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Paleosols in the transantarctic mountains: indicators of environmental change

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Abstract

The Transantarctic Mountains (TAMs), a 3500 km long chain that subdivides East Antarctica from West Antarctica, are important for reconstructing the tectonic, glacial, and climatic history of Antarctica. With an ice-free area of 24 200 km^2 (50 % of the total in Antarctica), the TAMs contain an unusually high proportion of paleosols, including relict and buried soils. The unconsolidated paleosols range from late Quaternary to Miocene in age, the semi-consolidated paleosols are of early Miocene to Oligocene age, and the consolidated paleosols are of Paleozoic age. Paleosols on unconsolidated deposits are emphasized in this study. Examples are given from the McMurdo Dry Valleys (78° S) and two outlet glaciers in the central and southern TAMS, including the Hatherton-Darwin Glacier region (80° S) and the Beardmore Glacier region (85°30′ S). Relict soils constitute 73 % of all of the soils examined; 10 % of the soils featured burials. About 26 % of the soils examined are from the last glaciation (< 117 ka) and have not undergone any apparent change in climate. As an example, paleosols comprise 65 % of a mapped portion of central Wright Valley. Paleosols in the TAMs feature recycled ventifacts and buried glacial ice in excess of 8 Ma in age; and volcanic ash of Pliocene to Miocene age has buried some soils. Relict soils are more strongly developed than nearby modern soils and often are dry-frozen and feature sand-wedge casts when ice-cemented permafrost was present. The preservation of paleosols in the TAMs can be attributed to cold-based glaciers that are able to override landscapes while causing minimal disturbance.

1 Introduction

In the soils literature, paleosols refer to buried, relict and exhumed soils with no assigned age (Ruhe, 1965; Nettleton et al., 2000) or to soils in which the chemical and physical characteristics are unrelated to the present-day climate or vegetation (Bronger and Catt, 1989). Many soils of ice-free areas of Antarctica, dominantly the Transantarc-

tic Mountains (TAMs), have been exposed to subaerial weathering since the early Quaternary to the Miocene (Bockheim, 1990, 2007; Hall et al., 1993; Prentice et al., 1993), and buried soils have been commonly reported (Bockheim, 1982; Bockheim et al., 1989). This study addresses the properties, distribution, and interpretation of paleosols
5 in the TAMs.

The TAMs extend more than 3500 km from North Victoria Land to the tip of the Antarctic Peninsula (Fig. 1) and reach elevations of over 4500 m. The TAMs contain about 50 %, or 24 000 km^2, of the ice-free area of Antarctica, form a natural barrier between ice in East and West Antarctica, and record the history of Cenozoic glacia-
10 tions of Antarctica (Mercer 1968; Denton et al., 1989; Bockheim et al., 1989). Valleys within the TAMs have been cut by major outlet glaciers that today are buttressed by the Ross Ice Shelf. These include, but are not restricted to, the Darwin-Byrd, Beardmore, Shackleton, Scott, and Reedy Glaciers. Each of these outlet glaciers contains a chronosequence of soils that ranges from the late Quaternary to the Pliocene or
15 Miocene in age and feature relict and buried soils (Bockheim, 1990).

Previous investigations in Antarctica have examined lithified paleosols of late Paleozoic to early Triassic age (Retallack and Alonso-Zarza, 1998; Mahaney et al., 2001) and well-known exposures of semi-lithified paleosols of Miocene age (Retallack et al., 2002; Mahaney et al., 2012). Relict soils along the edge of the polar plateau through-
20 out the TAMs have properties resulting from hyperarid conditions, suggesting that the climate has remained cold and dry since the Miocene (Marchant et al., 1994).

2 Study areas

The University of Wisconsin Antarctic Soils (http://nsidc.org/data/ggd221.html) and New Zealand Landcare Research (http://www.landcareresearch.co.nz/science/soils-
25 and-landscapes/antarctic-soils) databases were used in this study. The databases contain information about surface boulder weathering features and soils from some of more than 800 sites in the Transantarctic Mountains from North Victoria Land and South Vic-

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toria Land, with an emphasis on the McMurdo Dry Valleys (Fig. 1). For this study, seven chronosequences were selected from the TAMs, including those in Wright Valley from alpine glaciers and from grounding of ice in the Ross embayment, and sequences from outlet glaciers from the East Antarctic ice sheet, including the Taylor Glacier (Arena

5   Valley, Beacon Valley, and Taylor Valley), the Hatherton-Darwin Glacier, and the Beardmore Glacier. The chronosequences were selected on the basis of having a long time interval, the availability of numerical ages, and uniformity in parent material composition of member soils (Table 1). Individual sampling sites were selected on key moraines representing a particular glacial advance. Table 2 provides a provisional correlation of

10 glacial deposits in the TAMs.

The composition of the drifts can be grouped into two broad categories. Mixed, light-colored igneous (granites) and metamorphic (gneisses) materials dominate the three sequences in Wright and Taylor Valleys. The sequences in Arena and Beacon Valleys and the Hatherton and Beardmore Glacier regions are comprised of Beacon Sand-

15 stone and Ferrar Dolerite (Table 1). Locally, some of the drifts may contain primarily dark-colored volcanic materials or diabase dike rocks. All age categories have samples from both rock types except that they lack Miocene-aged soils derived from granite-gneiss.

