SOIL AND PERMAFROST DISTRIBUTION, SOIL CHARACTERISATION AND SOIL VULNERABILITY TO HUMAN FOOT TRAMPLING, WRIGHT VALLEY, ANTARCTICA

A thesis
submitted in fulfillment
of the requirements for the degree of
Doctor of Philosophy
at
The University of Waikato
by
Malcolm McLeod

THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

Hamilton
New Zealand
2012

ABSTRACT

Soils and shallow permafrost in Wright Valley, Antarctica were mapped at a scale of 1:50 000 to depict their spatial distribution, and sampled to determine the main drivers for the soil classification.

In the cold desert of Wright Valley the Gelisol order of Soil Taxonomy was used to classify the soils. Soils on younger surfaces, associated with Lower Wright Glacier, Upper Wright Glacier and alpine glaciers, contain massive ice within 100 cm of the soil surface and are classified as Glacic Haplorthels or Glacic Haploturbels where there is field evidence of cryoturbation. As a generalization, at either end of the valley, soil moisture recharge from moist coastal air masses (eastern end) and blowing snow drifts maintain the depth to permafrost in which ice-cement occurs at <70 cm. The resulting shallow effective soil depth restricts soil development. Soils associated with the Onyx River and those receiving overland or subsurface flow also have a shallow depth to ice-cemented permafrost. Where there is permafrost in which the depth to ice-cement is <70 cm the soils are classified as Typic Haplorthels, or Haploturbels where there is field evidence of cryoturbation. Field evidence of cryoturbation includes patterned ground, sand wedges, or post-depositional distorted layering within the soil. Soils near central Wright Valley often show more development compared with those at the eastern or western ends of the valley and, where permafrost without ice-cement extends to >70 cm, are classified as Salic or Typic Anhyorthels or, where there is field evidence of cryoturbation, Anhyturbels.

While mapping soils in Wright Valley, the distribution and nature of the shallow permafrost were also investigated. Three classes of permafrost were established to coincide with definitions or conditions within Soil Taxonomy *viz*: permafrost with ice-cement at <70 cm, dry permafrost to a depth of >70 cm, and massive ice.

A definition for a petrosalic horizon is proposed based on the properties of a salic horizon and the indurated nature of petrocalcic/petrogypsic horizons. The horizon is likely to occur only in the cold desert climate zones of Antarctica.

A rapid method to determine soil vulnerability to human foot traffic was developed. As vulnerability is the product of disturbance and rehabilitation, the method is based on the disturbance of 10 foot prints at a site multiplied by a soil rehabilitation factor based on the soil weathering stage. Although fine-grained aeolian sands are easily disturbed they also rehabilitate rapidly in the windy conditions of Wright Valley. In contrast, old stable soils have a tight cobbly desert pavement with reddish desert varnish and often show less foot print disturbance. When cobbles are overturned, however, fresh rock with thick salt accumulations and without desert varnish is exposed. It takes much time for the desert varnish to re-establish.

The spatial distribution of Soil Taxonomy soil classes, nature of the permafrost and soil vulnerability to human traffic are presented as three separate maps at 1:50 000 scale and as live GIS files.

ACKNOWLEDGEMENTS

I wish to thank my academic supervisors Dr Megan Balks and Professor Jim Bockheim – they have become friends. I also thank my colleague and friend Dr Jackie Aislabie who leads the Landcare Research Environmental Domains Classification for the Ross Sea Region programme. They have all shown scientific rigor and great enthusiasm.

Figure 1-1. Colleagues and friends in Wright Valley, Antarctica. From L-R, Jackie Aislabie, Megan Balks, Jim Bockheim.

Thanks also to Dr Brenda Hall, University of Maine, Orno, and Dr Mike Prentice, University of New Hampshire, for making their soil related data available.

My research in Antarctica would not have been possible without continued logistic support from Antarctica NZ and funding from the New Zealand Foundation of Research, Science and Technology under contract C09X0307. Allan Hewitt and Fiona Shanhun also assisted in the 2004/05 Austral field season.

Laboratory analyses were undertaken by Landcare Research staff of the Environmental Chemistry Laboratory, Palmerston North. Landcare Research also provided funding to undertake my university study.

Landcare Research also funded the speech recognition software which was used for part of this thesis.

