mechanically fractured rockscarps are intrinsically associated with periglacial blockstreams.[55] Observations suggest that a regional change in environmental conditions favoured a change in weathering mode from chemical to mechanical rock breakdown.

These qualitative, landscape-scale observations still rely on clast morphology (especially angularity) as an indicator of dominant weathering environment (that is, frost weathering). Such an interpretation remains, at best, unsupported by most recent weathering process studies. Local lithologies need to be understood in terms of their responses to freeze/thaw conditions under various temperature and moisture regimes. More importantly, careful evaluation is needed to address the dichotomy in approach between the results from detailed weathering process studies and the approaches in Quaternary studies using weathering products as palaeoenvironmental indicators. There is an apparent conflict in methods and outcomes from the two approaches. With each sub-discipline working at one extreme of the space/time spectrum, work is needed to reconcile the two and find common understanding of weathering processes and their products in the landscape and their environmental significance.

Mass wasting

Linton[11] describes several sites along the coast near Cape Town displaying coarse diamictons of sandstone-derived debris overlying deeply weathered granite. These diamictons blanket many slopes throughout the region and form infills in valleys cut into the weathered granite in many mountain passes in the Western Cape. Linton[76] interprets the deposits as 'a geliflual sludge', based on the angular and sub-angular nature of the clasts in the debris, and the occurrence of the material on slopes of 13°. This interpretation is strongly rejected by Butzer and Helgren,[74] Butzer[26] and Verhoef.[77] Butzer and Helgren[78] relate the deposits near sea level to 'sheetwash, creep and other gravitational mass movement with or without accessory frost generated motion'. No publications to date have provided any detailed sedimentological description of these materials to substantiate either interpretation. Verhoef[77] points out it may be difficult to differentiate between snow-meltwater deposits, fluvial sediments and deposits produced by a combination of freeze/thaw and snow. Although the debris covers are mostly present as single units of uniform and massive diamictons, Butzer[26] describes two units of coarse debris on the Cape south coast, interpreted as of Lower Wurm and Early Pleistocene age. Two units of massive diamictons with distinctly different weathering characteristics also occur in the vicinity of Cape Town[79] (Boelhouwers *et al.*, unpubl. data) and in the mountains of the interior.[79]

While the origin of lower altitude diamictons remains unclear, more consensus exists on the periglacial nature of slope deposits in the summit region of the Western Cape mountains. Butzer and Helgren[74] aver that true solifluction deposits exist at altitudes over 1500 m a.s.l., an observation confirmed by Hagedorn[80] for deposits/blockstreams at Groot Winterberg and Matroosberg. Sanger[54] argues for postglacial gelifluction at the summit of Matroosberg (2249 m a.s.l.). Subsequent work on the Matroosberg blockstreams and solifluction mantles has placed their time of formation around the Last Glacial Maximum, mainly by frost creep, under an environment of deep seasonal frost.[55] The MAAT is estimated to have been around 0°C, requiring a 7–8°C temperature lowering compared with the present. These temperatures are 1–2°C lower than those documented from speleothem records of Talma and Vogel[81] for that period but may reflect local variability.

Footslopes of the mountains often have large alluvial fans present. While Booysen[82] suggests some of these fans to be of Tertiary age, Sänger[54] relates their development to Weichselian flood events resulting from rapid seasonal melt of glacial ice and snow on the mountain summits. While Sänger's[54] arguments for a Pleistocene glaciation remain problematic (see discussion below), the case for rapid seasonal snowmelt causing alluvial fan building during the Late Pleistocene glacials is supported by Boelhouwers.[18] Boelhouwers *et al.*[83,84] highlight the importance of present-day and past debris flow activity on alluvial fans, documenting a major shift in magnitude of debris flows from over 20 000 m^3 in the Late Pleistocene/Early Holocene to less than 500 m^3, on average, at present.

Quaternary glaciation

General texts on the Quaternary in southern Africa state that this region was not glaciated in this period.[85,86] However, the topic has raised much debate and controversy.

Glacial activity in southern Africa during the Quaternary

While evidence for earlier glacial periods in southern Africa (for example, Dwyka Group sediments) is beyond question, literature supporting glaciation during the Quaternary is contentious. A number of researchers have interpreted sediments and landforms as being evidence for Quaternary glaciation. Forms are said to include glacial striations, moraines, kame

Table 2. Published material on glacial processes and landforms in the high Drakensberg and Lesotho mountains.[4] (Entries represent the best examples from references in the text and the table is, therefore, not a complete record of published material in the study area.)

