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Soils of western Wright Valley, Antarctica

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Abstract: Western Wright Valley, from Wright Upper Glacier to the western end of the Dais, can be divided into three broad geomorphic regions: the elevated Labyrinth, the narrow Dais which is connected to the Labyrinth, and the North and South forks which are bifurcated by the Dais. Soil associations of Typic Haplorthels/Haploturbels with ice-cemented permafrost at < 70 cm are most common in each of these geomorphic regions. Amongst the Haplo Great Groups are patches of Salic and Typic Anhyorthels with ice-cemented permafrost at > 70 cm. They are developed *in situ* in strongly weathered drift with very low surface boulder frequency and occur on the upper erosion surface of the Labyrinth and on the Dais. Typic Anhyorthels also occur at lower elevation on sinuous and patchy Wright Upper III drift within the forks. Salic Aquorthels exist only in the South Fork marginal to Don Juan Pond, whereas Salic Haplorthels occur in low areas of both South and North forks where any water table is > 50 cm. Most soils within the study area have an alkaline pH dominated by Na^+ and Cl^- ions. The low salt accumulation within Haplorthels/Haploturbels may be due to limited depth of soil development and possibly leaching.

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Introduction

Western Wright Valley, excluding the Labyrinth, has received scant attention from researchers in soils, geology or geomorphology except for a broad-scale geology map by Isaac *et al*. (1996), and reconnaissance-scale maps of glacial drift by Calkin *et al*. (1970), and Calkin & Bull (1972). Because of its challenging interpretation of mode of formation and visually striking appearance, the Labyrinth has received more scientific attention, e.g. Smith (1965), Cotton (1966), Selby & Wilson (1971), Shaw & Healy (1977). More recently, acquisition of high-resolution LIDAR imagery enabled Lewis *et al*. (2006) to detail flow volumes of subglacial floodwaters which would have been necessary to carve the Labyrinth. With respect to the western Wright Valley including the Labyrinth, Calkin *et al*. (1970) provided a brief description of four Wright Upper glacial advances and an uncontrolled map of their approximate distribution. They provide useful insight into the general maximum extent of at least the youngest three Wright Upper drifts but did not provide a detailed description of the nature of the drift units and their distribution. Within Western Wright Valley a detailed description of soils, their spatial distribution and chemical properties has not previously been undertaken. The desire for an environmental classification within a spatial framework (Waterhouse 2001) and the development of Environmental Domains for Antarctica (Morgan *et al*. unpublished) have led to the demand for more detailed soil maps. Eventually, a soil map of Wright Valley will form a spatial framework that will help regionalization of soil interpretations such as vulnerability to human traffic potential, biological "hotspots", and nature of the permafrost.

The objectives of this study are to map the soils in western Wright Valley, including the Labyrinth, Dais, North and South forks (Fig. 1), and describe their chemical attributes.

Study area

Western Wright Valley (Fig. 1), lying east–west and part of the ice-free McMurdo Dry Valleys, was carved in the middle Miocene by a westward flowing outlet glacier from the East Antarctic Ice Sheet (EAIS) into Precambrian metasedimentary basement containing Lower Palaeozoic acid plutonic and Jurassic Ferrar dolerite intrusions. Since then, the EAIS has been relatively stable (Denton *et al*. 1993, Marchant & Denton 1996), with at least four eastward glacial advances (Calkin *et al*. (1970). Whereas Calkin *et al*. (1970) identified four eastward Wright Upper glaciations (WU IV, III, II, I) and four westward Wright Lower glaciations (WL IV, III, II, I), Prentice *et al*. (1993) showed WU IV and WL IV to be the same eastward flowing, wet-based Peleus till. Prentice *et al*. (1993) hypothesized an *in situ* deposit of the Hart Ash (age 3.9 Ma) in central Wright Valley could not have survived intact the wet-based Peleus till event, thus the age of the Peleus till is constrained to > 3.9 Ma. In contrast, Hall *et al*. (1993) made a "probable" correlation of the Peleus till with the Asgard till, which constrained the age of the

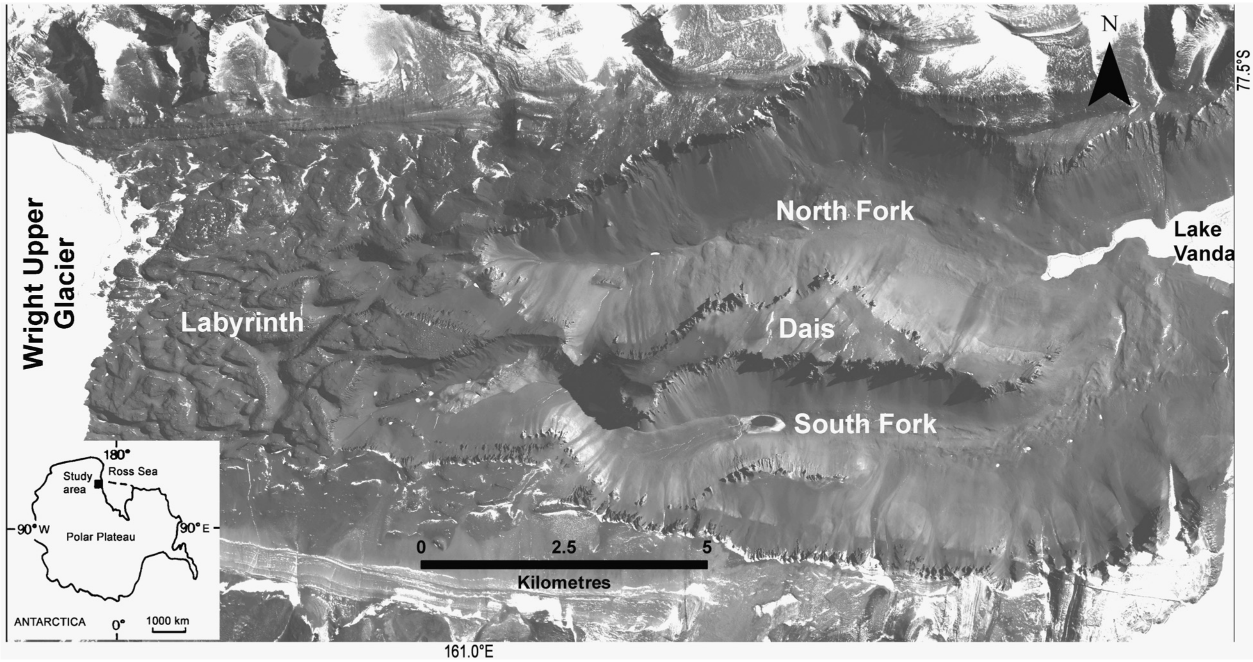

Fig. 1. Location and dominant geomorphic features of the western Wright Valley, Antarctica.

