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# Soil distribution in the McMurdo Dry Valleys, Antarctica

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#### Abstract

The McMurdo Dry Valleys (MDVs) are the largest ice-free area (ca. 6692 km<sup>2</sup>) in Antarctica. Here we present a reconnaissance (scale=1:2 million) soil map of the MDVs. The soil map units are subgroups as identified in the U.S. Department of Agriculture *Soil Taxonomy*. The dominant soil subgroups in the MDVs are Typic Anhyorthels (43%), Typic Haploturbels (36%), and Typic Anhyturbels (14%). Soils of the MDVs represent an evolutionary sequence that include Glacic Haploturbels/Anhyturbels on Holocene surfaces, Typic Haploturbels/Anhyturbels on late Quaternary surfaces, Typic Anhyorthels on late to mid-Quaternary surfaces, Salic Anhyorthels on mid-to early Quaternary surfaces, and Petrosalic/Petrogypsic/Petronitric Anhyorthels on Pliocene and older surfaces. Soils on silt-rich tills of Pliocene and older age generally are Typic or Salic Anhyorthels; they feature less weathering than younger soils because (i) they are derived from quartzose materials largely devoid of weatherable minerals and (ii) they have been subject to considerable wind erosion. © 2007 Elsevier B.V. All rights reserved.

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#### 1. Introduction

At 6692 km<sup>2</sup> the McMurdo Dry Valleys (MDVs) constitute the largest ice-free area in Antarctica. The vegetation, surficial geology, climate, soils, and other resources of the McMurdo Dry Valleys have been studied intensively and summarized by Tedrow and Ugolini (1966), Campbell and Claridge (1987), and Campbell et al. (1998).

Soils have played an integral role in elucidating the glacial history and paleoclimate of the Dry Valleys, particularly in identifying the spatial extent of drift sheets (Linkletter et al., 1973; Prentice et al., 1993; Hall et al., 1993; Bockheim and McLeod, 2006). The study of soil development rates has assisted in the establishment of glacial chronologies and prediction of ages on surfaces for which numerical ages are nonexistent (Bockheim, 1979a; 1990). Soils have been useful in regional and long-distance correlation of drift sheets in areas where soil-forming factors are similar (Bockheim et al., 1989). Buried, relict, and exhumed soils have validated moraine-crosscutting relationships, overriding of cold-based glaciers,

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and the identification of "windows" of older drift in more recent drift units (Bockheim, 1982). The 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 ca. 3.9 Ma (Marchant et al., 1994).

Over the past 35 years, we have collected data from more than 550 soils in the MDVs (http://nsidc.org/data/ggd221.html). The objective of this study is to use these data to develop a provisional soil map of the MDVs.

# 2. Study area

The MDV region as considered here ranges from 76° to 79°S and 158° to 170°E. We have attempted to show most place names mentioned here on Fig. 1; coordinates are given for sites not shown on the map. The largest ice-free areas are the Mount Discovery area (996 km<sup>2</sup>), which includes Minna Bluff and the Brown Peninsula; the Denton Hills (753 km<sup>2</sup>), which comprise the eastern foothills of the Royal Society Range; and the Convoy Range (661 km<sup>2</sup>), which includes the Convoy Range, the Allan Hills, and the St. Johns, Clare, and Willett Ranges (Fig. 1). Additional key ice-free areas include the Victoria Valley system (653 km<sup>2</sup>), which includes Barwick,

Balham, McKelvey, and Victoria Valleys, and Bull Pass; Taylor Valley (630 km<sup>2</sup>), which includes Marble and Gneiss Points; and Wright Valley (485 km<sup>2</sup>), which includes the Asgard Range. Smaller ice-free areas include the Quartermain Mountains (397 km<sup>2</sup>), the Ferrar Valley (348 km<sup>2</sup>), and Ross Island (209 km<sup>2</sup>).