Landforms and processes	Publications (see list of references)
Arête	Sparrow (1964[27], 1967[8]);
Cirque	Sparrow (1964[27], 1967[8]); Harper (1969)[10]; Dyer and Marker (1979)[61]
Fluvio-glacial deposition	Hall (1994)[91]; Hanvey *et al.* (1986)[13]; Grab (1996[92], 1997[2]); Lewis (1996)[89]
Glaciation	Harper (1969)[10]; Hanvey and Lewis (1990); Marker (1991)[66]; Lewis and Hanvey (1993)[72]; Hall (1994)[91]; Grab (1996[92], 1997[2], 2000[6]); Lewis (1996)[89]
Glacial erosion (pavements, striations and surfaces)	Harper (1969)[10]; Hanvey *et al.* (1986)[13]; Lewis and Hanvey (1993)[72]; Lewis (1996)[89]
Glacial polish	Harper (1969)[10]
Glacial striation	Lewis (1996)[89]
Glaciation	Grab (1996[92], 1997[2], 2000[6])
Hanging valley	Lewis (1996)[89]
Moraines	Sparrow (1967[8]); Lewis (1996)[89]
Niche glacier	Marker (1991)[66]; Hall (1994)[91]; Grab (1996)[92]
Roché moutonnée	Grab (1996[92], 1997[2])
Truncated spur	Lewis (1996)[89]

moraines, cirques, and glacially polished surfaces (Table 2). The majority of published material either suggests or implies that glaciation was marginal and limited to small plateau glaciers, cirque glaciers and niche glaciers during the Last Glacial Maximum and other cold periods during the Quaternary.[54,87–92] Lewis,[90,91] on the other hand, has suggested that there may have been an extremely cold period prior to the Last Glacial Maximum, during which valley glaciers existed in the Eastern Cape Drakensberg. The implications of the latter hypothesis are that temperatures at approximately 40 000 BP were between 19°C and 24°C colder than at present;[90,91] a finding that is contrary to the generally accepted values in the Quaternary literature.[59,81,85,86]

The arguments for Quaternary glacial activity in the escarpment and Lesotho regions of southern Africa are largely based on the notion that Antarctic polar fronts would have been displaced further north,[93] thereby increasing winter precipitation in the form of snow.[66,92] However, conclusive evidence for the Quaternary remains elusive and contradictory to other proxy information. The apparent lack of conclusive evidence for glaciation or permanent ice has resulted in the generally accepted view that southern Africa was never glaciated during the Quaternary.[85,86,94] A complicating issue is that it is difficult to verify whether glaciers did exist in the absence of evidence of glacial erosion or deposition and geomorphic changes that have taken place after the Last Glacial Maximum. The escarpment and Lesotho highlands, for instance, may have been an accumulation zone where no glacial evidence was generated.[4] Any features that may have been formed by glacial abrasion could have disappeared as a result of chemical weathering and fluvial action.[49]

It is apparent that considerable work is required to determine the extent of glacial activity in the high altitude regions of southern Africa. The perceived presence of glaciers, rock glaciers, protalus ramparts, and the attributing of angular material in sediments to a cold-climate origin, appear to be particularly problematic as there has been little consideration in published research of how the inferred results relate to other climatic information. Most published material for the Quaternary indicate a 5–10°C decrease in temperature for southern Africa during the Last Glacial Maximum.[59] During the coldest part of the Quaternary, conditions were also more arid than at present and precipitation in the high altitude regions of southern Africa are estimated to be 70% of current values.[59] Glacial conditions proposed by Lewis[90,91] would require a 19–24°C drop in temperature together with substantial amounts of precipitation in the form of snow;[88,89] contradicting the existing estimate by most (interdisciplinary) research of a 5–10°C drop in temperature and a relatively dry climate.[95] The indication is, therefore, that conditions at the Last Glacial Maximum in the Drakensberg, Eastern Cape and Lesotho mountains were likely to have been more arid and colder than present.[94] The drier environment would have inhibited periglacial activity.[95] It is, thus, possible that the most active landscape-forming process occurred during warmer interglacial periods under warm, moist conditions, rather than during colder and relatively dry periods.[95]

Beside the problems indicated above, field investigations do not support the presence of glaciers in southern Africa during the Quaternary. Striae identified and said to be of glacial origin in the Eastern Cape Drakensberg[89,90] are caused by angular clasts in colluvial mantles moving over and abrading sandstone bedrock (pers. obs.). Further, the macro-scale landscape is clearly not the result of glacial processes.[6,70] Sediments in the Drakensberg cutbacks, particularly those in Nhlangeni cutback that are said to be of glacial origin,[2,92] are more likely to originate from fluvial incision of deposits that are derived from highly jointed bedrock and do not come from above the escarpment as has been implied.[57,95] Topography and ice-mass balance studies indicate that the Nhlangeni deposits and similar ones in KwaNtuba and other passes are not glacial.[95] Further, the existence of patterned ground and openwork block deposits at similar aspects and equivalent and higher altitudes that would require a non-glacial palaeoenvironment suggest that the allocation of a glacial origin for cutback deposits is erroneous.[57,95] Evidence for the perceived presence of Quaternary glaciation is isolated to a few specific locations[89,90,92] and anomalous with palaeoenvironmental evidence elsewhere in the High Drakensberg and Lesotho mountains.