Peleus till to > 13.6 Ma. Hall *et al*. (1997) later revised the minimum age of the Peleus till to 5.5 Ma based on revision of stratigraphy at Prospect Mesa in central Wright Valley. Within Wright Valley the study area (110 km^2) extends from Wright Upper Glacier approximately 16 km eastward to the eastern end of the Dais, a central plateau that splits the North and South forks.

The study site can be divided into three broad geomorphic features (Fig. 1).

1. The Labyrinth lies immediately to the east of Wright Upper Glacier and comprises an orthogonal network of discontinuous channels up to 100 m deep carved into a planar surface of Ferrar Dolerite (Isaac *et al*. 1996). Catastrophic flood events, with flow rates of 1.6–2.2 × 10^6 m^3 s^{-1} resulting from failure of the ice dam constraining sub glacial lakes on the Polar Plateau (Lewis *et al*. 2006), have also shaped the landscape of the Labyrinth in westernmost Wright Valley. Lewis *et al*. (2006) distinguished three distinct erosional surfaces within the Labyrinth - Upper (ES1), Intermediate (ES2) and Lower (ES3), each occupying a specific elevation range around 1250, 950 and 850 m a.s.l., respectively.
2. Bockheim & McLeod (2008) describe the Dais as having two platforms tipping eastward, including a platform at an elevation of 800 m a.s.l. composed of frost-riven boulders of Ferrar Dolerite and a lower platform to the east at an elevation of 700 m a.s.l. that is carved into Beacon Sandstone. Isaac *et al*. (1996) mapped three areas of Asgard Till on the Dais.
3. Both North and South forks are steep sided with narrow floors containing rock glaciers, glacial drift, and areas of saline soils. The two forks have a similar longitudinal profile (Bockheim & McLeod 2008). Lake Vanda previously extended slightly into the mouth of the North Fork (Yoshida *et al*. 1975) where strandlines can be observed in the field and on LIDAR imagery.

Climate

Precipitation is relatively low as a result of the effects of adiabatically warmed, highly turbulent easterly winds (relative humidity 1–10%, Bromley 1985), which flow down-valley off the Polar Plateau (Keys 1980). Meteorological observations at the former Lake Vanda Station (1969–1970), approximately 7 km to the east of the study area, show mean annual air temperature to be -20°C (Thompson *et al*. 1971a) and an accumulated depth of snow of 8.2 cm and 0.7 cm for 1969 and 1970, respectively. Mean annual soil temperature at 46 cm depth was approximately -20°C (Thompson *et al*. 1971b) and those at Bull Pass, another 4 km further east, to be approximately -20°C at 42 cm depth (http://soils.usda.gov/survey/scan/antarctica/BullPass). Overall, the study area lies within climatic Zone 2 of Marchant & Denton (1996) where, because of the cold dry katabatic winds, meltwater is rare and significant soil moisture precluded. During our 2007 field season in the South Fork we observed meltwater flowing in polygon fissures, and other evidence of freeze-thaw activity in patterned ground, attributable to free soil water and which may reflect an unusually warm season.

Methods

Stereo pair aerial photographs of the Wright Valley were examined with preliminary soil boundaries plotted onto a GIS-based geo-referenced satellite image (http://usarc.usgs.gov/ant-ogc-viewer/declasdownload.htm) and a hill shade image built from a 2 m post-processed resolution LIDAR file (http://usarc.usgs.gov/ant-ogc-viewer/lidardownload.htm).

During the 2006/07 summer, fieldwork was undertaken to validate the preliminary boundaries and determine the nature of soils, permafrost and surface geology. Approximately 120 small soil pits were excavated, described and classified following USDA Soil Taxonomy and located by GPS. The soil pits were then backfilled. Sampling and observation pits located in drift units were mainly sited to reveal maximum soil development of the unit. Colour-development equivalents (CDE) were calculated from classed soil colour hue multiplied by chroma (Buntley & Westin 1965). Weathering stage follows Campbell & Claridge (1975), while salt stage follows Bockheim (1990). At 46 locations larger pits were dug to at least 70 cm (unless ice-cemented permafrost or boulders were encountered) and sampled by horizon. Both < 2 and > 2 mm fractions were weighed, and the < 2 mm fraction was retained for analysis in New Zealand when appropriate. A summary of general soil profile features for a selection of typical soils is given in Table I.

A 1:5 soil/water extract of subsamples was analysed for pH, EC, water soluble cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) and anions (Cl^{-}, nitrate-N^{-}, SO$_4^{2-}$) using flame atomic absorption/emission spectrophotometry with an air-acetylene flame and ion chromatography for anions following methods at http://www.landcareresearch.co.nz/services/laboratories/eclab/eclabtest_list.asp#water. Total soluble salts to 70 cm depth (TSS$_{70}$) were calculated over an area of 1 cm^2 using a factor of 640 to derive salt concentration from electrical conductivity and using a soil bulk density of 1.5 g cm^{-3} (Bockheim 1979).

Using ArcGIS 9.2© software, final soil polygon boundaries were plotted onto the 5 December 2006 ALOS PRISM image ALPSMN046065215 (2.5 m resolution) with sun elevation and azimuth of 28° and 56° respectively. To convert the ALOS PRISM image into GIS-useable form the image was processed through the Alaska satellite facility Convert tool (http://www.asf.alaska.edu).

The Pedodiversity Index (Bockheim 2007) has been calculated by dividing the area of the relevant geomorphic feature (km^2) by the number of USDA Soil Taxonomy subgroups that occur in the area.

