Periglacial and permafrost research in the southern hemisphere

The following pages feature reviews of current understanding of present-day and Quaternary permafrost and periglacial environments in the southern hemisphere. The articles were solicited from members of the Southern Hemisphere Permafrost Group of the International Permafrost Association (IPA). This working group was established in 1998 with the primary aim to facilitate information exchange between researchers within the southern hemisphere, as well as with their counterparts in the northern hemisphere. The working group intends to synthesize existing information and make it more accessible.

International awareness of southern hemisphere permafrost and seasonally frozen ground is limited. However, extensive areas of permanently or seasonally frozen ground exist in the southern hemisphere, including the Antarctic, the Andes and Patagonia, and the New Zealand Alps, as well as the mountain summits of Irian Jaya and Papua New Guinea. Evidence for Quaternary periglacial activity is also documented for the mountains of southern Africa and Tasmania, where spatially and temporally limited activity presently takes place. Reasons for the limited recognition of these areas, as in the case of South America, may be in part because the research is published in a language other than English, and/or because it is inaccessible due to publication in journals not readily available outside the country of origin. In addition, the work may have progressed, to some degree, in isolation from the scientific activities and debates in the northern hemisphere, where most of the permafrost terrain, and resources for their study, are concentrated. In the case of the Antarctic, including both the continent and peri-Antarctic islands, permafrost science has seldom been advanced through dedicated programmes. Rather, information is scattered throughout the literature of the life and earth sciences and frequently as observations related only indirectly to the main topic. An important limitation on the output of southern hemisphere permafrost science is the small capacity in many countries, in terms of both human and financial resources, compared with their northern hemisphere counterparts.

The outcome of this strong northern hemisphere influence and emphasis is a general lack of awareness of issues pertaining to southern hemisphere permafrost and periglacial science. Environmental conditions in the southern hemisphere in which frost processes occur may be very different from those encountered in northern, high-latitude environments. These differences pose new questions regarding the understanding of processes and the palaeoenvironmental significance of resulting forms. Such a situation is exemplified by the blockstreams of Tasmania and southern Africa; the non-periglacial interpretations of these forms in Tasmania have stimulated reconsideration of the origin of blockfields and blockstreams in northern, high-latitude environments. Similar examples can be identified for diurnal soil frost processes at low and mid-latitudes, as well as weathering in the hyper-arid Antarctic. Because of the differences, southern hemisphere perspectives have the potential to contribute substantially to the scientific understanding of basic driving mechanisms and boundary conditions in permafrost and periglacial processes.

This collection of reviews offers the first comprehensive access in English to the literature on southern hemisphere permafrost and periglacial research and the issues it contains. The articles offer a frank assessment of the current status of permafrost research in various regions. From the papers it will be clear that there are large differences in the level of scientific understanding that has been achieved to date. This can be easily understood taking cognisance of the context in which scientists in the various regions have worked. Even so, these papers are important in that they emphasize the existence of past and present periglacial environments, raise directly or indirectly the problems concerning research in these areas, and indicate the potential for meaningful research in these areas.

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

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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 palaeo-environmental reconstruction of the high mountain environments of southern Africa.5,6,25 At first, such studies related primarily to the Natal Drakensberg and Lesotho highlands,7,8 although Linton11 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.5,12–14 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.15,16

Southern African periglacial studies have been subject to frequent review in the past.7,17–19 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,20–25 the perceived lack of significance of periglacial studies in southern Africa,26–27 the complexities of the field evidence,28,29 and the need for a regional assessment of available data records.2,3,28–30 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.31

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 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.39–41 Snowfalls are seen to occur two to eight times a year on average,42,43 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.43

The low latitude, high insolation, and clear skies promote strong diurnal heating and large diurnal temperature ranges leading to diurnal frost cycles in winter.43,44 Diurnal, and sometimes more prolonged, freezing of the ground is a normal occurrence, but restricted to shaded sites above 3000 m.43,44–46 No direct evidence of modern permafrost has been recorded.42,44–47

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In the Eastern Cape, High Drakensberg, Maluti and Lesotho mountains microforms of sorted and non-sorted patterned ground have been observed. 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, but this distribution may be influenced by lithology and topography in addition to climate.

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.

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, 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, 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, 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. 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 Pakhluis 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-
tion results in snow cover on an average of 31 days a year, but this is highly variable between years. Diurnal frost is limited to 10–20 days a year at altitudes over 1600 m. Sänger 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 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 solifluxion detected over a period of five years. By contrast, isolated shale exposures near summits reveal active sorted micro-patterned ground and turf- and stone-banked steps. Here, needle-ice-induced frost creep occurs in the upper 6 cm of the sediment, which is characteristic of diurnal frost environments.

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 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 shows that in the sandstone-derived soils frost intensities are limited by the insulation provided by vegetation, the presence of snow and an efficient

| Sedimentary forms/processes | Blockfields and blockstreams | Linton (1969); Sparrow (1971, 1973); Hastenrath and Wilkinson (1973); Hagedorn (1984); Lewis and Dardis (1985); Boelhouwers (1994); Grab (1996, 2000); Lewis (1996); Grab et al. (1999); Sumner and Meinkejohn (2000) |
| Cryptoplanation | Hagedorn (1984); Grab et al. (1999) |
| Cryoturbation | Lewis and Dardis (1985) |
| Debris flows and fans | Harvey et al. (1986); Hall (1994) |
| Flarks | Backëus (1989) |
| Gelifluction | Harper (1969); Linton (1969); Nicol (1973); Hagedorn (1984); Lewis and Dardis (1985); Dardis and Granger (1986); Lewis (1988, 1996); Hann and Marker (1992); Boelhouwers (1994) |
| Needle ice | Hastenrath (1972); Hastenrath and Wilkinson (1973); Lewis (1988, 1996); Marker (1989); Boelhouwers (1991); Hann and Marker (1992); Grab (1996, 1999); Grab et al. (1999) |
| Patterned ground (sorted) | Harper (1969); Hastenrath (1972); Hastenrath and Wilkinson (1973); Dardis and Granger (1986); Lewis (1988, 1996); Boelhouwers (1991); Hann and Marker (1992); Grab (1996, 1998, 1999); Grab et al. (1999); Sumner (2000) |
| Scree (cryoclastic) | Sparrow (1967); Maker (1986, 1992); Lewis (1994) |
| Segregation ice | Boelhouwers (1994); Grab (1996) |
| Thufur | Harper (1969); Marker and Whittington (1971); Sparrow (1971); Hastenrath (1972); Hastenrath and Wilkinson (1973); Lewis (1988, 1996); Boelhouwers (1991); Hann and Marker (1992); Grab (1994, 1997, 1999); Grab et al. (1999) |
| Erosional forms/processes | Turf exfoliation | Hastenrath (1972); Boelhouwers (1991); Grab (1997) |
| Anomalous forms/processes | Grézes litées | Lewis and Dardis (1985) |
| Ice wedges and casts | Harper (1969); Lewis and Dardis (1985); Lewis (1994) |
| Protalus rampart | Nicol (1973); Marker (1989, 1990); Lewis (1994, 1996) |
| Rockglacier | Lewis and Hann (1993); Lewis (1994) |
| Other | Freeze/thaw weathering and ice-shattering | Marker (1992) |
| Permafrost | Fitzpatrick (1978); Boelhouwers (1994); Lewis (1996) |
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 clay content. Boelhouwers' 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 and where shale-derived sediment is present. 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. Such factors may have significant, but as yet unquantified, effects on the high altitude regions of southern Africa, 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, solifluxion 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 cryoplation 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. The valley sides display evidence of slow mass flow and creep in the form of solifluxion lobes and sheets, which in many cases mantle the entire valley. 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.) None of this evidence is diagnostic for permafrost and is interpreted as associated with deep seasonal frost. The occurrence of these widespread valleyfils is considered to be indicative of limited and seasonal snow cover, which is substantiated by most of the published proxy data 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’ (see below). While it has been proposed that the hollow forms are ‘bog-cirques’, the absence of significant saprolite at the contact between sediments and bedrock largely discounts this argument. Meiklejohn (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 that appear to be misinterpreted. In addition, the deposits interpreted as rock glaciers by Lewis and Hanvey lack any diagnostic features of such forms and are most likely debris flow deposits (Shakesby, pers. comm.). Similarly, so-called ice-wedge casts 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. The origins of such coarse clastic materials near sea level at Cape Town were first attributed to frost shattering by Linton. Butzer and Helgren 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.

Hall cautioned against the use of clast angularity as evidence for frost weathering, a point already addressed to by Butzer and Helgren. Boelhouwers 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 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 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. 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 describes several sites along the coast near Cape Town displaying coarse diamictons of sandstone-derived debris overlying deeply weathered granite. These diamictions blanket many slopes throughout the region and form infalls in valleys cut into the weathered granite in many mountain passes in the Western Cape. Linton 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, Butzer and Verhoef. Butzer and Helgren 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 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 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 (Boelhouwers et al., unpubl. data) and in the mountains of the interior.

While the origin of lower altitude diamictons remains unclear, a more consensus exists on the periglacial nature of slope deposits in the summit region of the Western Cape mountains. Butzer and Helgren aver that true solifluxion deposits exist at altitudes over 1500 m a.s.l., an observation confirmed by Hagedorn for deposits/blockstreams at Groot Winterberg and Matroosberg. Sanger argues for postglacial gelification at the summit of Matroosberg (2249 m a.s.l.). Subsequent work on the Matroosberg blockstreams and solifluxion mantles has placed their time of formation around the Last Glacial Maximum, mainly by frost creep, under an environment of deep seasonal frost. 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 for that period but may reflect local variability.

Foothills of the mountains often have large alluvial fans present. While Boosyten suggests some of these fans to be of Tertiary age, Sänger relates their development to Weichselian flood events resulting from rapid seasonal melt of glacial ice and snow on the mountain summits. While Sänger’s arguments for a Pleistocene glaciation remain problematic (see discussion below), the case for rapid seasonal snowmelt causing alluvial fan building during the Late Pleistocene glacial is supported by Boelhouwers. Boelhouwers et al. 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 m³ in the Late Pleistocene/Early Holocene to less than 500 m³, on average, at present.

**Quaternary glaciation**

General texts on the Quaternary in southern Africa state that this region was not glaciated in this period. 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...
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.\textsuperscript{43,44,48} Lewis,\textsuperscript{59} 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 \textsuperscript{BP} were between 19°C and 24°C colder than at present,\textsuperscript{41} a finding that is contrary to the generally accepted values in the Quaternary literature.\textsuperscript{54,65,66}

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,\textsuperscript{10} thereby increasing winter precipitation in the form of snow.\textsuperscript{46,48} 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.\textsuperscript{43,44,45} 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.\textsuperscript{4} Any features that may have been formed by glacial abrasion could have disappeared as a result of chemical weathering and fluvial action.\textsuperscript{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 ramps, 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.\textsuperscript{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.\textsuperscript{6,70} Glacial conditions proposed by Lewis\textsuperscript{59} would require a 19–24°C drop in temperature together with substantial amounts of precipitation in the form of snow;\textsuperscript{66,97} contradicting the existing estimate by most (interdisciplinary) research of a 5–10°C drop in temperature and a relatively dry climate.\textsuperscript{28} 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.\textsuperscript{24} The drier environment would have inhibited periglacial activity.\textsuperscript{25} 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.\textsuperscript{25}

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\textsuperscript{89} 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.\textsuperscript{4,72} Sediments in the Drakensberg cutbacks, particularly those in Nhlangeni cutback that are said to be of glacial origin,\textsuperscript{2,45} 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.\textsuperscript{30,95} Topography and ice-mass balance studies indicate that the Nhlangeni deposits and similar ones in KwaNdaba and other passes are not glacial.\textsuperscript{25} 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.\textsuperscript{50,97} Evidence for the perceived presence of Quaternary glaciation is isolated to a few specific locations\textsuperscript{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,\textsuperscript{8} 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,

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**Table 2.** Published material on glacial processes and landforms in the high Drakensberg and Lesotho mountains.\textsuperscript{1} (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.)

<table>
<thead>
<tr>
<th>Landforms and processes</th>
<th>Publications (see list of references)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arête</td>
<td>Sparrow (1964\textsuperscript{47}, 1967\textsuperscript{4});</td>
</tr>
<tr>
<td>Cirque</td>
<td>Sparrow (1964\textsuperscript{47}, 1967\textsuperscript{4}); Harper (1969\textsuperscript{54}, Dyer and Marker (1979\textsuperscript{54});</td>
</tr>
<tr>
<td>Fluvio-glacial deposition</td>
<td>Hall (1994\textsuperscript{64}); Harney et al. (1986\textsuperscript{6}); Grab (1996\textsuperscript{6}, 1997\textsuperscript{4}); Lewis (1996\textsuperscript{6});</td>
</tr>
<tr>
<td>Glaciation</td>
<td>Harper (1969\textsuperscript{54}); Harney and Lewis (1990\textsuperscript{94}); Marker (1991\textsuperscript{64}); Lewis and Harney (1990\textsuperscript{94}); Hall (1994\textsuperscript{6}); Grab (1996\textsuperscript{6}, 1997\textsuperscript{4}, 2000\textsuperscript{9}); Lewis (1996\textsuperscript{6});</td>
</tr>
<tr>
<td>Glacial erosion (pavements, striations and surfaces)</td>
<td>Harper (1969\textsuperscript{54}); Harney et al. (1986\textsuperscript{6}); Lewis and Harney (1993\textsuperscript{94}); Lewis (1996\textsuperscript{6})</td>
</tr>
<tr>
<td>Glacial polish</td>
<td>Lewis (1996\textsuperscript{94})</td>
</tr>
<tr>
<td>Glacial striation</td>
<td>Lewis (1996\textsuperscript{94})</td>
</tr>
<tr>
<td>Glaciation</td>
<td>Grab (1996\textsuperscript{6}, 1997\textsuperscript{4}, 2000\textsuperscript{9})</td>
</tr>
<tr>
<td>Hanging valley</td>
<td>Lewis (1996\textsuperscript{94})</td>
</tr>
<tr>
<td>Moraines</td>
<td>Sparrow (1967\textsuperscript{4}); Lewis (1996\textsuperscript{6})</td>
</tr>
<tr>
<td>Niche glacier</td>
<td>Marker (1991\textsuperscript{94}); Hall (1994\textsuperscript{6}); Grab (1996\textsuperscript{6})</td>
</tr>
<tr>
<td>Roché moutonnée</td>
<td>Grab (1996\textsuperscript{6}, 1997\textsuperscript{4})</td>
</tr>
<tr>
<td>Truncated spur</td>
<td>Lewis (1996\textsuperscript{94})</td>
</tr>
</tbody>
</table>
however, flaked 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.43 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 relic landforms,42 a lack of rigour in research,39 and insufficient data. Suggested hypotheses often lack supportive field data.43,52,62,63 Further, it can also be said that there is a general lack of proxy data from the Quaternary.4,27,35,92 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.46,62,63,76,92 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.48,26 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.49,52

Among the various obstacles to understanding indicated above, the classification and use of terminology for periglacial and glacial phenomena in southern Africa is problematic.4,27,97 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, it is 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.1 Thus, some of the main issues that relate to the interpretation of periglacial features in the high altitude regions of southern Africa are:

- Some phenomena are not clearly defined or well developed,3 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: 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.2,22,62
- 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) occurrences99,98 are used to generalize for the entire study region.
- Interpretation regarding altitudinal zonation of periglacial landforms and Pleistocene snowlines is confusing.29,101
- 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.1 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 analyses 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.

We thank the following persons and organizations for their invaluable contributions towards this publication: the National Research Foundation for financial assistance through core grants to both authors; the universities of the Western Cape and Pretoria for financial assistance to the two authors, respectively; the organizers of the 1999 INQUA congress for allowing a session on southern hemisphere periglacial environments; the International Permafrost Association and the Southern African Permafrost group, under whose auspices the INQUA conference sessions were held; the comments and criticism of two referees that helped to improve the scientific quality of the paper; and colleagues of the authors, in particular Paul Sumner, Kevin Hall and Steve Holness, for their comments, advice and assistance during fieldwork.

Periglacial landforms and deposits of Tasmania

Eric A. Colhoun*

Only limited parts of Tasmania were glaciated during the late Pleistocene. The extra-glacial realms exhibit many landforms and deposits that were developed at least partly by periglacial processes. Block streams, block fields and scree 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-pushsed 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 scarp 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. 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,

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occur between 1000 m and 1500 m altitude. The grabens are mainly underlain by Mesozoic sandstones and mudstones, and contain Cainozoic sediments and basaltic lavas. The largest graben forms the Midland Valley, with numerous smaller, linked grabens forming the Derwent Valley and the lowlands of the eastern coastal area. Sclerophyll forest, woodland and grassland cover most of the area below 1000 m. Over 1000 m, alpine heath and herb vegetation is widespread.

Climatically, Tasmania is strongly influenced by weather systems generated north of the Polar Front in the Southern Ocean, and in southern continental Australia. Westerly and southwesterly oceanic low-pressure systems are predominant and bring abundant precipitation (2500–3500 mm yr⁻¹), including frequent snowfalls, to the mountainous regions in winter. Continental high-pressure influences occur during summer and are accompanied by dry northwesterly winds that blow across the western mountains and Central Plateau. The winds descend with fohn-effect to the Midland and southeastern valleys. Very dry, hot conditions occur with temperatures reaching 35–40°C. Davies compared Tasmania with northwest Portugal and Spain, the climate being very wet in the west, cold in the mountains and dry to the east.

Tasmania has been glaciated numerous times during the Pleistocene. The glacial systems were located predominantly on the West Coast Range, on the western part of the Central Plateau and the Central Highlands, and in eastern plateau and mountain areas such as Ben Lomond, Mt Field and Hartz Mountains. In addition, many cirque and short valley glacier systems formed leeward of the major ridges, such as the Franklin and Arthur ranges in southwest Tasmania. The oldest glacial deposits are best represented in the west, south-central and north-central areas beyond the limits of last glaciation ice. They are regarded as of early Pleistocene age because associated lake beds have reversed magnetic polarity indicating an age of over 780 kyr.“ The youngest glacial landforms and deposits belong to the maximum phase of the last glaciation (LGM), dated at Dante Rivulet to c. 18 800 ± 500 14C yr BP (ANU 2533), and to later local ice advances in the highest mountain source areas. At the LGM, ice was most extensive on the western part of the Central Plateau and Central Highlands and only small mountain glacial systems occurred elsewhere. The extent of last glaciation ice was very much smaller than that of middle and early Pleistocene periods of glaciation. Beyond the ice limits and throughout the Pleistocene, a considerable variety of landforms and deposits were developed, some of which can be regarded as periglacial in origin.

Rock landforms
In Tasmania orbs of both the one-cycle and two-cycle varieties are widespread. Tors of the former type include pillars and prominent craggy masses of rock that occur on the higher slopes and crests of quartzite ridges in western Tasmania. Below the quartzite outcrops, 1–2-m-thick mantles of angular clasts cover hill slopes, fill gullies and are stabilized by thin peaty soils formed
during the Holocene. In addition, particularly on the dolerite plateau of Ben Lomond, tors consisting of several columns of dolerite surrounded by small amounts of clutter occur. Old Bills Monument (Fig. 3) on the northern part of Ben Lomond exemplifies this one-cycle variety. \(^{13,14}\) It consists of several columns 3–6 m high with angular blocks at its base, presumably dislodged by frost-wedging.

Two-cycle tors are exemplified by the many craggy hill summits that occur on the deeply weathered granites of northeastern Tasmania. In addition, prominent dolerite crags of tor-form occur on Ben Lomond, Mt Wellington, Mt Field and on eastern parts of the Central Plateau in association with deeply decomposed dolerite regolith that exhibits many core stones. Decomposition of the dolerite, largely by deep chemical weathering up to 5–30 m depth, \(^{14}\) is extensive and evacuation of the regolith by repeated episodes of gelification has been recorded west of Great Lake. \(^{15}\)

One-cycle tors occur outside areas covered by ice during the LGM in western Tasmania. On Ben Lomond, Caine \(^{19}\) suggested that tors occurred both inside and outside the LGM ice limits; those within the ice limits being one-cycle tors of periglacial origin and those outside the ice limits possibly being two-cycle tors. Revision of the age of glaciation of Ben Lomond to the \(\delta^{18}O\) Stage 6 cold period \(^{17}\) permits more time for tor formation since deglaciation.

The occurrence of former periglacial conditions on Ben Lomond is indicated by the presence of frost-heaved blocks of dolerite raised by up to 1 m from their original position in the bedrock, and left wedged in their raised position. \(^{15}\) This results from water that drained down the polygonal joints forming ice lenses in horizontal joints and gradually elevating the columns. This seems to require the development of small masses of

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**Fig. 2.** Sites of features referred to in text.

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**Fig. 3.** Old Bills Monument, isolated tor on the northern part of Ben Lomond Plateau.
seasonal, or even multi-year, ground ice at altitudes above 1200 m.

Block landforms and deposits

Landforms resulting from the accumulation of large, joint-bound dolerite blocks are common on and near the summits of plateaux and mountains of eastern and central Tasmania. They include accumulations that result from dilation of mountain summits, rock glaciers, block streams, block fields, glacis, scree and associated topples. Most features give the general impression of destruction of the bedrock by processes of physical fracture and mass movement, but many have complex origins and may be formed by several groups of processes operating concurrently or sequentially.

Mt Gould, a former nunatak in the Central Highlands, exhibits some of the largest block detritus in Tasmania. Individual blocks, slabs and broken columns attain 2–15 m or more in size and the entire summit is covered with such blocks, none being in situ. Small blocks are rare, and there is no fine matrix within the block mantle. The calibre of the blocks suggests that the accumulation is a result of dilation of the mountain summit by erosion of the landscape over many hundreds of thousands of years, or more.

Evidence of the presence of former rock glaciers occurs only above 1100 m in the mountains of central and northeast Tasmania. In central Tasmania, Derbyshire recorded rock glaciers on the southwestern slopes of Mt Olympus and Mt Gell, where they descend to 1188–1370 m and 1173 m, respectively. The rock debris consists of joint-bound and fractured dolerite blocks up to 3 × 2 × 2 m in size. The rock glaciers have been formed by rock-fall and talus formation from free-faces and steep valley walls. Their downslope movement was probably facilitated largely by the formation of interstitial ice and by snow avalanching. Field observations of the degree of alteration of the blocks and quantities of interstitial matrix suggest the possibility of several periods of development. Although confined to altitudes above 1100–1200 m in central Tasmania these rock glaciers are not considered to require permafrost for their development.

Rock glaciers have been recorded by Caine in northeast Tasmania. They occur above 1000 m on Mount Barrow and Ben Lomond, with most occurring on southern and eastern margins of the plateaux. The most impressive is the Sphinx Bluff rock glacier that originates in a shallow, block-filled valley head above the southern scarp of Ben Lomond just beyond the plateau ice limit. The rock glacier surface exhibits furrows on its surface of up to 3 m in relief that suggest it may have originated from a core of glacier ice. Most of the other rock glaciers do not appear to have had ice cores. Instead their movement was probably due mainly to development of considerable interstitial ice in a marginal permafrost environment.

Far more extensive, however, are the block streams that occur above c. 900 m on Ben Lomond, Mt Barrow, Mt Wellington, Mt Field (Fig. 4) and the eastern part of the Central Plateau in areas not glaciated during the last glaciation. In addition, at least one block stream occurs within the unglaciated window of the Walls of Jerusalem on the Central Plateau. The block streams occupy the axes of shallow valleys. They mainly have surface gradients of <5° inclination and do not exceed 20°. Mean block size varies from 25 to 60 cm in most streams that have a variety of fabric patterns indicating their former motion along the valleys. They often end in one or more arcuate banks or terraces of blocks. Usually there is a single block stream per valley, but at Talus Valley, now called Rodway Valley, in the central part of Ben Lomond several streams become confluent above a gap in the plateau edge.

Several factors probably contributed to the accumulation and movement of the block streams over long periods of time. Many of the surface blocks are sub-angular and appear to have been derived by mechanical processes from cliffs, scarp or outcrops adjacent to the upper parts of the streams. However, the terminal parts of block streams on Mt Wellington, Mt Field and on the eastern part of the Central Plateau are juxtaposed with thick sheets of transported clay-rich, dolerite debris that contains cobbles and cobblestones, weathered by prior chemical weathering. Downslope movement of the debris probably resulted from a combination of gelification and frost creep over a prolonged period. This suggests that some of the boulders in the block streams were derived from chemically weathered cobbles and cobblestones. The boulders of the block streams thus appear to represent lag deposits of more than one origin from which matrix materials have been removed either to depth or down-valley by washing-out; a process observable today, particularly at times of snowmelt.