Until widespread, general evidence of relict glaciation is found in the study area, the palaeoenvironment during the Last Glacial Maximum should be considered to be drier and colder than at present with at least deep seasonal ground freezing.

Western Cape mountains

In the Western Cape, a Weichselian glaciation has been proposed by Sänger,[54] who argues for cirque glaciation, based largely on aerial-photo mapping of the Western Cape mountains, from which cirque basins, moraines and outwash fans are identified based on morphological criteria. The analysis is, however, flawed as the steep valleyheads have developed in strength-equilibrium slopes of resistant quartzites, with a spatial distribution determined by structural control. Field inspection of moraines reveal these to be erosional remnants of bedrock related to the 'African' erosion surface in the intra-montane basins, based on data by Partridge and Maud.[96] While the fans are large and contain coarse debris, suggesting high discharges in the past, they provide no evidence for glacial outwash. Striated pebbles found at higher altitudes are invariably related to outcrops of Pakhuis tillite of Silurian age. Thus, evidence presented to date is easily refuted and no unequivocal indications for Quaternary glaciation in the Western Cape has, as yet, been presented. Instead, the widespread summit detritus, blockstreams and debris slopes point to a dominance of high rates of debris production in the Pleistocene and subsequent mass wasting, with seasonal snowmelt facilitating high-discharge events resulting in substantial debris flows.

Current research problems

The uncertainty regarding palaeoenvironments in the high altitude regions of southern Africa indicates that further research is required. Many of the problems arise from a lack of understanding regarding the specific nature of relict landforms,[42] a lack of rigour in research,[35] and insufficient data. Suggested hypotheses often lack supportive field data.[4,16,19,42,45,60] Further, it can also be said that there is a general lack of proxy data from the Quaternary.[4,37,63,69,91] Periglacial research is particularly affected, where poor spatial and temporal resolution of data, and inconsistent field techniques appear to have resulted in qualitative and contradictory results in the Drakensberg, Eastern Cape and Lesotho mountains.[4,26,35,37,45,97]

As indicated above, the spatial resolution reported in the periglacial and glacial literature is inadequate. Equally, there is poor temporal resolution within which to place the landforms. Datable evidence of periglacial environments from most sites in the High Drakensberg, Eastern Cape and Lesotho mountains is sparse. The only published data from Lesotho are from sediments in hollows, whose formation has been attributed to glacial and periglacial processes.[62,63] These data generally represent sediments that were deposited after the Last Glacial Maximum, thus making conclusive deductions about conditions during the coldest parts of the Quaternary difficult. The absence of datable material is attributed to aridity and rapid incision of landforms in the period after the Last Glacial Maximum.[45,62]

Among the various obstacles to understanding indicated above, the classification and use of terminology for periglacial and glacial phenomena in southern Africa is problematic.[4,37,97] A major influence on the interpretation of periglacial landforms in southern Africa is that, while most other areas where cryogenic activity currently dominates were previously glaciated, is it likely that southern Africa did not experience glacial conditions during the Quaternary. The absence of glacial sediments may thus prevent the use of generic examples, where periglacial activity normally occurs in glacial sediments, as surrogates for southern African conditions. Moreover, it is noticeable that investigations in the Drakensberg, Eastern Cape and Lesotho mountains continue to rely on the 'classic' literature to interpret landforms.[4] Thus, some of the main issues that relate to the interpretation of periglacial features in the high altitude regions of southern Africa are:[4]

- Some phenomena are not clearly defined or well developed,[5] making classification difficult.
- Confusing terminology exists for many landforms and processes that are attributed to periglacial and glacial processes; for example, rock weathering that occurs at and around the freezing point of water is variously referred to as: freeze–thaw, cryogenic and frost weathering, ice shattering and frost shattering, amongst others.
- Past moisture regimes are difficult to project from modern periglacial forms, especially those of the high mountain areas of the subcontinent.[42]
- Active cryogenic landforms in the High Drakensberg and Lesotho mountains are generally small in extent and of seasonal occurrence.[2,32,92]
- The rapid backward erosion of the escarpment may have truncated many of the larger glacial and periglacial landforms.[64]
- A few (in some cases single) occurrences[98,99] are used to generalize for the entire study region.
- Interpretation regarding altitudinal zonation of periglacial landforms and Pleistocene snowlines is confusing.[100,101]
- There is a lack of rigour in southern African periglacial studies.[35]
- Spatial and temporal resolution of periglacial and glacial evidence in southern African studies is poor.

