Periglacial landforms and deposits of Tasmania

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Only limited parts of Tasmania were glaciated during the late Pleistocene. The extra-glacial regions exhibit many landforms and deposits that were developed at least partly by periglacial processes. Block streams, block fields and screes are well developed above 900 m on the dolerite plateaux of central and eastern Tasmania, while slope deposits of angular clasts occur on the siliceous rocks of western mountain areas. Extensive fossil solifluction deposits extend down to c. 500 m in central Tasmania, whereas modern frost-creep terraces and solifluction lobes occur only locally above 900 m in poorly vegetated areas. Active sorted polygons may occur on bare areas down to 600 m and contemporary snowpatch erosion occurs above 1000 m. Fossil ice-push deposits 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 mountains 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 overlaying 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,
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 föhn-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 clays 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. 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, tors 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 hillslopes, fill gullies and are stabilized by thin peaty soils formed
Fig. 2. Sites of features referred to in text.

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. 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, is extensive and evacuation of the regolith by repeated episodes of gelification has been recorded west of Great Lake.

One-cycle tors occur outside areas covered by ice during the LGM in western Tasmania. On Ben Lomond, Caine 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 δ^18O Stage 6 cold period 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. 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

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 accumulation 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 x 2 x 2 m in size. The rock glaciers have been formed by rockfall 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 northeastern 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 escarp 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 are often 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 coredstones formed 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 coredstones. 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 perennially, and a long time.

Associated with the block streams are areas of block fields or felseen. 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 cored-stones 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 gisclis in which the blocks would have crept downslope either over the underlying matrix materials 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 lichen 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 hills are conducive to slope failure. These strata can be erosionally sapped allowing the plateau and scarp edges to rotate outward 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 mantles 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, 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, Scotts Peak, Lyell Highway and Strahan roads, where 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, fissil stratified-screes of such mudstone fragments have accumulated often up to 1–2 m thickness. The scree exhibit thicker (10–20 cm) coarser 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 clits."

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 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 13 180 ± 820 14C yr BP (Gak 5968) 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 33 800 14C yr BP (Gak 5623) from a palaeosol within quartzite scree at Scott's 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.20 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 Caine21 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 450 m, and occasionally to 300 m, as on the steep scarps edges of Ben Lomond.21 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,23 while others show distinct episodic deposition with phases of gley soil formation between successive sheets, as at Monpeelatana 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 siliceous 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 solifluculate in central and eastern Tasmania was derived from the underlying dolerite by periglacial-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 relic solifluctates as for the blockstream and blockfield deposits. Only one terminal Pleistocene radiocarbon age of 14 200 ± 700 14C yr BP (Gak 486) has been recorded. This comes from charcoal in the disturbed A horizon of a podsollized soil overlaia by solifluctate at 500 m altitude in the Florentine Valley west of Mt Field.22

Patterned ground

The combination of ice-scoured plateaux, block field and solifluction-mantled plateaux, coarse eolian 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 polygons at 1300 m altitude on Mt Rufus and these are currently active.23 Small (0.2–0.3 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.

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). 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. 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. The fan-gravel beds are occasionally interrupted by organic palaeosols dated by radiocarbon to between c. 33 and 24 14C kyr 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.

Examination of similar fans south of the Derwent River led Wasson 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 rainfall 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). 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 \(^{14}\)C yr BP (SUA 376).\(^{34}\) Around the same time, after 19,810 ± 360 \(^{14}\)C yr BP (SUA 153), a hollow was filled with dune sand at Pipe Clay Lagoon near Cremorne.\(^{35}\)

Lunette dunes have accumulated on the eastern margins of lagoons throughout the Tasmanian Midlands.\(^2\) 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.\(^{36–39}\)

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 \(^{14}\)C yr BP (I-11 448A) and 8300 ± 80 \(^{14}\)C yr BP (Beta 8190).\(^{36,40,41}\) 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\(^{36}\) has recently been dated by OSL and shown to have been active between 44 ± 4 kyr BP and 29 ± 3 kyr BP.\(^{44}\) This shows that dune formation had commenced in northeastern Tasmania by \(^{8}\)\(^{18}\)O 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 (\(^{8}\)\(^{18}\)O 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.\(^1,3\) 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.\(^2,3\) 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 the present.

![Fig. 13](image-url) Schematic distribution of the limits of selected periglacial phenomena on a SW–NE transect from Hibbs Bay to the coast near St Helens.
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.15

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,16 were formed on the northeastern coastal plain and Flinders Island by west-north-westerly to westerly winds.

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