Results

Soil classification

Soils were mapped using USDA Soil Taxonomy at Subgroup level to differentiate soil polygons (Fig. 2). All soils within

Table I. Properties of selected soils in western Wright Valley, Antarctica.

Profile	Location	Landform	Patterned ground	Weathering stage	Salt stage	Depth of visible salts (cm)	Depth of staining (cm)	Depth of coherence (cm)	Depth of rock ghosts (cm)	Max. CDE	Classification and notes
WV07-22	Labyrinth	Ground moraine	Fossil sand wedges in profile	5	2	24	> 80	> 80	8	30	Typic Anhyturbel
WV07-46	Dais	Flat surface sloping 5° south	None	6	3	45	> 60	> 60	22	24	Salic Anhyorthel
WV07-04	Don Juan pond	Pond margin	None	3.5	4	2	0	0	0	18	Salic Aquorthel Water table 32 cm
WV07-11	South fork	Wright Upper III moraine	None	47	1	47	0	20	16	9	Typic Anhyorthel
WP321	South fork	Small lake basin	None	3	3	20	34	> 71	0	12	Salic Anhyorthel
WV07-12	South fork	Colluvial fan	Strongly developed	2	1	1	22	22	0	18	Typic Haploturbel
WP203	North fork	Bedrock dyke	None	5	1	26	37	> 70	0	4	Typic Anhyorthel
WV07-33	North fork	Valley floor	None	3.8	2	46	> 100	> 100	0	24	Typic Anhyturbel Fossil sand wedges in profile
WV07-30	North fork	Valley floor	Moderately developed	2	1	1	37	37	24	9	Typic Haploturbel

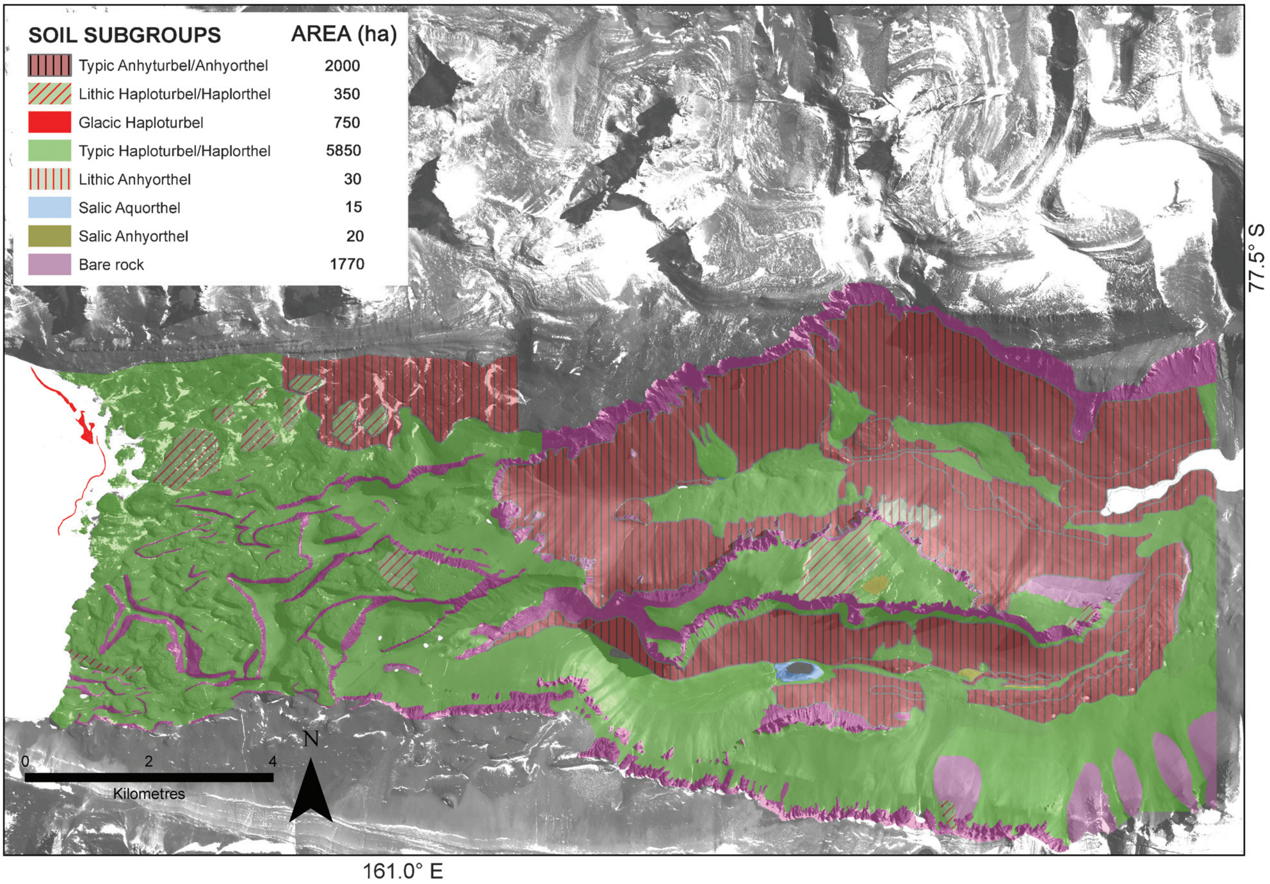

Fig. 2. Soil subgroup distribution within western Wright Valley, Antarctica.

the study site have permafrost within 100 cm of the soil surface, i.e. soil materials remain below 0°C for two or more years in succession, and therefore are classified under the Gelisol order.

Soil associations of Orthels and Turbels were commonly mapped in areas of active patterned ground, reflecting both the cryoturbation associated with the polygon fissure and the non-cryoturbated central part of the polygon. The association was also mapped where relict sand wedges were observed in soil pits.

