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

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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and ground-ice characteristics, and selected periglacial features are summarized from recent published literature and unpublished data by the authors for three eco-climatic regions of continental Antarctica: the Antarctic Peninsula and its offshore islands (*c.* 61–72°S), maritime East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 km^2, has the highest mean elevation (~3000 m) of any continent and experiences the lowest mean annual air temperature (–40°C according to Weyant[1]). 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 km^2 of glacial ice, respectively, which represents 90% of the world total.[2] 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.[2]

Less than 1% (55 000 km^2) of Antarctica is ice-free. Whereas the terrestrial ecosystems of Antarctica have a low biodiversity,[4] the Southern Ocean has among the most productive marine ecosystems on earth.[5] 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 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.[6] However, much of the landmass below the massive EAIS is above the pressure melting point and is unfrozen.[43] Realistically, 25% or less of the Antarctic region contains permafrost.[7]

Ground ice is common in Antarctica, especially in the form of rock glaciers[8] that have potential for reconstructing past environments of the region.[9] 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.[10] 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)[7] (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.[13]

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 km^2. The Antarctic Peninsula and its offshore islands comprise about 14% of the ice-free area of Antarctica (8000 km^2) 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 km^2), 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 km^2, including the Wolthat Mountains and the Sør Rondane Mountains), maritime East Antarctica (4.6%, or 2500 km^2, 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 km^2) and the Ellsworth Mountains (3.1%, or 1700 km^2).

These regions and sub-regions differ not only in climate but also in vegetation, soils, permafrost characteristics and periglacial processes. Blümel and Eitel[14] 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

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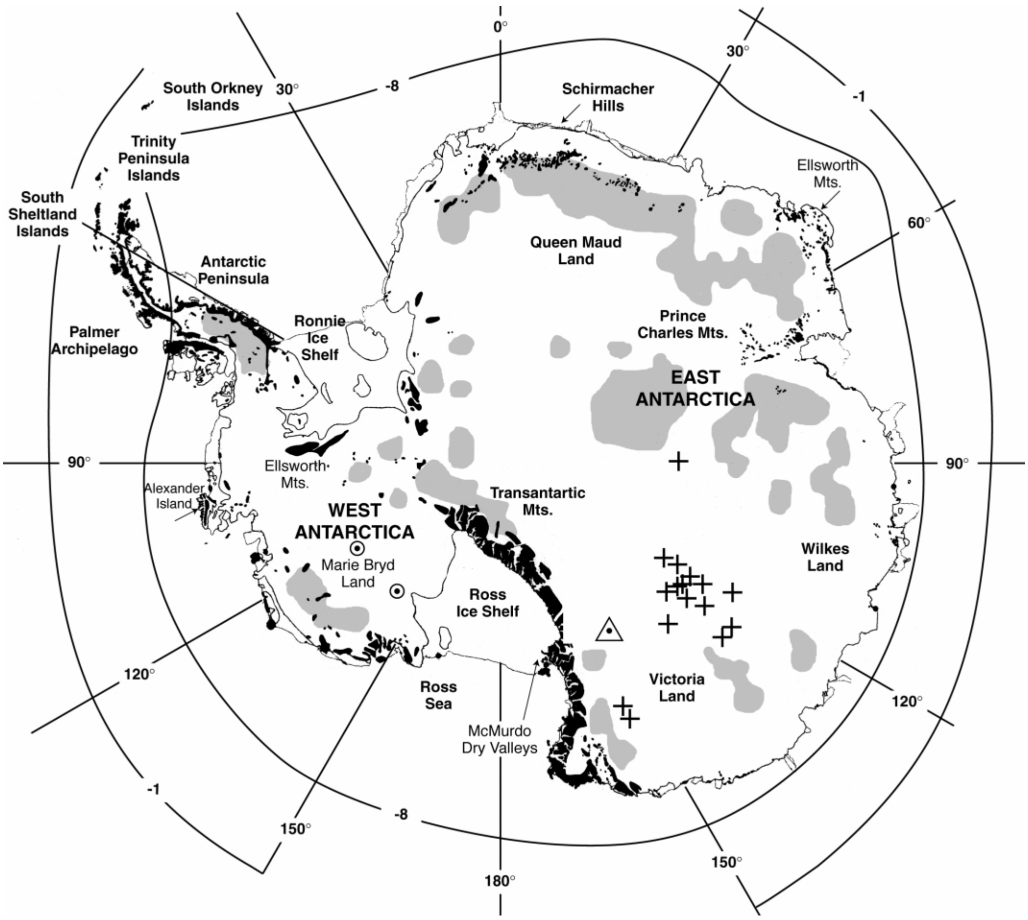