The MDVs can be subdivided into three climatic zones: subxerous (coastal areas), xerous (inland valleys), and ultraxerous (adjacent to the Polar Plateau) (Campbell and Claridge, 1987). Mean annual air temperature in the MDVs ranges from -20 to -35 °C, and mean annual water-equivalent precipitation ranges from less than 10 to 100 mm yr<sup>-1</sup> (Doran et al., 2002). Strong winds redistribute snow and exacerbate evaporation/ sublimation losses.

Surficial sediments are primarily glacial till derived from granitic rocks in the eastern portion of the study area and dolerite and sandstone in the west. Patterned ground is common in the MDVs, including ice-wedge polygons in the subxerous and xerous zones and sand-wedge polygons in the xerous and ultraxerous zones. Active-layer depths range from 5 cm at Mt. Fleming (77°33'S, 160°06'E) along the Polar Plateau to 80 cm at Granite Harbour along McMurdo Sound (75°06'S, 163°41'E) (Paetzold et al., 2004). Soils of the region are classified in the Gelisol order (Bockheim, 2002; Bockheim and McLeod, 2006). Soils with ice-cemented permafrost within 70 cm of the surface generally are cryoturbated and classified in the Turbel suborder; soils with dry-frozen permafrost and minimal cryoturbation are classified as Orthels (Fig. 2). Soils in the subxerous region are in Haplo-great groups, and soils in the xerous and ultraxerous regions are in Anhy-great groups because of the anhydrous soilmoisture regime. Soils of the MDVs are further differentiated at the subgroup level based on the amount and type of salts and other diagnostic features.

## 3. Methods

Approximately 550 soil pits were excavated on key geomorphic surfaces to a depth of at least 100 cm, unless bedrock, ice-cement, or large boulders prevented digging to that depth. Soil horizons were distinguished using standard soil horizon nomenclature (Soil Survey Staff, 1999). The identification of cryoturbation (Bockheim and Tarnocai, 1998) and salt stage (Bockheim, 1990) were critical for taxonomic purposes.

Samples were collected from each horizon and taken to the USA or NZ for characterization. Morphological and analytical data were put into spreadsheets and forwarded to the USA National Snow and Ice Data Center (NSIDC) for archiving (http://nsidc.org/data/ggd221.html). The analytical data file contains chemical and physical properties for 46% of the soils. We did not investigate soils in the Victoria Valley system. However, we predicted soil subgroups from the glacial history of the system (Calkin, 1971), which has been correlated with the glacial sequences in Wright Valley (Kelly et al., 2002) and from data collected by I.B. Campbell and G.G.C. Claridge (http://www.landcareresearch.co.nz/databases). Similarly, soils data from I.B. Campbell and G.G.C. Claridge were used to map soils in the Convoy Range, the Mt Discovery area, and Ross Island.

Soils were classified according to *Soil Taxonomy* (Soil Survey Staff, 2006).

Soil maps were prepared for major ice-free areas using glacial geomorphology maps as base maps, including the Convoy Range (Sugden and Denton, 2004), the Victoria Valley system (Calkin, 1971), the Denton Hills (Sugden et al., 1999), Taylor Valley (Bockheim et al., in review), Wright Valley (Prentice et al., 1993; Hall and Denton, 2005), and the Quartermain Mountains (Marchant et al., 1993a, 2002; Sugden et al., 1995). We were unable to find published glacial geomorphology maps of the Mount Discovery region. Data from the regional soil maps were transferred to a 1:2 million-scale base map of the MDVs generated from digitized 1:250,000 USGS topographic maps stitched to form a mosaic in a geographic information system (GIS) for preparing a soil map of the entire region. The areal distribution of each soil taxon by region was determined through the use of a GIS.