Anhydrous conditions relate to soil moisture status rather than climatic regime so Haplorthels were commonly mapped within the study area as ice-cemented permafrost (ICP) commonly occurring at a depth of less than 70 cm. Anhyorthels were restricted to soils on older surfaces or colluvial deposits where, in both cases, there was little soil water recharge and depth to ICP > 70 cm. Maximum CDE ranged from 8 in colluvium on the south wall of the South Fork to 30 on old drift in the Labyrinth and Wright Upper III moraine.

Descriptions and photographs of a representative range of soils are lodged online at http://myscenz-grid.org/packs/10.

Soil chemical properties

In the large majority of soils sampled the profile was dominated by sodium cations and chloride anions (Table II). Total soluble salts to 70 cm (TSS$_{70}$) ranged from < 10 mg cm^{-2} in young soils in the Labyrinth near the Upper Wright Glacier and in colluvium in the South Fork to *c.* 2500 mg cm^{-2} in old drift on the Dais. Saline soils in the vicinity of Don Juan Pond had TSS$_{70}$ in the range of 3380–4000 mg cm^{-2}. A soil developed in old drift in the Labyrinth had moderately acid pH, while younger soils in the Labyrinth generally have slightly higher pH being slightly acid to moderately alkaline. Sampled soils from the rest of the study area generally had near neutral to extremely alkaline pH.

The pH value of 1:5 soil:water extracts from the surface horizon ranged between 5.9 and 9.6 with the low value being on an old, highly weathered (weathering stage = 5) drift in the Labyrinth. The lowest subsoil pH in the study area also occurred in this soil. In contrast, on a highly weathered surface (weathering stage = 6) on the Dais total salt concentration of the extracts was higher, as was pH (8.2–8.4) while the concentration of sulphate ions was lower. Considering Anhyorthels within the study area,

Table II. Chemical properties of selected soils in western Wright Valley, Antarctica.

Site	Horizon designation	Depth (cm)	pH (water)	EC (1:5) (mS cm^{-1})	Total soluble salts to 70 cm (mg cm^{-2})	Calcium mg kg^{-1}	Magnesium mg kg^{-1}	Sodium mg kg^{-1}	Water soluble Potassium mg kg^{-1}	Chloride mg kg^{-1}	Nitrate-N mg kg^{-1}	Sulphate mg kg^{-1}
WV07-17	D	0–1	6.68	0.00	11	2.3	1.7	11.2	25.7	36.6	1.3	11.0
Labyrinth	Cox	1–10	6.23	0.04		2.0	1.3	8.7	41.5	57.6	0.7	16.4
	Cn	10–26	6.07	0.03		1.0	1.7	5.8	42.8	58.1	0.8	15.8
WV07-18	D	0–1	7.67	0.18	6	9.8	4.9	153	23.2	72.2	6.3	106
Labyrinth	Cn	1–9	7.45	0.05		1.8	1.0	35.3	31.2	44.1	1.4	13.5
	2Cox	9–38	8.58	0.01		12.6	7.9	17.8	15.6	68.1	0	13.0
WV07-19	D	0–1	6.42	1.19	36	235	180	241	33.9	375	102	160
Labyrinth	Coxjj	1–15	6.61	0.26		3.5	9.5	176	35.8	176	25.1	155
	Cn	15–20	6.77	0.05		0.8	2.5	24.6	46.5	68.7	1.3	20.6
WV07-20	D	0–1	5.89	5.28	343	2120	501	3170	61.6	645	214	11400
Labyrinth	Cox	1–17	5.98	0.96		558	124	298	46.6	173	38.3	2100
WV07-21	D	0–1	6.56	0.04	9	2.3	1.0	29.0	29.7	36.1	1.3	35.7
Labyrinth	Cox	1–13	6.73	0.03		2.3	1.0	14.9	47.7	57.2	1.3	12.4
WV07-22	D	0–1	5.87	1.98	940	160	347	441	36.9	1360	246	38.4
Labyrinth	Bwjj1	1–7	5.85	4.52		1890	647	1270	34.7	1570	377	6060
	Bwz	7–17	5.81	3.92		2010	638	1220	42.6	1060	324	8500
	Bwjj2	17–30	5.41	1.86		545	175	458	37.8	588	339	1320
	Bwjj3	30–53	5.64	2.17		375	288	604	30.5	813	181	1900
	Bw	53–80	5.75	3.14		504	274	962	38.1	945	186	4750
WV07-23	D	0–1	9.24	0.15	8	7.2	4.0	124	15.5	101	11.7	138
Labyrinth	Cox1	1–10	8.82	0.03		0	1.1	16.0	3.3	30.6	3.4	34.5
	Cox2	10–22	8.76	0.02		10.8	8.6	38.3	10.5	54.4	0	49
	Coxfm	22+	8.73	0.02		4.9	5.7	28.9	9.6	43.3	1.9	29.8
WV07-24	D	0–1	8.18	0.04	3	2.7	4.6	31.1	11.1	42.5	2.4	50.4
Labyrinth	Bw	1–9	8.15	0.02		1.1	2.4	15.5	11.6	28.8	1.3	16.5
	Cox	9–20	8.25	0.01		1.0	2.1	10.7	14.4	32.2	0	12.1
	Coxfm	20+	8.15	0.01		2.5	3.5	15.5	30.3	72.5	0	25
WV07-27	D	0–1	7.95	0.03	4	9.1	4.5	13.3	7.4	15.2	0.7	58.4
Labyrinth	Cn	1–25	8.31	0.01		1.8	1.1	12.4	17.4	28.8	0.7	13.9
	Cnfm	25+	8.12	0.01		2.1	1.0	14	14.1	47.1	0.7	27.2
WV07-28	D	0–1	8.67	0.08	6	10.7	10.9	47.2	25.3	72.2	6.6	50.5
Labyrinth	Bw	1–8	9.03	0.04		3.7	1.6	37.1	15.2	54.1	2.5	49.5
	Cn	8–16	7.62	0.01		0.2	0.9	12.9	32.9	52.1	0.9	14.3
	Cnfm	16+	7.88	0.01		3.4	1.8	11.6	35.8	53.5	0.6	12.6
WV07-29	D	0–1	9.26	0.03	5	1.0	0.7	34.1	18	37.1	0.9	21.4
Labyrinth	Cn1	1–8	8.57	0.02		7.0	1.1	28.3	35.3	78.3	1.2	27.5
	Cn2	8–29	7.97	0.01		2.3	8.9	14.7	23.5	56.0	1.1	23.7
	Cnfm	29+	8.44	0.02		5.3	2.1	20.2	10.9	28.3	1.8	17.9

