Periglacial research in New Zealand: a review

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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[1] 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.[2] Precipitation declines rapidly to the east, with a second maximum at the main divide before dropping to $\sim$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[1] 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[1] 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,[4] although allied components include the geomorphic work of snowpacks and rock fall.[5] 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[6,7] 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

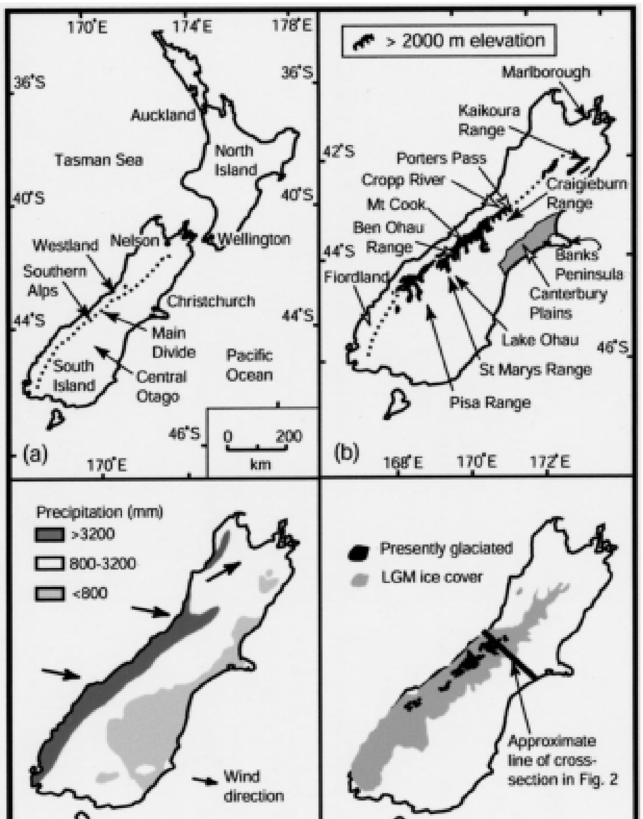

Fig. 1. Location map for New Zealand showing: (**a**) general setting; (**b**) locations mentioned in the text and major topographic elements; (**c**) broad precipitation patterns and dominant wind directions; (**d**) distribution of modern and last glacial maximum (LGM) glaciers. Modified from Suggate.[65]

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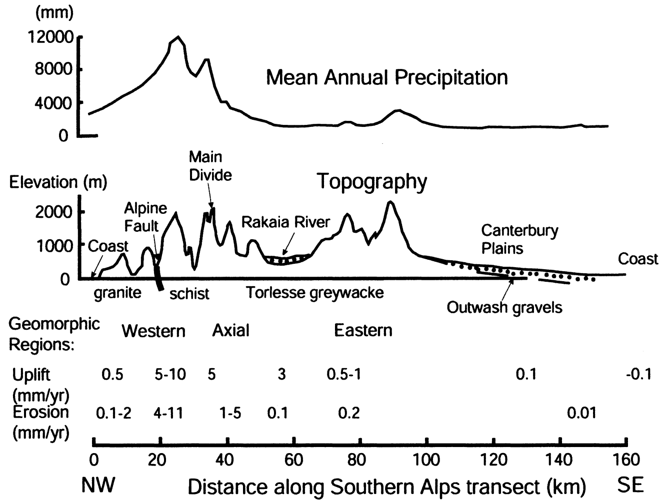

Fig. 2. Cross section through the central Southern Alps, New Zealand, showing mean annual precipitation, uplift and erosion rates. Modified from Whitehouse.[6]

and hills separated by intermontain basins. This area is subdivided into two subregions:[6] (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-braided river valleys. Pleistocene depositional landforms (moraines, terraces, fans) are well developed in the basins. Ridges are more rounded than in the western and axial regions but they remain narrow. Scree and coarse colluvium often veneer the slopes and cirques are common above 1500 m.

