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Soil formation in Wright Valley, Antarctica since the late Neogene

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Abstract

We investigated over 180 soil profiles on 15 drift units ranging from Recent to Pliocene or older in age in Wright Valley, Antarctica. The drifts originate from (1) post-valley cutting by an advance of the East Antarctic Ice Sheet, (2) advances of the Wright Lower Glacier from grounding of ice in the Ross Embayment, and (3) advance of alpine glaciers along the south valley wall. Holocene and LGM soils lack staining (from oxidation of iron-bearing minerals) and visible salts, contain ice or ice-cemented permafrost in the upper 0.5 m, and are classified as Glacic or Typic Haploturbels. Other soils of late Quaternary age are stained to <10 cm, contain ice-cemented permafrost in the upper 0.5 m, have stage 1 salts (encrustations beneath surface clasts) and <1000 mg salts cm^{-2} in the upper 70 cm of profile, and are classified as Typic Haploturbels. Soils of mid-late Quaternary age are stained to 20 cm, have ice-cemented permafrost at depths in excess of 1 m and stage 2 salts (flecks and patches covering <20% of the profile face), contain 1000–1700 mg salts cm^{-2}, and are classified as Typic Anhyorthels. Soils of early Quaternary to late Pliocene age are oxidized to depths >30 cm, have stage 3 salts (flecks and patches covering >20% of the profile face), contain 4000–4200 mg salts cm^{-2}, and are classified as Salic Anhyorthels. Soils of Pliocene age are deeply oxidized (>50 cm), have stage 5–6 salts (strongly cemented or indurated salt pans), contain 5000–7000 mg salts cm^{-2}, and are classified as Petrosalic Anhyorthels. Soils of early Pliocene or older age do not show the degree of development of younger soils because they are derived from Peleus till which contains highly erosive, fine-sandy, quartz-rich rock. Our data question the notion of high-level Antarctic lakes occupying most of the valley during the LGM and early Holocene.

Keywords: Soil chronosequence; Cold desert soils; Dry valleys; Soil classification; Gelisols

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1. Introduction

The glacial geology of Wright Valley, Antarctica has been studied for more than 40 years (Péwé, 1960; Bull et al., 1962; Nichols, 1971; Calkin and Bull, 1972; Vucetich and Topping, 1972). In the past 10 years, the late Tertiary Antarctic paleoclimate and ice-sheet dynamics of Wright Valley have been elucidated largely through the efforts of Denton et al. (1991), Hall et al. (1993, 1997), Prentice et al. (1993) and Prentice and Krusic (2005). Key recent findings include (1) the terrestrial glacial record extends much further back in time (ca. 5–10 Ma) than previously believed (e.g., Prentice et al., 1993; Marchant et al., 1993), (2) cold desert conditions have existed in the McMurdo Dry Valleys for at least the past 3.9 Ma (Marchant et al., 1994; Hall et al., 1997), (3) buried ice has persisted in the Dry Valleys for the past 8 Ma (Marchant et al., 1996), and (4) high-level lakes may have existed in the Dry Valleys during the late-glacial maximum (LGM) and early Holocene (Hall et al., 2001).

Soils have played an integral role in elucidating the glacial history and paleoclimate of the Dry Valleys, and Wright Valley in particular. Soils have been important in identifying the spatial extent of drift sheets (Ugolini and Bull, 1965; Everett, 1971; Linkletter et al., 1973; Bockheim, 1978; Prentice et al., 1993; Hall et al., 1993). The study of soil development rates has assisted in the development of glacial chronologies and prediction of ages on surfaces for which numerical ages are nonexistent (Bockheim, 1978; Bockheim, 1990). Soils have been useful in regional and long-distance correlation of drift sheets (Bockheim et al., 1989). Buried, relict, and exhumed soils have validated moraine-crosscutting relationships, overriding of cold-based glaciers, and the identification of “windows” of older drift in more recent drift units (Bockheim, 1982). The

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progressive increase in salts in Antarctic soil chronosequences and persistence of salts in Pliocene-aged soils attest to the existence of cold desert conditions for the past 3.9 Ma (Marchant et al., 1994).

The primary aim of this paper is to determine soil development rates on glacial deposits originating from three sources in Wright Valley over the past ca. 5 Ma.