Table II. Continued

Site	Horizon designation	Depth (cm)	pH (water)	EC (1:5) (mS cm^{-1})	Total soluble salts to 70 cm (mg cm^{-2})	Calcium mg kg^{-1}	Magnesium mg kg^{-1}	Sodium mg kg^{-1}	Water soluble Potassium mg kg^{-1}	Chloride mg kg^{-1}	Nitrate-N mg kg^{-1}	Sulphate mg kg^{-1}
WV07-45	D	0–1	8.52	7.88	900	2720	129	2930	38.3	3800	923	1790
Dais	Bwz	1–11	8.21	8.84		1920	283	2220	39.1	2540	483	2090
	Bw	11–28	8.50	2.52		814	32.5	374	11.7	483	76.7	933
	Cox	28–68	9.55	1.14		8.9	3.0	403	8.6	1070	150	66.8
WV07-46	D	0–1	8.36	3.01	2560	1380	74.2	750	34.8	2820	219	842
Dais	Bw1	1–9	8.16	5.87		1090	117	970	39.9	4460	281	2370
	Bwz	9–28	8.27	11.1		1120	129	2860	62.1	10000	325	2170
	Bw2	28–56	8.41	6.52		704	136	2360	58.8	9970	310	1010
WV07-1	D	0–1	8.02	0.01	7	3.7	2.1	9.8	14.1	30.6	0.8	15.6
South Fork	Cox	1–22	8.17	0.01		3.5	4.1	9.0	8.4	19.4	0	12.1
	Cfm	22+	7.90	0.03		7.6	4.8	16.2	20.1	66	0	15.3
WV07-4	Dz	0–2	7.57	53.6	3380	13400	187	23200	93.4	113000	153	2080
South Fork	Cnz1	2–15	7.82	8.11		2210	33	478	15.3	8790	5.3	260
	Cnz2	15–32	7.56	8.93		2840	44.7	493	21.3	11600	5.7	41.3
WV07-5	D	0–4	7.87	39.3	4000	2840	44.7	493	21.3	11600	5.7	41.3
South Fork	Coxz	4–26	7.85	8.10		2410	28.2	1130	14.8	7930	3.8	1100
	Cn1	26–40	7.69	6.39		2100	25.1	262	9.1	4330	3.6	746
	Cn2	40–60	7.41	13.6		3770	57.6	626	19.5	13600	0	166
WV07-6	D	0–0.5	9.23	0.34	360	81.8	6.5	168	28.2	558	7.2	129
South Fork	Bw1	0.5–7	8.73	1.45		176	32.7	396	13.2	2430	31.4	508
	Bw2	7–33	8.37	1.77		404	63.1	452	19.0	2560	54.0	979
		33–50	8.84	0.51	227		10.8	95.5	11.7	640	10.8	173
WV07-7	D	0–0.5	8.57	0.80	5	191	27.8	127	17.7	1180	7.5	133
South Fork	Coxjj	0.5–16	9.00	0.01		3.8	15.4	15.6	18.3	20.1	0	10
	Cn	16–31	8.37	0.01		5.1	25.4	12.0	24.0	17.1	0	12.7
WV07-11	D	0–1	9.09	0.37	1690	192	7.6	75.1	13.9	183	10.3	217
South Fork	Bw	1–20	8.40	14.7		1050	98	14200	45.5	23700	112	2360
	Cn1	20–47	8.78	1.94		344	27.1	491	26.7	2360	83.5	195
	Cn2	47–81	9.02	0.83		111	16.1	324	36.1	1080	55.5	68.4
WV07-12	D	0–1	8.93	0.10	10	6.4	2.1	72.9	7.1	72.7	2.5	108
South Fork	Bw	1–15	8.92	0.06		9.0	5.4	50.9	12.4	48.2	1.2	72.0
	Cox	15–22	8.43	0.01		5.1	10.3	13.5	20.3	25.1	0.6	11.1
	Coxfm	22–30+	8.71	0.02		27.5	7.3	18.3	11.5	32.3	1.8	23.9
WV07-13	D	0–1	9.41	0.30	16	37.9	9.7	178	9.7	175	15.8	289
South Fork	Bwjj1	1–14	9.37	0.18		19.8	13.4	114	35.8	183	8.2	169
	Bwjj2	14–22	9.08	0.02		9.6	8.0	31.1	18.8	34.9	0.6	24.0
	Cn	22–33	8.45	0.01		4.6	2.9	13.4	9.2	16.3	0	11.5
			8.66	0.02		5.4	5.6	21.5	18.4	25.1	0.7	16.5

Table II. Continued

Site	Horizon designation	Depth (cm)	pH (water)	EC (1:5) (mS cm^{-1})	Total soluble salts to 70 cm (mg cm^{-2})	Calcium mg kg^{-1}	Magnesium mg kg^{-1}	Sodium mg kg^{-1}	Water soluble Potassium mg kg^{-1}	Chloride mg kg^{-1}	Nitrate-N mg kg^{-1}	Sulphate mg kg^{-1}
WV07-30	D	0–1	6.26	0.07	80	2.6	0.5	16.9	52.8	78.3	1.9	43.4
North Fork	Cn	1–11	7.34	0.16		17.4	2.8	67.9	58.2	107	2.7	126
	2Bw	11–37	7.42	0.39		151	30.5	68.2	65.7	423	34.2	43.3
	2Cox	37–48	6.34	0.15		17.9	6.3	34.9	81.3	203	5.2	47.1
WV07-33	D	0–1	6.96	0.44	1800	58.5	26.9	244	36.7	404	40.4	168
North Fork	Bw	1–10	6.70	6.82		3380	707	2560	90.3	5300	665	7490
	Bwz	10–46	6.05	12.0		282	476	9600	105	16800	881	2360
	Cox	46–100	6.12	5.06		245	323	3840	111	5660	747	223

which are less likely to have leaching from soil water recharge, low pH values do not appear to be related to salt content as demonstrated for the Britannia/Darwin ranges (Bockheim & Wilson 1989) where salts were attributed to depressing the H-ion activity of the extracts. The low pH may be related to the acid-forming potential of the sulphate ions rather than total salt content. In this study low pH was often associated with higher SO_4^{2-}.