None of the block streams is moving today, and the boulders are variably encrusted with lichens and sometimes mosses. They are thus regarded as relict landforms, the movement of which required colder climatic conditions than present. Caine suggested mechanisms for movement of block streams on Ben Lomond that included sliding over underlying weathered yellow-brown clay during times of high pore water pressures. This could facilitate the development of segregated ice lenses or make the clay and blocks prone to frost-heaving. In addition, the accumulation of interstitial masses of ice associated with seasonal or periodic freezing of surface drainage water could assist gradual downslope movements. Under present conditions, ground freezing is only possible over short periods (a few days) and does not seem sufficient to cause down-valley movement. It is thus suggested that the block streams may have required substantial interstitial ice to be developed, either seasonally or perennally, and a long time.

Associated with the block streams are areas of block fields or felsenmeer. These also occur at altitudes over 900 m and generally in the same areas as the block streams. Davies described such features as block field saddles on Mt Wellington and Mt Barrow, and showed their close association with block streams such as the 'Ploughed Fields' southwest of Mt Wellington. Many of the blocks have probably been derived mechanically from bedrock sources with others being old cobbles concentrated through washing-out of matrix materials. The individual blocks are not in situ but probably have been transported only short distances by creep. In addition to dolerite block fields, block
fields are frequently found on mountain summits of quartzite in western Tasmania. The quartzite fragments are usually angular to sub-angular, vary in size from centimetres to about 1-m diameter and are clearly the result of physical, presumably frost, fracturing. Coarse quartzite block fields with clasts of 0.3–1 m size are well represented on the summit of Mt Campbell on the eastern side of Cradle Mountain National Park. Similar block fields of quartzite with clasts of only 5–20 cm size are widespread on Cradle Plateau.

A low-angle accumulation of dolerite blocks occurs west of Pine Lake on the Central Plateau at 1200 m. Blocks forming an apron with a 7° surface inclination extend from near the base of a steep dolerite scarp. While most of the blocks have probably been derived from the scarp at one time, they are not part of the line of scree that flank the immediate scarp-foot (Fig. 5). The landform appears to be entirely fossil and is comparable to a glacio in which the blocks would have crept downslope either over the underlying matrix material or as a result of the formation of interstitial ice masses during times of colder climate.

Dolerite scree, containing blocks up to 2 m size, are abundant adjacent to scarp and below plateau margins on Ben Lomond and Mt Barrow in the northeast. The most prominent scree on Mt Wellington occur below the ‘Organ Pipes’ on the road from Hobart to the summit. Scree are also extensive outside the limits of LGM ice cover at Mt Field, on the eastern and northern margins of the Central Plateau, and above the ice limits on Mt Olympus. Only rarely can recent rock falls be seen to add to the scree that for the most part have lignum on their surfaces, are undergoing minor chemical decomposition and are stable. It is difficult to ascribe the extent to which frost and climatically more severe freezing conditions contributed to scree production in the past. The rock walls and scarp could have yielded debris by mass movement processes at any time, yet there is little evidence for much movement during the Holocene. In addition, weak sandstones and mudstones underly the dolerite sills is conducive to slope failure. These strata can be erosional sapping allowing the plateau and scarp edges to rotate outwards and collapse as topples. Such topples are common north of Ben Lomond and on the northeastern slope of Mt Olympus.

In western Tasmania scree consist predominantly of quartzite debris that mantle steep slopes. They are stabilized by Holocene peat deposits, forest or heath. The scree mantles may be 1–3 m thick, increasing to 5 m in former gullies. The clasts are angular to subangular, are generally 5–20 cm size and have minor amounts of sandy matrix. The scree are largely massive in structure, though in places weak bedding or intervening silt beds and palaeosols indicate that some accumulated episodically over quite long periods (Fig. 6). Good examples can be observed adjacent to the Strathgordon, Scott’s Peak, Lyell Highway and Strahan roads, while the peninsula of Rocky Cape is extensively scree-mantled. All thick and extensive scree mantles occur outside LGM ice limits. Within these limits, only small scree accumulations are found close to the bases of high, formerly glaciated, cliffs.

Many valleys in northern and eastern Tasmania have been incised into weak Permian mudstones. Artificial exposure today allows the mudstones to break-up into a sheet of deposits composed of small angular fragments from 1–5 cm size. Beneath the forests and organic soil profiles on slopes, fossil stratified scree of such mudstone fragments have accumulated often up to 1–2 m thickness. The scree exhibit thicker (10–20 cm) coarse beds alternating with thinner (<10 cm) silty beds, indicating cyclic deposition, perhaps of a seasonal nature involving frost dislodgment of the fractured rock fragments and meltwater and surface washing of fine sand and silt. A good example occurs at Fairy Glade on the Great Lake to Deloraine road (Fig. 7). Similar deposits occur extensively in the Wilmot Valley, where the beds of coarse clasts exhibit extensive openwork structure with the character of grès litées."

Dating of the above landforms during the last 40 years has depended on the fortuitous discovery of interstratified organic deposits suitable for radiocarbon dating. Few organic deposits have been found, resulting in little dating and limited age control. Current conclusions on the ages of the landforms and
deposits thus depend largely on their geographic distribution in association with glacial landforms and deposits that are somewhat better dated. The geographical distribution of all the forms described being outside the last glaciation ice limits and their apparent stability under present (Holocene) conditions argues for a minimum age of formation during the last glacial cold stage. A radiocarbon age of $13,870 \pm 820$ yr BP (Gak 5948) from 1.9 m depth in quartzite slope deposits at Hardstaff Creek in northwestern Tasmania indicates slope instability at the end of the last glacial stage. A date of $\geq 33,000$ yr BP (Gak 5623) from a palaeosol within quartzite scree at Scotts Peak Dam, in southwest Tasmania (Fig. 6), separates two periods of slope instability, both probably occurring within the last glacial stage.

The great quantities of such deposits in areas not glaciated during the LGM and in parts not glaciated at any time suggest that similar deposits were formed on many occasions during much of the Pleistocene. The development of exposure-age dating during the last decade and its much greater age-range of resolution than radiocarbon should allow direct dating of many of these blocky landforms in the future and resolution of some of the temporal complexity involved.

**Solifluction landforms and deposits**

Today diurnal freezing may cause the growth of needle ice on bare soil at all altitudes and cause frost creep. However, bare slope debris over 900 m a.s.l. is particularly prone to frost-heaving, and downslope frost creep movements occur at 3–42 mm/yr on slopes of 1–10° on Ben Lomond.29 Such frost-creep may result in thin sheets, terraces and lobes of debris being formed. A flight of such terraces occurs at 850–900 m on Moonlight Ridge in southeast Tasmania (Fig. 8). Solifluction lobes occur at 1520–1540 m near Legges Tor on Ben Lomond, where Caine30 recorded stone movements of 26–87 mm yr$^{-1}$ on solifluction terraces with slopes of 3–12°.

However, by far the most extensive and thickest solifluction deposits are relic and occur on the dolerite plateaux and hills of eastern Tasmania outside the ice limits of the LGM. These solifluction deposits occur mainly above 500 m altitude but locally extend down to 480 m, and occasionally to 300 m, as on the steep scarp edges of Ben Lomond.31 They consist of subangular to subrounded clasts in a matrix of yellow-brown to brown clay. The deposits are generally 1–3 m thick but can exceed 10 m in thickness. They are generally unstratified but some sites show multiple sheets of solifluctate as west of Great Lake,32 while others show distinct episodic deposition with phases of gley soil formation between successive sheets, as at Monpeelyata Canal (Fig. 9). One of the main characteristics of the deposits is a concentration of dolerite boulders on the surface that is usually about 0.5–1.0 m thick.

There are few thick solifluction deposits in the predominantly silicic rock areas of western Tasmania, where slope mantles are usually not more than 1 m thick and consist mainly of poorly bedded scree. Apart from the contrast in rock type, the difference suggests that much of the debris referred to as solifluctate in central and eastern Tasmania was derived from the underlying dolerite by periglacially-induced mass-movement processes incorporating pre-existing chemically weathered and hydrothermally altered material. Many sections on the lower central and eastern parts of the dolerite Central Plateau and on Ben Lomond, Mt Field and Mt Wellington show the transition from decomposed dolerite with core-stones to overlying solifluction deposits. Their distribution outside the late Pleistocene ice limits but absence from most of the glaciated high Central Plateau suggests that the solifluctate was formed by slowly-operating processes of mass movement in a periglacial climate mainly during times of glaciation. If these interpretations are correct then a long period of time may be involved in the formation and movement of the dolerite solifluction deposits. The concentrations of boulders at the surface are probably also the result of washing-out of the matrix, analogous to that for the block fields. To judge by the ratio between matrix and boulders in the original solifluctate, great thicknesses of matrix must have been removed by eluviation to produce the surface boulder-lag deposits.

The same constraints exist on dating the relict solifluctates as for the blockstream and blockfield deposits. Only one terminal Pleistocene radiocarbon age of 14,200 $\pm$ 700 yr BP (Gak 4806) has been recorded. This comes from charcoal in the disturbed A horizon of a podsolized soil overlain by solifluctate at 500 m altitude in the Florentine Valley west of Mt Field.33

**Patterned ground**

The combination of ice-scoured plateaux, block field and solifluction-mantled plateaux, coarse clastic accumulations on the surface and steep slopes seems to limit the development of patterned ground forms. There is only one record of 2-m diameter, sorted polygons24 at 1380 m altitude on Mt Rufus and these are currently active.23 Small (< 0.2–0.5 m), active sorted polygons and circles also occur above 1400 m in thin dolerite debris on Ben Lomond. Similar small nets of sorted regolith relating to modern frost-sorting are known from 1460 m near Lake Nameless on the Central Plateau and at 1150 m from Mt Emmett south of Cradle Mountain.23 Modern processes of needle ice development and
frost-heaving and sorting are not limited to high altitudes but could occur anywhere on moist bare ground in winter, as indicated by the formation of sorted stone nets on the floor of a gravel pit at 600 m in the Mersey Valley.

**Snow and lake-ice effects**

The mountains of Tasmania are presently subject to frequent snowfalls in winter but, except for shaded and leeward sites, snow rarely persists for more than a week. The area that receives the most prolonged snow cover is the ski-fields around Legges Tor on Ben Lomond. At Legges Tor the boulders on the rounded dolerite surfaces above 1500 m creep downslope with the winter snowpack (Fig. 10) (N. Caine, pers. comm.). To what extent rounding of the dolerite in the Legges Tor area has resulted from ice erosion, or from subsequent removal of surface debris by such downslope creep of boulders beneath winter snowpack, is difficult to judge. However, the evidence for boulder-creep beneath present winter snowpack suggests such erosion of the rock surface is likely to have been more effective during glacial stages than during the Holocene.

Elsewhere in Tasmania, erosion of the land surface by snow accumulation in winter has been recorded mainly on siliceous rocks. A snow patch that rarely disappears before November and occasionally lies throughout summer occurs on the northwestern side of Frenchmans Cap, where it occupies a largely relict nivation cirque. This nivation cirque is similar to several others that probably contained and were deepened by a variety of processes associated with thick winter snow patches during the LGM. Examples occur at Adamsons Peak on the northeastern slope of Mt Campbell in Cradle Mt Park, on Mt Eliza (Fig. 11) and on Mt Gell.26

The effects of contemporary snow erosion are best seen by disturbance of the alpine vegetation cover as at Cradle Plateau, where many areas of bare quartzite rock and surface detritus interrupt the alpine heath and herb vegetation communities. At Cradle Plateau snow erosion occurs mainly by water from the melting snow banks, causing disintegration of the poorly cemented quartzite. The degree of contemporary erosion by processes associated with snow accumulation and melting has not been quantitatively assessed, but one would expect more severe effects to have operated on the Cradle Plateau during the LGM when the plateau stood above glaciers in the adjacent valleys.

Although some small lakes of the Tasmanian highlands freeze during winter, few large lakes do. However, two phenomena indicative of strong past seasonal freezing have been noted on some of the larger lakes. These include the formation of ice-pushed boulder shorelines that occur on lakes as large as Great Lake (c. 20 × 10 km size).27 In addition, mid-lake boulder ridges, formed by the transport of boulders by lake ice from different centres of freezing in shallow basins have been observed at Lake Ina, Double Lagoon, First Bar Lake and Second Bar Lake by Carey.28 None of these boulder landforms associated with lake-ice formation are developing today. The boulder shorelines and mid-lake bars thus point to a period of colder conditions when large lakes were frequently covered with thick and persistent ice in winter.

**Other landforms and deposits of Tasmanian extraglacial environments**

Pleistocene glacial and periglacial processes were accompanied by accentuated alluviation and debris-flow processes, due largely to reduction of vegetation cover in river catchments. In addition, the climate over much of eastern and central Tasmania was strongly rain-shadowed from westerly influences and gave rise to dune-building processes.

The effects of increased alluviation are best illustrated in the Rocky Cape area, where many small valleys in quartzite have fans at their outlets.31 The fan-gravel beds are occasionally interrupted by organic palaeosols dated by radiocarbon to between c. 33 and 24 14C yr BP that represent periods of stability on parts of the fan surfaces. Similar fans occur north of the Derwent River between New Norfolk and Bridgewater, where they have complex histories probably spanning more than one glaciation.32

Examination of similar fans south of the Derwent River led Wasson33 to conclude that the fans accumulated largely as a result of debris flows. Many other currently inactive fans, covered with Holocene peat and soil occur throughout western Tasmania and suggest that during the last glaciation strong rain-fall events caused more erosion in small catchments than they do today, even though total rainfall is probably now greater.

Accumulations of wind-blown sand are relatively common in Midland and eastern Tasmania. They occur in one of four forms: as source-bordering river dunes, isolated dunes, lunettes adjacent to lagoons, and as linear dune-fields.

Source-bordering river dunes are small accumulations of fine sand derived from the beds of adjacent rivers. They are fossil accumulations fixed by soil profiles up to 1 m in depth, and suggest both stronger alluviation and wind action affecting the river channels. At Granton, south of the Derwent River, a 2–3 m section of silt forms the only loess known in Tasmania (Fig. 12).34 It consists of two units separated by a palaeosol and probably...
represents two colder climatic stages. That strong aeolian events occurred throughout southeastern Tasmania during the later part of the last glaciation is indicated by the occurrence of an isolated dune near Richmond dated to 15,740 ± 700 14C yr BP (SUA 376). Around the same time, after 19,810 ± 360 14C yr BP (SUA 153), a hollow was filled with dune sand at Pipe Clay Lagoon near Cremorne.

Lunette dunes have accumulated on the eastern margins of lagoons throughout the Tasmanian Midlands. Most are crescent-shaped ridges of fine sand that were formed by material blown from the lagoon beaches and depressions. The lunettes are mainly fossil, as most lagoons are remnants of their former size with little water and inactive beaches. The greatest number of lunettes and the most complex systems, with multiple ridges, occur in northeastern Tasmania and Flinders Island. There, they are associated with systems of linear dunes similar to those formed on the margins of the Australian arid area during and shortly after the LGM.

The ages of the lunettes and linear dunes are poorly constrained. Only one lunette has been dated. This, the innermost of three at Rushy Lagoon in northeastern Tasmania, was formed between 8570 ± 135 14C yr BP (I-11448A) and 8300 ± 80 14C yr BP (Beta 8190). The outer lunettes contain both clay and fine sand beds, reflecting variations in water levels in the adjacent lagoon, and are probably approximately of LGM age. The longest linear dune in northeastern Tasmania, the Ainslie dune, which overlies interglacial marine sediment has recently been dated by OSL and shown to have been active between 44 ± 4 kyr BP and 29 ± 3 kyr BP. This shows that dune formation had commenced in northeastern Tasmania by δ18O Stage 3 and suggests that it would have been widespread during the LGM.

**Periglacial environments**

The studies reviewed in this paper indicate:

1. A considerable range of landforms and deposits were formed in cold environments, external to glaciated areas, probably during several stages of the Quaternary.
2. Considerable difficulty in assessing the ages of most of these landforms and deposits by radiocarbon dating.
3. Difficulty of assessing the climatic conditions that influenced the processes of formation because of the occurrence of steep environmental and topographic gradients.

There is need, however, to provide an interim assessment of the probable ranges of extraglacial environmental and climatic conditions as suggested from the geomorphological evidence.

Studies of former glaciation in western Tasmania suggest that during the last two major glaciations (δ18O Stages 2 and 6) mean annual temperatures were c. 6.5°C and 7°C colder than today, and the ice formed under humid maritime conditions. This resulted in snowlines being 1000–1200 m lower than present atmospheric freezing levels, and varying from c. 830 m in western Tasmania to over 1500 m in the northeast. The strong north–south trending western ridges and sharp, central and eastern plateau edges accentuated leeward accumulation of snow and rain-shadowing. There was a strong gradient in precipitation across the island from the mountainous and humid western areas leeward of the Southern Ocean to the strongly rain-shadowed Midland and eastern areas leeward of the mountains and Central Plateau that were sub-humid to semi-arid. The topography also contributed to enhanced cold air drainage in the valleys in winter. In summer, the effects of a strengthened and more southerly positioned continental high enhanced the descent of westerly and northwesterly airflows from the Central Plateau to the eastern valleys with föhn-effect.

Only at altitudes over 1000 m does the presence of rock glaciers and ice-thrust dolerite columns indicate the occurrence of permafrost in the Central Highlands and northeastern mountains of Tasmania (Fig. 13). Elsewhere the block streams and block field features, formed above 900 m in central and eastern Tasmania, were probably developed in climatic conditions close
to permafrost with strong seasonal or short-term freezing. No lowland features associated with permafrost, such as ice-wedge pseudomorphs or fossil pingos, have been found despite intensive searching.

Calculations using only the ELR (not adjusted for reduction in cloud cover and atmospheric moisture during the LGM) and based on modern temperature data adjusted for estimated depression of MAT by c. 6°C at the peak of δ18O Stage 2 give 0°C mean annual values for altitudes between 980 and 1125 m. Sporadic permafrost above this altitude is thus likely. Modern treeline coincides closely with this altitude throughout Tasmania. Mean temperature for the warmest summer month is c. 10°C and at the LGM would have been c. 4°C.

By contrast, during the LGM a mean value of 0°C for the coldest winter months would occur at an altitude between 270 and 450 m. Thus, during winter, given sufficient moisture predominantly from westerly winds, prolonged freezing could induce widespread solifluction and mass movement processes at mid-altitudes and on steep slopes. This is consistent with the known distribution of thick solifluction deposits and landforms of mass movement down to c. 500 m. Such instability would have been greatly facilitated by the absence of forest vegetation over wide areas and particularly on steep slopes.32

The lowland areas of the Midlands, Derwent and southeastern valleys, northeastern coastal plain and Flinders Island all appear to have experienced very much drier conditions during the cold stages. However, climatic conditions may have been more variable and more geomorphic events of higher magnitude may have occurred than at present, as suggested by the formation of debris-flows and large alluvial fans near sea level. The driest regions were characterized by ephemeral groundwater lagoons with single and multiple lunette dune systems. In addition, linear dunes, similar to the fossil dunes of western Victoria,33 were formed on the northeastern coastal plain and Flinders Island by west-north-westerly to westerly winds.

The data contained in this paper were observed over many years. The work was supported by the University of Newcastle, the University of Tasmania, the Australian Research Council and numerous colleagues and students who accompanied me in the field. This paper is Contribution No. 47 of the Geomorphology and Quaternary Science Research Unit, School of Geosciences, University of Newcastle.

Periglacial research in New Zealand: a review

Paul Augustinus*

Periglacial phenomena and activity in New Zealand are best developed in the South Island, especially in the block mountains of Central Otago and the ranges east of the axis of the Southern Alps. Most of the periglacial features are generally regarded as fossil features, although some are currently active. Permafrost is now considered to occur but is restricted to a narrow zone above c. 2000 m in the Southern Alps. Other significant developments since the last review of New Zealand periglacial phenomena include examination of current patterned ground activity in Central Otago and investigation of the timing and mechanisms of rock glacier formation in the central Southern Alps. This review indicates that there is a large body of information pertaining to the nature and distribution of the features and processes, but only limited understanding of the controls on their formation.

Introduction

Periglacial activity, both fossil and active, forms an important component of the landscape of the Central Otago highlands, the ranges on the eastern side of the Southern Alps, as well as the Marlborough area and Kaikoura Ranges, all of which are in the South Island of New Zealand (Fig. 1). The elevation of these ranges, combined with regular sub-zero winter temperatures, suggests that such processes should constitute important landscape-modifying agents. The Southern Alps are a 400 by 80-km mountain range trending SW to NE, and are asymmetric, rising steeply from the narrow coastal plain on the western side, to reach over 3000 m at the crest of the main divide. East of the divide the mountains decline in elevation through a series of ranges and basins and are dominated by gravel-filled, eastward-flowing valleys with gentle gradients and braided channels. The western side of the divide is in stark contrast, with rapid uplift and associated greater dissection having produced greater relief and steep stream gradients (Fig. 2).

The Southern Alps lie across the prevailing westerly wind system, so that precipitation rises rapidly from 5000 mm/yr at the western margin to a maximum of 12 000 mm/yr on the crest of the western ranges. Precipitation declines rapidly to the east, with a second maximum at the main divide before dropping to ~600 mm/yr in the driest parts of the eastern Alps (Fig. 2). Mean annual temperatures and the number of frosts per year vary with both altitude and latitude. Mean annual temperatures range from 8.4°C at 765 m to 3.8°C at 1550 m elevation. Temperatures rarely exceed 20°C or fall below 15°C. Frost frequency is high, with many areas receiving more than 100 frosts each year. Soons and Price produced a simple extrapolation of mean annual temperatures with increasing elevation to show that large areas of the South Island, and restricted areas in the central and southern parts of the North Island, are subject to sub-zero (°C) temperatures for several months of the year. Furthermore, in many of these areas there are frequent freeze-thaw cycles.

Soons and Price discussed a number of other features that are likely, but not unambiguous, indicators of former or present periglacial processes and conditions. Many of the features are clearly associated with cooler climates, but they considered it uncertain whether conditions were severe enough to warrant the description ‘periglacial’. Despite debate over the definition of periglacial geomorphology (see review of the debate in ref. 3, p. 142), there is general agreement that it incorporates all those landforms that have their genesis dominated by seasonal frost or permafrost, although allied components include the geomorphic work of snowpacks and rock fall. In this review, the broadest definition of periglacial geomorphology is used. Before the periglacial activity and landforms are examined, however, the character of this landscape will be discussed as it pertains to the distribution of periglacial landforms and the nature of many of the processes.

Geomorphological setting of the Southern Alps

Whitehouse described the geomorphology of the alps with respect to east–west variation in tectonic uplift, precipitation and erosion rates, and recognized three regions broadly paralleling the axis of the ranges: western, axial, and eastern regions. The eastern region is characterized by the lowest precipitation, uplift and erosion rates (Fig. 2), with a series of low mountain ranges rising steeply from the narrow coastal plain on the western side.

Fig. 1. Location map for New Zealand showing: (a) general setting; (b) locations mentioned in the text and major topographic elements; (c) broad precipitation patterns and dominant wind directions; (d) distribution of modern and last glacial maximum (LGM) glaciers. Modified from Suggate.

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and hills separated by intermontain basins. This area is subdivided into two subregions: (1) the eastern front range subregion, which displays little or no imprint of Pleistocene glaciation, with many ridges smooth and flat-topped. Moderately steep slopes are convexo-concave and often mantled with coarse colluvium. Fluvial dissection and infrequent mass failure of the hillslopes are the main erosional processes. (2) The basin and range subregion comprises a series of minor ranges separated by basins and wide-braced river valleys. Pleistocene depositional landforms (moraines, terraces, fans) are well developed in the basins and wide-braided river valleys. Pleistocene depositional range subregion comprises a series of minor ranges separated by hillslopes are the main erosional processes. (2) The basin and range subregion comprises a series of minor ranges separated by basins and wide-braced river valleys. Pleistocene depositional landforms (moraines, terraces, fans) are well developed in the basins and wide-braided river valleys. Pleistocene depositional range subregion comprises a series of minor ranges separated by basins and wide-braced river valleys. Pleistocene depositional landforms (moraines, terraces, fans) are well developed in the basins and wide-braided river valleys.

In this region periglacial processes and landforms are common at lower altitudes. In the axial belt, with sharp ridge crests separating cirques with Holocene moraines. Glacial erosion, rockfall and snow avalanches are the main land-forming processes. Slopes are typically steep, ridge crests narrow, and bare rock widespread. Talus and debris fans are common at lower altitudes.

Uplift, precipitation and erosion are greatest in the western region, resulting in an intensely dissected landscape characterized by steep, rectilinear slopes, narrow ridge crests, poor preservation of glacial landforms, rapid fluvial erosion and mass movement. In this region periglacial processes and landforms are poorly developed and preserved, largely as a consequence of the presence of extreme geomorphic activity due to rapid tectonic uplift and denudation, with the latter driven by precipitation.