Finally, I thank my wife Margaret McLeod for her support and endurance of summer holidays alone while I was in Antarctica

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1 INTRODUCTION

1.1 RESEARCH TOPIC

This research focuses on determining the spatial distribution and nature of soils and shallow ice-cemented permafrost in the Wright Valley, Antarctica. Wright Valley (Figure 1-1), centered at S77° 31' 06" E161° 51' 55", is part of the McMurdo Dry Valley system, the largest ice-free region in Antarctica covering about 4000 km^2 (Bockheim 2002).

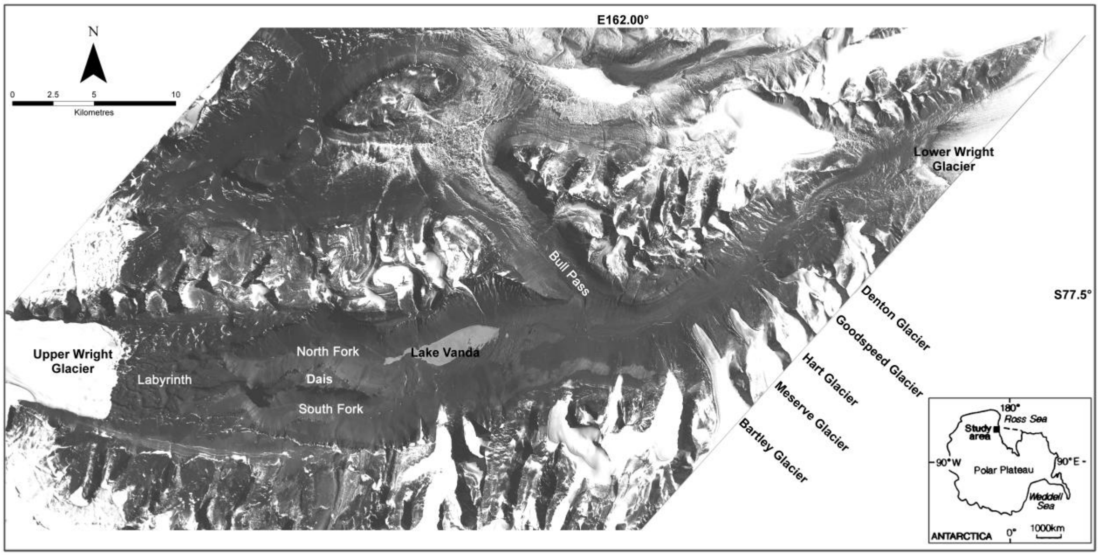

Figure 1-1. Satellite image of Wright Valley, Antarctica showing the main geographical features.

Wright Valley lies east–west, with approximately 50 km between Lower and Upper Wright Glaciers. The valley was carved into granitic basement rocks (including thick sills of Jurassic Ferrar Dolerite) of Granite Harbour Intrusives (Isaac et al. 1996) during the middle Miocene, prior to 9±1.5 My ago, by a westward flowing wet-based glacier from the East Antarctic Ice Sheet (EAIS) (Prentice *et al.* 1993). At 5.5±0.4 Ma "Wright Valley" was a fjord in which the Prospect Mesa Gravels were deposited (Prentice *et al.* 1993). Prior to 3.9 Ma a wet-based glacier draining the EAIS filled the valley and deposited the Peleus till. (Prentice *et al.* 1993). Subsequently, there have been at least four eastward advances of the Upper Wright Glacier (Calkin & Bull (1972), while Hall and Denton (2005) indicate at least seven drift units associated with the Lower Wright Glacier between the late Quaternary and the Pliocene.

Furthermore, there have been at least four advances of the alpine glaciers on the southern wall of the Valley. Advances of the alpine glaciers are out of phase with advances of the Lower Wright Glacier because during interglacial periods warm water around Antarctica increases the amount of water vapour in the atmosphere. As air masses move over the cold continent the water vapour is precipitated over the mountains, eventually supplying ice to the alpine glaciers (Prentice & Matthews 1991).

Where the braided Onyx River flows inland approximately 30 km to Lake Vanda it has created a sequence of alluvial terraces, some now covered with glacial drift from the Lower Wright Glacier. Evidence of the dynamic nature of the Onyx River can be seen where it now cuts into glacial drift capped alluvium (Figure 1-2) or where 36-year-old wheel marks end abruptly at a newly formed terrace edge. Lake Vanda, approximately 95 m above sea level, has a permanently frozen surface except for a narrow unfrozen moat during summer (Figure 1-3).