The chronosequences represent the three microclimatic zones identified in the

20 Transantarctic Mountains by Marchant and Head (2007), including a coastal thaw zone, an inland mixed zone, and a stable upland zone. The zones are defined on the basis of summertime measurements of atmospheric temperature, soil moisture, and relative humidity. Subtle variations in these climate parameters result in considerable differences in the distribution and morphology of: (1) macroscale features (e.g., slopes

25 and gullies); (2) mesoscale features (e.g., polygons, including ice-wedge, sand-wedge, and sublimation-type polygons, as well as viscous-flow features, including gelifluction lobes and debris-covered glaciers); (3) microscale features (e.g., rock-weathering processes/features, including salt weathering, wind erosion, and surface pitting); and, hence, soil development.

The approximate mean annual water-equivalent precipitation in these zones is 100–50 mm yr^{-1}, 50–10 mm yr^{-1}, and < 10 mm yr^{-1}, respectively. Most of the soil chronosequences span one soil climatic zone. However, the sequences in lower Wright Valley and along the Hatherton and Beardmore Glaciers span two soil climate zones, because their distance from the coast ranges from 35 to 220 km. The chronosequences range in elevation from 200 to 2200 m a.s.l. and span the time period from Holocene or late Quaternary to the Pliocene and/or the Miocene (Table 1).

3   Methods and materials

3.1   Field

Methods used in this study were described in detail by Bockheim (2010a,b) and will only be highlighted here. Soil pits were excavated to a depth of at least 100 cm, unless ice-cement or large boulders prevented digging to that depth. Detailed soil descriptions were taken using standard techniques (Schoeneberger et al., 2002). Samples were collected from each horizon and sent to the United States for characterization.

Several soil morphological features, which have proved useful for distinguishing among drift sheets in TAMs (Bockheim, 2010b), were measured in the field. The depth of staining refers to the thickness of the layers showing the strongest hues and chromas from oxidation of iron-bearing minerals and corresponds to the bottom of the Bw horizon. The depth of coherence refers to the thickness of consolidated soil from accumulation of weathering products such as salts and iron oxide; below the depth of coherence, soil readily caves into the pit. The depth of "ghosts" (pseudomorphs) refers to the depth to which highly weathered clasts were observed in situ; this parameter varies with rock type as well as soil age. The depth of visible salts refers to the maximum depth for which salt encrustations beneath clasts, salt flecks, and salt cementation are readily visible to the naked eye.

Bockheim (1990) developed a six-stage sequence in which the form of soluble salts was related to total dissolved salts from electrical conductivity (EC) measurements and soil age: 0 = no visible salts, 1 = salt encrustations beneath clasts, 2 = salt flecks covering < 20 % of the horizon area, 3 = salt flecks covering > 20 % of the horizon area, 4 = weakly cemented salt pan, 5 = strongly cemented salt pan, and 6 = indurated salt pan. The depth to ice or ice-cemented permafrost was determined. The active layer (seasonal thaw layer) in the Transantarctic Mountains varies between 15 and 60 cm. Material not cemented by ice beneath the active layer may contain "dry-frozen" permafrost, i.e. perennially frozen materials lacking sufficient interstitial water to cause cementation.

The weathering stage is an overall representation of the landscape/material based on the degree of surface boulder weathering, soil morphology, and patterned ground and permafrost forms (Bockheim, 2010b). The stages are: 1 = unstained angular boulders, no horizonation (Cn), stage 0 or 1 salts, ice cement within 70 cm of surface, and patterned; 2 = lightly stained subangular boulders, weak horizonation (Cox), stage 2 salts, may have ice cement, patterned ground; 3 = distinct polish and rounding of boulders, some cavernous weathering, distinct horizonation (Bw), stage 3 salts, moderately deep profile; 4 = strongly developed cavernous weathering, ventifaction, very distinct horizonation, stage 4 salts, deep profile; 5 = low surface boulder frequency, well developed desert pavement, very distinct horizonation, stage 5 salts, deep profile; and 6 = low surface boulder frequency, well developed desert pavement, macro-pits in dolerite, very distinct horizonation, stage 6 salts, shallow to deep profile with bedrock possibly occurring in the lower solum.

Buried soils were easily identified from marked changes with depth in staining, salt morphology, ghosts, and other weathering features. Buried soils occasionally contain a desert pavement with intact ventifacts; and burial generally was caused by glacier overriding but also by lava flows, volcanic ash deposition, and colluviation. Relict soils were distinguished from their relative age or assigned glacial deposit (Table 1) and from their degree of development when compared to soils on the most recent glacial

deposits in the area. For this study all soils on glacial deposits older than 117 ka were considered to be relict (Table 2). However, many of the non-relict soils ranged from < 10 to 24 ka in age.