Fig. 1. The map shows permafrost distribution in continental Antarctica and locations of areas mentioned in the text. Permafrost exists throughout the ice-free areas (shown in black). Subglacial permafrost beneath the Antarctic ice sheet may be restricted to the shaded areas.[43] Subglacial lakes are depicted with a cross; ice coring sites in Marie Byrd Land are identified with a circle containing a dot; and the Taylor Dome borehole is denoted by a triangle with a dot (base map after Bockheim[7]). The –8°C and –1°C mean annual air temperature isotherms are taken from Weyandt.[1]

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.

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

[a]Phillpot;[95] Weyandt;[1] Orvig.[96]
[b]Bliss.[15]
[c]Campbell *et al.*[22]

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

Eco-climatic region	Permafrost distribution	Permafrost		Active layer		Ground-ice features[b]
		Form	Moisture content (%)[a]	Thickness (cm)	Moisture content (%)[a]	
Antarctic Peninsula & islands	Discontinuous	Wet	16–20	40–150	5.8–21	icd, pi, rg, iw
Maritime East Antarctica	Continuous	Wet, dry (?)	6–22	60–150	1.5–28	iw, icd, th, pi
Transantarctic Mountains						
Coastal	Continuous	Wet	6.1–77	30–60	1.0–10	iw, icd
Inland valley floors	Discontinuous	Dry	1.6–9.5	20–40	0.3–3.0	iw, sw, rg, icd
Inland valley sides	Continuous	Dry, wet	—	20–30	0.3–2.0	iw, sw, rg, icd
Upland valleys	Continuous	Dry, wet	—	20–25	0.3–3.0	iw, sw, rg, icd
Plateau fringe	Continuous	Dry, wet	1.7–30	15–20	0.3–4.0	iw, sw, rg, icd

[a]Campbell *et al.*[22]
[b]Ground-ice features: iw, ice wedges; sw, sand wedges; rg, rock glacier; pi, pingos; icd, ice-cored drift (after Bockheim[7]).

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.[17] 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 psammiturbels/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.[18,19]

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%.[7,12,20,21] A gravimetric moisture content of at least 5% is generally required for the coarse-textured soils of Antarctica to be cemented by ice.[12,22] Therefore, much of the permafrost in interior Antarctica is 'dry'.[19, 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.*,[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.*[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.[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 [25] measured active-layer temperatures in the Bunger

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 shown were recorded under cloudless skies (Wilson and Bockheim, unpublished).

Location	Plot no.	Colour	Dark:light ratio	Albedo (footcandles)	Surface soil temp. (°C)	Salts, 0–30 cm (mg/cm^2)	Soil moisture 0–30 cm (g/cm^2)
Rhone Platform	1	Dark	19	28	17.4	2976	75.7
(77°40′S, 162°25′E)	2	Light	0.7	45	5.6	739	45.7
		Difference	18.3	17	13.7	2494	30
Hughes Glacier	5	Dark	1.7	60	9.6	609	102
(77°42′S, 162°30′E)	4	Light	0.5	72	7.4	564	74.0
		Difference	1.2	12	2.2	46	28.0
Rhone Platform	6	Dark	19	30	20.4	1978	81.5
(77°40′S, 162°25′E)	8	Light	1.4	50	15.1	346	33.4
		Difference	17.6	20	5.3	1632	48.1
Arena Valley	9	Dark	21.7	45	16.6	1594	138
(77°52′S, 160°58′E)	10	Light	0.4	72	9.0	912	57.3
		Difference	21.3	27	7.6	682	80.3
Arena Valley	11	Dark	9.6	45	14.2	420	24.6
(77°52′S, 160°58′E)	12	Light	2.1	57	9.7	208	25.5
		Difference	7.5	12	4.5	212	–0.9
Sollas Glacier	14	Dark	1.1	36	10.5	634	128
(77°41′S, 162°35′E)	13	Light	0.6	50	8.7	398	88.5
		Difference	0.5	14	1.8	236	39.1
		Probability level*	0.015	0.032	0.040	0.075	0.082