In the axial region of the Southern Alps the height and relief of the mountains is greatest, although uplift and erosion rates are less than in the western region. Precipitation ranges from 4000 to 8000 mm/yr.[6,7] Glaciers and glacial landforms characterize the region, with sharp ridge crests separating cirques with Holocene moraines. Glacial erosion, rockfall and snow avalanches are the main land-forming processes.[6,8,9] 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.[6] 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 associated landforms that are also found outside of the periglacial domain. The latter processes include slush avalanching, rock fall and solifluction, which are important geomorphic processes in the alpine nival zone and are crucial for the development of a range of 'classic' periglacial landforms (such as rock glaciers) in the Southern Alps. Furthermore, permafrost is of limited extent in the Southern Alps and probably occurs only sporadically in a narrow zone above 2000 m in combination with the –2°C isotherm, aspect and the 1500-mm isohyet.[10] Nevertheless, the probable climatic sensitivity of this alpine permafrost makes it an invaluable component of any study of the impact of regional global change on the alpine zone.

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.[11,12] In places the peneplain is preserved as a deeply and irregularly weathered surface beneath Tertiary sediments.[13] The depth of weathering on this surface has been lithologically and structurally controlled.[13,14] 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.[15] 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.[15]

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.[15] These terraces and solifluction lobes (Fig. 3c) are seasonally active and slow moving.[15,20]

Patterned ground of a range of forms has been described from the Central Otago ranges.[15,18,20–23] Soil hummocks and stripes as well as solifluction terraces, lobes and small sorted stone-stripes 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.[24] 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[25,26] 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.[27]

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[28] 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[29] suggested that the valley asymmetry is a relict periglacial feature: south-facing slopes are steeper that those with a northerly aspect as the latter would have experienced greater melt and more intense periglacial activity. Bell[25,26] 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.[26] This idea of structural control on valley side-slope asymmetry was extended by Augustinus,[8,9] 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[16,18] 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.[30] 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[14,19] suggested that the upland tors are produced by the combined effect of differential chemical weathering during interglacials and subsequent intense frost weathering during glacials. 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[14] 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[19] 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.[1]

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.[6] Other than glacial processes, modification of the slopes occurs largely by mixed snow and rock