It is apparent that considerable effort is required to improve the status and scientific image of high altitude southern African Quaternary geomorphology. Improved modelling techniques with computer-aided technology are being used to identify anomalies with respect to the interpretation of field data and then to process available information with a view to providing palaeoenvironmental predictions for southern Africa.[4] The qualitative nature of the current literature suggest that future emphasis should be directed towards sedimentary records by means of clay mineral, soil micro-structural and chemical analysis and dating to improve the reliability and accuracy of the interpretations and their spatial and temporal framework. The above problems are particularly evident in the High Drakensberg and Lesotho mountains; research in the Western Cape is apparently less controversial and of good quality. Quaternary periglacial and glacial research in southern Africa will, thus, provide ample opportunities for palaeoenvironmental research and stimulating debate for the foreseeable future.

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1. Troll C. (1944) Strukturboden, Solifluction und Frostklimate der Erde. *Geol. Rundschau.* **34**, 545–694.
2. Grab S. (1997). *An evaluation of the periglacial geomorphology in the high Drakensberg and associated environmental implications.* Ph.D. thesis, University of Natal, Pietermaritzburg.
3. Grab S. (1998). Periglacial research in Africa: past, present and future. *Prog. Phys. Geog.* **22**, 375–384.
4. de Villers S. (2000). *The development of a spatial database for research into cryogenic processes and landforms in southern Africa.* M.Sc. thesis, University of Pretoria.
5. Boelhouwers J. (1995). Some perspectives on southern African periglacial geomorphology. *S. Afr. J. Sci.* **91**, 163–165.
6. Grab S. (2000). Periglacial phenomena. In *The Cenozoic of Southern Africa,* eds T.C. Partridge and R.R. Maud, pp. 207–216. Oxford University Press, Cape Town.
7. Alexandré J. (1962). Phénomènes périglaciaires dans le Basutoland et le Drakensberg du Natal. *Biul. Periglac.* **11**, 11–13.