*Comparisons of values within a column for dark- *vs* light-coloured surfaces, based on ANOV and Fisher's PLSD.

Table 4. Permafrost characteristics in continental Antarctica.

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

[a]50-m depth; measured using electrical resistivity, or electromagnetically.
[b]Thermally stratified lake.[97]

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.[25] 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 soil-surface temperatures) in the highest and coldest environments.[22]

Active-layer temperatures and dynamics vary with eco-climatic region in Antarctica. Deep active layer and extensive cryoturbation occurs along the Antarctic Peninsula and its offshore islands. In the South Shetland Islands, Chambers[26] emphasized the dual nature of the active layer. Solifluction, ice segregation, and frost sorting were all concentrated in the upper 40 to 60 cm of the active layer. The lower 60 cm of the active layer played no apparent role in the formation or current activity of patterned ground. In maritime East Antarctica, MacNamara[27] reported an active layer thickness of 100 to 150 cm. Suspended materials were carried downward in moisture as films on soil particles and in soil macropores. Soil moisture decreased sharply during thawing and increased during freeze-up. In inland areas of the Transantarctic Mountains, solifluction and debris flows are absent,[28] and cryoturbation occurs only to a limited extent. In the Asgard Range of the Transantarctic Mountains, McKay *et al.*[29] reported an active zone (the depth in which melting could occur since temperatures exceeded 0°C) of about 12.5 cm by interpolating instantaneous temperatures between the surface and subsurface, below which was a 12.5 cm zone of dry permafrost overlaying ice-cemented permafrost at 25 cm. There was a net flux of water vapour from the ice to the atmosphere, resulting in a recession of the ice-cemented ground by about 0.4 to 0.6 mm yr^{-1}.

Permafrost distribution and properties

Permafrost is defined here as soil and/or rock that remains below 0°C for at least two consecutive years.[30] 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[19] 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).[31] 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.[32] Electrical resistivity was used to estimate permafrost thickness.[33,34] Subsurface temperatures were measured at discrete points in the hole with thermistor probes.[35] 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.[23] Permafrost characteristics have been studied in North Victoria Land,[23,24] Seymour Island,[36,36] and on King George Island in the South Shetland Group.[38–40]

Non-relict permafrost thickness can be estimated crudely as the product of mean annual air temperature and a lag rate of 33 m/°C.[41] 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.[35] 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.[42,43]

Environmental factors related to permafrost in the circum-Antarctic region were reviewed by Bockheim[7] and include air temperature, relief, vegetation, hydrology, glacier and snow cover, and soil and rock, and age of geomorphic surface. Bockheim[7] 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 from a map by Herterich[43] 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[44] reported pingos in the Vestfold Hills (68°40′S, 78°00′E), but Fitzsimons[45] 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.[45] Grigor'ev[46] 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.[44]

Nichols[47] 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[47] 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.*[23] 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.*[24] recorded a ground ice layer with a thickness of >60 m. In the ice-free areas of the Bunger Hills, Grigor'ev[46] 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.*[10] 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.*[47] 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.*[47] state, more detailed measurements from the field are still necessary.