**Regional distribution of periglacial processes and landforms**

Periglacial landforms and processes have their distribution controlled by the prevailing climate (especially precipitation and temperature), elevation, relief and rates of erosion. Consequently, the processes and their landforms are best developed and preserved in the eastern belt and, to a much lesser extent, the drier eastern sector of the axial belt. In the context of this review, processes and landforms considered to be typical of the periglacial environment are examined (those typical of seasonal/ daily freeze–thaw and permafrost such as rock glaciers and patterned ground), as well as several processes and their

**Central Otago**

Probably the best-known and studied periglacial phenomena in New Zealand are developed on the mountains of central Otago. Here, a peneplain occurs as a low relief surface cut in schist basement rock. In places the peneplain is preserved as a deeply and irregularly weathered surface beneath Tertiary sediments. The depth of weathering on this surface has been lithologically and structurally controlled. Environmental conditions in this area are extreme, with the Old Man range summit area at c. 1600 m having a mean monthly temperature ranging from 5°C in mid-summer to –7°C in winter. Freeze-thaw cycles occur for about 49% of the year, with temperatures on 31% of the days remaining below freezing. Furthermore, the soil at a depth of 10 cm remains continuously frozen for about 3 months in mid-winter.

The age and origin of the periglacial landforms developed on the Central Otago peneplain have been investigated in a number of studies (e.g. refs 11–14, 16–19). In this area, solifluction appears to be the main process, with well-developed lobes and terraces, up to 1.4 m high, a characteristic of slopes in the lee of the dominant snow-bearing winds from the west. These terraces and solifluction lobes (Fig. 3c) are seasonally active and slow moving.

Patterned ground of a range of forms has been described from the Central Otago ranges. Soil hummocks and stripes as well as solifluction terraces, lobes and small sorted stone-strips and nets are widespread (Figs 3a–c), but large features of this type are restricted to areas of low metamorphic grade chlorite schist and greywacke, implying a significant component of lithological control on their distribution and development. The activity of the solifluction lobes and terraces in the Old Man Range was measured by Mark, who ascribed relatively low average rates of surface movement to the absence of permafrost and the good site drainage. Hence, many of the periglacial features formerly thought to be remnants of more severe glacial stage environments are active and responding to present climatic conditions. Bell described surficial periglacial deposits on the K9 landslide in the Kawarau Valley, Central Otago. However, these may have their origins in landsliding and not through periglacial climate. Similarly, the large terraces attributed to a solifluction origin on the K9 landslide may be a consequence of slow mass movements over a long period rather than to past periglacial activity.

The St Mary’s Range (Fig. 1b) is the northernmost range with the characteristics of the Central Otago block mountains, with its broad summits displaying a range of features including soil terraces, a small rock glacier, blockfields and patterned ground. Most of these features, including the extensive blockfields, appear to be inactive. However, Orwin found that the fines in the centre of stone circles are being sorted during modern
diurnal freeze–thaw cycles. The ground surface is probably frozen and under snow for several months of the year, although freeze–thaw cycles occur frequently other than during winter.

Valley asymmetry is also common in the Central Otago area with the grain of the topography controlled to a large extent by the foliation in the schist. Leslie suggested that the valley asymmetry is a relict periglacial feature: south-facing slopes are steeper than those with a northerly aspect as the latter would have experienced greater melt and more intense periglacial activity. Bell recognized that the geomorphology of the Kawarau Valley had been strongly influenced by the structure of the schist, however, with failure preferentially occurring on slopes parallel to the foliation, so that a marked valley cross-profile asymmetry develops. The lower gorge of the Kawarau River is developed parallel to the foliation in the schist and the valley is strongly asymmetric with the foliation dip-slope mantled by extensive landslide and periglacial deposits.

This idea of structural control on valley side-slope asymmetry was extended by Augustinus, who demonstrated that structure and rock mass strength played a crucial role in controlling slope form in the schist and greywacke terrain of the axial Southern Alps.

Tors are particularly well developed on the schist in the mountains of Central Otago (Fig. 3d) and have been the focus of numerous studies (e.g. refs 14, 16, 17, 18, 30). The tors occur predominantly (but not exclusively) on the uplands and explanations for their origins range from exhumation of Tertiary landscapes to a recent periglacial origin whereby resistant and massively jointed schist blocks were preserved during periods of intense frost weathering and isolated by solifluction-driven removal of the debris. Wood suggested that as much as 15 m of schist may have been comminuted and removed under periglacial conditions associated with the last glaciation. However, the most recent detailed studies of these features suggested that the upland tors are produced by the combined effect of differential chemical weathering during interglacials and subsequent intense frost weathering during glacial periods. According to this model, the debris was largely removed from the summits by solifluction towards the end of glacial episodes leaving isolated tors, without the need to invoke formation by periglacial processes. Fahey recognized that while some of the tors on the higher surface may be the result of one set of processes, most are probably polygenetic, having formed as a response to different mechanisms at different times during the Quaternary. Furthermore, analysis of the weathering pits on the tors by Fahey indicated that frost weathering and hydration are current formative mechanisms on pits of all stages of development, with only the larger pits on exposed degraded schist tor surfaces thought to be older that the last glaciation.

Loess in Central Otago has been at least partially attributed by several workers to periglacial processes (e.g. ref. 29). However, there is little clear evidence for a periglacial origin for the loess, although it is accepted that in most cases the widespread loess sheets are associated with cold phases when outwash surfaces were extensive, unconsolidated silts were exposed on the continental shelf, and deflation was assisted by periglacial processes.

Axial ranges and Fiordland

In the high relief ranges near the main divide of the Southern Alps, periglacial processes and landforms are poorly developed and preserved due to the extreme level of erosion, with snow avalanching, intense free-thaw and rockfall the most important slope-modifying processes. Other than glacial processes, modification of the slopes occurs largely by mixed snow and rock

Fig. 3. Photographs showing characteristic fossil and modern periglacial landforms on the Pisa Range, Central Otago highlands: (a) frost-sorted polygons, (b) possible cryoplanation surface, (c) tors and (d) solifluction terraces. Periglacial features indicated by arrows.
avalanching, which often produces erosion of rock slopes through grooving of gullies.\textsuperscript{11} In the extreme relief mountains of Fiordland, mixed rock and snow avalanches may fall more than 2000 m to create impact craters termed avalanche tarns by Fitzharris and Owens.\textsuperscript{22} Large amounts of debris can be transported during these events and allow rapid production of talus fans.\textsuperscript{31,35}

The Cropp River basin in Westland is adjacent to the main divide and geomorphic processes are rapidly modifying the landscape, so that most soils are young.\textsuperscript{34} The foliation in the schist imparts a strong NE–SW grain to the landscape. Drainage density on the steep rectilinear slopes is high (50 km/km\textsuperscript{2}), the debris mantle is \texttextless\textless~1 m deep and discontinuous, and shallow debris avalanche scars are common.\textsuperscript{7,34} A wide variety of mass movements occur in the upper Cropp basin, with rock fall common above the vegetation limit. Deep-seated movement on steeply dipping joints causes mass creep of pelitic schist on the north side of the Cropp River basin.\textsuperscript{34}

In forest and scrub-covered areas, regolith failures are mainly episodic debris avalanches, slides and flows associated with high intensity rainfall events. Slow continuous mass movements are also common. Turf-banked terraces formed by solifluction are common under tussock grassland.\textsuperscript{24} Tension cracks across steep slopes also indicate creep. Snow avalanches, slushflow and related snow movement erosion are active at higher elevations within the basins.

Eastern Central South Island

The ranges on the eastern side of the main axial ranges are drier owing to the steep moisture gradient (Figs 1c, 2) with precipitation ranging from 400–600 mm/yr. In this area, rock fall and slush avalanching are the dominant geomorphic processes, although rock glaciers are present in a narrow belt on the eastern side of the divide\textsuperscript{35,36,38} associated with increasing continentality.\textsuperscript{1} Some of the features are probably relict, but many have apparently developed in debris from periglacial freeze–thaw processes and rock avalanches under present conditions.

Most research on rock glaciers in New Zealand has concentrated on identification and dating of periods of activity so as to extend the Holocene glacial chronology into the drier eastern ranges (e.g. refs 35, 37). Birkeland\textsuperscript{37} identified four periods of Neoglacial activity from weathering rind and lichenometric dating of moraines and rock glaciers in the central Ben Ohau Range, and suggested that many of the rock glaciers show signs of recent reactivation. Gellatly \textit{et al.}\textsuperscript{39} assumed that most rock glaciers are of glacial origin, although McGregor\textsuperscript{30} argued that a non-glacial origin is more likely. A recent study by Kirkbride and Brazier\textsuperscript{40} of rock glaciers in the Ben Ohau Range showed that all were formed during the Neoglacial, although differences were noted in the number of new rock glacier lobes formed by climatic fluctuations. Rock glacier formation can be explained in terms of: (1) an internal threshold involving the requirement of a climate cool enough to allow internal ice to form and build up within talus slopes; and (2) an internal threshold related to the accumulation of a talus blanket thick enough to generate the shear stresses needed to overcome resisting internal friction within the talus/vc ice mass.\textsuperscript{39}

Brazier \textit{et al.}\textsuperscript{40} classified landforms generated by ice and debris transport marginal to the formerly glaciated central Southern Alps (Ben Ohau Range) into: debris-covered glaciers; cirque-floor lobes; and talus-covered rock glaciers (Figs 4). Their classification and mapping of landforms revealed a distinct zonation in the Ben Ohau Range with respect to both landform type and activity (Fig. 5). They suggested that permafrost occurs in a narrow zone above 2000 m in this part of the Southern Alps, with topographic factors causing sporadic permafrost to be less widespread than expected solely on altitudinal grounds.\textsuperscript{40} This sporadic permafrost is delineated by the presence of the active rock glaciers and is determined by aspect-controlled variation in local topoclimates as well as the \textdegree C isotherm and mean annual precipitation of at least 1500 mm.\textsuperscript{40} The altitudinal spread of fossil talus rock glaciers (Fig. 5) suggests that the minimum permafrost level may have been depressed to less than 1700 m when they were active, although their ages are poorly constrained.

The active talus rock glaciers in the Ben Ohau Range occur close to the 1500-mm isohyet and where glacier equilibrium line altitudes (ELAs) exceed 2100 m (Fig. 5). Note that when the calculated maximum and minimum elevation of the present \textdegree C isotherm is compared with the distribution of active and fossil landforms, nearly all of the active talus rock glaciers and cirque floor lobes lie above the minimum elevation of this isotherm (Fig. 5). However, the present mean annual temperatures may not be representative of the conditions required to
activate the rock glaciers, so that the present active landform distribution probably reflects cooler late Holocene climates. Furthermore, the narrow zone of active rock glacier sites on the Ben Ohau Range is influenced by aspect control on insolation receipt, with buildup of ice in the rock glaciers most probably due to refreezing of water within talus exposed to favourable microclimates. Further east where precipitation and mountains are lower, active rock glaciers are absent, and ice-free talus slopes are presently the dominant means of debris transfer to the valley base.

Talus surfaces developed in the Craigieburn Range were examined by Pierson and Whitehouse and McSaveney. Whitehouse and McSaveney used surface colour and weathering rinds to show that age distributions on debris-flow taluses were indicative of irregular episodic accumulation of lobate debris flows, with intervening smoothing by snow glide and snow avalanching. Debris transport by avalanche in this region has been shown to be an important geomorphic process (e.g. refs 33, 43), especially in those sites favouring recurrent avalanche activity. These sites are usually steep, unvegetated slopes in the seasonal snow zone, with a southeastern aspect and partially sheltered from the prevailing westerly winds and lack evidence of long-term stability.

Pierson identified three scree types in the northern Craigieburn Ranges, each of which displays different hydrological characteristics related to the sorting, stratification, packing and texture of the debris: (1) non-stratified openwork gravels mainly associated with talus cones; (2) stratified gravel, sands and silts; and (3) scree sheets with a truncated silt-loam soil beneath the surface gravel. Stratified scree were first noted by Soons and later studied by Harris and McArthur. These types of deposits are typically over lain by modern soil and are no longer active. McArthur identified stratified scree as part of the fan depositional sequence in the Craigieburn Range and considered that they developed as seasonal responses to catchment thawing during glacial decay accompanied by heavy loess deposition. Similarly, Harris, in a study of stratified scree in the Porters Pass area (Fig. 1b) demonstrated that every 10 m of stratified scree contains at least 5 m of loess. Consequently, development of the scree was considered to be associated with more severe conditions than those persisting in these areas at present, and has a different origin from that suggested for stratified scree by European workers.

Canterbury Plains

Loess deposits are extensive in New Zealand, especially in Canterbury Plains and other lowland areas east of the ranges in the South Island, although they are generally not of periglacial origin, unlike their Central Asian counterparts. The loess sheets in New Zealand have been attributed to Quaternary glacial stages when outwash surfaces were extensive and deflation was aided by needle ice and other frost processes (e.g. refs 49, 50).

Deposition of loess has generally continued to the present, with the modern loess deposits, like the older deposits, being thickest immediately south of rivers and thinning rapidly away from the source. Hence, although some of the loess sheets in the South Island may have an origin due to frost action in rock in the uplands (e.g. ref. 29), most have probably evolved from deflation of fines from the extensive unvegetated outwash surfaces developed during glacial cold phases.

Harris described ice wedge-like features in the form of infilled fissures from the interface between two loess units in exposed locations on Banks Peninsula. The homogeneity of the infill suggested an origin as small ice-wedges, as does their form. However, Harris noted no other features that would support the presence of permafrost in the region, and suggested instead that they most likely had an origin as seasonal frost cracks due to their close spacing and size. Similarly, the infills lack the vertical stratification described from many fossil ice wedges. If they are ice wedge casts, they would require either permafrost or deep seasonal freezing for their formation, and if the former, they would have required cooling close to sea level of at least 16°C. Soons and Price suggested that the formation of the infilled fissure could have occurred as a response to local site conditions that promoted deep freezing. This explanation was considered to be more compatible with other evidence that suggests that the temperature depression in the area is approximately 10°C less than that required to produce ice wedges. Hence, the origin and significance of the ice-wedge-like features is problematic.

Wellington and Marlborough areas

Cotton developed the concept of alternating morphogenetic systems in which landforms in the Wellington area were considered to have been shaped largely by freeze–thaw processes during glacial and stadial periods, and fluvial erosion during interglacials and interstadials. In many higher areas, the greywacke slopes are covered by colluvial debris and solifluction deposits that undergo periodic instability under present-day conditions. The solifluction deposits (angular, frost-shattered clasts in a silt matrix) were initially identified by Cotton and Te Punga and in several places pollen analyses and 14C ages suggested that they were of Last Glacial Maximum affinity and hence probably of periglacial origin. A cold climate origin for the material is supported by the association of glacial loess with the solilfuction deposits.

Other deposits that have been attributed to periglacial (possibly even permafrost) conditions and processes by various workers are sediment-filled wedges, valley-fills and fan deposits, especially in the Marlborough and Wellington areas. Ice-wedge-like features near Wellington were described by Cotton and Te Punga and Te Punag. Infilled gullies in the Wellington region have been attributed to periglacial environments. In some cases the fills extend below modern sea level and hence have been attributed to cooler climatic conditions. However, a
periglacial origin for these features is disputed, and Crozier et al.\textsuperscript{26} referred to them as colluvium-filled bedrock depressions (CBDs).

Although the CBDs are fossil, they make a significant contribution to the location of landslides as these sites often exceed the critical depth required for slope stability. Consequently, they are more susceptible to landsliding than where there is limited regolith buildup, and an increased occurrence of failures at these sites seems to have occurred due to deforestation and removal of root cohesion.\textsuperscript{30} Hence, the fossil nature of the gullies is not an unambiguous indication of an origin due to freeze–thaw processes.

In the Marlborough-Nelson area there is widespread evidence of periglacial activity in the form of fossil gullies and screes to elevations down to 200 m. Here, fossil screes with palaeosols containing the 22 000-yr-old Kawakawa Tephra\textsuperscript{46} indicate that repeated cycles of slope erosion have occurred followed by infilling with scree and slope smoothing (cold climate aggradation).

Discussion and conclusions

This review of periglacial phenomena illustrates the range of features found in the New Zealand alpine landscape. Many of the periglacial landforms are fossil, but some are still active and may even indicate the former development of permafrost above the periglacial landforms are fossil, but some are still active and features found in the New Zealand alpine landscape. Many of

The distribution of the fossil and modern permafrost phenomena results from a combination of the local topography and lithology as well as climatological factors. The mountains that form the spine of the South Island have steep and rocky slopes which tend to display snow-related processes and landforms, such as avalanching and nivation, as well as talus fans and rock glaciers. However, patterned ground is uncommon in this terrain. The uplands of Central Otago and the more subdued peaks of Canterbury and Marlborough are located in the lee of the main axial range, so that they are exposed to greater temperature ranges and lower precipitation. As a consequence, patterned ground and solifluction are best developed in these areas. In all parts, availability of an appropriate size of material for movement by frost action is a crucial factor influencing the form of patterned ground. Lithology plays an important part in the development of periglacial features, especially the fissile and foliated schist that dominates the Central Otago highlands.

Extensive areas of the mountains experience sub-zero temperatures for several months of the year, but insolation intensity dictates that thawing will occur during the day in many places, resulting in optimal conditions for patterned ground development, especially in the Central Otago highlands (e.g. refs 18, 20). Furthermore, many of these solifluction lobes and terraces are still active, despite their fully-vegetated state, belying previous work that considered this condition to indicate current inactivity.\textsuperscript{7} Whilst the appropriate temperature and moisture conditions must be present, the virtual absence of frost-related features over a wide area where climatic conditions should allow it to develop appears to be mainly a function of topography. This is the case with the spatial and altitudinal distribution of both fossil and active talus rock glaciers in the Ben Ohau Range, where topographic shading of sites modifies the simple temperature-altitude controls on rock glacier distribution.\textsuperscript{10}

Willett\textsuperscript{11} first suggested that the non-glaciated highland parts of the South Island may have experienced a tundra climate during glacial episodes in the late Pleistocene. This idea gained support from the descriptions of ice-wedge-like features near Wellington\textsuperscript{55,57} and Banks Peninsula.\textsuperscript{51} Similarly, patterned ground in the Central Otago Highlands\textsuperscript{49,50} may be a result of permafrost, although Mark\textsuperscript{42} showed that despite the crests of soil stripes and hummocks remaining continuously frozen to at least 20 cm over winter, soil in depressions remained unfrozen at that depth. Recent work by Brazier et al.\textsuperscript{26} suggests that although permafrost occurs in the Southern Alps, it is restricted to a narrow zone above 2000 m and distribution within that zone is restricted by topographically controlled shading. This zone of discontinuous permafrost and associated rock glaciers is climatically sensitive and needs to be carefully mapped and monitored on a regular and long-term basis.

In an influential study of sedimentation in Ivory Lake, a proglacial formation immediately on the western side of the main divide in the central Southern Alps, Hicks et al.\textsuperscript{22} developed a sediment budget for the lake and argued that mechanical disintegration of the schist forming the walls of the basin provided approximately 60% of the sediment load. Schist debris was transported largely downslope by rockfall, snow avalanches and high-intensity rainstorm-induced mass flows, with glacially derived sediment only a minor component of the total. This work has been used by others to argue that fluvial erosion is more important than glacial erosion in mountain landscape development (e.g. ref. 63) and has engendered much discussion of the relative importance of the two processes.\textsuperscript{64–66} Hence, the activity and intensity of periglacial processes may play a powerful role in influencing the nature and rate of alpine landscape development, especially during interglacials and interstadials when glacier and snow cover is more restricted.

The fossil and active periglacial phenomena have important implications for reconstruction of late Quaternary palaeoclimates and the nature of present-day climate change. Although there are many periglacial features that could be used for palaeoclimatic interpretation, however, there has been little attempt at monitoring environmental conditions and evaluating the periglacial process controls necessary to enable this to be undertaken in New Zealand. In view of the marginal nature of the permafrost that persists, the Southern Alps of New Zealand would be an ideal place in which to monitor mountain permafrost in the context of projected global climate change. However, before this can happen the distribution of periglacial processes, their variability and related process controls must be adequately defined and understood.

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Review of Present and Quaternary periglacial processes and landforms of the maritime and sub-Antarctic region

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Present and past periglacial processes and landforms of the southern hemisphere are being reviewed as part of a new initiative by the International Permafrost Association. In this paper, details are provided regarding available information pertaining to both the maritime and sub-Antarctic region. All the islands within this broad zone have experienced glaciation during the Quaternary and many still support ice caps, of varying dimensions, today. These islands currently experience strong westerly winds and high precipitation. Temperatures are less severe than on the continent, with lower values to the south of the Antarctic Convergence and higher to the north. All locations, however, experience conditions conducive to active periglacial processes and landforms; some of the more southerly sites exhibit discontinuous permafrost. Three reviews1–3 have provided a broad outline of information on landforms in the Antarctic region today. The aim here is to give a more up-to-date account, and to review the information regarding relict features that indicate past, more severe, conditions. Although studies in the Antarctic are, in general, less sophisticated than their Arctic or alpine counterparts, there is nevertheless an extensive body of information that is not well known by many northern hemisphere workers. A wide range of landforms are currently active, including sorted patterned ground, protalus ramparts, blockstreams and stone-banked lobes, and those subject to solifluction, cryogenic weathering, and nivation. The strong winds found throughout this region impact significantly upon landform development, particularly the orientation of some features, to a far greater degree than is recorded for the northern hemisphere. Animals also exert a significant influence within the periglacial regime.

Introduction

The many isolated islands of the sub- and maritime Antarctic (Fig. 1) experienced varying degrees of glaciation during the last glacial.4 Some, such as Macquarie Island, due to its northerly position and low elevations, sustained only a few, very small glaciers. Others, such as Marion Island, had extensive but not a complete ice cover, whilst those closer to Antarctica (such as Bovetøya or Heard Island) were totally ice covered (see refs 4 and 5 for details). Today, ice is still extensive on the islands closest to the Antarctic but those further away support only limited ice caps or no ice cover at all. Thus, these islands represent a range of locations that have experienced, or are experiencing, a cryogenic environment of varying severity for varying periods of time. As a result, the islands abound in periglacial landforms, both active and inactive, associated with both permafrost and seasonal freezing. Brief details regarding the periglacial environment of the sub-Antarctic and Antarctic islands have been given in Walton1 and Hall.2 More extensive details are now available, however, and so it is appropriate to update the information and to place it in the context of recent theory and possible future climatic change.

Climatically, all of the islands, away from close proximity to the continent, are affected by a continuous stream of eastward-moving cyclonic depressions. These bring humid air masses; more temperate, humid air from the north, or colder, drier air from Antarctica can also periodically affect the islands.4 Climate is severely influenced by the location of any individual island with respect to adjacent land or sea masses as well as its position relative to the Antarctic Convergence. Land masses can produce a rain shadow effect, as in the case of South America with respect to the Falkland Islands. Islands to the north of the Antarctic Convergence (for instance the Falklands, Marion and Prince Edward Islands, and the Crozet Islands) experience milder temperatures and less snowfall than those to the south (for example Bovetøya or South Georgia). The islands become colder with increase in latitude.4 Thus, position has a very strong influence on the past and present extent of glaciation as well as the degree of cryogenic activity. It is also significant that not all the islands appear to have been affected by the Little Ice Age but all that were affected now experience marked glacier retreat.6 Details

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regarding past and present ice cover for the Antarctic islands can be found in refs 4, 6–8. More detailed information and an historical bibliography regarding climatic conditions for this area can be found in refs 9–16.

Against this background of past and present ice cover, I will discuss each island or island group individually. One significant limitation of this review, particularly in the light of the title, is that regarding process(es). Unfortunately, there has been very little in the way of true process studies; processes are usually inferred in most reports. This reflects, in part, logistical and instrumentation problems that are only recently being overcome, coupled with the relatively low importance of periglacial studies in most national programmes in recent years. That said, some detailed, instrumented studies have begun (see the recent work of Boelhouwers et al.17) in an attempt to investigate processes over long periods at some locations, but these are few and far between.