8. Sparrow G.W.A. (1967). South African cirques and arêtes. *J. Geog.* **2**, 9–11.
9. Sparrow G.W.A. (1967). Pleistocene periglacial topography in southern Africa. *J. Glaciol.* **6**, 551–559.
10. Harper G. (1969). Periglacial evidence in South Africa during the Pleistocene epoch. *Palaeoecol. Afr. Surround. Isl.* **4**, 71–91.
11. Linton D.L. (1969). Evidences of Pleistocene cryonival phenomena in South Africa. *Palaeoecol. Afr. Surround. Isl.* **5**, 71–89.
12. Lewis C.A. and Dardis G.F. (1985). Periglacial ice-wedge casts and head deposits at Dynevor Park, Barkly Pass area, north-eastern Cape Province. *S. Afr. J. Sci.* **81**, 673–677.
13. Hanvey P.M., Lewis C.A. and Lewis G.E. (1986). Periglacial slope deposits in Carlisle's Hoek, near Rhodes, eastern Cape Province. *S. Afr. Geog. J.* **68**, 164–174.
14. Marker M.E. (1986). Periglacial evidence from the eastern Cape, South Africa: the Amatola scree tongues. In *International Geomorphology II,* ed. V. Gardiner, pp. 901–913. Wiley, Chichester.
15. Boelhouwers J. (1991). Periglacial evidence from the Western Cape mountains, South Africa: a progress report. *Permafrost Periglac.* **2**, 13–20.
16. Grab S. (1994). Thufur in the Mohlesi Valley, Lesotho, southern Africa. *Permafrost Periglac.* **5**, 111–118.
17. Boelhouwers J. (1995). Present-day soil frost activity at Mt Superior, Hex River mountains, South Africa. *Z. Geomorphol.* **39**, 237–248.
18. Boelhouwers J.C. (1996). *The present-day frost action environment and its geomorphological significance in the Western Cape mountains, South Africa.* Ph.D. thesis, University of the Western Cape, Bellville.
19. Grab S. (1996). A note on the morphology of miniature sorted stripes at Mafadi Summit, high Drakensberg. *S. Afr. Geog. J.* **78**, 59–63.
20. Boelhouwers J.C. (1997). Sediment movement by frost in the Hex River Mountains, South Africa. *S. Afr. Geog. J.* **79**, 129–135.
21. Grab S. (1997). Analysis and characteristics of high altitude air temperature from northern Lesotho: implications for cryogenic occurrences. *Geoöko Plus.* **4**, 109–118.
22. Grab S. (1997). Thermal regime for a thufur and its adjoining depression, Mashai Valley, Lesotho, *Permafrost Periglac.* **8**, 437–445.
23. Grab S. (1997). Annually reforming miniature sorted patterned ground in the high Drakensberg, Lesotho, southern Africa. *Earth Surf. Proc. Land.* **8**, 437–445.
24. Boelhouwers J.C. (1998). Environmental controls on diurnal soil frost activity in the Hex River Mountains, South Africa. *Earth Surf. Proc. Land.* **23**, 211–221.
25. Grab S. (1999). A pilot study on needle ice induced stream-bank erosion in the Mashai Valley, Lesotho highlands. *S. Afr. Geog. J.* **81**, 126–134.
26. Grab S., Boelhouwers J., Hall K., Meiklejohn K.I. and Sumner P. (1999). Quaternary periglacial phenomena in the Sani Pass area, southern Africa. XV INQUA International Conference Field Guide, Durban, South Africa.
27. Sparrow G.W.A. (1964). Pleistocene periglacial landforms in the southern hemisphere. *S. Afr. J. Sci.* **60**, 143–147.
28. Sparrow G.W.A. (1971). Some Pleistocene studies in southern Africa. *J. Geog.* **3**, 809–814.
29. Sparrow G.W.A. (1973). Some Pleistocene periglacial problems in southern Africa. *Boreas* **2**, 103–107.
30. Butzer K.W. (1973). Pleistocene 'periglacial' phenomena in South Africa. *Boreas* **2**, 1–11.
31. Dardis G.F. and Granger J.E. (1986). Contemporary periglacial phenomena in the Natal Drakensberg, South Africa. *Palaeoecol. Afr. Surround. Isl.* **17**, 89–93.
32. Lewis C.A. (1988). Periglacial features in southern Africa: an assessment. *Palaeoecol. Afr. Surround. Isl.* **19**, 357–370.
33. Boelhouwers J. (1991). Present-day periglacial activity in the Natal Drakensberg: a short review. *Permafrost Periglac.* **2**, 5–12.
34. Hall K. (1991). The allocation of freeze–thaw weathering in geocryological studies: a critical comment. *S. Afr. Geog. J.* **73**, 10–13.
35. Hall K. (1992). A discussion on the need for greater rigour in southern African cryogenic studies. *S. Afr. Geog. J.* **74**, 69–71.
36. Le Roux J.S. (1990). Discussion of periglacial geomorphology at Golden Gate Highlands National Park, Orange Free State, South Africa. *S. Afr. Geog.* **17**, 129–131.
37. Hall K., Marker M.E. and le Roux J.S. (1991). The significance of periglacial geomorphology in southern Africa: a discussion. *S. Afr. Geog.* **18**, 134–139.
38. Sumner P. and Hall K. (1995). Cutbacks in the Natal Drakensberg Escarpment: comments on an hypothesis on their origin. *S. Afr. J. Sci.* **91**, 285–286.
39. de Villiers, S. and Boelhouwers, J.C. (2000). *Periglacial Geomorphology in Southern Africa: A Glossary and Bibliography.* Southern African Association of Geomorphologists, Occasional Publication No. 9.
40. Tyson P.D., Preston-Whyte R.A. and Schulze R.E. (1976). *The Climate of the Drakensberg.* Natal Town and Regional Planning Commission, Pietermaritzburg.
41. Backéus I. (1989). Flarks in the Maloti, Lesotho. *Geogr. Ann.* **71A**, 105–111.
42. Hanvey P.M. and Marker M.E. (1992). Present-day periglacial micro-forms in the Lesotho highlands: implications for past climatic conditions. *Permafrost Periglac.* **3**, 353–361.
43. Marker M.E. (1992). Periglacial landforms of southern Africa compared with those of Colorado and New Mexico, USA. *S. Afr. Geog. J.* **74**, 8–12.