To assist in classification of soils at the subgroup level, 1:5 soil:distilled water extracts were prepared and major cations (Na, Mg, Ca, and K) and anions (Cl,  $SO_4$ , and  $NO_3$ ) were measured (Soil Survey Staff, 1996). Cations were detected using flame photometry (Na, K) and atomic absorption spectrometry (Ca, Mg). Sulfate was measured turbidimetrically, Cl potentiometrically (chloridometer) and  $NO_3$  from either cation-anion balance or on an autoanalyzer. The dominance of particular salts was confirmed by X-ray diffraction of salt patches and pans (Bockheim, 1990).

# 4. Results

## 4.1. Mount discovery

Except at the higher elevations, soils in the Mount Discovery area are derived primarily from Ross Sea drift of late Quaternary age. The dark volcanic surfaces result in considerable melting and rejuvenation of ice-cemented permafrost. Therefore, Typic Haploturbels are dominant (90%) in the Mount Discovery area, followed by Glacic Haploturbels (10%) (Fig. 3; Table 1).

# 4.2. Denton Hills

Soils of valleys in the eastern foothills of the Royal Society Range are primarily Typic Haploturbels (95% of area) developed on Ross Sea drift (Fig. 3; Table 1). Ground ice is present throughout the region, particularly near Walcott Bay and the Koettlitz Glacier, and is accompanied by Glacic Haploturbels. A small patch ( $\sim 11 \text{ km}^2$ ) of pre-Ross Sea drift in upper Miers Valley contains dry-frozen permafrost with soils classified as Typic Haplorthels.

#### 4.3. Convoy Range

Based on limited data, we propose that Typic Anhyturbels comprise approximately 85% of the soils in the Convoy Range (Fig. 3; Table 1). Several areas in the Coombs Hills and Convoy Range have dry-frozen permafrost in the upper 100 cm and Typic Anhyorthels predominate. Lithic Anhyturbels occupy



Fig. 1. The McMurdo Dry Valley region with place names (base map United States Geological Survey, 1:1 million topographic map of McMurdo Sound area).



Fig. 2. Key for classifying Gelisols in the McMurdo Dry Valleys.

ice-free areas on nunataks in the region. To our knowledge, saltenriched soils have not been identified in the Convoy Range. Areas along the coast to the east of the Convoy Range contain Typic Haploturbels.

#### 4.4. Victoria Valley system

In the Victoria Valley system, Glacic Anhyturbels (~1% of total area) occur on ice-cored Holocene-aged drift at the margin of the Victoria Lower Glacier, in Barwick Valley, and around Lake Vashka (Fig. 3; Table 1). Typic Anhyturbels (4%) are present on Packard and Vida drifts and their associated deposits of late to mid-Quaternary age adjacent to the Victoria Lower Glacier, Victoria Upper Glacier, and the Webb Glacier. Bull drift of mid- to early Quaternary age and the silt-enriched Insel drift of Pliocene age contain Typic Anhyorthels interspersed with Salic Anhyorthels (95% of total area).

# 4.5. Taylor Valley

According to a recent soil map of Taylor Valley (Bockheim and McLeod, 2006), Glacic Anhyturbels (0.7% of area) occur on Alpine I drift of Holocene age. However, this area cannot be depicted on the 1:2 million-scale soil map. Soils in eastern Taylor Valley contain ice-cemented permafrost in the upper 70 cm of the solum and are strongly cryoturbated (Typic Haploturbels) (35% of area; Fig. 3; Table 1). The ice-cement results from melting of snow in the eastern part of the valley and the comparatively young geomorphic surfaces such as the late-Quaternary-aged Ross Sea, and Alpine II drifts. Typic Anhyorthels (44% of area) occur on Taylor III drift further upvalley in areas of dry-frozen permafrost. Soils on Taylor III in upper Taylor Valley often have relict patterned ground and presumably once contained ice-cemented permafrost. Salic Anhorthels (2.7%) occur on Taylor IV drift of Pliocene age on Andrews Ridge (77°38'S, 162°50'E), above 1000 m along alpine glaciers on the north valley wall, and in Pearse Valley. Salic Anhyorthels also occur on Alpine III and IV drifts of Pliocene age near alpine glaciers on the south valley wall. Soils with salt-cemented horizons (Petrosalic Anyhyorthels) are of limited extent (0.6% of area) in Taylor Valley and are restricted to Taylor IV drift on the Rhone Platform (77°42'S, 162°20'E) and in Pearse Valley and on Alpine IV surfaces near the Sollas (77°42'S, 162°35'E) and Stocking (77°43'S, 161°50' E) Glaciers. Because of scale issues, the distribution of Salic and Petrosalic Anhyorthels cannot be shown on the 1:2 millionscale soil map of the MDVs.