The Falkland Islands

The Falkland Islands (51–52°30'S, 60–61°30'W) comprise two main islands, East (c. 5000 km²) and West (c. 3500 km²) Falkland, and a further 250 smaller islands. The islands are to the north of the Antarctic Convergence and c. 500 km east of the Atlantic coast of southern Patagonia (Fig. 1). They are surrounded by a temperate sea (mean winter temperature at sea level is 2°C), and receive little precipitation (c. 600 mm yr⁻¹).1 The islands experience overcast conditions, with the percentage of available sunshine received being only 20% to 37% of that possible, strong westerly winds, the available precipitation fairly equally distributed throughout the year1 and only a small seasonal temperature range. As a consequence of these conditions, the climate does not encourage cryogenic activity except on the highest summits,2 although Wilson and Clark20 have found sorting taking place at 35 m a.s.l. (see below). However, only a small decrease in temperature would be required to initiate a periglacial regime.18

Clark18 provides a synthesis of information available in 1972. Features such as blockfields, altiplanation surfaces, tors, block terraces, stone runs, solifluction, thermokarst and scree slopes are all listed and discussed within their climatic context. One of the most significant works to come from the Falklands is that of Andersson,20 in which the concept of solifluction is first discussed. Andersson20,21 used the concept to help explain the extensive stone runs that occur amongst the Falkland hills (Fig. 2), features that Darwin22 first commented on and were later discussed by Davison.23 All discussions regarding stone runs18,21,24–27 identify them as of a periglacial origin. Important in this context is that during the Quaternary the Falklands were glaciated18,28–30 but limited to cirque glaciers. Clapperton1 identifies only 20 cirques and these are confined to the three highest massifs, and the largest glaciers were only of the order of 3 km in length. Thus, during the Quaternary at a time when the climate was clearly cooler than at present it nevertheless lacked the precipitation for the development of a substantial ice cover as, for instance, formed in Patagonia. This does indicate, however, that the greater part of the Falkland Islands was exposed to a more severe cryogenic environment during the Quaternary and that ‘...almost the whole archipelago is covered by sediment developed by periglacial mass wasting...’ (ref. 4, p. 232).

Solifluction deposits up to 3 m thick are exposed at some coastal sites (for example, Bull Valley), where as many as six phases of solifluction have been identified.24 Available radiocarbon dates30 suggest that the last interval of solifluction coincided with the Last Glacial Maximum (LGM). However, more recent 14C dates31 suggest that climatic amelioration occurred significantly earlier than was previously thought and so ended this period of solifluction activity. The solifluction deposits are now suggested31 to be the correlative facies of periglacial weathering and transport developed in lithologies other than those in which the stone runs are found (e.g. the quartzites and sandstones). Clark et al.20 dated Late Pleistocene organic-rich deposits, enclosed by products of periglacial mass wasting, between 36 and 28 kyr BP. They found a marked similarity between Late Pleistocene interstadial, Holocene and present-day pollen assemblages and suggest that this reflects the lack of sensitivity of the vegetation to climatic change and/or the lack of climatic variation during this period. Thick accumulations of aeolian and alluvial sands are considered to be derived32 from weathering of the local bedrock under periglacial conditions during the Late Pleistocene. In addition to extensive 'head' deposits, Clark33 also argues for the former existence of permafrost as evidenced (in the form of lakes) by fossil, degraded pingos and ice-wedge pseudomorphs.

The stone runs comprise ‘...extensive quartzite blockfields marked by valley axis boulder spreads, almost completely devoid of vegetation, that are attributed to solifluction in a periglacial climate’ (ref. 31, p. 36). Andersson20,21 suggested that these features resulted from flow-creep of frost-riven quartzite blocks, the quartzose sandstones producing the principal hill features. The hillside debris cover transforms into stone runs at

Fig. 2. Views of the stone runs that occur amongst the Falkland hills.

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the lower margins (Fig. 3) where the boulders are several metres in length (and match, in size, the joint-determined blocks of the outcrops); the stone run surface is very irregular and perched boulders are found. An important factor, noted by Joyce, is that some runs appear to pass completely over rounded hills but that this may reflect the juxtaposition of a stone run with an autochthonous blockfield. Strange declares that there is a contrast between the stone runs and the blockfields proper. The runs may have axial gradients as low as 1° with lateral gradients of 6° to 8°. The runs are more extensive than they appear as they both extend below sea level and are often covered by heathland vegetation (Fig. 3); the longest exposed run is approximately 5 km; details of this, the Andersson stone run, can be found in ref. 27. Bellosi and Jalfini found that there was a progressive decrease of block diameter and flatness downstream, whereas sphericity and roundness increased but there was only a weak trend in block orientation parallel to the overall flow direction. Although not suggesting a rock glacier origin, these authors indicate similarities with rock glacier attributes. Bellosi and Jalfini suggest that some of the block characteristics were developed after the creation of the stone run as a result of climatic changes at the end of the last glacial. Such ideas are in accord with the recording, by Clark, of deep chemical weathering which has had an effect on recent landscape development.

These stone runs remain a controversial feature. Joyce found it difficult to accept solifluction in their formation, except in a minor role. He cites the absence of stone runs on the south slope of Wickham Heights, where quartzites reach their highest point and where solifluction should operate, as a key factor. Joyce was also concerned about the ability of solifluction actually to transport such large material and its ability to do so without jamming the blocks. Joyce rather suggested that the location of the runs was purely a function of geological structure at the sites; whilst this can explain the hillside and near-summit occurrences, it does not account for valley accumulations. Strange also refers to work by Maling, Dodds and other workers, who each had different explanations. Dodds (cited in ref. 34) found that on summits the loose blocks were still in juxtaposition to each other and showed no sign of movement. Elsewhere, however, some form of transport has certainly taken place as quartzite blocks now cross lithological junctions or rest on other lithologies. Clapperton, based on morphological and internal characteristics, plus their spatial relationship to glacial features, concludes that they are an extreme form of sorted stripes.

Sorted patterned ground is not only described for the Falkland Islands but is also considered to be actively forming at this time. At a height of only 35 m a.s.l., Wilson and Clark found that sorting, in the form of miniature nets and stripes, took place in an area of recent soil erosion. This they attribute to the cool but relatively wet oceanic climate that can facilitate small-scale sorting. Clark notes frost sorting of the blockfield on Mt Usborne as well as in the debris mantle and stone runs at various locations in the Falklands. He also observes sorting of stony ramparts (protalus ramparts?) enclosing cirque lakes, as well as sorted stripes down...
to an altitude of 400 m a.s.l. developed in the coarse debris of hillslides. Clapperton,\(^{33}\) in a discussion of the stone runs, concludes that they were formed by processes similar to those that generate sorted stripes; the stone runs being but an exceptional form at an extreme scale. Clark,\(^{36}\) also argues for the former existence of non-sorted patterned ground associated with ice-wedges and uses these as an argument for the previous existence of permafrost in the Falklands. Should this have been the case, it would mean a 12–15°C drop in mean annual temperature from the present.

**Marion and Prince Edward Islands**

Marion and Prince Edward Islands (46°48’–46°59’S, 37°35’–37°55’E) are the small (290 km\(^2\) and 40 km\(^2\), respectively) peaks of a submerged volcano (Fig. 1). Located to the north of the Antarctic Convergence, the islands experience a cool, isothermal climate with extensive, year-round precipitation and continuous westerly winds. Although extensively glaciated during the Quaternary,\(^{37,38}\) there is presently only a very small (<3 km\(^2\)), rapidly receding ice cover at the very top (>1000 m a.s.l.) of the island (J. Boelhouwers, pers. comm.). Based on the reconstruction of glacial maximum equilibrium line altitudes, known lapse rates and from palynological data,\(^{37,39}\) a mean annual decrease in temperature of between 3° and 6°C is estimated for the last glacial. Such a decrease would give Last Glacial Maximum in temperature of between 3° and 6°C is estimated for the last glacial.

Early studies\(^{39,40,41}\) identified sorted stripes, stone-banked lobes, miniature sorted circles and vegetation-banked steps (Fig. 4). The stone-banked lobes were considered fossil, mainly due to their large size and apparent inactivity. The sorted stripes were unusual insofar as they were preferentially aligned parallel to the dominant westerly winds and, in the most exposed locations, were even found on horizontal surfaces. It was thought\(^{40}\) that their origin was related to sorting associated with diurnal freezing, the strong westerly winds and the formation, during calm clear nights, of needle ice. Recently, more detailed studies have been undertaken\(^{41}\) that have discerned an altitudinal distribution of features and identified a number of new forms. Several blockfields have been identified at higher altitudes and further data regarding the large stone-banked lobes have shown that they may have fronts up to 5 m high, and can be up to 20 m in length and several metres wide. Holness and Boelhouwers\(^{41}\) suggest that these forms are indeed relict and that they are similar to those described by Benedict\(^{18}\) from the Colorado Front Range. Two types of these large lobes are identified, one that develops directly from the weathering of bedrock outcrops (the largest form) and one that arises from platy, clast-rich till. Whilst the stone-banked lobes are currently active,\(^{38,41}\) It has been shown (ref. 41, Fig. 8) that there is an increase in lobe size with altitude, with riser heights in the order of 0.1–0.15 cm at 200 m a.s.l., rising to c. 0.9 m at a height of 500 m a.s.l. At some westerly oriented sites, miniature sorted stripes can be found on the almost horizontal tread of these features.

Sorted stripes are considered to be active on Marion and Prince Edward Islands (Fig. 4). They occur on a wide range of slopes, from 0° to 20° and generally have the coarse stripe wider than the fine: 140 mm relative to 84 mm is a typical example. Although Washburn\(^{44}\) argued that coarse stripes tend to be narrower than the fine, Hall\(^{40}\) found that the coarse were the widest in seven of twelve areas of study on Marion Island. Holness and Boelhouwers\(^{41}\) found that the maximum depth of sorting was between 10 and 15 cm. A full explanation for the association of the stripes with the westerly winds, particularly their development on horizontal surfaces (Fig. 4), or even across slopes (that is, parallel to the contours) as was found on Kerguelen\(^{46}\) is still needed. Holness and Boelhouwers\(^{41}\) also identified *Azorella* terraces (see Fig. 6) as presently active features, whilst solifluction terraces are seen as inactive. These two forms are also quite different; the *Azorella* terraces (*Azorella selago* is a cushion plant prevalent in this region) are not always orientated directly
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Terre refs 15 and 51. cryogenic activity at the higher elevations whilst, closer to sea Grand Terre such that more ground is being made available to the snowline is rising and that temperatures are increasing on information (see ref. 5, p. 223) indicates that glaciers are receding, the a more active environment, as was also suggested by Hall, during the early Holocene. Small debris flows, associated with frost-heaved gravel surfaces and the low permeability resulting from frozen ground, have recently been found on one of the volcanic scoria cones. These features are short-lived because it was observed that they were obliterated by subsequent frost heave activity. These observations regarding small debris flows are the first for this region and indicate the potential for significant numbers of such forms in this part of the Antarctic.

Kerguelen Archipelago

This is an extensive archipelago of 300 islands (48°27'–49°58'S, 68°25'–70°35'E) located just to the north of the Antarctic Convergence (Fig. 1). The main island, Grand Terre, has an area of c. 5799 km² and is about 10 per cent ice covered. The entire archipelago is about 6200 km² in area. Of volcanic origin, Grand Terre experienced substantial volcanic activity during the early Quaternary and still has active fumaroles. The main island experiences low temperatures (mean = 4.6°C), extensive cloud cover, frequent frosts and strong westerly winds. The bulk of the present-day glacier cover (c. 750 km²) comprises the Cook ice cap and its 40 outlet glaciers (c. 500 km²) around which peaks rise to 1960 m a.s.l. It is likely that during the last glacial the ice did not fully cover the island but it must have extended beyond the present coastline. Warming began around 12 kyr BP and culminated in major glacier retreat around 10 kyr BP. Available information (see ref. 5, p. 223) indicates that glaciers are receding, the snowline is rising and that temperatures are increasing on Grand Terre such that more ground is being made available to cryogenic activity at the higher elevations whilst, closer to sea level, seasonal and diurnal frost effects are decreasing. Recent information on climate change on Kerguelen can be found in refs 15 and 51.

Small-scale sorted patterned ground is common on Grand Terre and includes polygons, nets and stripes; at higher elevations some large-scale sorted patterns are found (Fig. 5). The strong stripe orientation parallel to the westerly winds observed on Marion Island (see above) is not so prevalent here as the terrain is far more rugged and dissected, thereby limiting exposure to the westerlies. However, the effects of katabatic winds were seen where sorted stripes were found parallel to the contours along the side of Alouette Valley in western Kerguelen. These stripes cut across a 5° slope orientated to 201° such that the stripe axis was 60–240°, roughly parallel to the valley. Elsewhere there was found to be an increase in stripe width and in the fine stripe width such that at the lower elevations the coarser stripe was wider but above c. 200 m a.s.l. the fine became wider (Fig. 5). At an elevation of 613 m on Mt Paris ‘stripes-within-stripes’ were found (ref. 45, Fig. 2), where small-scale stripes were found developing within the fine stripe of a set of large-scale stripes. The larger stripes had a fine width of c. 1.17 m and a coarse width of c. 0.42 m, whereas the small-scale stripes were 0.17 m and 0.11 m, respectively. It is suggested that these two sets of stripes result from the combination of large annual freeze cycles to form the large stripes, whilst diurnal cycles produce secondary sorting within the larger fine stripe. Small-scale sorting also accounted for the polygons and nets found at a number of locations (ref. 38, Fig. 2). Fine centres varied between 0.64 and 0.21 m (mean = 0.35 m) in maximum dimension, whilst the coarse borders varied between 0.09 and 0.67 m (mean = 0.27 m) at their widest. It was noticeable that forms developed in a trachyte that weathered to platy fragments showed clasts with their a/b planes vertical at the borders but horizontal at the centres (ref. 38, Fig. 3). Interestingly, forms resulting from solifluction, although not absent, are not common, nor are such as the stone-banked lobes found on Marion Island. This may reflect a lack of study but may also be due to the longer duration ice cover and the significant regrowth of ice during the Little Ice Age that may have removed some features. Frenot et al. discuss the impact of freeze–thaw cycles on particle movement and translocation within the context of initial soil development.
Crozet Islands (îles Crozet)

The Crozet Islands (46°–46°30’S, 50°30’–52°30’E) are five islands situated roughly half way between Marion Island and Grand Terre (Kerguelen) and to the north of the Antarctic Convergence (Fig. 1). Like Marion and Prince Edward Islands, the Crozets are all of volcanic origin and experience a similar climate and so it is not unreasonable to expect landforms and processes to be similar to those found on Marion. The islands are only 233 km² in area with a highest elevation of 934 m and presently have no permanent snow or ice cover.20

There is little information regarding the nature of Quaternary glaciations on these islands but they may have experienced ice at some time.2 Bougere (ref. 61, Fig. 15) observed moraines, drumlins, cirques, glacial valleys and roches moutonnées. Chevallier22 and Giret23 suggest that there was a large ice cap on Île de la Possession about 400 kyr BP, with ice cover likely also on other islands in the group, and that it was this ice that formed the large valleys. Evidence regarding cryogenic activity is also sparse, although Frenot24 provides information on the effects of freeze–thaw cycles on the fellfield above 150 m a.s.l. Small-scale sorted stripes and polygons have been recorded20,25 as well as solifluction.26 The most detailed information available is that of Bougere,24 who studied Quaternary history, soil formation and periglacial activity on Île de la Possession. Extensive information regarding solifluction, sorted stripes, sorted nets, frost weathering and even cryoplanation (ref. 61, Figs 47–49) is given. Evidence regarding the action of both pikkrake and segregation ice is presents, both of which are considered important in present-day landscape activity. The role of these in the formation of miniature patterned ground is presented, including a detailed assessment of patterns, their size and granulometry for 34 sites (ref. 61, Table 13). Freeze–thaw weathering is suggested, largely on the basis of laboratory experimentation, to be operative and details of the granulometry of the weathered basalt is given (ref. 61, Fig. 37). Wind is considered a major factor in fashioning the landscape, causing abrasion of rock outcrops (ref. 61, Fig. 40) as well as deflation hollows (Fig. 39). Bougere identified a number of slopes that he interprets as of a cryoplanation origin, with frost action weathering the riser and gelification moving material downslope on the tread. A typical example is cited for Plateau Jeannel, where the form is at an altitude of 550 m a.s.l. orientated towards 175°. The occurrence of an extensive lichen cover on the rock debris of the terrace suggests it is now a fossil form. The extensive data regarding the landforms and processes given by Bougere24 are only available in his thesis and so are not readily accessible. Frenot24 notes that chemical weathering of the basalt is very active, likely a result of the wet climate coupled with temperatures close to, or above, 0°C.

Macquarie Island

Macquarie Island (54°37’S, 158°54’E) is a small, ice-free island situated to the north of the Antarctic Convergence and exposed to the full force of the dominant westerly winds (Fig. 1). There has been some controversy regarding the nature and degree of glaciation (see ref. 5 for details) but present thoughts suggest that the low altitude of the island could sustain only a few very small glaciers during the Quaternary. The identified cryogenic landforms are similar to those of Marion Island and the Crozets, namely small-scale sorted polygons, nets and stripes, solifluction features and Azorella terraces.6–7,21 Bunt21 suggested that the sorted stripes were the result of an interaction between needle ice and water action, with the water removing fines from the coarse stripes, and that the wind may well influence the freezing pattern of the ice needles. Selkirk71 refers to the occurrence of sorted stone polygons up to 100 mm in diameter.

Taylor64 observed that there were differences in solifluction terraces between the windward and leeward slopes. Azorella selago inhibited the movement of both when it was able to establish itself (Fig. 6). The leeward terraces were considered to be more stable once established and able to grow laterally to sizes larger than those on the windward side. Although formed in a similar manner, the windward terraces were slow moving (as opposed to the stabilized leeward ones) and were not able to join up laterally and produce terraces as large as those on the leeward slopes. Löfler et al.70 suggested that the size of these terraces was related to solifluction under a former, colder climate but that there was also a strong relationship between vegetation, wind exposure and slope processes. Colhoun and Peterson70 argue that during the last glacial the freeze–thaw events on Macquarie Island were more intense, even though they may have increased in number only slightly. It is because of the more intense nature of the freeze events that the larger turf-banked solifluction terraces are thought to have developed. More recently, Selkirk71 has provided detailed measurements of vegetation-banked terrace movement on Macquarie Island. It is argued (ref. 71, p. 483) that the terraces are not relict, as suggested by Löfler et al.,70 but rather active with surface gravel movement in the order of 38–138 mm yr⁻¹. Selkirk observes that the presence of water, frequently from groundwater seepage, is important in determining particle movement rates.

Heard Island

Heard Island (53°06’S, 73°31’E) is a volcanic cone that is 81% covered by permanent snow and ice,66 situated to the south of the Antarctic Convergence (Fig. 1). Summers are short22 and air temperature fluctuations are limited, with the mean annual temperature (0.5°C) close to zero.73 The snowline is situated at 300 m a.s.l., whilst the highest point rises to 2745 m. With precipitation on 280–300 days per year, the island has little exposed ground. Only at the lowest elevations is there any vegetation or cryogenic activity, and both are found mainly on a series of Pleistocene moraines.6 The island has been ice covered for some considerable time and thus there has been little opportunity for the development or survival of periglacial landforms. All periglacial forms found on Heard Island are the product of activity after ice retreat.73

Bouvetøya

Bouvetøya is another volcanic island (54°25’S, 3°21’E), very similar in character and history to that of Heard Island (Fig. 1).
Only 50 km² in size, it is about 500 km south of the Antarctic Convergence and is some 93% ice covered. Like Heard, any periglacial forms found on the island are thought to be largely the product of processes since glacial retreat. However, above the north coast there is a blockfield that may or may not be the result of preservation from an earlier period. Surface weathering is also notable in some areas, especially as nightly frosts are considered frequent. No other features have been described although there is evidence, in the form of extensive lichen cover, that areas have been ice free for some time and that some of the rock is particularly prone to freeze–thaw weathering.

South Georgia

South Georgia (54°20'S, 36°40'W) is a long, narrow island (160 km long, 5–36 km wide) with an axial ridge of mountains, situated just to the south of the Antarctic Convergence (Fig. 1), that experiences a dynamic cryogenic environment in the ice-free areas. At sea level the mean annual temperature is 2°C, with a summer mean of 4.5°C and a winter mean of –1.2°C. Approximately 58% of the island is presently ice covered and most of the ice-free ground is along a coastal fringe below 70–110 m a.s.l. where, according to Thom, the ground freezes to a depth of 0.5 m for up to 26 weeks a year and permafrost may be present at the higher elevations During the Quaternary the island was completely ice covered except for a few nunataks.

Annenkov Island, close to South Georgia, also experienced extensive ice cover and periods of periglacial activity that correlates with that experienced by South Georgia. Walton and Headland provide bibliographies listing the glacial and periglacial literature on South Georgia.

A primarily descriptive catalogue of the various types of patterned ground on South Georgia was made by Thom. Stone refers to the formation of sorted stripes on a number of moraines and scree in northeast South Georgia. Stripes were measured at 5–10 cm in width and in some cases were now overgrown, indicating that they were no longer active. Sorted patterned ground was also identified in the form of nets, approximately 1.5 m mesh diameter, as well as large (c. 1 m wide), non-sorted stripes on some of the gentler slopes. Some terracing was observed within the areas of sorting. Stone also refers to an ‘unusual’ form of patterned ground found at Cooper Bay on South Georgia, where lines of the tussock grass Poa flabellata form large-scale, non-sorted stripes. On some ridges Poa flabellata occurs in lines approximately 25 cm high and 40–50 cm wide, whilst the furrows between are covered with mosses, the whole producing stripes that are about 1 m apart. Aerial photographs of these stripes (ref. 80, Fig. 1) show that they are obvious features on 25–30° southwest-facing slopes. Stone suggests that although there is no sign of present-day movement, the features probably began along slurrries of fine material that moved over active scree (somewhat similar to the small debris flows of Boelhouwers et al. 7).

Heilbronn and Walton provide more detail regarding small-scale sorted stripes and larger non-sorted stripes, large non-sorted circles and two types of solifluction lobes (one type with a bare terrace and one which is completely vegetated). Heilbronn and Walton measured the small stripes as having an amplitude of 10–20 cm and a depth of sorting of only 6–7 cm. Spectral analysis of point quadrat data showed that the stripes had three principal wavelengths at 120, 55 and 21 cm. The 21-cm stripes were found from near sea level to an altitude of >250 m and generally on slopes of 6–18° with a northerly aspect. They measured an increase in the percentage of material >2 mm in both the coarse and fine stripes with an increase with altitude, which they attributed to greater downwash or deflation of the fine material from the exposed higher elevations. Large unsorted stripes occurred on a range of slopes up to 30° but mainly on northerly or northeasterly aspects. Crest-to-crest wavelength was measured at 90–120 cm with trough depth between 15 and 30 cm. All the stripes were completely vegetated with the grass Festuca contracte dominating on the drier crests, whilst mosses and liverworts were found in the wetter troughs. Large non-sorted circles (diameter = 1–2 m) were found on an outwash plain (Hestesletten), some of which were completely vegetated and others still had bare centres that exhibit small, sorted nets; needle-ice activity was found to be common in the bare centres. Solifluction lobes and benches are described as common on South Georgia. They vary in size and include both turf-banked and stone-banked forms. Heilbronn and Walton note that all the periglacial forms are developed in till and that the general small scale of the forms agrees well with the absence of permafrost but requires an annual, deep freezing event. Regarding the formation of the large, non-sorted stripes, those observed by Heilbronn and Walton differ from those of Stone; Thom could find no convincing explanation for their formation and neither could Heilbronn and Walton. Smith and Walton and Heilbronn monitored rates of downslope movement on a variety of slopes. Walton and Heilbronn found that gelification took place to a depth of 12 cm at very active sites but to only 8 cm at most other sites. Most of sorting was found to take place in autumn, as was also observed by Smith. As in many cases, the observations here regarding mass movement and patterned ground indicate the need for longer-term, more detailed monitoring.

Cryogenic weathering has been well considered for South Georgia. Stone suggested that the fissile bedrock was particularly prone to frost shattering and that this was the cause of the abundant scree and the formation of felsenmeer (blockfields) at higher elevations (Fig. 7). Gordon (ref. 84, p. 45) suggested that weathering has been particularly effective on South Georgia for the past 10 000 years and that the effects of this are most noticeable on the snow- and ice-free mountains below c. 700 m. Gordon cites an example, at an altitude of 300 m, where break-down is proceeding along bedding planes and producing blocks c. 0.5 m thick whilst, for the same lithology, the foliation is further breaking the rock down into platy fragments a few millimetres to a few centimetres thick. The propensity for frost weathering, given adequate water, is probably high as, in the year 1975, Thom measured 214 freeze–thaw cycles in the air at sea level. Even with many of these not being of adequate amplitude or duration or being effective on the rock, the potential for some cycles...
affecting the rock remains. With this assumption, Gordon\textsuperscript{44} postulates a series of weathering zones that vary altitudinally, spatially and seasonally. The winter maintains continuous freezing conditions in bedrock except at the coast where some cycling still occurs. In summer, frequent freeze–thaw cycles are believed to prevail at intermediate altitudes. At high elevations local combinations of insolation, aspect, cloudiness, snow cover and time of day will determine the nature and extent of freeze–thaw cycles. This assessment of the weathering regime of South Georgia by Gordon\textsuperscript{44} was extended to incorporate weathering with mass movement as an explanation for the landforms on the island.\textsuperscript{85}

Gordon and Birnie (ref. 85, Fig. 12) integrated debris production with the mechanisms of debris transfer and the resulting landforms and deposits for South Georgia using a simple model. As they state (p. 42), they do not ‘...seek to view individual landforms as unique or special features in mountain geomorphology...’ but rather aim to focus ‘...on the integration of glacier, rock glacier, talus and weathering subsystems.’ In this regard they show that debris supply and character are determined by the local lithology coupled with available processes and that where lithologies resistant to weathering are present, so too are resultant landforms and sediments. This may seem obvious but they actually consider landform distribution within this context. Further, they make detailed observations regarding the rock characteristics and the nature and degree of weathering, including the observation that, despite the cold, chemical weathering does occur. Within the periglacial assemblage of landforms, they identify sorted patterned ground, gelification lobes, and rock glaciers that appear to have a glacial ice core. The value of this study is in the identified relationships between bedrock, weathering, transport processes and resultant landform(s). Birnie and Thomson\textsuperscript{10} identify two rock glaciers on South Georgia that are thought to occur largely as a result of debris supply rather than zonal climate. This point is reiterated by Humlum\textsuperscript{8} in that these South Georgia rock glaciers plot outside of the –2°C lower limit of permafrost but may have originated under cooler-than-present conditions and have been maintained by the high debris supply that prevented melt of the ice core. Thus, the relationship of debris supply to landform assemblage is important in this region.