Soils were classified into the Gelisol order to the family level (Soil Survey Staff, 2010); mineral soils showing cryoturbation are classified as Turbels; mineral soils without obvious cryoturbation are Orthels. Both suborders are divided into great groups on the basis of soil climate and other soil properties. Many soils of the Transantarctic Mountains have anhydrous conditions (i.e. the mean annual precipitation is less than 50 mm water equivalent) and are classified into the great groups, Anhyturbels or Anhyorthels. Equivalent soils with greater moisture contents are classified into the great groups, Haploturbels or Haplorthels. The soils are further divided into subgroups on the basis of presence of soluble salts (e.g. salic, gypsic, nitic, petrogypsic, and petronitric), depth to bedrock (lithic), or other (typic) soils.

We have developed a multiple-parameter, relative chronology of the TAMs based on the parameters previously described (Bockheim and McLeod, in revision). Normally, the surface-boulder weathering and soil weathering values are similar. However, in the case of overriding by cold-based glaciers, boulder-belt moraines or scattered boulders may be left on the landscape, creating buried or relict soils.

3.2   Laboratory

Electrical conductivity, pH, and dominant cations and anions were determined on 1 : 5 soil : distilled water extracts using a conductivity bridge and cell, pH meter, and atomic absorption spectroscopy (APHA et al., 1975). Particle-size distribution was done with the hydrometer method (Day, 1965); and Fe was extracted using the citrate-dithionite-carbonate procedure (Mehra and Jackson, 1960).

4 Results

Of the 763 soils examined in TAMs, 10 % contained burials and 73 % were relict (Table 3). Only 26 % of the soils did not contain burials or occurred on deposits from the most recent glaciations, considered to be < 117 ka.

4.1 Evidence for burial

Burial was evidenced primarily from lithologic discontinuities, marked changes in soil horizonation and properties, and relict cryoturbation or periglacial features. In the TAMs, drift from wet-based glaciers of Pliocene and older age is enriched in quartz of silt and very-fine sand size (100–2 µm) with few clasts, primarily from overriding outcrops of the Beacon Supergroup. These materials are whitish in color and are resistant to weathering. In contrast, drifts from cold-based glaciers have a sandy matrix and abundant coarse fragments (> 2mm) and contain iron-rich minerals that provide a distinctive reddish color (5YR-7.5YR) upon weathering. Deposits of Miocene-age from wet-based glaciers include the Sirius Group at high elevations throughout the TAMs, Altar and Quartermain drifts in Arena Valley (Marchant et al., 1993a), Asgard and Sessrumnir drifts in the Asgard Range (Marchant et al.,1993b), Insel drift in Victoria Valley (Calkins, 1971), and Peleus drift in Wright Valley (Hall et al., 1993; Prentice et al., 1994). These materials may have been buried by drift from cold-based glaciers (Fig. 2a) or reworked into the drift of cold-based glaciers (Fig. 2b). Pliocene- or Miocene-aged volcanic ash (Fig. 2c) and lava flows (Fig. 2d) may also bury soils.

Eolian events that lead to coarse gravelly mega-ripples (Gillies et al., 2012) may have reworked the upper parts of soils (Fig. 3a); although these events do not constitute burials, they likely reflect a change in climate. Changes in levels of Lake Vanda from climate change have produced strandlines below which buried soils occur (Fig. 3b).

Soil horizonation also provides clues of burials in the TAMs. Approximately 82 % of the 80 burials observed in the Transantarctic Mountains featured readily distinguishable buried B horizons (Fig. 3c). The key soil properties for identifying buried soils include

sudden changes in depth in color, salt content or stage, ghosts, cohesion, and the appearance of buried in situ ventifacts.

Morphological evidence for burial often is corroborated by laboratory data. Pedon 75-19 shows dramatic increases in Na, Cl, SO_4, Fe_d, silt and clay from the Taylor IV
relict soil to the buried soil derived from Miocene-aged drift (Table 4; see also Fig. 2a).

4.2 Evidence for relict soils

Relict soils are predominant in ice-free areas of the TAMs. These soils commonly have abundant salts, are deeply weathered, contrast with soils on younger glacial deposits nearby, or have remained undisturbed for long periods of time (Fig. 4a).

Relict periglacial features are common in the TAMs, including former cryoturbation (Fig. 4b) and sand-wedge casts (Fig. 4c). These soils no longer have ice-cemented permafrost in the upper 1 m to sustain these processes; rather, they contain dry-frozen permafrost from depths of 0.2 to 1 m or more from a progressive loss in soil moisture following the onset of hyperarid conditions.

I used the surficial geology map of central Wright Valley (Hall and Denton, 2005) to delineate areas of relict, buried, and modern soils. Approximately 55 % of the soils are relict and approximately 10 % of the area contains buried soils (map not shown).

5 Discussion

5.1 Cold-based glaciers

The abundance of relict and buried soils in the TAMs may be attributed to the activity of cold-based glaciers (Bockheim, 2010b). Our observations suggest that cold-based glaciers are able to drop boulder-belt moraines and isolated boulders over minimally disturbed landscapes. When observed in plan view, the boulder belts in some cases are separated by drift of the same age; in other cases the boulder belts overlie older drift (Bockheim, 1982).