Rock glaciers are cited by a number of authors for different areas of Antarctica. Barsch *et al.*[48] 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.[49] Mayewski[50] and Mjagkov[51] studied rock glaciers in the Transantarctic Mountains. Guglielmin *et al.*[23] 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[52] and Strelin and Sone[53] 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[52] suggested that most the rock glaciers are glacier-derived but that there are also a few talus-derived forms. Strelin and Sone[53] 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[54] 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.[54] 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[54] 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 but 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[54] 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 tensional 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.[55]

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.[19,50,56] The rock glaciers and buried ice in Arena and Beacon valleys contain less than 1 m of drift over pure ice.[8] 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.[57] Ice-wedge polygons are common throughout the dry valleys, particularly in coastal areas.[19,20,58,59]

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.[55,60] 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,[61] in which, with respect to East Antarctica, he cited the creation of '...small cwms by 'nivation'...' Taylor[62] also refers to nivation ('erosion by thaw and freeze') in his explanation of landscape development in the Royal Society Range. Taylor[61,62] observed processes that appear very similar to what Groom[67] would later term 'niche glaciers' — forms that relate very strongly to 'longitudinal nivation hollows'.[63] Souchez[64,65] also notes the role of nivation in creating hollows, below which are found stratified deposits (*grèzes litées*). Nichols[47] and McCraw[66] discuss the occurrence of 'nivation cirques' in the McMurdo Dry Valleys. Nichols[99] 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[99] estimated that as much as 1.52 to 1.83 m of sediment had been removed. In nearby Taylor Valley, Nichols[99] 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.*[68] 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[69] 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[70] referred to nivation within the Schirmacher Oasis, while Sekyra[71] 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[7] summarized data on cryoplanation terraces in Antarctica; Hall[72] added further references regarding cryoplanation. Previous reports suggested that cryoplanation terraces occur along the east coast of the Antarctic Peninsula[73] and in maritime East Antarctica.[71,74,75] More recently, Hall[55,72,76] 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° (ref. 72). Although Hall[72] 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[77] 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[62] 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.[55,72,76] In mountainous areas of Enderby Land, 'relic' cryoplanation features occur,[71] 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[77] 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.[55,72] Derbyshire[78] 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-croyplanation' 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.[79]

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.[68,80–82] Bardin[82] 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[82] 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[83] show that in such situations it is very likely that there is active chemical weathering taking place. Markov *et al.*[68] provided data regarding water temperatures (≥30°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[62] showed the development of small 'tors' developed in weathered kenyte boulders. Zhang and Peterson[85] identified what they consider to be frost-shattered bedrock summits with remnant upstanding blocks about 1 m high, while those found by Derbyshire[78] were 3–4 m high and those reported by Selby[84] 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,[72,76] it is worth noting that Derbyshire[78] 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.[86] 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.[55,76,86] Sekyra[71] referred to the development of tors ('castle- and tower-shaped forms') in massive gabbro-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[84] argued for salt weathering as the dominant process, Derbyshire[78] and Zhang and Peterson[85] suggested frost weathering, and Hall[72,76] 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[85] refer to the occurrence of block slopes in the Vestfold Hills, while

Brook[79] observed mantles of *in situ* weathered sandstones and siltstones on cliff tops in the Theron Mountains.

Baroni[87] suggested that the surface of the hills near Terra Nova Bay '...is shattered and produces blockfields (Felsenmeer).... Block sheets occur on steeper slopes.' Nichols[100] noted that although *felsenmeer* are found in the McMurdo Sound region they are not common. Nichols[100] 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[100] 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-tor-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.[12,88–91] These impacts include contamination of soils and vegetation, disturbance of wildlife, and the importation of alien organisms. Campbell *et al.*[12] 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.[12] 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.[12] 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.[12]

The polar regions are especially sensitive to global climate change.[92] Bockheim[11] 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).[93]
(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[23] and relate it to landform age.[29]
(6) Drill and equip boreholes for long-term measurement of permafrost temperatures.
(5) Monitor soil and rock temperatures to understand the rates of weathering, patterned ground formation, and soil creep.[94]

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, so 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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