#### 4.6. Wright Valley

In Wright Valley Glacic Haploturbels ( $\sim 1\%$ ) occur adjacent to Holocene-aged alpine glaciers, including the Wright Lower Glacier and alpine glaciers along the south valley wall (Fig. 3; Table 1). In addition, hummocky drift to the east of the Loop Moraine contains buried ice in places (Bockheim, 1979b). Typic Haploturbels comprise 12% of the area and occur in the floodplain of the Onyx River, on deposits of late Quaternary age, including the Brownworth, Loke, and hummocky drifts (H1), and on Trilogy drift, which is considered by Hall and Denton (2005) to be of mid-to early Quaternary age (Bockheim and McLeod, 2006). Typic Anhyorthels (80%) occur on deposits of mid-to late-Quaternary age, including hummocky (H2) and alpine II drifts. Salic Anhyorthels ( $\sim 3\%$ ) occur on Onyx and Wright drifts of likely early Quaternary age; and Petrosalic Anhyorthels ( $\sim 4\%$ ) exist on deposits of Pliocene age, including Valkyrie, alpine III and IV, and Loop drifts. Central Wright Valley may contain the largest occurrence of soils with saltpans in Antarctica. Soils on the oldest deposits, the



Fig. 3. Reconnaissance soil map (1:2 million scale) of the McMurdo Dry Valleys (base maps 1:250,000 topographic maps from U.S. Geological Survey).

Table 1 Distribution of soil subgroups in the McMurdo Dry Valleys

Location	Total	No. of soil pits	GAt	GHt	LAo	Lat	Area (km <sup>2</sup> ) LHt	Ps/PnAo	TAt	TAo	ТНо	THt
Mt. Discovery-Black Is.	996	0		95					7			894
Convoy Range-Coombs												
Hills,-Allan Nunatak	661	0				29	5		555	72		0
Denton Hills	753	19		8							3	742
Victoria Valley system	653	0	7.3						23	623		
Taylor Valley	630	152	0					4		418		208
Wright Valley	486	281		3.5						424		58
Quartermain Range	397	98	14.5					18.4	130	218		16
Ferrar Valley	348	0							168	76		104
Ross Island	209	0			32					130	15	32
Other	1559	0	0	0	0	73	197	0	62	893	0	334
Total	6692	550	21.8	106.5	32	102	202	22.4	945	2854	18	2388
	% of total	100	0.3	1.6	0.5	1.5	3.0	0.3	14.1	42.6	0.3	35.7

GAt = Glacic Anhyturbels, GHt = Glacic Haploturbels, LAo = Lithic Anhyorthels, LAt = Lithic Anhyturbels, LHt = Lithic.

Haploturbels, Ps/PnAo = Petrosalic/Petronitric Anhyorthels, TAt = Typic Anhyturbels, TAo = Typic Anhyorthels, THo = Typic.

Haplorthels, THt = Typic Haploturbels.

silt-rich Peleus drift (>3.9 Ma), are anomalously poorly developed and are classified as Salic or Typic Anhyorthels.

## 4.7. Quartermain Mountains

Small lateral valleys in upper Beacon Valley contain extensive ( $\sim 4\%$ ) ground ice and have Glacic Anhyturbels (Fig. 3; Table 1). Typic Anhyturbels (33%) are present on Taylor II drift adjacent to the Taylor Glacier in both valleys and on rock-glacier deposits from the Ferrar Névé in Beacon Valley. Soils on Taylor III and IV drifts in both valleys are predominantly Typic Anhyorthels (70%), but Gypsic and Petronitric Anhyorthels (5%) may occur locally, possibly as relict soils of older glacial deposits.