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Buried soils and recycled ventifacts are found in drifts ranging from the Last Glacial Maximum to Miocene (> 15 Ma) in age. They are especially prevalent in drifts from dry-based portions of outlet glaciers, which tend to be thin, ranging from < 1 to about 5 m in thickness. With each subsequent glacial advance, the drift with its soil mantle is either overridden by a dry-based glacier or is incorporated into the most recent drift. For this reason, a young drift may contain clasts that range from fresh to highly weathered. We have observed boulders with fresh striations etched into a strongly developed desert varnish. Similarly, we have noted clasts at the base of alpine glaciers that reveal previous weathering cycles. For example, we have observed fragile weathering features such as taffoni entrained within dry-based glaciers. This phenomenon may lead to problems when cosmogenically dating boulders that are spatially in-between boulder-belt moraines.

5.2 Environmental implications

The soils of Antarctica preserve a climate and geologic record of when Antarctica was part of Gondwana, the gradual isolation of the continent, the buildup of a continental ice sheet, and the conversion from warm-based glaciers to cold-based glaciers, culminating in the development of hyper-arid, polar conditions. The continental ice sheet developed during 40–34 Ma as Gondwana broke up and Antarctica became isolated.

From ca. 19–14.8 Ma the polar regolith formed (Sugden and Denton, 2004). Cold-based glaciers overrode the TAMs during 14.8–13.6 Ma, creating dramatic scabland topography with drainage basins, channels, plunge pools, and giant potholes. Relict soils remain in several areas. These soils tend to be thin and support highly weathered dolerite clasts. Beginning in 13.6 Ma, hyper-arid, polar conditions formed in the TAMs. Soils contain abundant salts; ice wedges on Miocene through early Pleistocene surface have sublimated, leaving thermokarst topography; permafrost tends to be dry-frozen; desiccation cracks become common in the soils; strongly developed desert pavements underlain by a vesicular layer are formed, and mega-ripples from strong katabatic winds become prevalent. During this period the TAMs become one of the

driest places on Earth. Anion ratios can be used to show changes in air masses and contribution of salts from marine aerosols during these climate changes. Pedon 84-49 has had greater proportions of SO_4 and NO_3 relative to Cl during the Quaternary than during the Pliocene when the Wright Valley was a fjord (Table 4; see also Prentice and Krusic, 2005).

The Anthropocene is an informal geologic chronological term that serves to mark the evidence and extent of human activities that have had a significant global impact on the Earth's ecosystems. The TAMs have not been immune to the consequences of a warming climate. A recent report identifies the southern TAMs as among the most rapidly warming regions on Earth (Bromwich et al., 2012). Historical observations by the author include melting of semi-permanent snowbanks, yielding nivation hollows with permafrost closer to the surface than in adjoining areas, flushing of salts from soils along valley walls, the development of hyporheic zones distant from water bodies from melting of snow in high-elevation catchments that flows downslope above the ice-cemented permafrost table, and milder summer temperatures accompanied by rising lake levels and periodic flooding of the Onyx River in Wright Valley. As the climate continues to warm in the TAMs, we can expect dramatic changes in the permafrost regime, thickness of the seasonal thaw layer, geomorphic processes, and soil development.

6 Conclusions

Relict soils constitute 73 % of all of the 800 pedons examined in the Transantarctic Mountains (TAMs); 10 % of the soils featured burials. About 26 % of the soils examined are from the last glaciation (< 117 ka) and have not undergone any apparent change in climate. In central Wright Valley, where detailed surficial geology and soil maps are available, paleosols comprise 65 % of the ice-free area.

The preservation of paleosols in the TAMs can be attributed to cold-based glaciers that are able to override landscapes while causing minimal disturbance. Paleosols illustrate the dramatic changes in climate that have occurred in Antarctica, particularly

during the mid-Miocene when the climate shifted from cool temperate to hyper-arid and during the Anthropocene when rapid warming is increasing the availability of liquid water and causing leaching of salts from the soils.

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Table 1. Site factors of soil chronosequences in the Transantarctic Mountains.

Area	Total No. pedons	Glaciation	Drifts[a]	Age span	Drift composition	Soil climatic zone[b]	Elevation range (m)	References	
								Soils	Parent material
Wright Valley	58	alpine	A1, A2, A3, A4	3.7 ka–>3.7 Ma	granitic-gneiss	inland mixed	250–950	Bockheim an McLeod (2006)	Hall et al. (1993); Hall and Denton (2005)
Arena Valley	54	Taylor	T2, T3, T4a, T4b, Ar, Al, Q	117 ka–>15 Ma	dolerite-sandstone	stable upland	900–1500	Bockheim (2007)	Marant et al. (1993a)
Beacon Valley	20	Taylor	T2, T3, T4, Al	117 ka–15 Ma	dolerite-sandstone	stable upland	800–1350	Bockheim (2007)	Bockheim (2007)
Taylor Valley	64	Taylor	T2, T3, T4a, T4b	117 ka–2.7/3.5 Ma	granitic-gneiss	inland mixed	200–1350	Bockheim et al. (2008)	Wilch et al. (1993)
Wright Valley	42	Wilson Piedmont	B, H1, L, H2, T, O, W, V, Lp	3.7 ka–>2 Ma	granitic-gneiss	coastal thaw, inland mixed	275–350	Bockheim and McLeod (2006)	Hall and Denton (2005)
Hatherton Glacier	53	Hatherton	Ha, Br1, Br2, D, I, pre-I	8 ka–>600 ka	dolerite-sandstone	inland mixed, stable upland	100–2200	Bockheim et al. (1989)	Bockheim et al. (1989)
Beardmore Glacier	38	Beardmore	Pl, Be, M, pre-M, D, S	14 ka-2 Ma	diorite-sandstone	inland mixed, stable upland		Bockheim, 1990	Denton et al. (1989); Ackert and Kurz (2004)