2. Experimental site

With an area of about 470 km^2 below the 1000 m contour, Wright Valley is the second largest of the McMurdo Dry Valleys (Fig. 1), which at 4800 km^2 is the largest ice-free area in Antarctica. The valley extends 52 km from the Wright Lower Glacier, a lobe of the Wilson Piedmont Glacier, to the Wright Upper Glacier, an outlet glacier from the East Antarctic ice sheet that has been relatively inactive since original fjord cutting ca. 5.5 Ma ago due to uplift of the Transantarctic Mountains (Prentice et al., 1993).

Bedrock in east-central Wright Valley consists of Precambrian to Paleozoic metasediments, granite-gneisses, and lamprophyre and rhyolite porphyry dikes, as well as Jurassic-age dolerite sills (McKelvey and Webb, 1962). Basaltic cones of the Cenozoic McMurdo Volcanics occur on the southern valley wall to the east of Bartley Glacier. Western Wright Valley contains the Beacon Supergroup of Devonian-to-Jurassic age, which contains primarily sandstones and is intruded by the Jurassic Ferrar Dolerite (McKelvey and Webb, 1962).

Glacial deposits in Wright Valley represent three interacting systems. Original valley cutting was from a wet-based outlet glacier originating from the East Antarctic Ice Sheet which passed westward down the valley about 9±1.5 My ago, at which time the mountains were less than 400 m below their present elevation (Prentice et al., 1993). The valley was largely ice-free at 5.5±0.4 Ma. The Peleus till, the oldest drift recognized in the valley, was deposited before 3.9 Ma by a wet-based glacier draining the East Antarctic Ice Sheet that filled Wright Valley (Prentice et al., 1993). The second system represents grounded ice from the Ross Sea Embayment (Wright glaciations), which advanced westward into Wright Valley on at least seven occasions to at least 21 km beyond the margin of present-day Wright Lower Glacier (Hall and Denton, 2005). These advances are believed to be contemporaneous with Northern Hemisphere glaciations. The third system includes five alpine glaciers existing along the south valley wall, which advanced on at least four occasions out-of-phase with the Wright glaciations (Calkin and Bull, 1972; Hall et al., 1993). Details on uncertainties in deposit mapping, age and climate history of the McMurdo Dry Valleys recently were discussed by Prentice and Krusic (2005) and are not the focus of this paper.

Hall et al. (2001) reported the existence of millennial-scale, surface-level changes of closed-basin Antarctic lakes during the LGM and early Holocene. For example, at its high-stands Glacial Lake Wright would have extended up to 480 m above present-day lakes and up to 566 m above sea level, stretched 50 km from the Wright Lower Glacier into the North and South Forks, and covered an area of ca. 210 km^2.

Wright Valley may be divided into four eco-climatic units, including the Inland Valley Floor (85–300 m), Inland Valley Sidewalls (300–1250 m), Upland Valleys or cirques in the surrounding Asgard and St. Johns Ranges (1250–1500 m), and the Plateau Fringe (>1500 m). Only the first two eco-climatic units are considered in this study.

Wright Valley has a cold desert climate. The mean annual temperature ranges from −17 °C to −20 °C (Bromley, 1985; Doran et al., 2002), and the mean annual precipitation is <50 mm water equivalent, with as little as 7 mm recorded by direct observations (Bromley, 1985). Arid conditions in Wright

Fig. 1. A land satellite image showing Wright Valley and the surrounding area.

Valley are exacerbated by low precipitation relative to sublimation, low surface albedo, and dry katabatic winds descending from the Polar Plateau (Clow et al., 1988).

As with the glacial geology, considerable effort has gone into the study of soils in Wright Valley. Ugolini (1964) and Ugolini and Bull (1965) described soils of lower Wright Valley. Everett (1971) characterized soils on alpine drift adjacent to the Meserve Glacier. A key finding is that ionic migration and weathering occur in frozen soils of Wright Valley (Ugolini and Anderson, 1973; Ugolini and Jackson, 1982; Gibson et al., 1983). Bockheim (1978) discussed relative age and origin of soils in eastern Wright Valley. In addition, soils have played a significant role in elucidating the glacial chronology of Wright Valley (Hall et al., 1993; Prentice et al., 1993).