Arena Valley is unique in Antarctica in that despite being a small valley it contains drifts ranging from 113–117 ka (Taylor II, Bonney drift) to >11.3 Ma (Altar till) (Marchant et al., 1993a). Soil mapping is complicated by the fact that some advances of the Taylor Glacier left only boulder belts and relict soils are common in inter-moraine areas (Bockheim, 1982). The oldest drifts in the area, comprised of silt-enriched Quartermain, Brawhm, Arena, and Altar tills of Miocene age (Marchant et al., 1993a), are classified predominantly as Typic Anhyorthels.

# 5. Discussion

Typic Anhyorthels (40%) are the dominant soil in the MDVs, occupying xerous and ultraxerous regions in areas where dry-frozen permafrost is pervasive (Fig. 3). Typic Anhyorthels occur on geomorphic surfaces of mid-Quaternary age and also may exist on highly erosive silt-enriched soils of Pliocene and Miocene age.

Typic Haploturbels (38%) occupy soils in the subxerous zone containing ice-cemented permafrost within the upper 70 cm along the McMurdo Sound coast on surfaces primarily of late Quaternary age (Fig. 3). Typic Anhyturbels comprise 13% of the exposed soil area of the MDVs and occur primarily in ultraxerous regions along the Polar Plateau. The remaining 7%

ice-free area contains Lithic Haploturbels in coastal areas where bedrock is within 50 cm of the surface, Glacic Haploturbels in areas along the coast with ground ice, Lithic Anhyturbels, Lithic Anhyorthels, Petrosalic Anhyorthels on old surfaces in the central Wright Valley and Arena Valley, Glacic Anhyturbels, and Typic Haplorthels.

Soils of the MDVs 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 their position in *Soil Taxonomy* (Soil Survey Staff, 1999), whereby Glacic and Typic Haploturbels and Anhyturbels are found on the youngest (Holocene) surfaces, Typic Anhyorthels occur on surfaces of intermediate age (mid- to early-Quaternary), and Salic and Petrosalic Anhyorthels exist on geomorphic surfaces of early Quaternary and older ages. Petronitric Anhyorthels may be limited to Taylor IV surfaces in Arena Valley.

Soils on the oldest (Pliocene and Miocene-aged) surfaces derived from silt-rich drifts present an enigma to our model of soil evolution in the MDVs. The silt-rich drifts include the Insel drift in Victoria Valley system (Calkin, 1971), Peleus till in Wright Valley (Prentice et al., 1993), Asgard and Inland Forts tills in the Asgard Range (Marchant et al., 1993b), and the Arena and Altar tills in the Quartermain Mountains (Marchant et al., 1993a). These drifts are derived from sediments of the Beacon Supergroup that contain primarily quartz and low amounts of weatherable minerals. Moreover, these soils may have been subject to considerable deflation by wind erosion since deposition. Therefore, traditional soil properties used to identify weathering stages are not applicable for these materials.

## 6. Conclusions

Here we present a 1:2 million-scale subgroup map for the MDVs. Dominant soil subgroups include Typic Anhyorthels (40%), Typic Haploturbels (38%), and Typic Anhyturbels (13%). The soils represent an evolutionary sequence that

includes Glacic Haploturbels and Anhyturbels on late Holocene surfaces, Typic Haploturbels and Anhyturbels on late Quaternary surfaces, Typic Anhyorthels on late to mid-Quaternary surfaces, Salic Anhyorthels on mid-to early Quarternary surfaces, and Petrosalic/Petrogypsic/Petronitric Anhyorthels on Pliocene surfaces. Soils derived from silt-rich till of Miocene age are anomalously poorly developed, ca. Typic and Salic Anhyorthels.

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