[a] Drift names: A = Alpine; Al = Altar; Ar = Arena; B = Brownworth; Be = Beardmore; Br = Britannia; D = Danum; H = Hummocky; Ha = Hatherton; I = Isca; L = Loke; Lp = Loop; P = Peleus; Pl = Plunket; O = Onyx; Q = Quartermain; S = Sirius; T = Trilogy; V = Valkyrie; W = Wright.

[b] Soil climate zones after Marant and Head (2007).

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Table 2. Provisional correlation of glacial deposits[1] in the Transantarctic Mountains

Geologic time scale	Taylor V. Taylor Gl.	Wright V. Alpine	Wright V. Wilson Pied. Gl.	Arena V. Taylor Gl.	Beacon V. Taylor Gl.	Hatherton Glacier	Beardmore Glacier	Numerical Dating
Holocene		A1				Hatherton	Pl	3.7 Ky
Late Quaternary			B			Br1, Br2	Be	10 Ky
	T2	A2a		T2	T2			117 Ky
			H1			D	M	
	T3	A2b		T3	T3			200 Ky
Middle Quaternary			Loke, H2			I	pre-M	
			T					
Early Quaternary	T4a			T4a	T4a			1.–1.1 My
	T4b			T4b	T4b			1.1–2.2 My
Pliocene			O, W			pre-I	Do	< 3.4 My
		A3						< 3.5 My
			V					
		A4						> 3.7 My
			Lp					
			P					
Miocene							S	7.7 My
				Al, Ar	Al			> 11.3 My
References	Brook et al. (1993); Wilch et al. (1993); Higgins et al. (2000)	Hall and Denton (2005)	Hall and Denton (2005)	Marant et al. (1993a)	Bockheim (2007)	Bockheim et al. (1989)	Denton et al. (1989); Ackert and Kurz (2004)	

[1] Drift names: A = Alpine; Al = Altar; Ar = Arena; B = Brownworth; Be = Beardmore; Br = Britannia; D = Danum; Do = Dominion; H = Hummocky; Ha = Hatherton; I = Isca; L = Loke; Lp = Loop; M = Meyer; P = Peleus; Pl = Plunket; O = Onyx; Q = Quartermain; S = Sirius; T = Trilogy; V = Valkyrie; W = Wright.

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Table 3. Distribution of buried, relict, and modern soils in the Transantarctic Mountains by area and type of glacier.[a]

Area	Type of glacier	Buried	Relict	Modern[b]	Total	Buried	Relict	Modern
Arena Valley	outlet	12	45	13	70	17	64	19
Arena Valley	overriding	2	15	0	17	12	88	0
Asgard Range	overriding	2	23	0	25	8	92	0
Beacon Valley	overriding	0	11	0	11	0	100	0
Beacon Valley	outlet	1	11	5	17	6	65	29
Beardmore Glacier	outlet	7	35	29	71	10	49	41
Beardmore Glacier	overriding	5	25	0	30	17	83	0
Beardmore Glacier	(not glacial)	0	0	2	2	0	0	100
Darwin Glacier	outlet	14	50	15	79	18	63	19
Ellsworth Mtns.	alpine	1	2	19	22	5	9	86
North Victoria Land	outlet	0	3	10	13	0	23	77
Royal Society Range	grounding	0	15	4	19	0	79	21
Taylor Valley	alpine	0	14	37	51	0	27	73
Taylor Valley	outlet	8	90	18	116	7	78	16
Wright Valley	grounding	3	70	19	92	3	76	21
Wright Valley	(not glacial)	8	57	4	69	12	83	6
Wright Valley	alpine	17	72	20	109	16	66	18
Wright Valley	overriding	4	20	0	24	17	83	0

[a] Note: some pedons are relict but also have burials.
[b] Modern is assumed to be since the last glaciation, which is < 117 ka.

Table 4. Laboratory data for buried soils in the Transantarctic Mountains.