3. Methods and materials

3.1. Field

Methods used in this study were described in detail by Bockheim (2002) and will only be highlighted here. During the period 1976–1987, Bockheim et al. described 188 soil profiles in Wright Valley. In 2005 and 2006 the authors described and sampled an additional 24 profiles, which were selected on the basis of recent revisions in the glacial chronology by Hall and Denton (2005) (i.e., differentiation of Brownworth, and Loke drifts in eastern Wright Valley and identification of Valkyrie drift in central Wright Valley).

Soil pits were excavated to a depth of at least 100 cm, unless ice-cement or large boulders prevented digging to that depth. 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 measurements and soil age, including 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. We also determined the depth to ice or ice-cemented permafrost. The active (seasonal thaw) layer in Wright Valley varies between 20 and 50 cm; material below this depth that is not cemented by ice contains

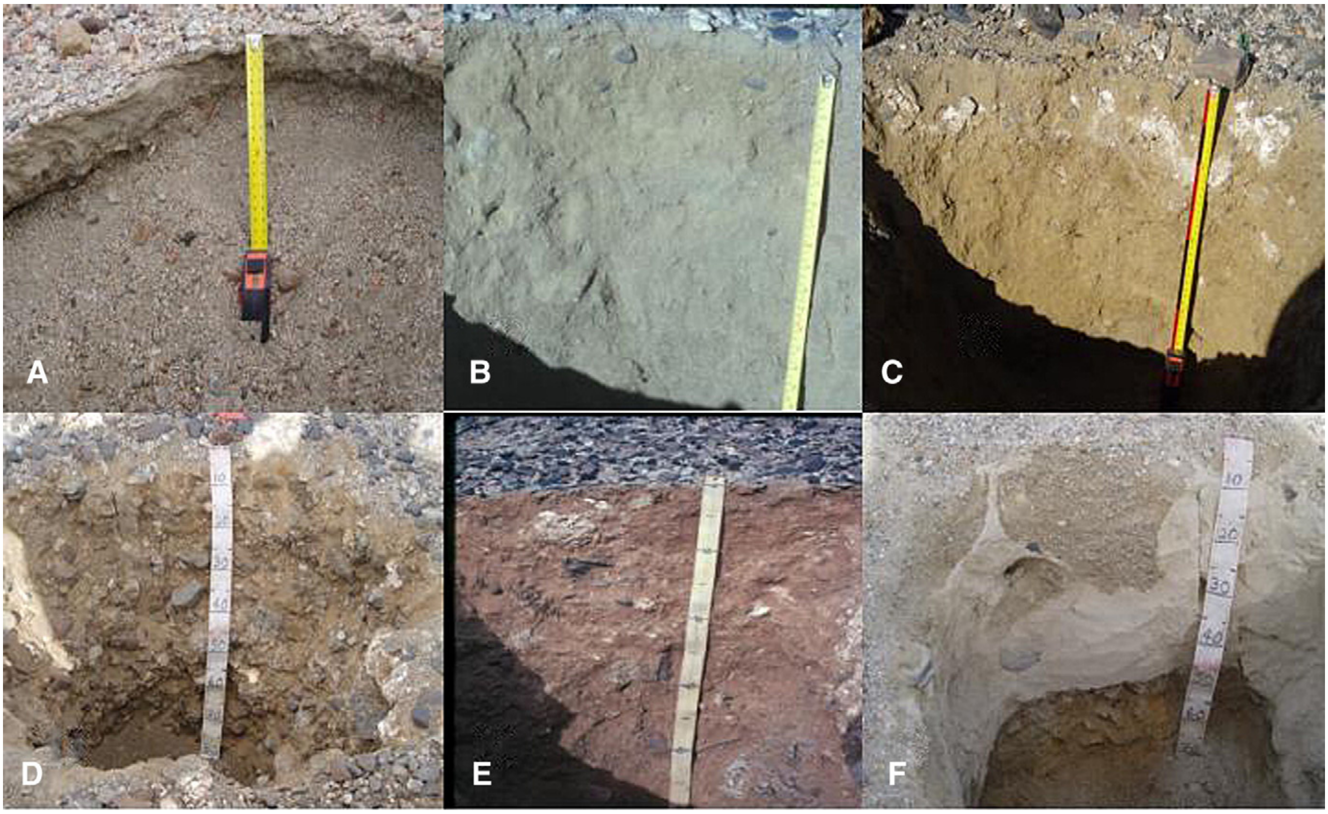

Fig. 2. Representative soils in Wright Valley, including (A) a soil on a Late Glacial Maximum surface, (B) a soil on mid to late Quaternary (H1) aged hummocky drift, (C) a soil on early Quaternary (Wright) drift, (D) a soil on the Pliocene-aged Valkyrie drift, (E) a soil on the Pliocene or older Alpine IV drift, and (F) a groundsoil and buried soil on the 3.9 My Hart Ash.

"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 and Wilson, 1992), including 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.

Soils were classified into the Gelisol order to the family level (Soil Survey Staff, 2003); 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. Whereas soils of eastern Wright Valley are moist during the summer months, soils of central and upper Wright Valley have anhydrous conditions (i.e., the mean annual precipitation is less than 50 mm water equivalent). The soils in lower Wright Valley are classified as Haploturbels and those in the upper valley are Anhyturbels or Anhyorthels. The latter soils are further subdivided into subgroups on the basis of presence or absence of soluble salts (e.g., salic, gypsic, nitric, petrosalic, and petrogypsic).