While there was an overall trend for more highly weathered (older) soils to contain more salts calculated to a depth of 70 cm, the relationship was not clear and may depend on physiographic position to some extent controlling atmospheric deposition. All Anhyorthels had TSS $70 > 400$ mg cm^{-2}.

Discussion

Soils of the Wright Upper glacier margin and Labyrinth

We interpret the narrow sinuous zone of drift within the eastern margins of the Wright Upper Glacier to be WU I (Calkin *et al*. 1970, Calkin & Bull 1972). Soils on WU I drift are comparable to those adjacent to the Wright Lower Glacier in eastern Wright Valley (http://nsidc.org/data/ggd221.html). Because they have cryoturbation and contain ground ice within 100 cm of the soil surface, they are classified as Glacic Haploturbels.

Calkin *et al*. (1970) described the WU II advance to extend westward about 2.5 km from Wright Upper Glacier. Within this zone in the base of the Labyrinth, where ice-cemented permafrost (ICP) commonly occurs at < 50 cm depth, we described Typic Haplorthels and Haploturbels developed on drift between steep walls of dolerite. Cryoturbated soils (Haploturbels) occur on the polygon margins and fissures, while soils without obvious cryoturbation are restricted to central portions of polygons. The steep walls or bluffs have little soil development and are mapped as Bare Rock. Aerial, satellite and LIDAR hill shade images all show more dissection of this area of the Labyrinth which lies within ES3 of Lewis *et al*. (2006). From our reconnaissance, on interfluves we mapped Typic and Lithic Haplorthels rather than Anhyorthels (which have ICP deeper than 70 cm) as: i) interfluve soil at WV07-20 is developed in a residual surface of thin aeolian material over dolerite with ICP at 29 cm and was classified as a Typic or Lithic Haplorthel, ii) the presence of snow patches in aerial and satellite images suggests recharge of soil moisture which in turn maintains ICP at less than 70 cm, and iii) Bockheim *et al*. (1990) postulated that dark doleritic surfaces promoted melting of snow rather than ablation with consequent downward movement of salts. We suggest the downward movement of salts is accompanied by water which is available to recharge the ice table.

In the north-east of the Labyrinth, on a higher surface (ES1 of Lewis *et al*. 2006) we show Typic Anhyturbels

(WV07-22) on drift with weathering stage 5, salt stage 2 and maximum CDE of 30. Depth of oxidation, coherence and depth to ICP exceeded 80 cm. There were fossil sand wedges in the soil. All of these soil factors, except for the low salt stage, suggest an old soil, with Bockheim & McLeod (2008) suggesting the parent material may be Asgard Till (Bockheim & Ackert 2007). Marchant *et al.* (1993) tentatively correlate Asgard and Peleus tills with a minimum age, constrained by $^{40}Ar/^{39}Ar$ analyses of tephra, of 13.6 Ma. In this old soil the relative lack of salts compared with younger soils to the east is enigmatic. The low salt concentration (Table II) may be a result of low input from the dominant easterly katabatic winds off the polar plateau, occasional leaching from snowmelt or wind erosion of the profile (Bockheim & Ackert 2007). The description of WV07-22, taken where patterned ground was absent but with fossil sand wedges observed in the profile, is given in http://myscenz-grid.org/packs/10.

Based on the apparent angularity of surface boulders in stereo-pair air photographs, elevated surfaces in this region, approximately 40–50 m higher than surrounding channels, are mapped as Lithic and Typic Haploturbels. Lithic subgroups contain coherent material within 50 cm of the soil surface.

In the north-west of the Labyrinth, in lower parts of the landscape, we describe Typic Haplorthels/Haploturbels with weathering stage 3, salt stage 1 and maximum CDE of 16–24. Depth to ICP was approximately 20 cm. Parent material was till and, based on weathering stage, judged to be WU II (Calkin *et al.* 1970, Calkin & Bull 1972). For a soil with ICP of about 20 cm the CDE is anomalously high, as ICP at shallow depth generally restricts soil development (Bockheim 1979). In this area the elevated CDE can probably be attributed to the reddish hue of the doleritic parent rock.

Soils sampled in the Labyrinth generally had very low TSS_{70}, at less than around 12 mg cm^{-2} except for two profiles, WV07-22 and WV07-20. Low TSS_{70} is consistent with the sample locations on relatively young surfaces with shallow depth to ICP. While WV07-20 has $TSS_{70} >$ 12 mg cm^{-2}, it probably reflects extrapolation of salt content in the upper part of the ICP to a depth of 70 cm without decreasing concentration with depth.

Soils of the Dais

Soils on the western end of the Dais below a prominent dolerite peak are Typic Haplorthels developed in bouldery doleritic colluvium with ICP at approximately 10 cm. While much of the Dais is mapped as having Typic Haplorthel/Haploturbel soils because of the shallow depth to ICP, the provenance of the soils is more variable. Slightly to the east are patches of weathering stage 3 doleritic patterned-ground till containing sub-rounded cobbles and ICP at 35 cm. Salts are limited to coatings on the underside of stones. In places, the effect of cryoturbation can be seen from large upstanding boulders but there is no visible surface polygonation.

Profiles WV07-45 (Table II) and WV07-46 (Tables I & II) from central Dais developed in drift with weathering stage 6. In the field the soil map units were immediately distinguishable because of their well-developed desert pavement with pitted, varnished dolerite and low surface boulder frequency. Depth to ICP was deep compared with other soils on the Dais, with maximum CDE of 24 at both sites, all suggesting an old surface of Pliocene or Miocene age. The soil material was clast supported rather than comprised of "silt-rich" material indicative of the pulverulent Peleus till. Interestingly, profile WV07-45 contained relict ice wedge casts, ICP at 68 cm and had TSS_{70} of 900 mg cm^{-2}, while in contrast depth to ICP in profile WV07-46 was > 70 cm and TSS_{70} were 2560 mg cm^{-2}. A horizon within the profile had sufficient electrical conductivity (EC) and thickness (15 cm) to qualify as a Salic Horizon, thus the pedon is classified as a Salic Anhyorthel. The profile description of WV07-46 is given in http://myscenz-grid.org/packs/10. Many soils on the eastern part of the Dais contain distinctive mixed pulverulent material indicative of Peleus till.