Horizon	Depth (cm)	EC (dS m⁻¹)	pH	Na⁺	Ca²⁺	Mg²⁺	K⁺	Cl⁻	SO₄²⁻	NO₃⁻	Fed	Sand	Silt	Clay	Moist. (%)	Cl/SO₄	Cl/NO₃
75-19 Typic Anhyorthels, Taylor III/Taylor IV/Quartermain; Arena Valley																	
D	0–1	0.06	5.5	7.6	0.2	0.2	0	0	6.2	1.7	0.15	99.2	0.5	0.3		0.000	0.00
Bw	1–14	1.43	6.4	143	0.7	1.1	0.1	0.1	144	0.6	0.22	93.6	2.7	3.7		0.001	0.17
BC	14–28	0.17	6.1	16.3	0.2	0.4	0	0	16.9	0	0.16	96.9	1.7	1.4		0.000	0.00
Db	28–30	1.93	5.8	219	0.7	1	0.1	1.8	209	10.1	0.14	97.2	2	0.8		0.009	0.18
Bwb	30–52	4	6	415	1.1	1.5	0.1	88.3	414	0	0.27	84.1	4	11.9		0.213	
BCb	52–65	2.96	5.8	305	1	1.3	0.1	2.7	294	10.3	0.27	76.7	12	11.8		0.009	0.26
Cb	65-100	1.68	5.9	172	0.6	0.9	0.1	1.4	167	5.5	0.19	83.9	4.8	11.3		0.008	0.25
77-28 Typic Anhyorthels; upper Lake Vanda shoreline; Wright Valley																	
Cox	0.5–20	2.4	7.8	12.0	10.0	2.7	0.5	22.0	1.9	0.64						11.6	34.4
2Bwb	20–40	5.1	7.7	34.0	16.0	6.2	0.9	54.0	2.2	0.85						24.5	63.5
2Cnb	40–65	2.6	7.6	15.0	7.8	2.4	0.6	22.0	2.8	0.64						7.9	34.4
79-08 Typic Haploturbels; undifferentiated drift; Labyrinth, Wright Valley																	
Bw	0.5–13	2.9	6.9	23.0	1.6	8.5	0.2	17.0	7.2	7.6						2.4	2.2
Cn	13–29	0.83	7.0	7.8	0.1	0.5	0.1	4.9	1.0	2						5.1	2.5
Cf	29–37	0.63	7.1	5.1	0.1	0.3	0.1	2.9	1.2	1.1						2.4	2.6
83-41 Petrosalic Anhyorthels; ripples/Alpine 3b/Peleus; Conrow Glacier, Wright Valley																	
Cn	0–14	5.3	7.3	47.3	13	1.6	0.6	32.4	18.8	1.67					0.9	1.7	19.4
2Bwzb	14–28	80	7.8	1089	36.9	111	2.6	748	227	77.0					3.74	3.3	9.7
2Bwb	28–70	9.3	7.1	100.4	14.2	10.1	1	78.1	28.3	1.79					0.69	2.8	43.6
3Bwb	70–120	3.6	6.4	16.2	9.3	13.5	1.6	17	17.3	1.59					1.41	0.98	10.7
84-47 Petrosalic Anhyorthels; Alpine 3b; Meserve Glacier, Wright Valley																	
Bw1	0–4	4.8	7.0	21.9	34.4	7.6	1.1	18.2	45.9	3.64					1	0.40	5.0
Bwz1	4–20	80	7.1	820.4	16.1	83.7	7.5	948	157.6	23.6					2.04	6.0	40.1
Bwz2	20–42	31	6.9	302.2	6.4	55.0	6.6	269	50.4	20.1					1.42	5.3	13.4
Bw2	42–85	4.4	6.7	30.3	2.3	7.4	2.7	30.6	7.7	4.75					0.75	4.0	6.4
84-49 Salic Anhyorthels; Alpine 3/Peleus; Bartley Glacier, Wright Valley																	
Bw	0–4	5.6	7.4	28.0	34.8	5.1	1.5	26.8	44.5	0.56					1.21	0.60	47.9
Bwz	4–33	18	6.2	198	35.9	15.9	3.3	225	34.4	11.5					0.86	6.5	19.5
BC	33–61	6.5	7.0	54.2	9.9	17.0	2.9	64.4	10.0	8.5					1.05	6.4	7.6