Soil horizons were distinguished using standard soil horizon nomenclature, except that the symbol "D" was used for desert pavement and the terms "Cu" and "Cox" were used for unoxidized and oxidized parent materials, respectively. The depth of each horizon was determined from a control section representative of the four exposures in the soil pit. The percentages of stones (>30 cm) and cobbles (7.6–30 cm) were estimated for each horizon on an area basis. The percentage of gravel (0.2–7.6 cm) was distinguished from the fine-earth fraction (<2 mm) in the field by sieving and weighing.

3.2. Laboratory

Electrical conductivity (EC) was determined on 1:5 soil/distilled water extracts using a conductivity bridge and cell (U.S. Salinity Laboratory Staff, 1954). Profile quantities of salts (mg/cm^2) to a depth of 70 cm were calculated from the formula (Bockheim, 1978):

$$\text{Profile salts} = \text{Electrical conductivity (dS/m)} \times \text{thickness (cm)} \times 4.8$$

No corrections were made for coarse fragments >2 mm as they readily accumulate salts. Salts are reported to 70 cm, because this depth represents the maximum extent of staining; moreover, ice cement below this depth does not markedly affect cryoturbation.

Means of selected morphological and chemical properties of soils within a glacial system (alpine or Wright glaciations) were compared using analysis of variance (Minitab, Inc., 2000).

4. Results

There is a distinct relation between soil development and age of drift unit, with some notable exceptions. Holocene and LGM

Table 1
Properties of soils of drift units in Wright Valley, Antarctica (mean values are followed by ±1 standard deviation in parenthesis)