44. Schulze B.R. (1965). *Climate of South Africa.* Part 8, General Survey. WB 28. South African Weather Bureau, Pretoria.
45. Meadows M. and Meadows J. (1988). The Quaternary vegetation history of the Winterberg Mountains, Eastern Cape, South Africa. *S. Afr. J. Sci.* **84**, 253–259.
46. Marker M.E. (1995). Further data for a Pleistocene periglacial gradient in southern Africa. *Trans. Geol. Soc. S. Afr.* **50**, 49–58.
47. Fitzpatrick R.W. (1978). Periglacial soils with fossil permafrost horizons in southern Africa. *Ann. Natal Mus.* **23**, 475–484.
48. Lewis C.A. (1996). Periglacial features. In *The Geomorphology of the Eastern Cape, South Africa,* ed. C.A. Lewis, pp. 103–119. Grocott & Sherry, Grahamstown.
49. Boelhouwers J.C. and Hall K. (1990). Sani Pass. In *Field Guide to Geocryological Features in the Drakensberg,* ed. P.M. Hanvey, Field Guide to UNESCO/IGCP Project 297, Rhodes University, Grahamstown.
50. Boelhouwers J. (1994). Periglacial landforms at Giant's Castle, Natal Drakensberg, South Africa. *Permafrost Periglac.* **5**, 129–136.
51. Grab S. (1998). Non-sorted patterned ground in the high Drakensberg: some new data. *Geog. J.* **164**, 19–31
52. Sumner P.D. and Meiklejohn K.I. (1997). Comments on proposed Pleistocene periglacial gradients in southern Africa. Presentation at *XIIIth SASQUA Biennial Conference,* Rhodes University, Grahamstown, 14–17 July.
53. Grab S. (1999). A pilot study on needle ice induced stream-bank erosion in the Mashai Valley, Lesotho highlands. *S. Afr. Geog. J.* **81**, 126–134.
54. Sänger H., (1988). Vergletscherung der Kap-Ketten im Pleistozän. *Berliner Geographische Studien* **26**.
55. Boelhouwers J. (1999). Relict periglacial slope deposits in the Hex River Mountains, Western Cape, South Africa. *Geomorphology* **30**, 245–258.
56. Grab S. and Morris C. (1999). Soil and water resource issues of the eastern alpine belt wetlands in Lesotho. In *African Mountain Development in a Changing World,* eds H. Hurni and J. Ramamonjisoa. African Mountains Association, African Highlands Initiative, and United Nations University.
57. Sumner P. (2000). Relict sorted ground near Sani Pass — evidence for Pleistocene deep freeze. Programme and Abstracts, SAAG 2000, 6th Biennial Conference, Hammanskraal, 9–12 July 2000.
58. Grab. S. (2000). Stone-banked lobes and environmental implications, high Drakensberg, southern Africa. *Permafrost Periglac.* **11**, 177–187.
59. Partridge T.C. (1997). Cainozoic environmental changes in southern Africa, with special emphasis on the last 200 000 years. *Prog. Phys. Geog.* **21**, 3–22.
60. Marker M.E. and Whittington G. (1971). Observations on some valley forms and deposits in the Sani Pass area, Lesotho. *S. Afr. Geog. J.* **53**, 96–99.
61. Dyer T.G.J. and Marker M.E. (1979). On some aspects of Lesotho hollows. *Z. Geomorphol.* **23**, 256–270.
62. Marker M.E. (1994). Sedimentary sequences at Sani Top, Lesotho highlands, southern Africa. *The Holocene.* **4**, 406–412.
63. Hanvey P.M. and Marker M.E. (1994). Sedimentary sequences in the Tlaeeng Pass area, Lesotho. *S. Afr. Geog. J.* **76**, 63–67.
64. Marker M.E. (1989). Periglacial geomorphology at Golden Gate Highlands National Park: a note on its fieldwork potential. *S. Afr. Geog.* **16**, 147–153.
65. Marker M.E. (1990). Nivation evidence from a north-facing slope? Golden Gate, eastern Orange Free State. *S. Afr. Geog. J.* **72**, 15–18.
66. Marker M.E. (1991). The evidence for cirque glaciation in Lesotho. *Permafrost Periglac.* **2**, 21–30
67. Grab S. and Hall K (1996). North-facing hollows in the Lesotho/Drakensberg mountains: hypothetical palaeoenvironmental reconstructions? *S. Afr. J. Sci.* **92**, 183–184.
68. Meiklejohn K.I. (1992). Some aspects of valley asymmetry in the high Drakensberg. *S. Afr. Geog. J.* **74**, 49–53.
69. Meiklejohn K.I. (1994). Valley asymmetry on south-eastern Alexander Island, Antarctica, and valley forms in the high Drakensberg, southern Africa. *S. Afr. Geog. J.* **76**, 68–72.
70. Meiklejohn K.I. (1996). Pleistocene climates in the Drakensberg mountains of southern Africa: what does current research indicate? Abstracts, 28th International Geographical Congress, The Hague, 4–10 August 1996.
71. Meiklejohn K.I. (2000). Structural control on landscape evolution in the Drakensberg and Lesotho mountains. Programme and Abstracts, SAAG 2000, VIth Biennial Conference, Hammanskraal, 9–12 July 2000.
72. Lewis C.A. and Hanvey P.M. (1993). The remains of rock glaciers in Bottelnek, East Cape Drakensberg, South Africa. *Trans. R. Soc. S. Afr.* **48**, 265–289.
73. Moon B.P. (1991). The forms of rock slopes in the Cape Fold Mountains. *S. Afr. Geog. J.* **66**, 16–31.
74. Butzer K.W. and Helgren D.M. (1972). Late Cenozoic evolution of the Cape coast between Knysna and Cape St. Francis, South Africa. *Quatern. Res.* **2**, 143–169.
75. Boelhouwers J. (1993). A discussion regarding weathering in the Western Cape mountains: implications for Pleistocene cryoclastic weathering. *S. Afr. Geog. J.* **75**, 46–52.
76. Linton D.L. (1969). Evidences of Pleistocene cryonival phenomena in South Africa. *Palaeoecol. Afr. Surround. Isl.* **5**: 82.
77. Verhoef P. (1970). Kwartêr-geomorfologie van Suid-Afrika — 'n oorsig. *Commun. Univ. Pretoria* **A.62**, 1–32.
78. Butzer K.W. and Helgren D.M. (1972). Late Cenozoic evolution of the Cape coast between Knysna and Cape St. Francis, South Africa. *Quatern. Res.* **2**, 143–169.