2Bwb	61–99	11.8	7.2	77.6	19.8	53.1	4.1	13.2	7.9	26.3					5.36	1.7	0.50
3Bwb	99–115	5.5	7.7	27.4	7.3	29.2	1.5	45.0	0.6	0.76					3.95	78.9	59.2
Peleus pan	115 +	75	7.8	1168	41.9	31.1	15.9	900	38.5	319					1.75	23.4	2.82
78-33 Typic Anhyorthels; undifferentiated drift; Darwin Mountains																	
Bw	0.5–7	2.8	6.1	11	13	11	0.49	2.4	18	13						0.13	0.18
BC	7–15	1.3	6.9	7.3	0.59	6.3	0.4	2.3	1.8	8.6						1.28	0.27
Cn	15–26	2.1	6.8	10	3.8	11	0.56	2.7	6.4	13						0.42	0.21
2Db	26–30																	
2Bwb1	30–41	1.6	5.3	6.7	4	7	0.3	2.4	7.9	8.1						0.30	0.30
2Bwb2	41–53	1.1	6.9	6.5	0.16	3.8	0.21	2.5	0.8	8.1						3.13	0.31
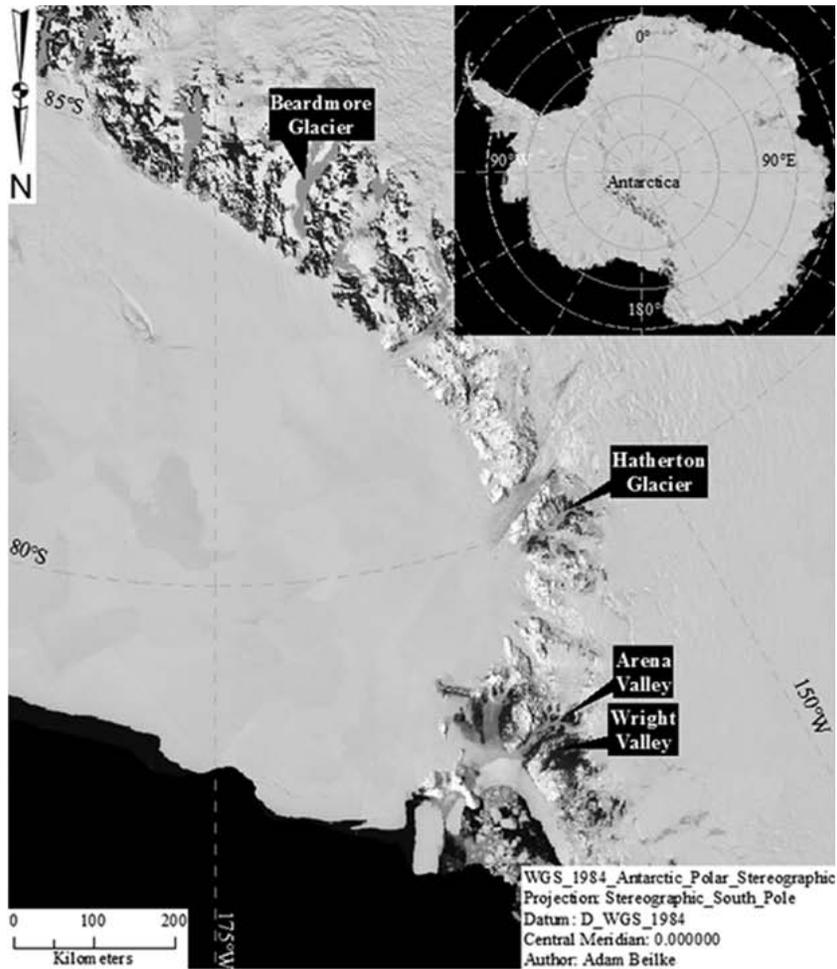
Fig. 1. Study areas in the Transantarctic Mountains.
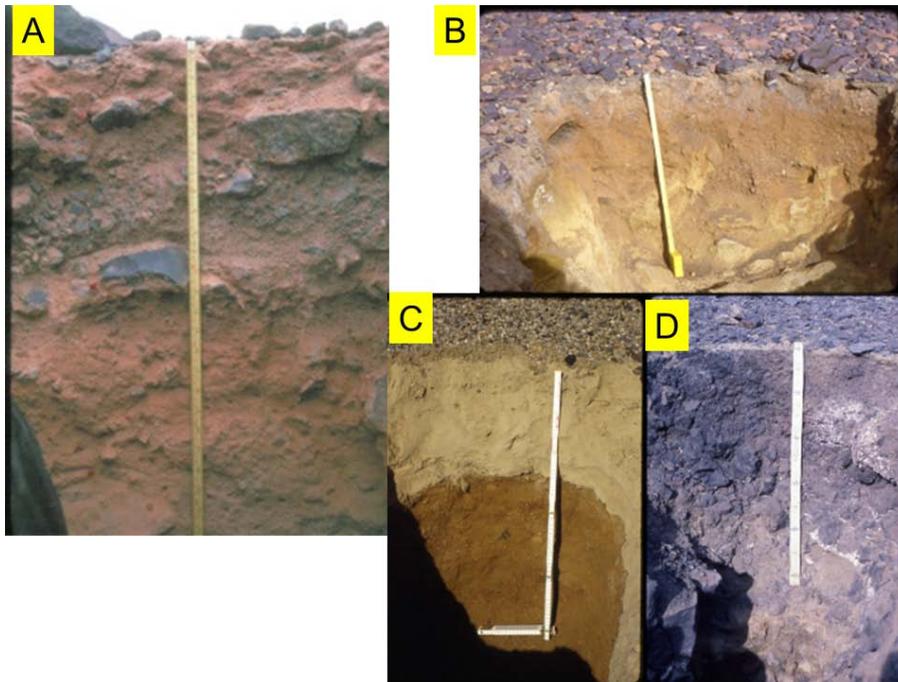
Fig. 2. Examples of buried soils in the Transantarctic Mountains: **(A)** this soil in upper Arena Valley shows multiple burials including scattered Taylor III boulders of 200 ka age on the surface (not visible from image) over Taylor IV drift of early Pleistocene or late Pliocene age (the upper soil), which then buries Quartermain drift of Miocene age (Notice the buried desert pavement including the intact ventifact on top of the buried Quartermain soil) (pedon 75-19); **(B)** a soil derived from early Pleistocene-aged drift containing pieces of formerly frozen Pliocene-aged drift in the Darwin Mountains (pedon 78-33); **(C)** the 3.9 Ma Hart ash burying a strongly developed soil from colluvium in central Wright Valley (pedon 87-29); **(D)** a lava flow burying an intensively developed soil in Taylor Valley containing abundant salts (pedon 84-05). K-Ar dating of lava flows can provide limiting ages of buried soils.
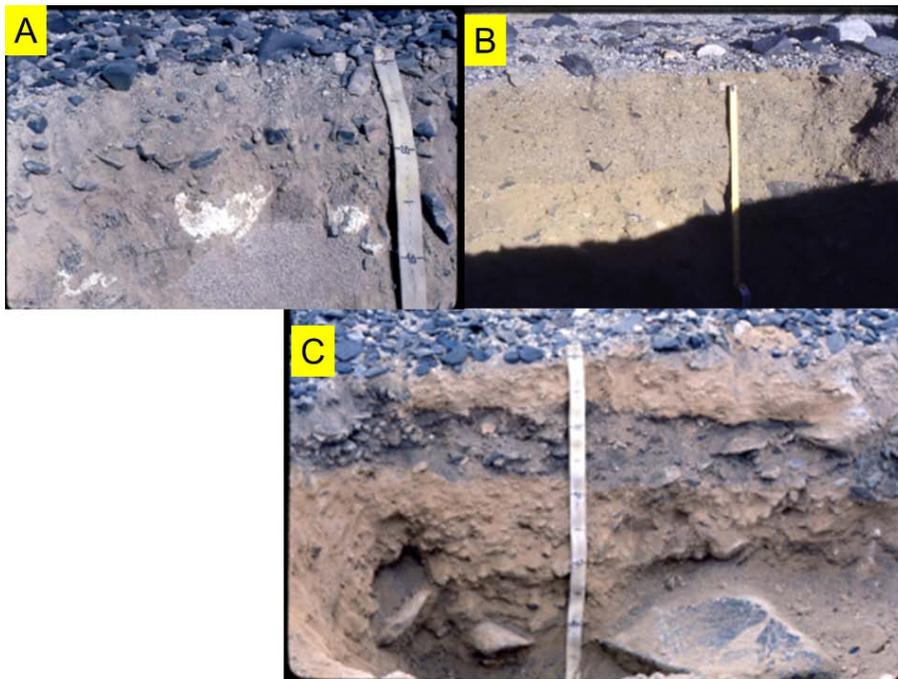
Fig. 3. Further xamples of burial soils in the Transantarctic Mountains: **(A)** a mega-ripple of unknown age that has developed down to the salt pan of a soil developed on Alpine IIIb drift on the west side of the Conrow Glacier, central Wright Valley (pedon 83-41); **(B)** the upper strandline at Lake Vanda in upper Wright Valley showing lacustrine material burying a strongly developed soil of possible Pliocene age (pedon 77-28); **(C)** a soil derived from Alpine IIIa drift in Wright Valley that buries an intensely developed soil of Alpine IIIb or Alpine IV age (pedon 83-38).