Drift unit (est. age)	No. of pedons	Depth (cm)					Salt stage[a]	Weathering stage[a]	Profile salts to 70 cm (mg/cm^2)	Soil subgroup[b]
		Staining	Coherence	Visible salts	Ghosts	Ice cement				
Alpine I (Recent)	5	0 (0)	5 (4)	0 (0)	0 (0)	12 (8)	0 (0)	1 (0)	75 (42)	GHt
Lacustrine (Holocene)	1	0	5	1	0	50	0	1		GHt
Brownworth (>49 ka)	5	0 (0)	23 (26)	3 (5)	0 (0)	48 (18)	1 (0)	1 (0)	317 (206)	THt
Hummocky, H1 (late Quaternary)	13	7 (8)	19 (22)	19 (21)	2 (5)	55 (18)	1 (1)	2 (1)	974 (921)	TAo
Loke (mid- to late Quaternary)	2	0	31	17	0	33	1	2	8	THt
Hummocky, H2 (mid-late Quaternary)	7	33 (32)	>34	9 (19)	13 (7)	>97	2 (2)	3 (1)	1515	TAo
Alpine II (<3.3 Ma)	24	15 (7)	35 (23)	18 (18)	4 (5)	>65	2 (1)	3 (1)	1715 (954)	TAo
Trilogy (early-mid Quaternary)[c]	5	13 (22)	21 (29)	1 (1)	7 (12)	39 (7)	1 (1)	2 (2)	52 (40)	THt
		38	**54**	**>100**	**20**	**>100**	**1**	**4**		**TAo**
Onyx (<3.3 Ma)	10	29 (15)	45 (25)	32 (22)	13 (8)	>82	3 (2)	4 (1)	4689 (2992)	TAo-SAo
Wright (<3.4 Ma)	11	>27	>30	22 (17)	16 (16)	>90	3 (2)	4 (1)	4720 (2483)	TAo-SAo
Valkyrie (Pliocene?)	3	>44	>94	>40	39 (27)	>94	5 (1)	5 (0)	7094 (2164)	PsAo
Alpine III (<3.5 Ma)	15	>43	>56	48 (15)	21 (19)	>103	4 (1)	6 (1)	7084 (3273)	PsAo
Alpine IV (>3.7 Ma)	18	>55	>100	>63	19 (11)	>100	6 (1)	6 (0)	6103 (2590)	PsAo
Hart Ash (3.9 Ma)	2	>50	>75	>75	20	>75	2	4		TAo-SAo
Loop (Pliocene or Miocene)	4	>60	>88	44 (9)	9 (4)	>88	5 (1)	6 (1)	2822	PsAo
Peleus (>3.7 Ma, Pliocene or older?)	6	24 (13)	>100	17 (4)	10 (5)	>100	4 (1)	5 (1)	3922 (1374)	TAt

[a] See text for explanation.

[b] GHt = Glacic Haploturbel; THt = Typic Haploturbel; TAt = Typic Anhyturbel; TAo = Typic Anhyorthel; SAo = Salic Anhyorthel; PsAo = Petrosalic Anhyorthel.

[c] Profile 06-30 given in bold face.

soils lack staining, contain few visible salts, have ice or ice-cemented permafrost in the upper 55 cm, and are classified as Glacic or Typic Haploturbels (Fig. 2A, Table 1). Other soils of late Quaternary age are stained to a depth of <10 cm, have ice-cemented permafrost in the upper 50 cm and stage 1, contain <1000 mg salts cm^{-2} in the profile, and are classified as Typic Haploturbels. Soils of mid- to late Quaternary age, except those on Loke drift, are stained to around 30 cm, have ice-cemented permafrost at a depth in excess of 100 cm and stage 2 salts, contain 1000–1700 mg salts cm^{-2}, and are classified as Typic Anhyorthels (Fig. 2B). Soils of early Quaternary to late Pliocene age, except those on Trilogy drift, are oxidized to depths >30 cm, have stage 3 salts, contain 4000–4200 mg salts cm^{-2}, and are classified as Salic Anhyorthels (Fig. 2C). Soils of Pliocene age, except for those developed on the Hart Ash, are deeply oxidized (>50 cm), have stage 5–6 salts, contain 5000–7000 mg salts cm^{-2}, and are classified as Petrosalic Anhyorthels (Fig. 2D, E and F). Soils of early Pliocene age or older on Peleus till (Typic Anhyturbels) are less developed than younger soils; this will be discussed later.

5. Discussion

5.1. Soil evolution in Wright Valley

The results of this study illustrate long-term soil evolution and suggest that despite ca. 5 Ma of exposure to subaerial weathering soils of Antarctica do not reach a dynamic steady state in terms of development. The degree of soil development in Wright Valley is best expressed by salt stage and weathering stage. Soils derived from Holocene to Pliocene-aged materials contain salts of stages 0 (Holocene), 1 (late Quaternary), 2 (mid-late Quaternary), 3 (mid-early Quaternary), 4 (early Quaternary–late Pliocene), 5 (mid-early Pliocene), and 6 (early Pliocene), respectively (Table 1). These trends support the view that the salts originate primarily from marine aerosols (Bockheim, 2002) and are not inherited from fjord deposits. The same trends occur relative to weathering stage. The relatively uniform rate of soil development that extends to the mid-Pliocene age further casts doubt on the suggested warming of 2–5 °C during this time (Webb et al., 1984).