**South Orkney Islands**

The South Orkneys comprise two large islands, Coronation and Laurie, plus two smaller ones, Powell and Signy (60°30’S, 44°25’–46°10’W). With the exception of Signy Island, the islands are extensively ice covered; permafrost occurs in the ice-free areas. All the islands experience a typical cold, oceanic climate with some rain possible in January and February but with snow, which predominates, for the rest of the year; mean annual precipitation is only in the order of 400 mm yr\textsuperscript{–1}. The mean monthly temperature is c. –4°C and radiation inputs are low due to the extensive cloud cover, and wind speeds average 26 km h\textsuperscript{–1}.

Information is available on cryogenic weathering, sorted and unsorted patterned ground, solifluction and stone streams. The most detailed study on patterned ground in the South Orkneys is that of Chambers.\textsuperscript{88–90} He studied sorted polygons, circles and stripes, together with solifluction, in substantial detail and considered temperature regimes, mechanical analyses of the sediments, and frost heave measurements. Both short-term\textsuperscript{89} and long-term\textsuperscript{90} experiments on the patterned ground were undertaken. Miniature sorted patterns were found to reform within three years; the mechanism of formation was quite different from that of the large sorted types, contraction cracks being the main factor in determining the origin and location of the miniature forms. The active layer was found to be about 1.2 m deep but the top 40–60 cm of this was the main zone within which sorting, ice segregation and solifluction occurred.\textsuperscript{89} Below this depth, no activity was monitored and, in some instances, a distinct line could be seen dividing these two zones of the active layer. Chambers\textsuperscript{90} also found that at depths below 10 cm the annual freeze cycle effected movement of stones towards the ground surface and that it is the mass of the coarse borders that helps displace wet, fine sediment plugs up into the fine centres — a principal factor in the development of the larger sorted forms. Chambers also notes that it is not a convective movement that is involved in moving material to the surface but rather the upwelling of fines in plugs — an issue dealt with more recently by Washburn.\textsuperscript{92}

On slopes both creep and solifluction occur and, in the case of miniature sorted forms, creep was considered more significant in moving stones downslope.\textsuperscript{90} In the large sorted forms, particularly the large sorted stripes, solifluction plays a major role. Indeed, Chambers suggests that, with respect to large sorted stripes, ‘The dominant process in bringing about the patterning appears to be streamlining of solifluction in areas unobstructed by large boulders’. Large solifluction lobes are also found on Signy Island\textsuperscript{8} and on Coronation Island (pers. obs.). Where the solifluction lobe becomes ‘...so extended ... it takes the shape of a stone stream, winding down the hillside...’ (ref. 88, p. 32). The stone streams have the form of a wide band of coarse stones bordering a small central band of fines, but these features are unlike the large sorted stripes insofar as they do not occur in a series across a broad slope. In the stripes, flow was greatest at the surface and in the centre of the fines. These features were considered to be related to solifluction of old till deposits.

Weathering of bedrock on these islands was first cited by Grange (in ref. 93) and a detailed study of weathering processes was undertaken in the 1980s.\textsuperscript{95–102} Detailed information on rock properties, rock temperature, rock moisture content, rock moisture chemistry and the rate of weathering were obtained for quartz micaceous, one of the common lithologies on Signy Island. In a five-year study, weathering rates were found to be very slow, with something in the order of 2% mass loss per 100 years.\textsuperscript{99} Whether the rock was a loose block, subject to omnidirectional freezing, or in situ bedrock, subject to unidirectional freezing, was found to be significant, with the latter experiencing a rate of breakdown 50 times slower than the loose blocks. Thus, cliffs were considered to be weathering at a very slow rate. In this regard, the effects of weathering in cold regions may not, everywhere, be as great as is frequently assumed or portrayed in many texts.

**South Shetland Islands**

A wide range of periglacial landforms and processes have been identified in the South Shetland Islands. These are a mountainous and extensively glaciated group of islands that include King George Island, Livingston Island, Deception Island, Elephant Island and Clarence Island as well as numerous islets (61°–63°30’S, 53°30’–62°45’W).\textsuperscript{106} The climate of these islands has a strong maritime influence, with a mean annual temperature between −1°C and −3°C, with a large annual range, frequent precipitation, some in the form of rain, extensive glacier cover and areas of permafrost.\textsuperscript{105–106} The observed temperature range coupled with substantial precipitation has led many authors to suggest freeze–thaw weathering to be a major factor in landscape development (e.g. refs 106–113) and freezing and thawing of the soil to have a major impact on patterned ground forms (e.g. refs 103, 108, 114–118). The cool temperatures together with...
the substantial snowfall has also led Simonov, Stäblein and Vtyurin and Moskalevskiy to suggest that nivation is active on these islands, and for Zamoruev and Dutkiewicz to identify active solifluction. Zhu et al. also recorded many talus forms including a rock glacier. The combination of cold temperatures, the presence of permafrost and the availability of water has also created argillaceous mounds with a pure, crystalline ice core. These palsa-like mounds have a height of 2 to 3 m and a diameter of c. 6 m.

Zhu et al. state that both the rock glacier and sorted stripes are active during the summer period on the Fildes Peninsula. Sorted polygons comprise penta- and hexagonal polygons 0.5 to 1.5 m in diameter with coarse borders of stones 10 to 20 cm in size. Some of these forms are interpreted (ref. 110, p.15) as inactive as they are lichen covered. Xiong and Cui studied the mechanisms associated with sorted circles on King George Island and found that circles developed well when border material was smaller than 15 cm. Araya and Hervé observed sorted circles with a centre of fine-grained mud surrounded by a circular ring of angular clasts. The circles were up to 2.0 m in diameter, but there was secondary sorting with small (1.5–5 cm) clasts filling polygonal cells within the muddy centre (much as was described for the South Orkney islands by Chambers). These circles were developed above permafrost measured at 0.05 to 0.25 m below the mud core and 0.1 to 0.15 m below the coarse borders. Some growth of mosses and lichens was observed within the centres, with the vegetation encroaching via the stones within the secondary polygons. This is suggested to indicate that the interior polygons are less active than the unvegetated borders. Araya and Hervé found that as slopes approached 3° so polygons started to become elliptical and changed in to sorted stripes. Stripe widths are cited as being 5 to 10 cm. Hall observed that on Livingston Island, despite the presence of permafrost that suggests sorted stripes would be large, the majority of sorted stripes were miniature forms with stripes widths very similar to those described by Araya and Hervé. A preferred stripe orientation associated with the presence of snowbanks was found: sorting occurred on windward slopes where snow accumulation was least (snow insulates the ground from freeze–thaw cycles on the leeward slopes). Solifluction was found to be common (e.g. ref. 104) and on some slopes there were seen to be sudden slides of mud and boulders due to an excess of water in the ground. Hall saw slides of muds and boulders, associated with escape of water, that was due to permafrost thaw. Such permafrost thaw slumps may have been the cause of the features observed by both Araya and Hervé, and Simonov.

The water in the ground was frequently associated with melting of snowbanks that are said to play a major role in relief formation. In some instances the water from snowbanks is sufficient to cause erosion. On Livingston Island, I observed extensive sediment accumulations along major outwash channels from snowbanks, in some instances the sediments were up to 1.4 m thick. Further, this water availability, coupled with the generally low temperatures, underpins the arguments in favour of freeze–thaw weathering. However, Hall showed that rock moisture data indicated that weathering by wetting and drying as well as chemical weathering processes are extremely active. These data showed that the southern, lee side of obstacles have high moisture levels during snowmelt and that chemical weathering was enhanced there (as also suggested by Blümel) but that the northern aspects experienced more wetting and drying cycles and so underwent enhanced mechanical weathering. Rock temperature data from the summer showed that, despite the high rock moisture levels, freeze–thaw weathering was not active. It is suggested that weathering due to wetting and drying may be prevalent on northern aspects and that chemical weathering is active on southern aspects. The high moisture contents of the rock indicate that under freezing conditions extensive damage could occur as a result of freeze–thaw weathering. Blümel refers to weathering due to thermal stresses induced in the rock as a result of radiative heating. Simonov identifies ‘biogenous’ weathering as also active.

Conclusions

The above synopsis of the work undertaken throughout this area gives some idea of the extent and depth of the material available and of the investigations conducted during the past century. The diversity of climate in the cold but very wet sub-Antarctic region, through to the colder and somewhat drier southern maritime Antarctic locations, coupled with the degree and timing of glacial retreat, produces a wide range of periglacial landforms. The extent of Antarctic cryogenic processes and landforms is all the greater when the variations of the continental climate (see ref. 121 in this issue) are also considered. Nevertheless, the extent, nature and depth of cryogenic information varies greatly between islands and, in some cases, even within an island itself (for example, for the east compared with the west of Kerguelen), such that meaningful comparisons, or prediction of future behaviour, remain impossible. Simply put, we have primarily field observations and inference (and even this varies greatly in quality) rather than hard data as the basis of any form of synthesis.

The northward shift of the Antarctic Convergence, and the associated more severe climate, during the last glacial has left its legacy in the form of fossil landforms, some associated with permafrost, in the more northerly sub-Antarctic islands. Thus, many of these Antarctic sites may provide an analogue for northern hemisphere locations during the Quaternary and, as such, are able to offer insights into landform development that are not readily available in the north. One such example might be that of active cryoplanation in Antarctica, which may offer insights into this little-quantified landform of the north. There are detailed studies (such as those of Chambers on sorted patterned ground) that are comparable with northern studies but which are little known by many northern hemisphere workers. However, there is still a great need for more long-term studies and better evaluation of processes within the Antarctic periglacial field.

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Permafrost, active-layer dynamics and periglacial environments of continental Antarctica

James G. Bockheim* and Kevin J. Hall

Active-layer dynamics, permafrost and ground-ice characteristics, and selected periglacial features are summarized from recent published literature and unpublished data by the authors for three eco-climatic regions of continental Antarctica: the Antarctic Peninsula and its offshore islands (c. 61–72°S), maritime East Antarctica (c. 66–71°S), and the Transantarctic Mountains (c. 71–87°C). Active-layer thickness and depth to ice-cemented permafrost are related to regional climate, proximity to glaciers, and albedo of surface rocks. In the McMurdo Dry Valleys, the active layer is commonly underlain by dry permafrost, which can be detected only from frost tubes or temperature measurements. Permafrost thickness ranges from zero near thermally stratified saline lakes in dry valleys and beneath parts of the Antarctic Ice Sheet to ~1000 m. Permafrost temperature measurements are scant and range between ~14 and ~24°C at a depth of 50 m. Ground ice is present as rock glaciers along the polar plateau and in upland valleys and as ice-cored moraines, buried glacial ice, and ice wedges near the coast. Cryoplanation and nivation are evident along the Antarctic Peninsula. Recommendations are made for future periglacial work in the region.

Introduction

Antarctica, the fifth largest continent with a summer area of 14 million km², has the highest mean elevation (~3000 m) of any continent and experiences the lowest mean annual air temperature (~40°C according to Weyant). Although the Antarctic region technically includes all oceans and land south of 60°S, ‘Antarctica’ as used here refers solely to the Antarctic continent and islands offshore of the Antarctic Peninsula (Fig. 1). Antarctica is commonly divided into two parts that are roughly bisected by the Transantarctic Mountains: East Antarctica, a high-elevation land mass capped by the massive East Antarctic Ice Sheet (EAIS), and West Antarctica, an archipelago buried by ice from the West Antarctica Ice Sheet (WAIS) (Fig. 1). East and West Antarctica contain 10.2 and 2.3 million km² of glacial ice, respectively, which represents 90% of the world total. According to many investigators (e.g. ref. 3), the EAIS has remained comparatively stable during the Pleistocene and the WAIS has periodically disintegrated, resulting in global increases in sea level by approximately 6 m. The behaviour of the WAIS corresponds with northern hemisphere glacial/interglacial cycles. Less than 1% (55 000 km²) of Antarctica is ice-free. Whereas the terrestrial ecosystems of Antarctica have a low biodiversity, the Southern Ocean has among the most productive marine ecosystems on earth. This is due primarily to the Antarctic Convergence, a zone that features upwelling of nutrient-rich sediments due to mixing of warm subtropical waters and cold

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Periglacial Research

sub-Antarctic waters. Antarctica acts as a heat sink and exerts a strong influence on the earth’s atmospheric and cryospheric systems.1

Antarctica contains 37% of the world’s permafrost. However, much of the landmass below the massive EAIS is above the pressure melting point and is unfrozen.2,3 Realistically, 25% or less of the Antarctic region contains permafrost.7

Ground ice is common in Antarctica, especially in the form of rock glaciers4 that have potential for reconstructing past environments of the region.5 For example, ice buried 50 cm below the ground surface in Beacon Valley (77°51’S, 160°35’E) may be eight million years old.8 Human effects on the active layer and permafrost have received recent attention.11,12

The objective of this paper is to summarize relevant data on active-layer dynamics, permafrost and ground ice, and periglacial features and environments of Antarctica, with an emphasis on data published since 1994 and unpublished observations and data by the authors.

Eco-climatic regions of Antarctica

Antarctica may be divided into three eco-climatic regions: the Antarctic Peninsula and its offshore islands (c. 61–72°S), maritime East Antarctica (c. 66–71°C), and the Transantarctic Mountains (c. 72–87°S) (Fig. 1). The McMurdo Dry Valleys have been further sub-divided from environmental factors into sub-regions, including coastal, inland valley floors, inland valley sides, upland valleys and the plateau fringe.9

The Transantarctic Mountains, which extend from northern Victoria Land to the Pensacola Mountains (Fig. 1), comprise the largest proportion of the ice-free area of Antarctica at 55%, or 30 400 km². The Antarctic Peninsula and its offshore islands comprise about 14% of the ice-free area of Antarctica (8000 km²) and include the South Orkney Islands, islands to the west of the Antarctic Peninsula (the South Shetland Islands, the Palmer Archipelago, the Biscoe Islands, Adelaide Island, and Alexander Island), islands to the northeast of the Trinity (Antarctic) Peninsula (for example, Joinville, Snow Hill, James Ross, and Seymour islands), Thurston Island, Peter Øy, and the Balleny islands (Fig. 1).

Marie Byrd Land contains 12% of the ice-free area (6600 km²), primarily in the Ford Ranges and the Executive Committee Range. Lesser proportions of ice-free areas exist in Queen Maud Land (4.8%, or 2600 km², including the Woldt Mountains and the Sør Rondane Mountains), maritime East Antarctica (4.6%, or 2500 km², including the Schirmacher Hills, Enderby Land, the Vestfold Hills, the Queen Mary Coast, Wilkes Land, the Adélie Coast, and the Wilson Hills), the Prince Charles Mountains (4.4%, or 2400 km²) and the Ellsworth Mountains (3.1%, or 1700 km²).

These regions and sub-regions differ not only in climate but also in vegetation, soils, permafrost characteristics and periglacial processes. Blumel and Eitel13 provided geoecological divisions of Antarctica based on periglacial features, suggesting that the lower latitude maritime Antarctic system ‘...can be used as a model for the ecodynamic in western mid-latitudes during
certain Pleistocene phases.'

The mean annual air temperature (MAAT) along the Antarctic Peninsula and its offshore islands commonly ranges between −2.7 and −3.7°C (Table 1). In maritime East Antarctica, MAAT ranges from −9.4 to −11°C. In the Transantarctic Mountains, MAAT ranges from −15 to −20°C in coastal areas and −35°C along the polar plateau. Mean annual precipitation ranges from 400 to 1000 mm yr$^{-1}$ in the Antarctic islands to <100 mm of water-equivalent precipitation along the polar plateau (Table 1).

Bliss$^{15}$ classified vegetation of continental Antarctica in the 'Polar Desert Biome.' Major subdivisions included grass-herb-fellfield communities in the Antarctic islands and maritime Antarctica, maritime moss communities in maritime Antarctica and coastal areas of the Transantarctic Mountains, and lichen barrens in maritime Antarctica and in the Transantarctic Mountains. Aleksandrova$^{16}$ provided much the same geobotanical subdivision, although she grouped the islands south of the Antarctic Convergence with the polar deserts of the continent, which may underestimate the biodiversity and productivity of these islands compared to the continent. To some extent Aleksandrova$^{16}$ rectified this concern by generating the 'northern subregion of the Antarctic polar deserts' (the southern sub-region being the continent proper) in which some of the maritime Antarctic islands are included.

**Table 1.** Eco-climatic regions of the Antarctic climate.

<table>
<thead>
<tr>
<th>Eco-region</th>
<th>Latitude (°S)</th>
<th>MAAT (°C)</th>
<th>MAP (mm)</th>
<th>Vegetation</th>
<th>Soil taxa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antarctic Peninsula &amp; islands</td>
<td>61–72</td>
<td>−2.7 to −3.7</td>
<td>400–1077</td>
<td>Grass-herb-fellfield</td>
<td>Haploturbel, haplorthels, psammiturbels, psammorthels</td>
</tr>
<tr>
<td>Maritime East Antarctica</td>
<td>66–71</td>
<td>−9.4 to −11</td>
<td>190–850</td>
<td>Grass-herb-fellfield, maritime moss, lichen barren</td>
<td>Haploturbel, haplorthels, psammiturbels, psammorthels</td>
</tr>
<tr>
<td>Transantarctic Mountains$^c$</td>
<td>71–87</td>
<td>−15 to −20</td>
<td>150–200</td>
<td>Lichen barren, continental moss</td>
<td>Anhyturbels, anhyorthels</td>
</tr>
<tr>
<td>Coastal</td>
<td>−20 to −25</td>
<td>100–150</td>
<td>Lichen barren</td>
<td>Anhyturbels, anhyorthels</td>
<td></td>
</tr>
<tr>
<td>Inland valley floors</td>
<td>−20 to −25</td>
<td>100–150</td>
<td>Lichen barren</td>
<td>Anhyturbels, anhyorthels</td>
<td></td>
</tr>
<tr>
<td>Inland valley sides</td>
<td>−20 to −25</td>
<td>100–150</td>
<td>Lichen barren</td>
<td>Anhyturbels, anhyorthels</td>
<td></td>
</tr>
<tr>
<td>Upland valleys</td>
<td>−25 to −30</td>
<td>100–150</td>
<td>Lichen barren</td>
<td>Anhyturbels, anhyorthels</td>
<td></td>
</tr>
<tr>
<td>Plateau fringe</td>
<td>−30 or colder</td>
<td>&lt;100</td>
<td>Lichen barren</td>
<td>Anhyturbels, anhyorthels</td>
<td></td>
</tr>
</tbody>
</table>

$^a$Phillpot; $^b$Weyandt; $^c$Orvig; $^d$Bliss; $^e$Campbell et al.
Antarctic soils are classified as Gelisols, that is, soils with permafrost within 100 cm of the surface or soils with gelic materials within 100 cm of the surface and permafrost within 200 cm of the surface.\(^\text{25}\) Gelisols are divided into three suborders: histels (soils in which ~40% of the upper 50 cm contains organic materials), turbels (mineral soils that have one or more horizons showing cryoturbation), and orthels (other soils). Histels are uncommon in Antarctic and occur primarily in small bogs in the Antarctic islands and maritime Antarctica. Soils in the Antarctic islands and maritime East Antarctica lacking anhydrous conditions and abundant salts are primarily psammoturbels/psammorthels (if less than 35% fragments >2 mm) or haploturbels/haplorthels (if more than 35% fragments >2 mm). Soils of the Transantarctic Mountains have anhydrous conditions (that is, are exceptionally dry) and are dominantly anhyturbels and anhyorthels.

**Active-layer dynamics**

The concept of an active layer applies to the Antarctic Peninsula and its offshore islands and to maritime East Antarctica but is less meaningful in interior Antarctica. The main reason for this is that the active layer and near-surface permafrost in interior Antarctica have an exceptionally low moisture content, i.e. less than 3%.\(^\text{17,18,22,24}\) A gravimetric moisture content of at least 5% is generally required for the coarse-textured soils of Antarctica to be cemented by ice.\(^\text{17,22}\) Therefore, much of the permafrost in interior Antarctica is ‘dry’\(^\text{18,21}\).

The maximum active-layer thickness in Antarctica is dependent on eco-climatic region and albedo of the ground surface materials. In the comparatively mild Antarctic islands, the active layer commonly ranges between 40 and 150 cm (Table 2). Maritime East Antarctica has a cooler but drier climate with an active-layer thickness of 60 to 150 cm. However, active-layer depths in East Antarctica may be overestimated as dry permafrost probably occurs there. In the Transantarctic Mountains, the active-layer thickness is dependent on proximity to the coast and elevation, ranging from 30 to 60 cm in coastal areas to 15 to 20 cm along the polar plateau (Table 2). Based on a detailed study by Guglielmin et al.,\(^\text{23}\) the active layer in the northern foothills of northern Victoria Land ranged from 5 to 30 cm. Also working in north Victoria Land, Gragnani et al.\(^\text{24}\) suggested that seasonal melting-refreezing occurs to depths of 30 to 90 cm.

Surface albedo is an important factor with regard to active-layer thickness and dynamics in Antarctica.\(^\text{22}\) Wilson and Bockheim (unpublished) monitored soil temperature and moisture on six pairs of plots with dark- and light-coloured desert pavements in the McMurdo Dry Valleys. Plots with an abundance of dark-coloured, mafic rocks had significantly (\(P < 0.05\)) lower albedoes, greater soil temperatures, and more soluble salts in the upper 30 cm than adjacent plots with a light-coloured surface (Table 3).

Wójcik\(^\text{25}\) measured active-layer temperatures in the Bunger

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### Table 2. Permafrost characteristics and ground-ice features in Antarctica.

<table>
<thead>
<tr>
<th>Eco-climatic region</th>
<th>Permafrost distribution</th>
<th>Permafrost</th>
<th>Active layer</th>
<th>Ground-ice features*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Form</td>
<td>Moisture content (%) (^a)</td>
<td>Thickness (cm)</td>
<td>Moisture content (%) (^b)</td>
</tr>
<tr>
<td>Antarctic Peninsula &amp; islands</td>
<td>Discontinuous</td>
<td>Wet</td>
<td>16–20</td>
<td>40–150</td>
</tr>
<tr>
<td>Maritime East Antarctica</td>
<td>Continuous</td>
<td>Wet, dry (?)</td>
<td>6–22</td>
<td>60–150</td>
</tr>
<tr>
<td>Transantarctic Mountains</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coastal</td>
<td>Continuous</td>
<td>Wet</td>
<td>6.1–77</td>
<td>30–60</td>
</tr>
<tr>
<td>Inland valley floors</td>
<td>Discontinuous</td>
<td>Dry</td>
<td>1.6–9.5</td>
<td>20–40</td>
</tr>
<tr>
<td>Inland valley sides</td>
<td>Continuous</td>
<td>Dry, wet</td>
<td>—</td>
<td>20–30</td>
</tr>
<tr>
<td>Upland valleys</td>
<td>Continuous</td>
<td>Dry, wet</td>
<td>1.7–30</td>
<td>15–20</td>
</tr>
<tr>
<td>Plateau fringe</td>
<td>Continuous</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)Comparisons of values within a column for dark- vs light-coloured surfaces, based on ANOV and Fisher’s PLSD.

\(^b\)Ground-ice features: iw, ice wedges; sw, sand wedges; rg, rock glacier; pi, pingos; icd, ice-cored drift (after Bockheim\(^\text{17}\)).

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### Table 3. Surface characteristics, temperature, and salt and moisture contents of soils on paired dark and light plots in the McMurdo Sound area. All temperature and albedo readings were recorded under cloudless skies (Wilson and Bockheim, unpublished).