Soils of the South Fork

In the South Fork, west of Don Juan Pond, a rock glacier with a leading face 35 m high fills the base of the narrow valley. On the southern wall we observed many "mini-terracettes" nearly to the top of the observable wall which we interpreted as being the result of gelifluction processes and thus classified the soils as a Typic Haploturbels/Haplorthels association. Chemical analyses of soils developed in the dolerite-rich colluvium (WV 07-01) and rock glacier (WV 07-06, WV 07-07) are consistent with soils where soil development is restricted by ICP at 22–50 cm. They have low total salt contents with dominant water soluble cations and anions of sodium and chloride respectively. Although maximum CDE is ≥ 12, it probably reflects weathering of doleritic parent material rather than strong soil development. As we did not observe widespread gelifluction deposits on the north wall we judge ICP to be below 70 cm thus the soils are classified as Typic Anhyorthels.

Even though soils surrounding Don Juan Pond contain free water, they remain unfrozen to depth because of their high salt concentration (Isaac *et al.* 1996). There is sufficient salt to satisfy the requirements for a salic horizon, and as the soils are continuously saturated with concomitant reducing conditions (Nakaya *et al.* 1984) they are classified as Salic Aquorthels. Apart from the D horizon, which contains whitish evaporate deposits probably of antarcticite (Torii & Ossaka 1965), the soils are dominated by calcium and chloride ions. The D horizon is dominated by sodium ions. A typical soil adjacent to the water margin developed in lake sediments is given in http://myscenz-grid.org/packs/10 as WV07-04.

On the outer extent of the lake basin about 100 m from the salt playa the profile is similar but the soils do not have aquic conditions within 50 cm of the soil surface and are classed as Salic Haplorthels (not depicted on soil map). Chemically the soils are similar (Table II), with high EC in the surface where a salt crust is observed, and high TSS_{70}. Interestingly, TSS_{70} is not as high in these Salic soils as in some Salic soils to the east, which have visible salt accumulations within the soil (McLeod *et al*. 2008). At Don Juan Pond free water within the soil profile constrains the maximum salt content. Once again dominant water soluble cations and anions were calcium and chloride respectively, except in the D horizon where sodium was the dominant cation.

McLeod *et al*. (2008) discussed the nature of WU III moraine within the South Fork. Our observations during this study indicate similar soils (Typic Anhyorthels/Anhyturbels association) but with lower salt concentrations in the west. North of, and parallel to, WU III moraine and separated by a 100–200 m wide channel there is another sinuous deposit approximately 30–50 m wide and 10–20 m above the channel, which may be a northern lateral WU III moraine. We note the desert pavement at profile WV07-11 on this sinuous feature has a low boulder frequency, similar to WU III moraine. The full profile description of the soil with weathering stage 4 is given in http://myscenz-grid.org/packs/10 as WV07-11.

Based on soil morphology, lack of patterned ground, and chemical analyses (Table II), the soil is classified as a Typic Anhyorthel. The landscape position, lack of surface boulders, weathering stage 4 and TSS_{70} of 1690 mg kg^{-1} combine to suggest the soil is associated with WU III moraine (McLeod *et al*. 2008). In contrast, maximum CDE is 9, a low value generally occurring in soils near the coast or those subject to soil moisture recharge where ICP close to the soil surface has restricted soil development.

In the aforementioned channel, in small basins, there are patches of secondary deposited Peleus till on sand. These small basins may be former lakes with lacustrine redistribution of Peleus till. A brief soil description is given in http://myscenz-grid.org/packs/10 as WP321.

On the south side of the large WU III moraine, colluvium from the south wall of the South Fork has built up a large flattish sloping apron against WU III moraine. The patterned ground surface of this mixed dolerite and granite colluvium has well-developed, flat-centred 20 × 20 m polygons containing 20 cm deep troughs, recently reamed soil on the trough side and fallen stones in the troughs. In early January 2007 we observed running water in some polygon troughs. In other troughs, salt-cemented soil exposed on trough sides suggested recent fluvial activity. Indeed, Levy *et al*. (2008) suggest polygon troughs contribute to gully water transport. While Levy *et al*. (2008) investigated polygons close to gully systems, it probable that this channelized flow can extend for hundreds of metres, modulating spatial water distribution within the distal hyporheic zone (Levy *et al*. 2008). Soils in this map unit have weathering stage 2. A typical profile on a 3° slope is given in http://myscenz-grid.org/packs/10 as WV07-12.

The chemistry (Table II) of this Typic Haploturbel is typical with low TSS_{70} and alkaline pH. Water-soluble extracts are dominated by sodium and chloride cations and anions. Whereas soil development is restricted by the shallow depth to ICP, a maximum CDE of 24 is remarkably high for a soil with ICP at shallow depth. Most likely the CDE reflects a doleritic influence in the parent material rather that strong *in situ* weathering of the soil. The LIDAR image clearly shows the morphologic boundary between this unit of Haploturbels and the Anhyorthels of WU III moraine. The presence of Haploturbels adjacent to Anhyorthels demonstrates that in the USDA Soil Taxonomy Gelisol Order soil water regimes are correctly based on soil water rather than inferences from precipitation regime. Indeed, the importance of local scale environmental variability has been recognized by Cannone *et al*. (2008), who noted local climate, including water availability, had a greater influence on site conditions than regional climate. Cannone *et al*. (2008) confirmed this by the occurrence of biodiversity "hotspots" irrespective of latitudinal gradient.