79. Boelhouwers J. and Rooy W. (1993). Excursion guide to periglacial landforms in the Western Cape mountains. Excursion guide for the first SAPG workshop, Bellville, 5–9 April 1993.
80. Hagedorn J. (1984). Pleistozäne Periglazial-Formen in Gebirgen des südlichen Kaplandes (Süd-Afrika) und ihre Bedeutung als Paläoklima-Indikatoren. *Palaeoecol. Afr. Surround. Isl.* **16**, 405–410.
81. Talma A.S. and Vogel J.C. (1992). Late Quaternary paleotemperatures derived from a speleothem from the Cango Caves, Cape Province, South Africa. *Quatern. Res.* **37**, 203–213.
82. Booysen J.J. (1974). Alluviale waaiers in die middel Breerivier bekken: 'n morfometriese vergelijking. *S. Afr. Geog.* **4**, 390–394.
83. Boelhouwers J.C., Duiker J.M.C. and Van Duffelen E.A. (1998). Spatial, morphological and sedimentological aspects of recent debris flow activity in the Du Toitskloof Valley, Western Cape mountains. *S. Afr. J. Geol.* **101**, 73–89.
94. Boelhouwers J.C., Craemers F.C.W. and Helsen M.M. (in press). Geomorphic evolution of debris fans in the Du Toit's Kloof, Western Cape mountains. *S. Afr. Geog. J.*
85. Tyson P.D. (1986). *Climatic Change and Variability in Southern Africa.* Oxford University Press, Cape Town.
86. Deacon J. and Lancaster N. (1988). *Late Quaternary Palaeoenvironments of Southern Africa.* Oxford University Press, Cape Town.
87. Nicol I.G. (1973). Landforms in the Little Caledon Valley, Orange Free State. *S. Afr. Geog. J.* **55**, 56–68.
88. Borchert G. and Sänger H. (1981). Research findings of a Pleistocene glaciation of the Cape mountain-ridge in South Africa. *Z. Geomorphol.* **25**, 222–224.
89. Lewis C.A. (1996). Glacial features. In *The Geomorphology of the Eastern Cape, South Africa,* ed. C.A. Lewis, pp. 120–135. Grocott & Sherry, Grahamstown.
90. Lewis C.A. (1994). *Field Guide to the Quaternary Glacial, Periglacial and Colluvial Features of the East Cape Drakensberg.* Field Guide Number One, Southern African Society for Quaternary Research, Rhodes University, Grahamstown.
91. Hall K. (1994). Cutbacks in the Natal Drakensberg escarpment: a hypothesis on their origin. *S. Afr. J. Sci.* **90**, 263–264.
92. Grab S. (1996). Debris deposits in the high Drakensberg, South Africa: possible indicators for plateau, niche and cirque glaciation. *Z. Geomorphol.* **103**, 389–403.
93. Howard W.R. (1985). Late Quaternary southern Indian Ocean circulation. *S. Afr. J. Sci.* **81**, 253–254.
94. Preston-Whyte R.A. and Tyson P.D. (2000). *The Atmosphere and Weather of Southern Africa.* Oxford University Press, Cape Town.
95. Sumner P. and Meiklejohn K.I. (2000). Landscape evolution in a changing environment. In *The Geography of South Africa in a Changing World,* ed. R. Fox and K. Rowntree, pp. 304–325. Oxford University Press, Cape Town.
96. Partridge T.C. and Maud R.R. (1987). Geomorphic evolution of southern Africa since the Mesozoic. *S. Afr. J. Geol.* **90**, 179–208.
97. Hall K. (1988). Freeze–thaw weathering: new approaches, new advances and old questions. In *Geomorphological Studies in Southern Africa,* ed. G.F. Dardis and B.P. Moon, pp. 325–335. Balkema, Rotterdam.
98. Grab S. (1999). Block and debris deposits in the high Drakensberg, Lesotho, southern Africa: implications for high altitude slope processes. *Geogr. Ann.* **81A**, 1–16.
99. Lewis C.A. (1994). Protalus ramparts and the altitude of the local equilibrium line during the last glacial stage in Bokspruit, East Cape Drakensberg, South Africa, *Geogr. Ann.* **76A**, 37–48.
100. Hastenrath S. (1972). A note on recent and Pleistocene altitudinal zonation in southern Africa. *S. Afr. J. Sci.* **68**, 96–102.
101. Hastenrath S. and Wilkinson J. (1973). A contribution to the periglacial morphology of Lesotho, southern Africa. *Biul. Periglac.* **22**, 157–167.