<table>
<thead>
<tr>
<th>Location</th>
<th>Plot no.</th>
<th>Colour</th>
<th>Dark:light ratio</th>
<th>Albedo (footcandles)</th>
<th>Surface soil temp. (°C)</th>
<th>Salts, 0–30 cm (mg/cm(^2))</th>
<th>Soil moisture 0–30 cm (g/cm(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rhone Platform</td>
<td>1</td>
<td>Dark</td>
<td>19</td>
<td>28</td>
<td>17.4</td>
<td>2976</td>
<td>75.7</td>
</tr>
<tr>
<td>(77°40'S, 162°25'E)</td>
<td>2</td>
<td>Light</td>
<td>0.7</td>
<td>45</td>
<td>5.6</td>
<td>739</td>
<td>45.7</td>
</tr>
<tr>
<td>Hughes Glacier</td>
<td>5</td>
<td>Dark</td>
<td>1.7</td>
<td>60</td>
<td>9.6</td>
<td>609</td>
<td>102</td>
</tr>
<tr>
<td>(77°42'S, 162°30'E)</td>
<td>4</td>
<td>Light</td>
<td>0.5</td>
<td>72</td>
<td>7.4</td>
<td>564</td>
<td>74.0</td>
</tr>
<tr>
<td>Rhone Platform</td>
<td>6</td>
<td>Dark</td>
<td>1.9</td>
<td>30</td>
<td>20.4</td>
<td>1978</td>
<td>81.5</td>
</tr>
<tr>
<td>(77°40'S, 162°25'E)</td>
<td>8</td>
<td>Light</td>
<td>1.4</td>
<td>50</td>
<td>15.1</td>
<td>346</td>
<td>33.4</td>
</tr>
<tr>
<td>Arena Valley</td>
<td>9</td>
<td>Dark</td>
<td>21.7</td>
<td>45</td>
<td>16.6</td>
<td>1594</td>
<td>138</td>
</tr>
<tr>
<td>(77°52'S, 160°58'E)</td>
<td>10</td>
<td>Light</td>
<td>0.4</td>
<td>72</td>
<td>9.0</td>
<td>912</td>
<td>57.3</td>
</tr>
<tr>
<td>Arena Valley</td>
<td>11</td>
<td>Dark</td>
<td>9.6</td>
<td>45</td>
<td>14.2</td>
<td>420</td>
<td>24.6</td>
</tr>
<tr>
<td>(77°52'S, 160°58'E)</td>
<td>12</td>
<td>Light</td>
<td>2.1</td>
<td>57</td>
<td>9.7</td>
<td>208</td>
<td>25.5</td>
</tr>
<tr>
<td>Sollas Glacier</td>
<td>14</td>
<td>Dark</td>
<td>1.1</td>
<td>36</td>
<td>10.5</td>
<td>634</td>
<td>128</td>
</tr>
<tr>
<td>(77°41'S, 162°35'E)</td>
<td>13</td>
<td>Light</td>
<td>0.6</td>
<td>50</td>
<td>8.7</td>
<td>398</td>
<td>88.5</td>
</tr>
</tbody>
</table>

*Comparisons of values within a column for dark- vs light-coloured surfaces, based on ANOV and Fisher’s PLSD.
Oasis (66°18'S, 100°43'E), showing that daily fluctuations are greatly influenced by diurnal temperatures and external factors such as cloud cover. Partial cloudiness, full cloudiness, and full cloudiness plus snow all affected the vertical temperature profile, with temperature gradients being greatest during cloud-free days. Temperature gradients decreased as autumn approached. Temperature fluctuations in the bedrock active layer were highly conducive to mechanical weathering. In coastal areas of the McMurdo Dry Valleys, maximum soil-surface temperatures are mainly radiation-controlled, while minimum temperatures are strongly linked to air temperatures, thereby generating the greatest temperature ranges (of minimum temperatures) at ground level. Temperature fluctuations in the bedrock active layer were highly conducive to mechanical weathering. In coastal areas of the McMurdo Dry Valleys, maximum soil-surface temperatures are mainly radiation-controlled, while minimum temperatures are strongly linked to air temperatures, thereby generating the greatest temperature ranges (of minimum temperatures) at ground level. Temperature fluctuations in the bedrock active layer were highly conducive to mechanical weathering.

Permafrost is defined here as soil and/or rock that remains below 0°C for at least two consecutive years. Moisture in the form of water or ice may or may not be present.

Accordingly, there are two kinds of permafrost in the cold deserts of Antarctica. With the exception of the inland valley floors and sides of the McMurdo Dry Valleys, most of Antarctica contains ice-cemented permafrost. In the McMurdo Dry Valleys, Bockheim showed that dry permafrost is prevalent in the region, occurring in 42% of the pits examined, with ice-cemented permafrost being restricted to (1) Ross Sea drift 12–20 kyr in age in coastal areas, (2) alpine drift <74 kyr in age in the dry valleys, (3) sediments at elevations above 2000 m in upland valleys and along the edge of the polar plateau, and (4) below the dry permafrost at depths exceeding 100 cm.

Compared with the circum-Arctic region, very little is known regarding the thickness, properties, and age of permafrost in Antarctica. The most extensive database for permafrost in Antarctica is from the Dry Valley Drilling Project (DVDP). During this study, 15 boreholes were drilled in the McMurdo Dry Valleys to depths ranging from 4 to 381 m. Descriptions of the strata were taken, including notes of whether or not the sediments were wet-frozen. Electrical resistivity was used to estimate permafrost thickness. Subsurface temperatures were measured at discrete points in the hole with thermistor probes. Because many of the boreholes were located near lakes and have filled with water, they are no longer suitable for monitoring permafrost temperatures (G. Clow, U.S. Geological Survey, pers. comm. to J. Brown). Three boreholes were established at the Italian research station in North Victoria Land. Permafrost characteristics have been studied in North Victoria Land, Seymour Island, and on King George Island in the South Shetland Group.

Non-relict permafrost thickness can be estimated crudely as the product of mean annual air temperature and a lag rate of 33 m/°C. Therefore, in ice-free areas permafrost thickness would be expected to be least in the Antarctic islands and greatest in the interior of Antarctica. On King George and Seymour islands permafrost is between 20 and 180 m thick (Table 4). We were unable to locate data for permafrost thickness in East Antarctica. In interior Antarctica permafrost may approach 1000 m in thickness. Based on limited data, the temperature of Antarctic permafrost at a depth of 50 m ranges from −13 to −24°C (Table 4). However, radio-echo sounding of the East Antarctic ice sheet, where the ice thickness greater than 3000 m, suggest that the presence of saline lakes may preclude the existence of sub-glacial permafrost.

Environmental factors related to permafrost in the circum-Antarctic region were reviewed by Bockheim and include air temperature, relief, vegetation, hydrology, glacier and snow cover, and soil and rock, and age of geomorphic surface. Bockheim provided a preliminary map of permafrost distribution in the Southern Circumpolar Region that related the northern occurrence of permafrost to the −1°C isotherm for mean annual air temperature. Sub-glacier permafrost was determined

### Table 4. Permafrost characteristics in continental Antarctica.

<table>
<thead>
<tr>
<th>Area</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Eco-climatic region</th>
<th>Permafrost thickness (m)</th>
<th>Permafrost temperature (°C)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Victoria Land</td>
<td>74°45'S</td>
<td>164°E</td>
<td>Transantarctic Mtns</td>
<td>3–20</td>
<td>−15</td>
<td>23</td>
</tr>
<tr>
<td>Seymour Island</td>
<td>64°15'S</td>
<td>56°45'W</td>
<td>Antarctic Peninsula</td>
<td>48–180</td>
<td>−24</td>
<td>37, 98, 36</td>
</tr>
<tr>
<td>King George Island</td>
<td>62°12'S</td>
<td>58°57'W</td>
<td>Antarctic Peninsula</td>
<td>20–100</td>
<td>−16</td>
<td>35</td>
</tr>
<tr>
<td>Dry Valley Drilling Project</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>McMurdo (no. 3)</td>
<td>77°51'S</td>
<td>166°40'E</td>
<td>Trans. – coastal</td>
<td>440–500</td>
<td>−15</td>
<td>35</td>
</tr>
<tr>
<td>Lake Vanda (no. 4)</td>
<td>77°31'S</td>
<td>161°32'E</td>
<td>Trans. – inland</td>
<td>0°</td>
<td>−14</td>
<td>35</td>
</tr>
<tr>
<td>Lake Vida (no. 6)</td>
<td>77°23'S</td>
<td>161°48'E</td>
<td>Trans. – inland</td>
<td>800–970</td>
<td>−18</td>
<td>35</td>
</tr>
<tr>
<td>New Harbor (no. 8, 10)</td>
<td>77°35'S</td>
<td>163°31'E</td>
<td>Trans. – coastal</td>
<td>240–310</td>
<td>−15</td>
<td>35</td>
</tr>
<tr>
<td>Commonwealth Glacier (no. 11)</td>
<td>77°35'S</td>
<td>163°25'E</td>
<td>Trans. – coastal</td>
<td>405</td>
<td>−18</td>
<td>35</td>
</tr>
<tr>
<td>Lake Leon (no. 12)</td>
<td>77°38'S</td>
<td>162°51'E</td>
<td>Trans. – inland</td>
<td>350</td>
<td>−13</td>
<td>35</td>
</tr>
<tr>
<td>Don Juan Pond (no. 13)</td>
<td>77°33'S</td>
<td>161°10'E</td>
<td>Trans. – inland</td>
<td>0°</td>
<td>−16</td>
<td>35</td>
</tr>
<tr>
<td>North Fork (no. 14)</td>
<td>77°32'S</td>
<td>161°24'E</td>
<td>Trans. – inland</td>
<td>350–360</td>
<td>−16</td>
<td>35</td>
</tr>
</tbody>
</table>

*50 m depth, measured using electrical resistivity, or electromagnetically.

*Thermally stratified lake.

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* Computed using the circum-Arctic average temperature of −18°C.
from a map by Herterich that was based on a three-dimensional model of the Antarctic ice sheet. Since the preliminary permafrost map was issued, virtually no new data for the distribution of permafrost in Antarctica have been published.

**Ground ice in Antarctica**

As might be expected, there is extensive ground ice in Antarctica, primarily in the form of rock glaciers, ice-cored drift, and buried glacial ice, and ice wedges. Pickard reported pingos in the Vestfold Hills (68°40’S, 78°00’E), but Fitzsimons later refuted the interpretation. Rather than ‘growth’ features indicative of a pingo, the 4-m-high, 12-m-diameter features were argued to be residual landforms resulting from the decay of an ice-cored moraine, that is, a form of thermokarst. Although the features are pingo-like in form, the environmental conditions necessary for pingo growth preclude their origin as pingos. Grigor’ev also refers to the occurrence of thermokarst features on the moraines in the Bunger Hills, an area similar to but to the east of the Vestfold Hills. The lack of pingos in Antarctica is probably related to the absence of suitable sites in addition to the lack of suitable conditions.

Nichols refers to large areas in the McMurdo Dry Valleys covered by ice-cored moraines. The buried glacier ice in this area produces a topography characterized by ‘knobs and mounds’ as well as ‘valleys and kettles’ and ‘inverted topography’, where what were pond sediments now occur on ridge tops due to protection of the underlying ice from melting. Nichols cites ice-cored moraines that ‘cover hundreds of acres,’ which are composed of ice c. 16 m thick that may be of ‘some antiquity’, photographs of these features were also provided as figures 30–34. Based on resistivity data, Guglielmin et al. showed the occurrence of sub-sea permafrost in raised beaches of northern Victoria Land as well as permafrost with a very high ice content. Also working in northern Victoria Land, Gragnani et al. recorded a ground ice layer with a thickness of >60 m. In the ice-free areas of the Bunger Hills, Grigor’ev observed ‘ground ice inclusions in the form of ice-cement, segregation ice, and multiveined ice... within the Quaternary deposits. The predominant form of ice, by volume, was multiveined ice which, when melting occurred, produced ‘settling and sink phenomena’. However, thermokarst development was inhibited by multiveined ice below the depth of seasonal thawing (1.5–1.7 m) that was only c. 0.4 m.

Sugden et al. reported the existence of glacier ice lying beneath 50 cm of sediment in Beacon Valley in the McMurdo Dry Valleys that may be of Miocene age. Hindmarsh et al. provided a detailed analysis regarding sublimation of the ice through the overlying sediments. Questions arise as to the age of this ice (8 Myr BP) as the calculated rates of sublimation through the overlying sediments suggest that it must be much younger. If this is so, then this brings in to question much of the geomorphic dating of surfaces in this region. Conversely, the thermodynamic modelling of sublimation is in error and thus, as Hindmarsh et al. state, more detailed measurements from the field are still necessary.

Rock glaciers are cited by a number of authors for different areas of Antarctica. Barsh et al. referred to the occurrence of active ‘talus rock glaciers’ on King George Island (South Shetland Islands) in an area of shallow but continuous permafrost. These rock glaciers are moving at an average speed of 30 cm yr⁻¹ and are crossing a raised beach that was formed c. 500–1000 yr BP. Mayewski and Mjagkov studied rock glaciers in the Transantarctic Mountains. Guglielmin et al. described rock glaciers in northern Victoria Land and measured geoelectrical properties of the rock-glacier ice. Based on resistivity measurements, they were able to distinguish between ice-cemented rock glaciers and those with an ice core (considered to be probably glacier ice). Humlum and Strelin and Sene reported rock glaciers on James Ross Island (64°S, 58°W) on the eastern side of the Antarctic Peninsula. The island is in an area of continuous permafrost and numerous rock glaciers are found in the northwest corner of the island, which is ice-free. Humlum suggested that most the rock glaciers are glacier-derived but that there are also a few talus-derived forms. Strelin and Sene refer to ‘protalus lobes’ and ‘protalus ramparts’ as landforms not associated with glacier ice but rather may have ice-cemented interiors.

‘Ice-cored talus aprons’ were described in the Thiel Mountains of the Antarctic interior as well as associated processes that cause debris movement and sorting. The talus aprons, located near to and south of latitude 84°S, have an underlying ice core that, when subject to sudden temperature changes, cause ‘shaking’ of the surface such that sorting of material takes place. This area experiences a mean annual temperature of −36°C but the ground can undergo rapid temperature changes as a result of variations in radiation input or winds. Not only is this one of the few descriptions of massive ice at this latitude but also it is used to explain a most unusual form of sorting, one not yet observed in the northern hemisphere.

Further, Ford and Andersen suggest that in addition to the features observed as a result of debris movement due to shaking resulting from ice contraction, there are what appear to be protalus ramparts. This unusual sorting mechanism is seen to produce stripes of surficial debris averaging 3 m long which can be as great as 10 m, and are uniformly spaced 3 m apart. From their observations it is not clear whether the ice within the apron is aggrading or degrading, but there are certainly rock particles within the ice. Ford and Andersen cited other authors who refer to the ‘snapping and popping’ associated with thermal changes to ice and ground in Antarctica resulting from shadows falling across previously warmed ground at a time when air temperatures are substantially below zero. The thermal contraction that produces tensile stress in the surface layer, said here to be the cause of the sorting, may also help explain the pseudo-sorting of thermal contraction cracks cited by Hall.

In the McMurdo Dry Valleys, rock glaciers and buried ice are prevalent in upland valleys and along the edge of the polar plateau such as Arena and Beacon Valleys. The rock glaciers and buried ice in Arena and Beacon valleys contain less than 1 m of drift over pure ice. Ice-cored drift is common in lower Wright Valley on Holocene drift from the Wright Lower Glacier and on alpine moraines in Taylor and Wright valleys that are of Holocene age. Buried ice that is possibly 75 kyr in age occurs in central Wright Valley. Ice-wedge polygons are common throughout the dry valleys, particularly in coastal areas.

**Cryoplanation/nivation**

Part of the problem with the consideration of ‘cryoplanation’ is its intimate interaction with ‘nivation’ such that it is almost impossible to consider one without the other. Thus it is pertinent to consider references to both processes and their association within the Antarctic region. One of the first clear references to either process is that of Taylor in which, with respect to East Antarctica, he cited the creation of ‘small cwms by nivation...’ Taylor also refers to nivation (erosion by thaw and freeze) in his explanation of landscape development in the Royal Society Range. Taylor observed processes that appear very similar to what Groom would later term ‘niche glaciers’ — forms that...
relate very strongly to ‘longitudinal nivation hollows’.

Souchez also notes the role of nivation in creating hollows, below which are found stratified deposits (grès litées). Nichols describes hollows which still had snow present that were 8.2 m long, 6.7 m wide, and 0.76 m deep, with a surface gradient of c. 10°. Nichols estimated that as much as 1.52 to 1.83 m of sediment had been removed. In nearby Taylor Valley, Nichols observed ‘nivation cirques’ up to 30 m wide and 30 m long, and near Marble Point he found similar cirques cut in bedrock that were ‘...hundreds of yards wide...’

Markov et al. noted that in the mountains of Queen Maud Land nivation processes are currently active and the formation of cirques in this region may be due to nivation during warmer periods when these processes were more vigorous. Bardin also referred to the role of nivation in the mountains of Queen Maud Land. These workers noted the influence of aspect with the north-facing slopes being preferential for the action of nivation. Bardin referred to nivation within the Schirmacher Oasis, while Sekyra specifically mentioned the occurrence of cryoplanation terraces in the Schirmacher Oasis; the processes (primarily frost weathering) associated with these forms were seen as major contributors to the development of the present-day landscape.

In his review of permafrost and periglacial processes in the Southern Circumpolar Region, Bockheim summarized data on cryoplanation terraces in Antarctica; Hall added further references regarding cryoplanation. Previous reports suggested that cryoplanation terraces occur along the east coast of the Antarctic Peninsula and in maritime East Antarctica. More recently, Hall examined cryoplanation benches on Alexander Island (71°50’S, 68°21’W) near the Antarctic Peninsula. The terraces on Alexander Island were 2–12 m in width, 6–200 m long, with risers 0.8–2.0 m in height, while treads were at an angle of 1–10°.

Although Hall found a distinct structural control, terraces showed a clear influence of aspect with a preference (despite equal opportunity of exposure) for the southwest through north to northeast sector. Of importance to the broader concepts was the observation on the cryoplanation terraces of certain lithologies weathering to well-rounded rather than angular forms (see below).

Jordan and van der Wateren reported that mechanical weathering of bedrock in northern Victoria Land can result in ‘subrounded to well rounded’ rock fragments. Although no discussion was provided, several photographs and drawings by Taylor show granite boulder said to be in situ that are well rounded rather than angular in form. Thermal stress is probably a, if not the, major process associated with terrace formation. In mountaneous areas of Enderby Land, ‘relief’ cryoplanation features occur, although this same author notes that among the processes causing the greatest remodelling of the relief in areas such as the Schirmacher Oasis are those of cryoplanation processes.’ Jordan and van der Wateren suggested the occurrence of cryoplanation terraces in ice-free areas of the Litell Rocks in northern Victoria Land. The terraces are in the order of 2–6 m wide, 20–60 m in length, and with a tread slope of a few degrees on the wider features to >10° for the narrower terraces. Risers at the back of the terraces range from almost vertical on the smaller terraces to c. 60° for the wider terraces. The formation and location of the terraces may be structurally controlled. From the descriptions these forms appear to be extremely similar both in form and origin to those described by Hall. Derbyshire identified tors (see below) that he considered to be developed above cryoplanation surfaces in southern Victoria Land.

Forms that could be considered associated with ‘nivation-cryoplanation’ processes include tors, blockfields and ‘rock furrows’ for which some literature exists. Running water is more prevalent in the Antarctic than is often recognized. Although it is temporally and spatially constrained, largely to where radiative heat from rock outcrops causes snow to melt during the short summer, nivation can play a role in not only debris transport but also in creating erosional features.

Several Russian authors have identified a peculiar form of ‘rock furrow’ that they attribute to the melting of snow on north-facing slopes that, by a combination of fluvial action and freeze-thaw weathering, generate parallel furrows c. 0.5 m wide, 0.3 m deep, and tens of metres long. Bardin notes that although the period when melt water is active is very limited, the presence of the water facilitates intense frost weathering such that distinct ‘furrows’ are created on vertical granite walls on the sunny north-facing slopes; this process of frost weathering and running water, to help remove the debris and re-wet the rock, is said to be a daily occurrence in summer. Bardin also notes that on horizontal surfaces the availability of melt-water causes ‘potholes’ — again the origin being the frost weathering of the rock as a result of water being available. More recent studies show that in such situations it is very likely that there is active chemical weathering taking place. Markov et al. provided data regarding water temperatures (≥20°C) for the Bunger Oasis that would certainly facilitate active chemical weathering in these spatially restricted sites.

There are several references to the occurrence of tors (e.g. refs 71, 78, 84, 85) that relate to the periglacial environment and the operation of both mechanical and chemical weathering — often associated with water from snowmelt. Taylor showed the development of small ‘tors’ developed in weathered kenyte boulders. Zhang and Peterson identified what they consider to be frost-shattered bedrock summits with remnant upstanding blocks about 1 m high, while those found by Derbyshire were 3–4 m high and those reported by Selby were as high as 20 m. In the light of the above discussion regarding cryoplanation and the shape of the materials on terraces by Hall, it is worth noting that Derbyshire suggested that the observed summit tors of well rounded rock blocks standing above a ‘...surface of cryoplanation poses a problem in interpretation.’ The issue is that, as argued above, most workers assume that mechanically weathered debris should be angular and thus the finding of rounded material is in conflict with a cryogenic origin. As discussed earlier, without the assumption that the mechanically weathered material must be angular the problem does not exist and there is no conflict in finding rounded summit blocks above a cryoplanation terrace — the rounding being a function of mechanical breakdown that results in curvilinear cracks rather than chemical weathering. Sekyra referred to the development of tors (‘castle- and tower-shaped forms’) in massive gabro-granites but unfortunately provides no measurements of the features. Tors cited in the above references occur in dolerites, granites, gneisses and sandstones, the largest being in granites, the smallest in gneiss. While Selby argued for salt weathering as the dominant process, Derbyshire and Zhang and Peterson suggested frost weathering, and Hall found the cause of weathering to most likely be thermal stress fatigue.

With respect to blockfields (felsenmeer) and block slopes, there are a number of references that indicate such forms exist on the tops and/or sides of many nunataks. Zhang and Peterson refer to the occurrence of block slopes in the Vestfold Hills, while
Brook observed mantles of *in situ* weathered sandstones and siltstones on cliff tops in the Theron Mountains. Baroni suggested that the surface of the hills near Terra Nova Bay is shattered and produces blockfields (Felsenmeer). Block sheets occur on steeper slopes. Nichols noted that although *felsenmeer* are found in the McMurdo Sound region they are not common. Nichols suggested that *felsenmeer* results from a combination of frost shattering and removal of fine material by the strong winds. In some areas there may be confusion between tills and *felsenmeer*, but Nichols suggested that the latter may be discerned by their more angular debris, that it is matrix deficient and that, in some places, the fragments can be fitted back together again showing that they were developed *in situ*.

The significance of this nivation-cryoplanation-blockfield assemblage of features is currently uncertain. The terminology associated with these features has been, historically, used extremely loosely such that it is not always clear as to what is being described (for example, a ‘transverse nivation hollow’ or a ‘cryoplanation terrace’ — are they morphologically different?). Equally the definition and significance of tors and blockfields (and block slopes, stone runs, and a whole host of loosely used terms) are presently also under debate with respect to their morphology, terminology, significance and age. Thus, despite application of these terms in Antarctic descriptions and/or discussions of landscape evolution, caution should be exercised in attaching any significant meaning to outcomes dependent upon these features. What is becoming clear, though, is that contrary to earlier perceptions it now appears likely that many of these features can be very old indeed (that is, many millions of years).

The limited available process data suggest that development rates can be very slow indeed; moreover, evidence seems to be forthcoming that, particularly in Antarctica, the overriding by cold-based ice has no impact on the evolution of these landforms beyond developmental process inhibition during these times; that is, there is no landform modification during times of glaciation. There also seems to be some evidence that many blockfield-type forms may be more related to warmer conditions than the oft-cited periglacial environments with which they are usually associated. Today, the safest conclusion may be that the genetic and climatic implications of these landforms are unclear but that they are very old landforms and that there needs to be some clarity as to their meaning in the context of understanding the larger landscape evolution of the Antarctic.

**Human effects on permafrost and periglacial environments in Antarctica**

Humans have had significant direct impacts on the terrestrial ecosystems of Antarctica. These impacts include contamination of soils and vegetation, disturbance of wildlife, and the importation of alien organisms. Campbell et al. refer to the effect of humans on permafrost by runway construction and active layer removal. Where active layer removal occurred, warming of the exposed ice-cemented permafrost took place causing melt-out and surface subsidence. However, an active layer depth was re-established after a few days but with volumetric moisture content higher than at undisturbed sites.

The moisture content of ice-cemented permafrost was significantly lowered on cut surfaces at Marble Point (77°25’S, 163°41’E) in the McMurdo Sound area. No significant re-establishment of icy permafrost has occurred in disturbed soils in 30 years since disturbance. Additional evidence for the release of moisture from the active layer and permafrost during construction activities includes the formation of intermittent streams, thermokarst, and salinization.