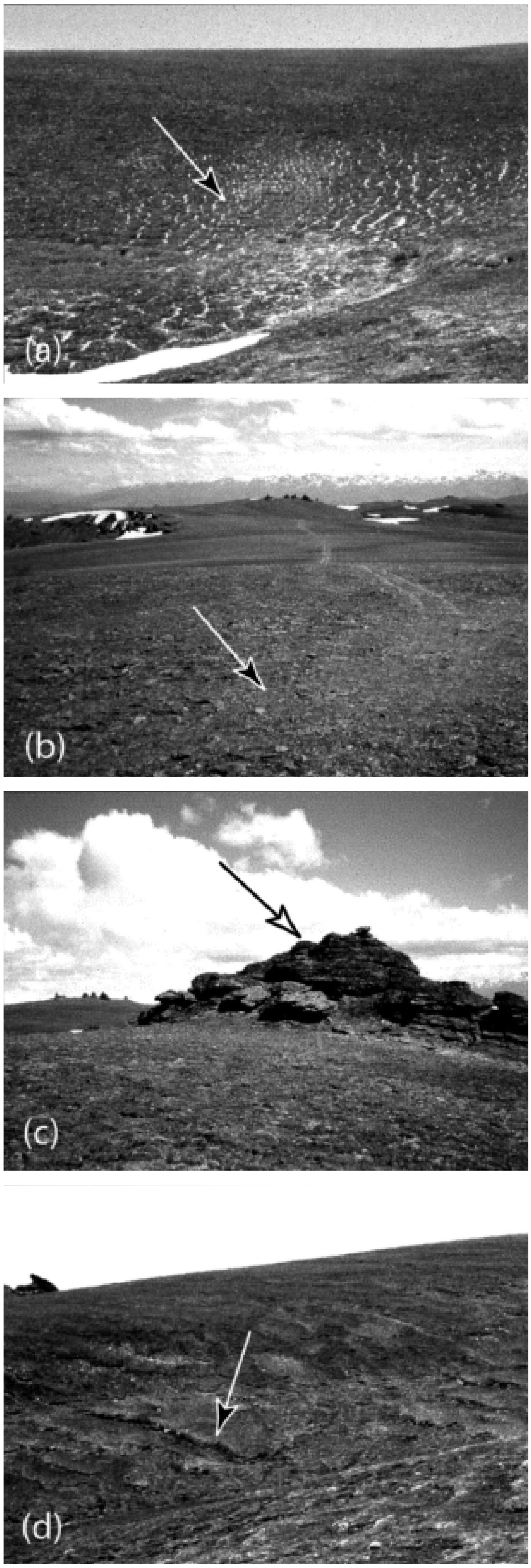

Fig. 3. Photographs showing characteristic fossil and modern periglacial landforms on the Pisa Range, Central Otago highlands: (**a**) frost-sorted polygons, (**b**) possible cryoplanation surface, (**c**) tors and (**d**) solifluction terraces. Periglacial features indicated by arrows.

avalanching, which often produces erosion of rock slopes through grooving of gullies.[31] 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.[32] Large amounts of debris can be transported during these events and allow rapid production of talus fans.[31,33]

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.[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^2), the debris mantle is <1 m deep and discontinuous, and shallow debris avalanche scars are common.[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.[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.[34] 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[35,36,38] associated with increasing continentality.[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[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 *et al.*[39] assumed that most rock glaciers are of glacial origin, although McGregor[35] argued that a non-glacial origin is more likely. A recent study by Kirkbride and Brazier[38] 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/ice mass.[38]

Brazier *et al.*[10] 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

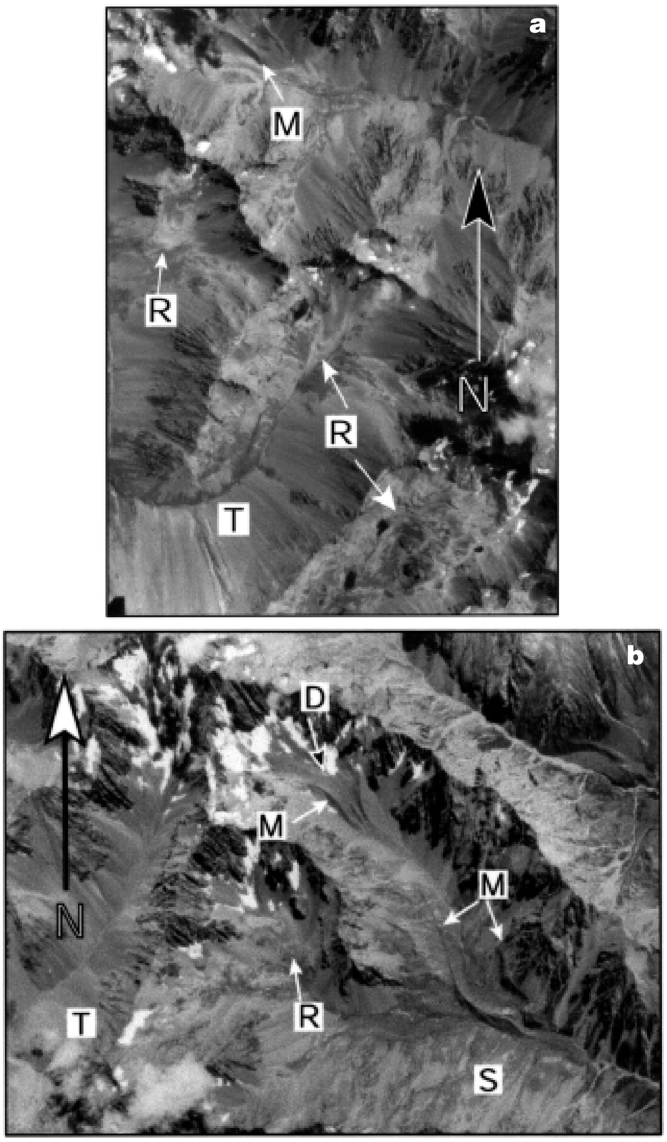

Fig. 4. **a**, Aerial photograph (SN 8595, G/14) showing glacial deposits (M = moraine), active rock glaciers (R) and active talus fans (T) in part of Ben Ohau Range; **b**, aerial photograph (SN 8595, G/14) showing debris-mantled glaciers (D), active talus fans, moraines (M), snow avalanche tracks (S) and active rock glacier (R) in central Ben Ohau Range.