Periglacial landforms and deposits of Tasmania

Eric A. Colhoun*

Only limited parts of Tasmania were glaciated during the late Pleistocene. The extra-glacial regions exhibit many landforms and deposits that were developed at least partly by periglacial processes. Block streams, block fields and screes are well developed above 900 m on the dolerite plateaux of central and eastern Tasmania, while slope deposits of angular clasts occur on the siliceous rocks of western mountain areas. Extensive fossil solifluction deposits extend down to *c.* 500 m in central Tasmania, whereas modern frost-creep terraces and solifluction lobes occur only locally above 900 m in poorly vegetated areas. Active sorted polygons may occur on bare areas down to 600 m, and contemporary snowpatch erosion occurs above 1000 m. Fossil ice-pushed shoreline features occur on some lakes on the dolerite Central Plateau, while stabilized terrestrial sand dunes occur at lower altitudes in the Midlands and east. Few of these landforms and deposits are yet well dated, and many may have been formed during several cold stages of the Pleistocene. There is little evidence for Pleistocene permafrost below 1000–1200 m on the island.

Introduction

The definition of many landforms and deposits formed extraglacially mainly during the cold stages of the Pleistocene as periglacial is difficult in Tasmania. This is because of strong temperature gradients between sea level and highland areas, high scarps and steep slopes inducing cold air drainage and structural geological conditions conducive to slope failure. In addition, records of vegetation history demonstrate major changes during the cold stages with much more surface instability and extensive alpine vegetation in western mountainous regions, and grassland and woodland in eastern areas. Thirdly, lowering of sea level increased the continentality of Tasmania during the cold stages, giving reduced rainfall and a steepened precipitation gradient from west to east across the island.[1] This paper considers the range of *extraglacial* landforms and deposits developed during the predominantly colder and drier conditions of the Pleistocene, and provides an assessment of the significance and severity of periglacial processes in their development. In so doing, attention is focused on the increased effects of frost action, possible ground-ice development, induced mass movements, snow and lake ice effects, enhanced alluviation, increased aeolian effects, and placement of the forms, deposits and processes within temporal constraints. The locations of field areas are given in Fig. 1 and sites mentioned in the text in Fig. 2.

Tasmanian environments

Tasmania, the most southerly state and one of the most mountainous regions of Australia, exhibits an extensive range of cold climate glacial and periglacial landforms and deposits. Forming the extension of the Australian Eastern Highlands south of Bass Strait and extending from 39 to 42°S, Tasmania consists mainly of rugged mountain ridges, plateaux and grabens (Fig. 1). The western third consists mainly of steep, north–south striking ridges with intervening valleys extensively mantled by rainforests, wet sclerophyll forests, scrub and heath vegetation. Many ridges exceed 1000 m, the altitude of the present treeline, and the highest are 1300–1500 m. The ridges are composed mainly of Precambrian and Palaeozoic quartzite, conglomerate and volcanic rocks, with limestones flooring a number of the valleys. The central and eastern parts of Tasmania comprise extensive plateaux of Jurassic dolerite overlying Triassic sandstones and Permian mudstones. The high plateau areas, notably the Central Plateau, Ben Lomond in the northeast, and Mt Field, Mt Wellington and Hartz Mountains in the southeast,

*School of Geosciences, The University of Newcastle, New South Wales, Australia 2308. E-mail: ggeac@cc.newcastle.edu.au