The polar regions are especially sensitive to global climate change. Bockheim discussed the potential effects of climate change on the terrestrial ecosystems of Antarctica, including changes in ice-free areas, in active-layer thickness and moisture content of permafrost, shifts in vegetation and microbial populations, and changes in rates of soil-forming processes such as salinization.

**Recommendations for future work**

The following lines of future investigations are recommended for continental Antarctica:

1. Establish an observational network of active-layer monitoring sites in Antarctica and interface with the Circumpolar Active-Layer Monitoring programme (CALM).
2. Develop a protocol for measuring active-layer thickness and differentiating it from dry permafrost using frost tubes and thermistors.
3. Develop site-specific descriptions of the relation between active-layer thickness, albedo due to lithology, and climatic parameters.
4. Investigate and analyse short- and long-term variations in soil temperature and soil moisture at selected sites.
5. Measure the thickness of dry permafrost using ground-penetrating radar and vertical electrical soundings and relate it to landform age.
6. Drill and equip boreholes for long-term measurement of permafrost temperatures.
7. Monitor soil and rock temperatures to understand the rates of weathering, patterned ground formation, and soil creep. Reference to recent literature, as cited in the preceding discussions, suggests that a number of topics long taken as ‘understood’ are now being questioned. The reconsideration, while central to cold regions research, may be particularly applicable to a number of Antarctic research directions. Indeed, it may well be that the Antarctic is the ideal place for the necessary more detailed, and perhaps longer duration, studies. While Arctic studies have elucidated much concerning rock glaciers and non-sorted patterned ground, the results of which are applicable to the Antarctic, the same cannot be said for the more conceptual problems with cryoplanation terraces or blockfields.

The value of Antarctica may reside in the analogue it may provide for many northern hemisphere locations at the time of the Late Glacial Maximum. Thus, Antarctica can play an important role in the investigation of processes no longer active in the Arctic or which are severely spatially constrained. Equally, the great spatial investigation of Antarctic permafrost may provide additional insights beyond the limited investigations that have taken place in the McMurdo Dry Valleys.

Finally, there is an unequivocal need for more dating of landforms/sediments in Antarctica. Some of this may be possible, given adequate access and resources, but some forms (such as cryoplanation terraces) remain enigmatic with respect to a meaningful means of dating them. Even then, it may require theory to provide a valid foundation for observation to be sure we know exactly what it is we are dating, so that the results can be placed within a meaningful framework. Last, with the potential impact of climate change on active-layer/permafrost dynamics, and thus the need for more extensive data on these, the impact of human activity, particularly with the increase in tourism, needs more careful monitoring. The Antarctic has much to offer future research, especially when the relatively spatially constrained nature of recent data is taken into account.
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60. Thorn C. and Hall K.J. (in press). A discussion regarding the concepts of patterned ground ‘‘cryoplanation.’’ Progress in Physical Geography.
Periglacial phenomena in the high mountains of northwestern Argentina

Ana Lia Ahumada*

Periglacial processes and features occur at high elevations in the mountains of the Sierras Subandinas, Sierras Pampeanas, Cordillera Oriental, Puna and Cordillera del Limite of Argentina (22–28°S, 65–68°W). This paper outlines our knowledge of these periglacial processes and landforms, as reported in the literature over the last 80 years. Landforms investigated include active and inactive rock glaciers, patterned ground, solifluction, proglacial lakes and other processes such as mineral segregation and concentration. Fossil periglacial landforms are an indication of past climates. Knowledge of geocryological phenomena in the northwest of Argentina has contributed to a better understanding of climate change.

Background

The northwest of Argentina is an almost unexplored region that has been little studied in terms of its periglacial and geocryological characteristics. However, its geographic position and its significance for human settlement during the Quaternary call for a detailed analysis of its geomorphological and palaeoclimatic record.

The region is located between 22° and 28°S and from c. 65° to 68°W, covering four distinctive, morphostructurally different regions, which have a N–S orientation and increase in altitude towards the west. From west to east these are: the Puna de Atacama, the Sierras Subandinas, the Cordillera Oriental, and the Pampean Sierras of the north (Fig. 1). The high mountains and relief areas are of particular importance for their effect on climate and the drainage system. The Cordillera del Limite, at the western limit of this region, is characterized by the presence of volcanic craters of Tertiary and Quaternary age, some of them now extinct. The highest summits range between 5200 m and almost 6900 m a.s.l. (Fig. 1). The most important summits are the Cerro Panizos (5259 m a.s.l.), the Cerro Vilama (5678 m), the Nevado San Pedro (5750 m), the Volcán Socompa (6301 m), the Cerro Llullaillaco (6723 m), the Volcán del Azufre (5680 m), the Cerro del Laudo (6400 m), the Cerro de Incahuasi (6620 m) and the Volcán Ojos del Salado (6885 m). The eastern limit, also called Prepuna, comprises the Cordillera Oriental, with the summits ranging between 4200 m and almost 6400 m: the Sierras Santa Victoria (Cerro Negro, 5029 m) and Zenta, which continue towards the south as the Sierras de Chañi (Nevado de Chañi, 6200 m), Acay (5950 m), Nevados del Palermo (6120 m), Nevados de Cachi (6380 m), Nevados de Catreal and Nevados de Chuscha (5468 m), the extensions of which combine with the extensions of the Sierras Pampeanas in the north; Cumbres Calchaquies, Sierra del Cajón or Sierra de Quilmes (Cerro Negroaroa, 4200 m) and further south, the Sierra del Aconquija with the Cordón de las Animas and the Nevados del Aconquija (Morro del Zarzo, 5064 m; Cerro Negro, 4700 m; Cerro del Bolson, 5500 m and Nevado del Candado, 5450 m). These mountain ranges or belts, with an average height of over 5000 m, converge in the Puna region, a high-altitude plateau with an average elevation of over 3500 m, with salt pans, an arid climate and a markedly reduced humidity. The orographic belts lie above the 0°C isotherm (4600 m a.s.l.) but, at present, hardly any evidence of glaciers is found. During the Pleistocene, however, these belts were covered by glaciers at least three times.1

In this geographical setting the climatic changes during the Quaternary, and in particular during the Late Pleistocene and Holocene, left geomorphological evidence that may be associated with the intense action of a periglacial environment, taking into account the region’s altitude with pronounced annual temperature variations and strong mechanical weathering, only one of many indicators of a periglacial high mountain environment.

Numerous authors since the beginning of the last century have referred to present and past periglacial conditions in the northwest of Argentina. Their observations are summarized here.

Climate setting

Owing to its proximity to the Tropic of Capricorn, the study area experiences a warm climate with little seasonal variation of daylight hours. However, the altitudinal diversity, the N–S orientation of the mountain ranges as well as its continentality are responsible for a complex mosaic of climatically different regions, temperature variations depending on altitude, and a variable distribution of mean annual precipitation, with a pronounced rainfall peak in summer. This creates extreme situations: very warm and humid climates in the eastern valleys and cold deserts on the plateau of the Puna region.

Rainfall is intense in summer, with a marked east to west gradient, and is associated with easterly winds from the Atlantic which penetrate as NE flows into the mountain reliefs. On the eastern borders of the mountains, orographic precipitation falls at two main levels: the one at an altitude of 1500–1800 m with annual precipitation between 1000 and 2000 mm, with a steep decline towards the west until it reaches values of less than 100 mm in the Puna region (some areas receive at little as 50 mm).2 In some cases, in the Sierra del Aconquija and at Cumbres Calchaquies, the first orographic barrier to the easterly winds, mean annual precipitation of 2500 mm (at 2500 m) has been recorded.3 Above this level, rainfall declines on the eastern slopes of these mountains to 600–500 mm/yr.2

In the Puna region the mean annual air temperature (MAAT) is less than 5°C, with a large daily amplitude. The mean annual maximum and minimum temperatures are 16°C and –4°C, respectively. An occasional very strong effect is caused by the so-called ‘white winds’. They cause snowstorms produced by the entry of westerly winds from the Pacific, which at heights above 5000 m penetrate the area in winter. In the Puna region, winds blow predominantly from the west; their frequency and intensity increase slightly during the dry winter season. Humid easterly winds blow in summer. Despite their relatively rare

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Fig. 1. Map of the study area.
occurrence, the easterly winds bring 88–96% of the area’s precipitation. In summary, the Puna region receives precipitation mainly during the summer, with a general decrease towards the west. The evapotranspiration is high, with the result that the mean annual relative humidity is less than 40%. The global annual mean annual relative humidity is 79%, which is less than the western global average of 88%.

Meteorological data for this part of the country are sparse and concentrated on the eastern slopes of the valleys. Weather stations in the Puna region are scarce and the few existing ones have records of a few years only. To obtain a better idea of the climatic conditions which favour a periglacial environment in a high mountain area, more climatic data will have to be collected, so that the circumstances that enhance its presence can be defined more precisely. The available climatic data for the region have been compiled by Minetti.

Periglacial regions in the northwest of Argentina

The relation between mountain permafrost and climate is poorly understood. Mountain permafrost is the result of a complex interaction of environmental factors, the most important of which is climate. The general climatic conditions in high mountain areas depend mainly on latitude, height and continentality and, less importantly, on local conditions which produce variations on a limited geographical scale.

In high mountain areas the periglacial environment may be classified into different zones as a function of altitude. Gorbunov introduced a classification of relations between permafrost/soil and temperature/vegetation based on an index of continentality. The latter is based on the difference between the elevation of the glaciers’ equilibrium line and the lowest permafrost limit. This index allows us to distinguish five different types of permafrost along the Andes: the Equadorian type, the Himalayan type, the Central Andean type, the Tibetan type, and the New Zealand type. The study area belongs to the Central Andean type.

Corte, in his map of current geocryological processes in Argentina, established the lower permafrost limit at 4000 m on the latitude of Salta, following a method similar to Gorbunov’s, as part of a periglacial inventory of the area.

Garleff and Stingl argued for a 9°C depression of the present annual air temperature during the Pleistocene for the Puna region. On the evidence of geomorphological data, among others, the corresponding descent of so-called ‘almost continuous permafrost’ and strong cryogenic activity is estimated to have been 1000 m in the NW of Argentina.

Glacial and periglacial processes and phenomena

Table 1 summarizes the glacial and periglacial processes and landforms in the northwest of Argentina that have been reported in the literature of the last 80 years.

<table>
<thead>
<tr>
<th>Site (range)</th>
<th>Mountain name</th>
<th>Reference</th>
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<tr>
<td>Puna</td>
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<td>4000</td>
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<td>4500</td>
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<td>Cordillera Oriental</td>
<td>35</td>
<td>–</td>
<td>Proglacial lakes</td>
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Glacial and periglacial processes and phenomena

Table 1 summarizes the glacial and periglacial processes and landforms in the northwest of Argentina that have been reported in the literature of the last 80 years.

Present-day glacial conditions. There are several records of glacial cirque floors; Penck determined contemporary glacial cirque floors at 5000 m. The average height of these features on the eastern slopes of the Sierra Aconquija is 4300 m. On the western slopes of the Aconquija, glacial cirque floors are formed at over 4400–4600 m. In the Sierra de Quilmes and Nevados de Chuscha (5468 m), glacial cirques are at 4200–4700 m and are now occupied by several small rock glaciers. In Cumbres Calchaquies, there are glacial features at Quebrada del Matadero (c. 4700 m) and in the Alto de la Mina Mt (c. 4700 m), in the Laguna de Huaca Huasi area.

Rock glaciers. Keidel’s studies on Puna were the first to describe block or rock slopes as characteristic of the region. He probably included rock glaciers in these deposits. He described their lower levels up to 4000 m a.s.l., did not observe any activity, but recognizes their palaeoclimatic importance and considers them an example of morphology characteristic of cold deserts.

Catalano et al. referred to glacial action in Puna and pointed out the presence of rocks agglomerated by ice and flowing under gravity as a glacier. He named these forms litho glaciers. Igarzábal noticed the presence of an ice nucleus covered by detritus in the Nevado del Queva (6130 m) and Granadas Mt (5707 m), that fed permanent streams. He called them glacialitic deposits, using Corte’s classification of rock glaciers.

Igarzábal compiled an inventory of active and inactive rock glaciers in the Acay region and the Nevados de Cachi, and determined the lower limit of rock glaciers at 4500 m.

In the Sierra de Santa Victoria, Corte et al. observed active rock glaciers at 4500 m a.s.l. In the same region Zipprich et al. distinguished three generations of rock glaciers, with presently active glaciers, and determined the lower limit of periglacial
processes at 700 m, at a temperature of 6°C, corresponding to c. 27 980 ± 190 BP.

Ahumada stressed the importance of setting high basins in the Sierras Pampeanas in order to detect rock glaciers that feed local rivers. She compiled an inventory of active and inactive rock glaciers of the northernmost region of Sierra del Aconquija. Figure 2 shows the location of rock glaciers in Cordón de las Ánimas, on the eastern slopes of the Sierra del Aconquija. Frost-depth measurements. Corte et al. measured the freezing depth in Pirquitas mine (4000 m a.s.l.) and found a stable temperature of 0°C at a depth of 1 m. This observation corresponds to a depth of 1.30 m, according to thermistor readings. Cobos and Corte registered a 70-cm-deep seasonal frost in permafrost at 4700 m, on the Volcán Ojos del Salado.

Needle ice. Halloy described the action of needle ice on the grassland around Huaca Huasi lagoon, in Cumbres Calchaquíes, at 4000 m a.s.l. In a nearby region, at a lower elevation, Ahumada et al. described the action of needle ice as leaving a rake-like pattern on the ground, on slopes of less than 5° at 2500 m, indicating diurnal freezing.

Cryoweathering. Penck, Keidel and Catalano attributed the mechanical weathering phenomenon in Puna to the great daily and seasonal temperature variation. Igarzábal reported the extensive cryoweathering of Puna’s land surface, that causes generalized surface erosion.

Patterned ground. Corte identified patterned ground associated with the Tuzgle (5480 m) and Socompa (6031 m) volcanoes. Halloy found small areas of patterned ground in Cumbres Calchaquíes, at 4000 m.

Solifluction. Auer reported that, at 27°C, the solifluction limit has descended 2000 m and is now at 2600 m. Sayago and Collantes described solifluction processes in the smoothing of the Tafi Valley’s slopes. Ahumada et al. described solifluction grounds at El Rincón, Sierra del Aconquija, in a seasonal freeze-thaw environment, between 2500 and 4000 m a.s.l.

Cryoplanation. Keidel was one of the first to mention cryoplanes and he called them ‘summit’ cryoplanation surfaces. Though he did not indicate specific sites, he recognized their palaeoclimatic importance in Puna.

In the Sierras del Aconquija and Cumbres Calchaquíes, at over 4000 m, Halloy described a high plain modified by glacier and periglacial action, with beach-like terraces.

Mass wasting. The big clastic deposits surrounding the Sierras del Aconquija and Cumbres Calchaquis have been described in the literature by Bossi and Porto and Danielli as fanglomeratic deposits accumulated by alluvial and/or periglacial activity.

Sayago and Collantes described large cenoglematic clastic accumulations over the covered glais of the eastern slopes of the Sierra del Aconquija and the Cumbres Calchaquis. They concluded that they originated as deposits under gravity at the same time as the glacial episodes detected in the peak area, which they considered to be of periglacial origin.

Peatlands. Halloy noted the existence of mountain peatlands under conditions of seasonal freezing in the high peaks of the Sierra del Aconquija and Cumbres Calchaquis. Ahumada et al. described peatland deposits at 2800 m, in the Reales River basin, in a seasonal freezing environment.

Proglacial lakes. Proglacial lake sequences have been described by Sayago and Collantes and Sayago et al. in the Mollar region, Sierra del Aconquija. Ahumada and Vides deduced periglacial conditions in the lake deposits of Cordillera Oriental.

Chemical segregation in freezing conditions. Ahumada and Vides identified mirabilite (Na₂SO₄·10H₂O) by X-ray diffraction in lake sequences of the southern region of Cordillera Oriental. The presence of hyper-hydrated sulphate indicates a cooling of the water due to the proximity of glaciers. Mirabilite is produced by the segregation of pure sodium sulphate crystals. These deposits are evidence for an active periglacial environment, and were dated by Trauth and Streeker as 35 650 ± 380 yr BP.

Heavy minerals concentration. Ahumada and Heinrich analysed the Pb, Sn and Ag content of 230 drillings in the alluvium terraces at Pirquitas mine in Puna. The metals were concentrated mainly at a depth of 1.10–1.30 m. They attributed these concentrations to the seasonal freezing and thawing that took place after mineral deposition during the Late Pleistocene.

Altitudinal zonation. Garleff and Stingl defined the regional characterization of periglacial activity in relation to altitude. More recently, Ahumada et al. established the elevation of periglacial processes in the Reales River basin (Sierra del Aconquija), and distinguished two levels: a lower level, from 2500 to 4000 m, with seasonal frosts, needle ice action and solifluction; and an upper level, from 4000 to an average of 4500–5000 m, with intense gelifraction, active and inactive rock glaciers, talus, old moraine deposits, and glacial cirques.
Conclusions

Many periglacial landforms have been reported from the high mountains of northwestern Argentina. They include rock glaciers, sorted polygons, frost weathering, solifluction, lakes, and periglacial mass wasting. Some periglacial phenomena, such as rock glaciers, solifluction, and frost weathering are active today. No investigations involving instrumented measurements of actual conditions have been conducted. Several authors deduced, however, that during the Last Glacial Maximum the altitude of periglacial activity descended between 1000 and 700 m below the present, corresponding to a temperature decrease of approximately 9°C to 6°C.

Among the questions to be addressed regarding periglacial phenomena in northwestern Argentina are the following:

- What is the extent and character of large-scale landforms in the high mountains?
- How much did climate permit the development of such geological features in a subtropical region?
- What is the relationship between the nature and altitude of fossil periglacial phenomena and past climate?

Improved knowledge of the character of the periglacial environment in this region will contribute to the development of models for sustainable development. These models may assist in the protection against natural disasters caused by anthropogenic interference in the environment.

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Inventory of fossil cryogenic forms and structures in Patagonia and the mountains of Argentina beyond the Andes

Dario Trombotto

This article summarizes the most important observations of fossil cryogenic forms and structures in Patagonia and the mountains of Argentina beyond the Andes. The chronological history of cold episodes was based mainly on the dating of two important glaciations: the Great Quaternary Glaciation of 1.2 Myr ago, which represented a maximum of permanently frozen ground, and the expansion of permafrost during the last glaciation of 18-20 kyr ago. Special emphasis is given to those cryogenic indicators that irrefutably mark the occurrence of permafrost. In the earlier glaciation, the maximum expansion, which supposedly reached the Rio Colorado, left epigenetic ice wedge casts in North Patagonia, which penetrated soil profiles to a depth of over 3 m and express differences of up to 10°C from the present mean annual air temperature (MAAT). In the most recent glaciation, temperatures differed from MAAT by at least 14°C. The associated pseudomorphs are smaller in size than for the Great Quaternary Glaciation and so far have been found only in South Patagonia. They not only indicate a tundra environment near the glacial limits identified by Caldenius, as in the area of the Río Deseado, for example, but are even to be found at the coast at the present day.

Introduction

The cryogenic processes of the Neogene left fossil traces in southern South America that are found in the Quaternary stratigraphy of Patagonia and may be observed clearly in mountain areas, particularly in the Andes. Mesol- and microforms and structures indicate how the cold extended into the steppe. They also reveal the palaeoclimatic characteristics shaped by the cold episodes (cryomeres), when the extreme temperature minima of the Quaternary affected South America and even predominated at the higher latitudes of the southern part of the continent.

Both classic and recent publications on the Quaternary of Argentina describe, for example, the marine terraces of the Patagonian coast and discuss the difficulty of their topographical or chronological interpretation. Many authors (see refs 1, 4-10, for example) have attempted to define the glacial environment at different times in the geological past, leaving many questions unanswered. The advance of the older glaciations has been intensively discussed.1,3,11,12

Minor local glaciations (glacioldastos or nudos glaciares in Spanish and in the terminology of Groeber) beyond the Andes are hard to imagine in Patagonia today, although an intensified aridity obviously prevailed in Patagonia, at least during the Last Glacial Maximum (LGM), but their occurrence cannot be ruled out completely for other glacial times. It is possible to define past glacial environments with certainty by means of end moraines, which clearly mark the termination of cold episodes. Evidence is also derived from the great Andean glacial lakes, and landforms and structures that are characteristic of a glacial environment, such as drumlins and varves.

Trying to explain periglacial environments, however, is a more difficult task as such typical landforms are not always present. It is assumed that the periglacial structures in South America were the result of complex and sometimes atypical climatic, geological or regional conditions. This was certainly true for Patagonia and it may explain why periglacial environments in South America have hardly been taken into account by researchers concerned with the palaeoenvironment.

Czaja1 was one of the first to interpret fossil periglacial processes in South America in order to explain the Palaeogroundscape, but his interpretations necessarily implied an extra-Andean glaciation. I have argued for a sequence of climatic denudation cycles, which display a tundra-loessic phase during the LGM, for example. This was when the netlike structures of a periglacial ice wedges were created, according to Czaja, and when the loess was deposited on the Pampean steppe and dunes and coarser sediments on its margins (the Pampean borders).

Clapperton, in his Quaternary Geology of South America, briefly summarized periglacial features. In order to establish a chronological order of cold episodes based on the interpretation of periglacial forms, Trombotto13-15 drew up the first inventory of cryogenic evidence. The present review is a new inventory of fossil cryogenic forms that may help to improve our understanding of the paleoclimatic history of southern South America.

The periglacial and palaeoclimatic background

Today, South American permafrost (also called Andean permafrost) is a mountain permafrost type localized exclusively in the Andes. At the 31st International Geological Congress in Rio de Janeiro, Trombotto13 presented a preliminary regionalization of the main cryogenic areas in South America, including the possible occurrence of permafrost. A more comprehensive study, however, allowed classification of Andean permafrost into a variety of subtypes.16 With the help of this taxonomy, it was possible to correlate permafrost types with hydrological and climatic conditions associated with global warming on the one hand and with the two great divisions characterizing the Andes of southern South America: the Dry (Desert and Central Andes) and the Wet Andes (Lakes Region and Patagonian Andes).

Permafrost occurs in equilibrium with environmental conditions. Thus, certain periglacial landforms are reliable indicators of climatic conditions such as temperature and precipitation. Morphogenesis within the ecosystem of fossil cryogenic environments is usually explained in terms of the characteristics and the morphodynamics of present cold environments.

The arid conditions, the dynamics of cryogenic processes as well as cryogenic mechanisms in volcanic petrology, and basaltic
terrace in Patagonia in particular, raised many questions about the ambiguity of certain Patagonian structures and landforms. Their identification is complicated and the evolution of cryogenic processes in the past remains in doubt, so that further research is required.

Discontinuous (creeping) permafrost is found at 32–33°S in the Central (Arid) Andes of Mendoza, at 3600 m a.s.l., and island permafrost even persists at altitudes as low as 3450 m. In the Central Andes of San Juan at approximately 30°S, discontinuous permafrost is detected at 4150 m a.s.l. in the Los Lenguas rock glacier, Agua Negra. In the 1990s, cryogenic phenomena combined with permafrost were registered 400 m below the 0°C isotherm. Regional and conditions seem to reinforce the effectiveness of periglacial processes. Garleff and Stingl argued along these lines and introduce a de facto limit of ‘quasi continuous permafrost’ (a term that refers particularly to topography and exposure that creates landforms and important cryogenic activity). This limit is presently delimited by the -2°C to -4°C isotherms (4500 m at 33°S) in the Central Andes with an annual precipitation of 500–900 mm, and by the -1°C to -2°C isotherms with a precipitation of 300 mm in the Puna region of northwest Argentina.

At this limit of 4500 m a.s.l. and below, there is still a belt over 1 km wide that displays marked cryogenic phenomena. In the Southern or Humid Andes, permafrost was reported at 51°30’S in Santa Cruz between 1977 and 1978 at an altitude of 980–1100 m, while in the Lakes Region (between 35° and 45°S) in the province of Chubut, permafrost is today detected close to Lago Vittore at c. 44°S at an altitude of 2000 m (C. Bianchi, pers. comm.).

Garleff and Stingl have long insisted that there are different factors that distinguish and characterize cryogenic activity in the Arid and Humid Andes of southern South America. In the arid Central Andes it is temperature that determines the occurrence of permafrost and cryogenic phenomena, whereas in the Southern or Humid Andes precipitation plays a more decisive role. These differences imply that there may be disynchroneity in the evolution of the phenomena, and this must be taken into account when establishing palaeoclimatic and cryogenic chronologies. In contrast with current theories of Quaternary palaeoclimate and the circumstances which allowed cryogenic and morphodynamical activity, Garleff and Stingl and Garleff et al. suggested that a temperature decrease during the LGM reinforced the growing aridity of the South American Arid Diagonal (the region between c. 25° and 45°S) and increased the influence of the westerlies without any shift of these western winds northwards as some authors argue. Groeber pointed out the importance of westerly winds to explain the deposition of aeolian sediments in the Pampa region during the glaciations. But he based his assumptions about the atmospheric circulation on a model that is now questioned. Garleff and Stingl assumed that the mean annual air temperature (MAAT) today differed by approximately 15°C from that for the Central Andes and by 9°C for the Puna region during the LGM. Trombott, based on the presence of ice wedge casts, calculated the depression of the MAAT during the LGM to be 14°C for South Patagonia. This value coincides with Garleff’s estimates of between 10° and 15°C for the region.