Morphological and chemical properties are comparable for soils of equivalent age on deposits from the three glacial sources. For example, the depth of staining (Fig. 3A), salt stage (Fig. 3B), and weathering stage (Fig. 3C) are comparable for member soils of alpine and Wright glacial sequences of Holocene, mid- to late Quaternary, and Pliocene-aged soils. Similarly, soil properties are comparable for alpine and Wright glacial sequences of Pliocene age.

There are four anomalies in soil development relative to presumed age of the drift. The Trilogy drift was considered by Hall and Denton (2005) to be early to mid-Quaternary in age. However, soils on Trilogy drift are less strongly developed that those on hummocky drifts of mid- to late Quaternary age (Table 1, Fig. 3). Trilogy drift occurs primarily on the valley floor in eastern Wright Valley where there is abundant snowfall, ice-cemented permafrost is close to the surface, and cryoturbation is an active process (Bockheim, 1979). During 2006 we examined a Trilogy soil on the south valley wall near the Denton Glacier that had properties consistent with an early to mid-Quaternary age. Therefore, cryoturbation of Trilogy soils on the valley floor may preclude the full expression of the soil. Similarly, the Loke drift, which occurs in the comparatively moist eastern part of the valley and is considered by Hall and Denton (2005) to be mid- to late Quaternary in age, lacks soil development commensurate with its assigned age.

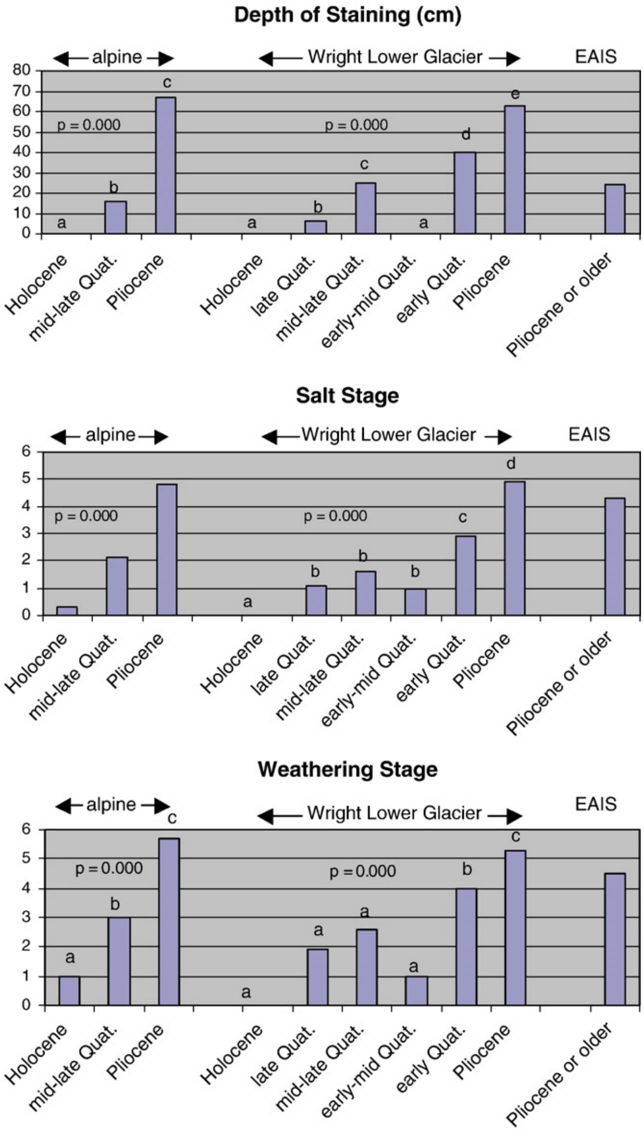

Fig. 3. Relations between (A) depth of oxidation, (B) salt stage, and (C) weathering stage for soils of on alpine drifts and drifts from the Wright Lower Glacier. Differences in small-case letters imply statistically significant differences in mean values at $p<0.05$. Specific drift units within an age class are given in Table 1.