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.[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 –2°C isotherm and mean annual precipitation of at least 1500 mm.[10] 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 –2°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

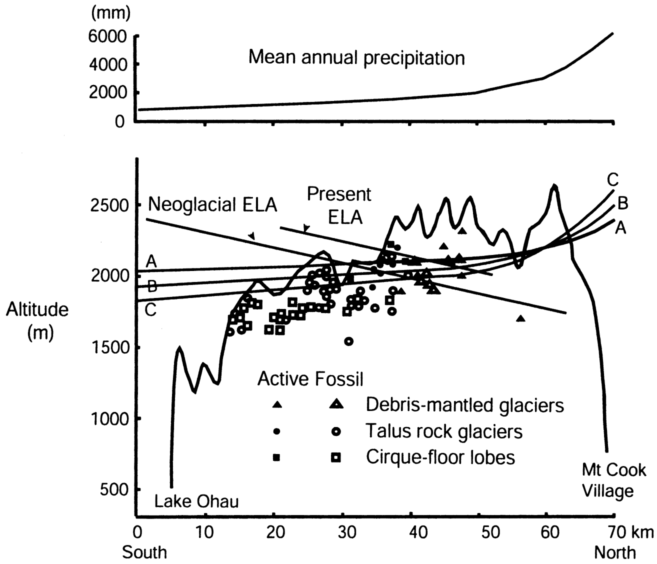

Fig. 5. Profile of the Ben Ohau Range showing the distribution of active and fossil rock glacier sites. Postulated range of the –2°C isotherm indicated by lines A to C. ELA = glacier equilibrium line altitude. Modified from Brazier *et al.*[10]

activate the rock glaciers, so that the present active landform distribution probably reflects cooler late Holocene climates.[10] 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.[10]

Talus surfaces developed in the Craigieburn Range were examined by Pierson[41] and Whitehouse and McSaveney.[42] 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[33] and lack evidence of long-term stability.[42]

Pierson[41] 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 screes were first noted by Soons[44] and later studied by Harris[45] and McArthur.[46] These types of deposits are typically overlain by modern soil and are no longer active.[1] McArthur[46] identified stratified screes 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,[45] 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.[45]

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.[48] 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 loesses, like the older deposits, being thickest immediately south of rivers and thinning rapidly away from the source.[49] 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[51] 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.[51] 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.[51] Soons and Price[1] 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[52,53] 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[54] and in several places pollen analyses and ^{14}C ages suggested that they were of Last Glacial Maximum affinity and hence probably of periglacial origin.[55] A cold climate origin for the material is supported by the association of glacial loess with the solifluction deposits.[56]

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.[1] Ice-wedge-like features near Wellington were described by Cotton and Te Punga[54] and Te Punga.[57] Infilled gullies in the Wellington region have been attributed to periglacial environments.[57,58] In some cases the fills extend below modern sea level and hence have been attributed to cooler climatic conditions.[58] However, a periglacial origin for these features is disputed, and Crozier *et al.*[59] 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.[59] 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[60] 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 2000 m on the eastern side of the main divide of the Southern Alps.[10] It appears that the climatic gradient from west to east across the Southern Alps is manifest in the landscape as a systematic sequence of landform types (Fig. 2). This zonation of landforms is reflected in transition from mainly glacial to periglacial landforms as distance from the main divide increases, and has been attributed by Brazier *et al.*[10] to a reduction in the relative proportion of ice to rock debris input at the heads of valleys.

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.[24] 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.[10]

Willett[61] 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[55,57] and Banks Peninsula.[51] Similarly, patterned ground in the Central Otago Highlands[18,20] may be a result of permafrost, although Mark[24] 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.*[10] 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.*[62] 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.[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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