Soils of the North Fork

The North Fork has some similarities with the South Fork, including i) a similar longitudinal profile (Bockheim & McLeod 2008), ii) Salic Haplorthels in dry ponds in the base of the valley, iii) observable gelifluction deposits at least two thirds of the way up the south wall (Typic Haplorthels/Haploturbels association), iv) WU III drift deposits on both sides of the valley (Typic Anhyorthels/Anhyturbels), and v) rock glaciers (Typic Haploturbels/Haplorthels). However, the arrangement of the geomorphological units is slightly different. The North Fork appears to have a block of glacially moulded resistant basement rock centrally located in the valley. The basement rock in places appears to be cut by resistant dykes, with Peleus till trapped in the lee of the dykes. A brief profile description of a soil developed in Peleus till is given in http://myscenz-grid.org/packs/10 as WP203.

Compared with the rock glacier that plugs the central valley of the South Fork, two prominent rock glaciers emanate from the north wall of the North Fork (Bockheim & McLeod 2008). Although WU III lateral moraine can be traced along parts of both walls it is not as prominent or dominant as in the South Fork. Associated with this moraine, in both forks, there are deposits of well oxidized sand with Bw horizon hue of 10YR or redder. While we are uncertain as to the mode of emplacement of this type of material, the sometimes sinuous or fan-like nature of some of the deposits may suggest deposition by water. During the

2007 summer, glacial side-streams carrying substantial sand and gravel load have been observed near Lake Wellman in the Darwin Mountains, thus a warmer climate than present would not have to be invoked to account for the features. However, further morphological mapping is required to present a realistic hypothesis. A typical profile is given in http://myscenz-grid.org/packs/10 as WV07-33.

At the eastern end of the North Fork soils are formed within the zone of a former extension of Lake Vanda. Desert pavement boulders and stones are flattened, presumably through former wave action and free water within the profile facilitating settling of the stones. Similar flattened boulder/stone desert pavements were seen in other low areas of the landscape that had, or had the potential to have, free water. Fine material within the lake-affected soil profile contained a highly vesicular porosity and fine laminations 3–10 mm thick. In addition, the upper part of the oxidized subsoil material was massive *in situ* and weakly cemented. These features are not common to drift deposits unaffected by the former lake.

A profile description of a soil developed in lake-affected material with moderately developed flat-centred polygons 15 × 15 m is given in http://myscenz-grid.org/packs/10 as WV07-30.

As Lake Vanda receded these soils would probably have contributed organic matter and organisms, associated with wind redistributed detritus, into Wright Valley (Hopkins *et al*. 2008). Currently, the desert pavement cover ($95\% > 2$ mm) would minimize uplift of organic-rich fines from below the desert pavement.

Relationship to soils to the east in Wright Valley

Surficial geology in the western Wright Valley is of a similar age range to that in more eastern parts of the valley. However, soils in the western Wright Valley differ from those in more eastern parts in that many are developed in doleritic parent material which can give them higher CDE for a similar weathering stage. Salts accumulate to high concentrations in low-lying moist areas as a result of seepage from higher ground e.g. Don Juan Pond. In contrast, strongly cemented salt pans (derived from primary aerosol deposition) similar to those which occur in central areas of the valley are generally absent and we attribute this to lack of aerosol deposition of salts rather than leaching from greater precipitation as is the case at the coastal, eastern end of Wright Valley. In common with the rest of the Wright Valley and other MDV soils the soils can be considered as cold desert soils.

Pedodiversity Index

Bockheim (2007) calculated the Pedodiversity Index (PDI) for individual valleys in the McMurdo Dry Valleys (MDV). The PDI was 0.19 for the small Arena Valley (68 km^2), while other regions of the McMurdo Dry Valleys had lower PDI of 0.05 to 0.026. For our small study area (110 km^2) we calculated a PDI of 0.08, which indicates a smaller range of soil subgroups than in the Arena Valley but a range similar to the MDVs. Calculating the PDI for the Dais alone (19 km^2) returned a very high PDI of 0.37. High PDIs are perhaps typical of areas containing old, strongly weathered soils as increasing age brings the opportunity for salt accumulation in snow-free areas and near-surface ICP where snowmelt recharges the ice table. Furthermore, steep frost-riven slopes give rise to Lithic soils on the Dais. However, caution must be exercised when quoting PDI for small areas as PDI will tend to decrease with increasing area as the number of soil subgroups is constrained, by USDA Soil Taxonomy, to less than 30 in the drier ice free areas.

Conclusion

A soil map of western Wright Valley reveals Typic Haplorthels/Haploturbels cover the largest area and have a range of soil morphologies. Separation within the subgroup based on a soil property would be useful. Maximum CDE can often be used as a discriminator but can be confused by parent material differences.

While soils developed in the study area are related to the geomorphic feature on which they are developed, the maximum soil development is commonly affected by recharge of soil water, which maintains ICP at shallow depth and restricts soil development. This leads to the situation where Haplorthels and Anhyorthels can occur as adjacent map units within a previously defined climatic zone based on precipitation. Regardless of soil classification or salt concentration, extracts of water soluble cations and anions are generally dominated by sodium and chloride respectively.

Anhyorthels developed in possible *in situ* Peleus till were identified on the Labyrinth, Dais and in the North Fork. These are the oldest soils, with weathering stage 5–6 being of Pliocene or Miocene age. In contrast to similarly aged soils further east in Wright Valley they have comparatively low salt content. Anhyorthels are also mapped on WU III till but their weathering stage does not exceed 4.

Salic Aquorthels are associated with the margin of Don Juan Pond where high salt concentration prevents freezing of the water. Other low areas of the landscape contain Salic Haplorthels.

While caution must be exercised interpreting a Pedodiversity Index, the value of 0.08 for the upper Wright Valley is within the range of that calculated for other McMurdo Dry Valleys.

Soils in the western Wright Valley differ from those in more eastern parts in that many are developed in doleritic parent material which can give them higher CDE for a similar weathering stage. While salts accumulate in low-lying moist areas, strongly cemented salt pans (derived from primary aerosol deposition) similar to those which occur in central areas of the valley are generally absent.

In common with the rest of the Wright Valley and other MDV soils the soils can be considered as cold desert soils.

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