The oldest glacial sediment identified in Wright Valley, the Peleus till, features unusually low soil development, particularly given that it is of Pliocene (Prentice and Krusic, 2005) or possibly even of mid-Miocene age (Marchant et al., 1993). This may be due to that the soils are derived from light-colored, fine sandy, quartz-rich rock flour which does not exhibit the degree

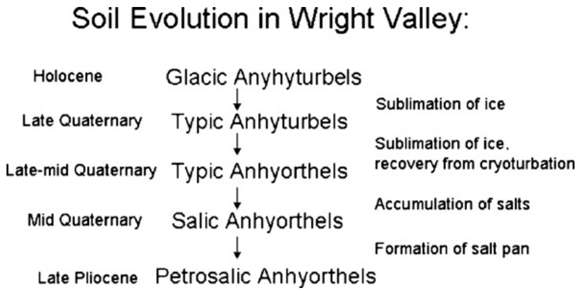

Fig. 4. Proposed evolution of soil taxa in Wright Valley.

of soil weathering as soils from drifts derived from mixed sources of rock and the soils have been deflated by wind erosion and the properties do not reflect their true age (Hall et al., 1993; Prentice et al., 1993). Another anomaly is the lack of soil development on the 3.9 My Hart Ash. We attribute this phenomenon to the high percentage of rhyolitic glass and minor quantities of iron-bearing minerals within the soil.

The trends in soil development are confirmed by soil taxa, with Glacic Haploturbels occurring on recent sediments, Typic Haploturbels on other glacial deposits of late Quaternary age, Typic Anhyorthels on drift of late-mid Quaternary age, Salic Anhyorthels on drift of early Quaternary age, and Petrosalic Anhyorthels on drift of Pliocene age or older (Fig. 4).

5.2. Development of dry permafrost

The concept of "dry-frozen" permafrost is controversial to scientists working in the northern hemisphere. Dry-frozen permafrost may be restricted globally to the dry valleys of Antarctica (Bockheim and Tarnocai, 1998). Permafrost containing >5% moisture (ice) tends to be ice-bonded in the McMurdo Dry Valleys. Although ice-cemented permafrost exists in the upper 1 m of soils of LGM or younger, it is absent in the upper 1 m of soils derived from glacial deposits of mid-Quaternary age. Soils of early Quaternary age and older seldom contain permafrost in the upper 1.5 m except in Upland Valleys and along the Plateau Fringe. These results confirm earlier suggestions (Ugolini, 1964; Bockheim, 1990; Bockheim and Wilson, 1992; Bockheim, 2002) that dry-frozen permafrost is formed over time as interstitial ice is sublimated from Antarctic soils.

5.3. Soils in relation to high-level Antarctic lakes during the LGM and early Holocene

While our study does not contribute directly to the question of the existence of Glacial Lake Wright during the LGM and early Holocene, we have some concerns regarding the concept of high-level lakes in Wright Valley during the LGM and early Holocene. Despite detailed examination of more than 200 soils (not counting test pits) in Wright Valley, we have not observed widespread lacustrine sediments or evaporative salts from these lakes. Lakes of the magnitude suggested by Hall et al. (2001) should yield some sediments and considerable evaporative salts as occur beneath Lake Vanda today (Spigel and Priscu, 1998). The only reports of lacustrine sediments are deltas below Clark Glacier and a limited distribution of "orange-colored lacustrine sediments" within the Brownworth drift unit (Hall and Denton, 2005).