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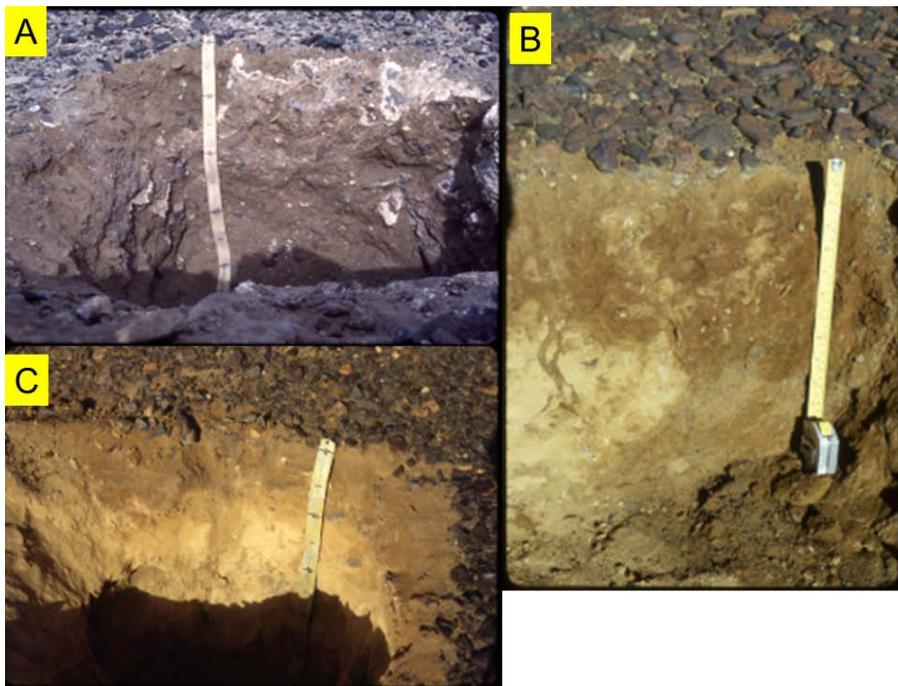
Fig. 4. Relict soils and features in the Transantarctic Mountains: **(A)** one of the most strongly developed soils we have observed in the Transantarctic Mountains, this soil is derived from Alpine IV drift in central Wright Valley, contains stage 6 salts, and is likely of Pliocene age (pedon 84-47); **(B)** cryoturbation in a soil now containing dry permafrost in the Labyrinth, upper Wright Valley (pedon 79-08); **(C)** a fossil sand wedge that passed through a soil derived from Taylor IV drift (Pliocene) and into a soil derived from Altar drift (Miocene) in upper Arena Valley (pedon 87-34).