With evidence that included geomorphological data, the depression of the lower limit of the permafrost and strong cryogenic activity was calculated to be 2500 m in the northern part of the Humid Andes (in the Lakes Region), 3000 m in the Central Andes and 1000 m in the northwest of Argentina.

In the Central Andes around Mendoza, creeping permafrost associated with rock glaciers supposedly reached down to 1200–1800 m a.s.l. at 32–33°S during the Great Quaternary Glaciation, in the sense of Mercer and when the Early Pleistocene glaciation reached its maximum expansion, whereas it is assumed that in the southern part of the province of Mendoza it penetrated as Patagonian permafrost (36°S) (Fig. 1).

During the Last Glacial episode (18–20 kyr), the surface covered by permafrost must have included the major part of the Patagonian steppe, possibly comprising more than the area that is affected by seasonal freezing today (Fig. 2).

During the Early Quaternary glaciation, temperatures were much lower, and the advance of the LGM limit was further north, occupying probably all of Patagonia and also lowering the altitude of the mountain permafrost limit. This doubling occurred in earlier times too, according to the Neogene advances reported by Schellmann.

Traces of past cold episodes

Fossil rock glaciers

The fossil rock glaciers of the Andes may be identified as landforms associated with active rock glaciers or as their geomorphological prolongation. Their activity is detected by means of geomorphology, geophysical prospecting and ground temperature profiles. Fossil debris rock glaciers are a direct link with present glaciers or Pleistocene ice-covered regions and their terminal moraines, as is often the case in the Central Andes. The talus rock glaciers, on the other hand, represent independent landforms.

Fossil rock glaciers have the following characteristics and associations:

a) Traces of cirques and excavation hollows in mountainous areas subject to cryowathering;
b) Traces of snow-debris or nivodetic channels on the slopes of the mountains, which functioned as a means of transport of cryowathered material. These channels cut the cirque transversely and are of primary importance for the interpretation of talus rock glaciers, where the cirque is less significant or not recognizable with certainty;
c) Lobe- or tongue-shaped relic forms. The rock glaciers left bulges as hanging tongues on the mountain slopes and piedments, and at the foot of the mountains with a postfrontal depression;
d) Ridges of debris (Halskarven) left at the edges by the faster moving central channel of the glacier;
e) Slopes with a predominantly southerly orientation;
f) Rock glacier sediments may consist of large blocks and angular clasts on the surface but with a predominance of fine, angular sediments in their interior;
g) Scanning electron microscopic analysis of superficial fine sediments, consisting of quartz grains of the size of medium and coarse sand by scanning electron microscopy (SEM), indicates a so-called glacier-like texture. These particles have the following general characteristics in an SEM: high relief, angular shape and conchoidal fractures, blocks, arch-like steps, and chattermarks. Deposition and dissolution of silica is also frequently found (see ref. 28) on the surface of the quartz grains;
h) Sediments are sorted vertically at the front of a tongue;
i) Blocks and clasts may be oriented with their major axis sloping downwards, but may also display marked surface damage and a subsurface of mixed orientation;
j) The petrological component in talus rock glaciers may be monogenic but frequently of varied petrology in debris rock glaciers with glacial origin.
Fig. 2. Cryogenic structures and landforms in Patagonia assigned to the Last Glacial Maximum (18–20 kyr ago), according to various authors. Numbered sites as in Fig. 1.
Recurrence of the fossil rock glaciers in slopes of similar orientation.

The rock glaciers of the Cordón del Plata (at c. 33°S) show symptoms of inactivity at 3400 m a.s.l. Down to 3200 m, these glaciers may contain ice below 3000 m they are considered to be fossil. At this altitude they were active only during the last glaciation. Wayne and Corte mentioned a sequence of fossil rock glaciers within the morainic Morenas Coloradas rock glacier at Vallecitos, Mendoza. Their interpretation is based mainly on the altitude, inclination and erosional modification of the fronts, weathering of surface clasts, and thickness of loess and vegetation cover. These parameters are not always clearly observable because of the disharmony in the permafrost creeping of different parts or identifiable bodies, which respond to subsurface ice. There may also be a superposition of the main body by talus rock glaciers, so that the main body presents active parts at lower altitudes, despite inactive parts at greater height. This occurs frequently in such extensive Andean cryogenic forms as this one (over 4 km long and with an average width of 600-800 m). The inactive phase of a rock glacier often represents a state of transition that is hard to assess chronologically.

The so-called Dragon rock glacier at 34°S in the Cordillera Frontal of Mendoza, with a SE orientation, is one example of such a state. It has two different sectors: one is at an altitude of 3300 m and has a front tongue with an inclination of 28°; the other part at 3200 m has a front with an inclination of 26°. It is furthermore an example of glacial origin. The fossil part of it - easier to identify - begins at approximately 3175 m a.s.l. and has a maximum inclination of 15° at its front.

Fossil rock glaciers have also been sought in the geologic regions Precordiller (province of Mendoza), Sierras Pampeanas [in this case the occurrence of cryogenic sedimentary slopes (Schachthänge) cannot be excluded], Sierras Australes and in the northwest of Argentina. Table 1 indicates the most important findings concerning the mountains of medium altitude.

The presence of fossil rock glaciers indicates a mean annual palaeoprecipitation of 500-600 mm; the termini of their tongues signify mean annual palaeotemperatures of around -1°C.

The surface textures of quartz grains (of sand size) from fossil rock glaciers were analysed by scanning electron microscopy by Trombotto. Those cases listed in Table 1 indicate that the SEM technique detected textural characteristics of cryogenic origin in samples from Ventania, for example, whereas it was not satisfactory for specimens from Tomolata, for which weathering and chemical processes largely obscure mechanically fashioned microstructures. In the case of the Quebrada de los Árboles fossil rock glacier it was possible to identify typical evidence of mechanical working, such as the 'washboard texture'. This was also obtained experimentally by compression, although 70% of the samples displayed deposition or dissolution of silica.

**Cryoplanations and relic nivation hollows**

Keidel was one of the first in South America to mention cryoplanation surfaces, which he called *penillantanas cuspidales*. Although he did not give exact geographical positions, he emphasized their palaeoclimatic importance for the Puna region. More recently, Ignezábal and Rivelli reconsidered palaeocryogenic effects in the Cordillera Oriental, a geological region close to Puna, in order to explain the flattened land of the batholite of Tastil in a humid periglacial environment.

In the Andes in the province of San Juan, cryoplanation surfaces on mountain tops at 30°S can be found together with quasi-continuous permafrost at 5000 m and above, where temperatures are ≤4°C. At the Lagunita del Plata (33°S, Mendoza), the cryoplanation surface starts to become inactive at 4000 m and below, with a mean annual temperature of about -2°C and a mean annual precipitation of c. 600 mm.

Cryoplanation surfaces are found throughout the Cordillera Frontal and Cordillera Principal regions of Mendoza. Fossil cryoplanation surfaces and relics of tors are also known for the Falkland Islands, for example at Mt Kent at approximately 480 m, Mt Challenger and Wichmann Heights. The Falkland Islands, with their great variety of cryogenic fossil forms, indicate the significance of a past periglacial maritime climate (see ref. 9). Cryoplanation surfaces are closely related to nivation hollows. Nevertheless, they have been little considered for inventory-taking and their palaeoclimatic importance is underestimated.

Seasonal nivation hollows, with their inherited depressions from former perennial or more intense nivations, are frequently observed in the Central Andes between 3000 and 4000 m, depending on their orientation. The oldest forms display characteristic concavities with a threshold close to the cryogenic excava- tion. The bottom and centre of the nivation hollow accumulate fine sediments and more abundant vegetation.

Corte reported on nivation hollows in the Sierras Pampeanas of San Luis. Clark found them on the Falkland Islands at mounts Osborne, Adam and Maria (50°S); and Magnani reported on such forms on the plateaus of South Patagonia near Lake Cardiel (48°S). In the basaltic region of the Meseta de las Lagunas sin Fondo at 47°S in Patagonia, relic nivation hollows have been identified with a southerly aspect.
Cryogenic sedimentary slopes, asymmetrical valleys and dells

Cryogenic sedimentary slopes were reported early in Argentina. Keidel\(^6\) called them detritic slopes (pendientes de escoriros) and presented them as characteristic of the Puna region. It may be assumed that he also included rock glaciers under this term. He placed their lower limit at 4000 m without considering their degree of activity but he was conscious of their palaeoclimatic importance during previous cold episodes. Czajka (ref. 37, table 1) lowered the limit during the Pleistocene to 2600 m.

In the Sierra de Famatina (29°S), Richter denudation slopes (Glätthänge) are restricted in their activity to an altitude of 4000 m.\(^6\) Detritic slopes (Selatthänge) and relict periglacial valleys abound in the Andes in Mendoza and San Juan, below or close to the present periglacial level, but further investigations are necessary for a detailed inventory.

Garillet\(^7\) et al. made an inventory of dells for the elaboration of the geomorphological map of La Junta–Agua Nueva, interpreting morphodynamics and palaeoclimatic changes at the borders of the Andes at 35°S. Magnani\(^7\) and Corte\(^7\) reported on asymmetric valleys in South Patagonia. The surface textures of quartz grains (sand size) from relict cryogenic sedimentary slopes were analysed by SEM by Trombitto\(^7\) in an investigation of fossil cryogenic processes.

Solifluction forms, stone runs, blockfields and heads

Different types of solifluction forms in southern South America were described very early. Andersson\(^7\) was one of the first to mention this topic and to introduce the term solifluction to the international bibliography for the stone runs on the Falkland Islands. Blockfields (Felsenmeer) and stone runs (Blockströmme) were investigated later by Clark,\(^6\) Bellosi and Jalfin\(^6\) and others in different parts of the Falklands.

Fossil solifluction layers have been reported in Patagonia where only seasonal frozen ground is recorded today. Magnani\(^8\) described solifluction forms for the Patagonian mesetas but without mentioning any sites in particular. It should be remembered, though, that Caldenius, as early as 1940, referred to solifluction in order to explain the dispersion of the Patagonian Gravel (Rodados Patagónicos) (fluvial, fluvioglacial or polygenetic gravels),\(^8\) and Czajka\(^9\) questioned whether certain features, for instance in Pampa del Castillo, Patagonia, were solifluction or glacial phenomena (kames). Auer\(^10\) stated that the solifluction limit descended by 2000 m down to 2600 m at 27°S, while at 33° in the piedmont of the Cordillera Frontal, Winderböcke begin to become inactive only at an altitude of 2500 m.

Solifluction layers of Pleistocene age were also described by Regáraz at 2200 m for this site.\(^11\) For Corte,\(^12\) however, the lower solifluction limit lies at 1500 m in the Precordillera of Mendoza and in the Sierras Pampeanas of San Luis and Córdoba. This limit extends even to 500 m in Ventania (Buenos Aires) at 35°S. Abraham de Vázquez and Garillet\(^12\) detected fossil solifluction layers at La Junta–Agua Nueva at approximately 1800 m a.s.l. (34°–35°S).

The solifluction levels of the Patagonian profiles are recognizable but not as pronounced or as common as one would expect according to postulated palaeoclimatic models. This may be explained by petrology and the restrictions imposed by very low precipitation, which has characterized this area since the formation of the Andean chain. Nevertheless, solifluction layers of different undefined ages may be found from North Patagonia — on the southern slopes of the Meseta del Sumoncura, for example — and southwards.\(^13\)

Auer\(^10\) mentioned evidence for solifluction in the Sierras Australes (Buenos Aires), but played down the importance of solifluction in Patagonia because of few findings and insufficient precipitation there.

In South Patagonia at approximately 46°S there are several representative levels which are related to fossil ice wedge casts and were associated with the Last Glaciation\(^14\) (Figs 4, 6, 9 and 10). Corte\(^15\) reported on fossil solifluction on the slopes of the southern Andes and Lake Buenos Aires.

On the Falkland Islands with their beaches from the pre-Holocene, Clapper and Roberts\(^16\) related solifluction layers to cryoturbation. Veit and Garillet\(^12\) described solifluction layers with a thickness of 50–70 cm south of 42°S (72°20'W); north of this altitude such layers appear less frequently and are restricted to the SE part of the Valle Longitudinal and the Cordillera de la Costa (41°S, 72°20'W). The latter were assigned to the Llanquihue Glaciation (equivalent to the LGM).

Grèzes litées

Sedimentary layers of varying degrees of coarseness deposited by supra- or intratidal processes were classified as relict grèzes litées and described by various authors, especially for the Central

Fig. 3. Polygonal cryoturbation caused by epigenetic ice wedge casts which affected the sandstones of the Puerto Madryn Formation of the Upper Tertiary (Mocena), near the city of Puerto Madryn, Chubut; palaeocryogenic site no. 5, denominated L7. Length of spade: 65 cm. The rest of the reddish structure with calcrite inside can be observed on the left. On the upper part of the profile are the Rodados Patagónicos (Patagonian Gravel), a fluvial conglomerate of acidic igneous rocks, which penetrated the cryogenic structure.

Fig. 4. Ice wedge casts from the Last Glacial Maximum, Hetrich-Pampa del Castillo, Chubut; palaeocryogenic site no. 3. Length of hammer: 31.8 cm. The pseudomorphs penetrate up to 90 cm into the marine Oligocene and are filled with a solifluidal head (13–15 ky'). The filling has more than 80% sandy material (quartz grains also show aeolian characteristics). On top of the ice wedge casts a palaeosol indicates a warm episode (>15 ky').
Andes. Hitherto, however, it has not been possible to compile a
detailed inventory or chronology.

The active deposition limit lies at approximately 3500 m a.s.l.
according to Corte.24 In the Precordillera of Mendoza, in
Villavicencio at about 33°S, such fossil sediments appear at an
altitude of approximately 2500 m.

Beyond the Andes, Corte24 reported on grès liées for the
Sierras Pampeanas (Cerro Pelado, San Luis) and Sierras Austral-
es (Ventania, Buenos Aires) at 1500 m and 600 m, respectively,
but they have not yet been studied in detail.

The quartz grain surface texture of grès liées was analysed by
SEM by Trombottost. These samples revealed not only a
‘frost texture’ characterized by conchoidal fractures and large
blocks, ovoid fractures on the edges, arch-shaped conchoidal
fractures and irregular diagenetic surfaces to name a few, but
also signs of subaerial impressions due to nivofluvial activity.

Pattered ground and fossil cryoturbation

Stingl and Garleff25 found evidence of fossil cryoturbation in
the Sierras de Famatina (29°S) at 4200 m a.s.l. in the Central
Andes of Mendoza, as well as at La Junta–Agüa Nueva26 at
1800 m at c. 34°40’S. In Villavicencio, in the Precordillera of
Mendoza at 33°S, it was detected at approximately 2500 m,
marking an important lower limit of fossil cryogenesis.

Auer27 mentioned traces of cryoturbation in connection with
the Patagonian Gravel, from Stroeder (40°S) southwards to
50°30’S and he also quoted cases from Ventania at 38°S. In
general, these forms were reported together with indicators that
support the argument for minor local glaciations. Czajka28 asso-
ciated the system of valleys at Pampa del Castillo (South
Patagonia) with glacial processes (dead ice of kames). In 1967
Corte explained involutions and cryoturbation foldings in the
area of Río Callegos in terms of cryogenic criteria only. The
cryoturbation forms affect Tertiary rocks—mainly sandstone—as in
Salinas Chicas (southern part of the province of Buenos Aires)
and Puerto Madryn (North Patagonia). From their stratigraphy,
the forms at the sites of Holdich–Pampa del Castillo and
Romberg (South Patagonia) were assigned to the LGM.14,15,24
Cryoturbation also affects the lower and upper and/or interme-
ciate levels of the Patagonian Gravel.29,32

Very few examples of relic, patterned ground have been
found or reported. In the area of Vallecitos in the Central Andes
of Mendoza, some examples were identified by Trombottto at
3000 m, but they are badly preserved. Magnani28 reported on
polygonal ground for the area of Lake Cardiel in South
Patagonia (at c. 49°S) at 500 m a.s.l.

Less pronounced patterned ground with deformations due to
inclination (Kometenschliff type29), however, also appear in areas
away from the Andes such as the Meseta El Pedrero, in the
province of Santa Cruz.30

Fossil ice wedges and polygonal cryoturbation

Fossil ice wedges are the most important cryogenic structures
in the Patagonian stratigraphy. Cryoturbation is also usually
linked with ice wedge casts and polygon development.

Although mentioned previously by Auer, Czajka31 and
Corte,30 fossil ice wedges were little considered in the interpreta-
tion of Patagonian stratigraphy and palaeoclimatic. The discov-
ery of fossil ice wedges, among other indicators, led to the belief
in the extension of Pleistocene permafrost up to the Rio Negro,32
a limit that later was extended to the Rio Colorado by Corte.31
The characteristics of very old epi- and syngenic ice wedge
casts in North Patagonia were described by Trombottto.33,34
The casts extend to a depth of nearly 3 m and indicate a tempera-
ture difference of at least 16°C compared to present MAAT and a
much lower annual precipitation than today (500 mm/yr). Those

Fig. 5. Cryoturbation, Cerro Kenseil, Santa Cruz; palaeocryogenic site no. 28.
Diameter of the camera lid: 5.4 cm. See Fig. 6.

Fig. 6. Ice wedge cast from the Last Glacial Maximum, Cerro Kenseil, Santa Cruz;
palaeocryogenic site no. 28. Length of hammer: 31.8 cm. The filled material is rich
in sand (c. 75%), whereas the host material is rich in CaCO3 clay and gravel. The
dark patches are indications of cryoturbations in a scilifluidal layer. On the top of the
pseudomorphs a palaeosol indicates a warm episode.

Fig. 7. Fossil polygonal network with upheaval on the borders (German Randwülste) indicating ice pressure. Las Heras (N), Santa Cruz; palaeocryogenic
site no. 27. Length of the measure: 1 m. See Fig. 8.
Ice wedge casts assigned to the Last Glacial are less well developed. They have a maximum depth of 90 cm and a width of 30 cm and appear only in South Patagonia. The structures (at 46°S) indicate a temperature difference from the present MAAT of at least 14°C and are good examples of hexagons with convex borders (Fig. 7). The fine and medium sand that fills the wedges displays a certain inner orientation into thin vertical layers with little or no lateral pressure of adjacent sediments. The paleocryogenic sites investigated were Holdich-Pampa del Castillo, Romberg, Las Heras and Cerro Kensei.13-45

The northernmost cases of pseudomorphs were reported by González and Corte16 at approximately 38°S, 60°W at 200 m a.s.l. in the province of Buenos Aires, and by Grosso and Corte24 in the west of Argentina, with two generations identified in the area of Río Diamante (34°S, 825 m a.s.l.) in the province of Mendoza. Pseudomorphs were also identified in the Sierras Azul and Media Luna (1640 m a.s.l.) at 38°16′S in the Cuyo region (Mendoza)25 at a critical altitude in terms of the cold Quaternary climate.

Table 2 summarizes the latitudinal permafrost advance in Patagonia characterized by ice wedge casts at important paleocryogenic sites, some of which are illustrated in the photographs (Figs 3–10).

Other forms: pingo traces and orientated lakes

Although Clark26 mentioned orientated lakes at Choisel Sound and Lafonia as well as fossil pingos on the Doyle River (Falkland Islands), these forms are scarcely reported on for Patagonia, presumably for lack of investigation.

The so-called pequeños bajos sin salida (small basins without outlets27) of Patagonia have sometimes been taken into account because of their genesis. Some authors considered them to be traces of the Patagonian periglacial environment of the Pleistocene. Certain bajos sin salida (German Kavern) in the province of Santa Cruz were interpreted as pingo traces by Garleff.28 Corte reported on a fossil pingo on basaltic rock at La Leonora in South Patagonia, but this has to be confirmed by further research. The same author28 identified orientated lakes at the mouth of the Santa Cruz River and on the plains of the Río Deseado and mentioned fossil palsas near Lake Cami (Fagnano) in Tierra del Fuego.

A detailed inventory of peatlands (moor) or fossil mallines (a kind of anmoor with a genesis similar to a fenmoor) for a reconstruction of palaeoclimate still has to be compiled.

Conclusions and recommendations: towards a chronology of cold episodes in southern Argentina

Neogenic cryogenic processes left structures and fossil forms in Patagonia that may be observed in the stratigraphy and in the southern Andes below 2000 m a.s.l. at 44°S and even at 1000 m at 51°30′S. The limits of permafrost extension during the Neogene varied according to the cold episodes, and were particularly pronounced in southern South America. The exact permafrost limit, periglacial geomorphology and cryogenic structures, however, are still not well defined but hold important clues for understanding the climate in the Tertiary–Quaternary of Patagonia.

Two cold episodes have been examined that are based on datings with glacial, marine and other indicators:27,58-60 (a) the Great Quaternary Glaciation of 1.2 Myr ago, which represented a maximum of permanently frozen ground; (b) the expansion of permafrost during the latest glaciation of 18-200 kyr ago, which affected the uppermost parts of the geological profiles in the South Patagonian stratigraphy.
Corte, however, assigned the tills of South Patagonia of 3.5 Myr and 1.2 Myr (lower and upper till) to two generations of very old ice wedge casts in Río Gallegos–Chimen Aike. A third generation of pseudomorphs was assigned to the peak of the LGM 40 kyr ago. He compiled a first draft of a chronostratigraphical order of cryogenic events by applying different dating techniques. Cryogenic forms in Mendoza, for example, were assigned to an age of 450 ± 60 kyr (in relation to the ‘pyroclastic pumice association’, a volcanic, petrological sequence). In the case of the El Aspero fossil rock glacier, however, it was assumed that one part of it had been buried by volcanic ash of the age mentioned. The fossil ice wedge casts and cryoturbation in the area of Río Diamante were dated on this assumption and taking into account the sequence of flu vial terraces.

The ages of fossil ice wedges and cryoturbation in Puerto Madryn were questioned by Trombotto, who considered the structures to be much older (possibly of the Old/Oldest Pleistocene glaciation, called the ‘Interglacial’) than those resulting from CaCO₃ datings of the ice wedge cast filling and their exterior CaCO₃ datings that were assigned to the cold maximum of the LGM (see refs 61, 62). Trombotto and Ahumada proposed that their age coincided with the most intense cryogenic advance with increased humidity, the Penfordd cryomere, which even extended into North Patagonia.

Solifluction limits have been identified in Patagonia but they are less developed and not as common as expected, probably owing to the restrictions of low precipitation, which characterizes the regions since the rise of the Andean chain. Solifluction layers may nevertheless be observed in North Patagonia as, for example, on the southern slopes of the Meseta del Somuncura.

The conditions of the LGM approximately 20 kyr ago created significant cryogenic forms, such as ice wedge casts, only in South Patagonia. The latter may probably be correlated with solifluction layers and cryoturbation recorded by Clapperton and Roberts on the Falkland Islands, based on a palaeosol dated to approximately 26 kyr.

Whereas the Falkland Islands display the most varied periglacial forms of a past oceanic climate, the Patagonian periglacial is influenced by very low precipitation and extremely low temperatures very different from today.

Pingo traces and a possible fossil rock glacier have been reported in the area of the basalt Meseta El Pedrero and require further research.

The most recent pseudomorphs in South Patagonia are covered by solifluction layers assigned to a cold episode in the Last Glacial of the Upper Pleistocene (13–15 kyr ago), accompanied by a glacial advance reported by Mercer (c. 1.2 Myr) that follows an interstadial represented by a palaeosol frequently found in South Patagonia. A characteristic profile at the penultimate fluvial terrace of the Río Deseado, however, reveals that the structures supposed to be of pleniglacial age also cut across an older solifluction layer and extend downwards. Towards the lower part of the profile there even appear relics of structures or even older pseudomorphs. The sequence of sedimentary structures and forms coincides closely with the last oxygen isotope stages but absolute datings are required to confirm this.

The most recent events are called the Romberg cryomere after the name of the estancia near the profile. Recently, Shellmann dated Last Glacial ice wedge casts from San Julián, which are cryoturbating coastal levels containing molluscs. These pseudomorphs share the same characteristics as those found at Romberg, Kensei, Holdich, Las Heras and recent findings at Telken (province of Santa Cruz).

The palaeoclimatic history of southern South America remains poorly known. The dating of cryogenic structures and landforms in Patagonia in particular will make an important contribution to our understanding of this history.

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