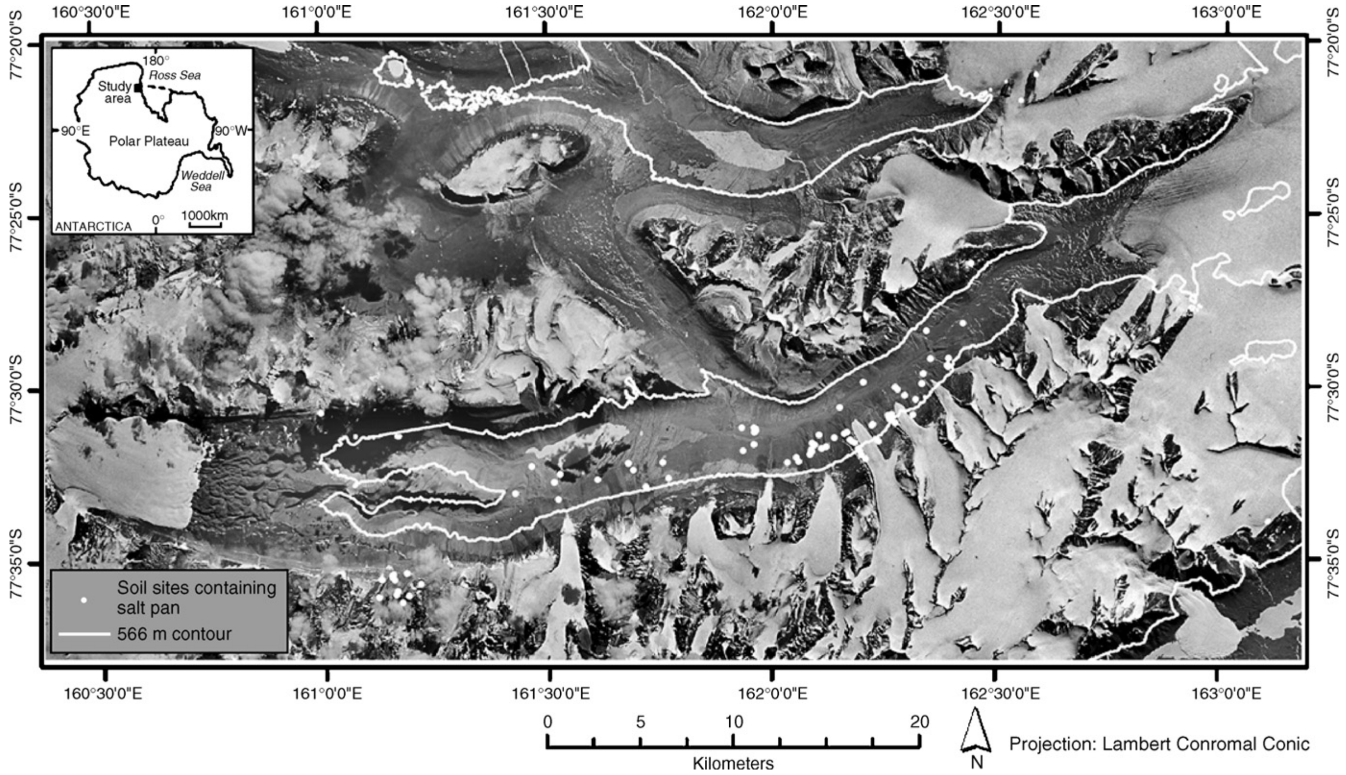

Fig. 5. Location of soils with saltpans in Wright Valley along with the 566-m contour line that represents the maximum level of the proposed Glacial Lake Wright.

Secondly, a mechanism must be sought whereby the salts in soils of Wright Valley, which are dominantly the highly soluble NaCl (Bockheim, 1978) and are strongly correlated with drift age, are not leached from the soils. If Glacial Lake Wright was 566 m above sea level at its maximum extent, soils of early Quaternary age and older, which contain considerable salts in the form of patches and pans, should have been flushed of salts. In fact, most of the soils containing saltpans examined in this study occur below the 500-m contour (Fig. 5). Similarly, the ice core in the hummocky drifts pervasive along the valley floor from the Denton Glacier to the Bartley Glacier should have melted. For example, Lake Vanda acts as a solar trap, and the water at the base of the lake has a temperature of 25 °C (Spigel and Priscu, 1998).

6. Conclusions

Soils of Wright Valley have developed over the past >3.9 Ma in response to fluctuations of the Wright Upper Glacier (East Antarctic Ice Sheet), the Wright Lower Glacier (grounded ice in the Ross Embayment), and alpine glaciers. Soils can readily be distinguished on the basis of morphological properties, particularly the amount and distribution of soluble salts, and the degree of chemical weathering. These changes are reflected in *Soil Taxonomy*, whereby Glacic and Typic Haploturbels are found on younger surfaces in eastern Wright Valley, Typic and Salic Anhyorthels occur on surfaces of intermediate age (mid-early Quaternary), and Petrosalic Anhyorthels exist on geomorphic surfaces of Pliocene and older ages.

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