Figure 1-2. Onyx River cutting into drift-capped alluvium during the 2010/2011 austral summer.

Figure 1-3. Lake Vanda is permanently frozen except for a narrow moat during summer.

The region is extremely dry and cold with mean annual precipitation <100 mm and mean annual temperature of –20°C (Keys 1980) leading to soils classified exclusively under the Gelisol order of USDA Soil Taxonomy. While Gelisols have been mapped in other parts of the world, notably in the Arctic, the Antarctic Gelisols in the McMurdo region are distinctly different in that they have very low (<0.5%) carbon values throughout except for ornithogenic soils, which do not occur in Wright Valley. Furthermore, unless affected by soil moisture recharge, the non-ice-cemented upper layers often have low (<0.5%) water content.

Using field-observable soil properties as a base, this study develops a new system for rapidly identifying the vulnerability of Antarctic Dry Valley soils to human foot trampling. The soil vulnerability ranking can be used to identify preferred campsites and or walking routes for future visitors.

Reasons for understanding the spatial distribution and nature of soils and ice-cemented permafrost in the Wright Valley, Antarctica include:

- a basis on which to select sites for future scientific studies e.g. microbial assemblage
- a basis to assess soil vulnerability to human traffic
- development of soil-landscape relationships to allow rapid mapping of soils in the Ross Sea region
- input into Environmental Domains Analysis, a classification which uses a comprehensive set of variables to determine similarities in environmental space, but which is currently lacking soil layers in Antarctica
- contributing to the Global Soil Map initiative allowing the global inventory and analysis of soil resources
- correlation of glacial drift units based on soil morphology and chemistry between valleys where no numerical age exists
- interpretation of data from new technologies, e.g., quad polarisation synthetic aperture radar which has the potential to identify subsoil layers.

1.2 PREVIOUS WORK

Wright Valley, especially eastern-central Wright Valley, has been the subject of intensive surficial geology investigations in order to elucidate the glacial history of the region (Ugolini 1964; Everett 1971; Nichols 1971; Calkin & Bull 1972; Bockheim 1979; Hall et al. 1993; Hall & Denton 2005; Prentice & Krusic 2005 Bockheim & McLeod 2006; McLeod et al. 2008; McLeod et al. 2009). Examination of soils has been integral to these studies to identify where younger drifts have over-ridden older drifts (Bockheim 1978) and to establish ages of drift material based on soil development tied to established chronologies.

Necessarily, these studies concentrated on geomorphic positions where maximum soil development was anticipated, e.g., on the ends or elevated parts of moraines.

However, there was no spatial depiction of soil classes for the valley similar to those of the Arctic or more temperate regions of the world. In contrast, while extensive soil descriptions by Bockheim (http://nsidc.org/data/ggd221.html) and surficial geology maps by Hall and Denton (2005) and Prentice and Krusic (2005) have been incorporated into the soil map, this study concentrates on a spatial distribution of the soils within the valley by also examining soils on a range of geomorphic surfaces including areas of sub-optimal soil development.

A new 1:50 000 scale soil map has been developed to provide a spatial framework for further scientific research. It can be used as a guide for site selection for other scientific research which requires knowledge of soil developmental sequences or soil conditions. For example, it has already been used to determine where soils should be sampled for microbiology to explain the relationship of edaphic factors to soil microbiological abundance/diversity. Barrett et al. (2006) noted the lack of a soil map while investigating soil carbon turnover in the McMurdo Dry Valleys. The soil map is, in part, a response to Waterhouse (2001), who identified the need for a spatial framework for environmental protection. Lack of detailed spatial data on soil properties hindered development of Environmental Domains for Antarctica (Morgan et al. 2007). Soil-landscape relationships developed in Wright Valley will allow faster mapping of soil attributes in the rest of the McMurdo Dry Valleys and contribute to the current and on-going environmental domains analysis of the Ross Sea region.

The main research questions addressed in this thesis are:

- What is the spatial distribution of USDA Soil Taxonomy Subgroups within Wright Valley, Antarctica?
- What is the general chemical nature of the soils?
- What is the spatial distribution and nature of the shallow ice-cemented permafrost within Wright Valley, Antarctica?
- Do the different soils differ in their vulnerability to human foot trampling?
- Can recommendations be made about preferred campsites/walking routes for future researchers and visitors?

1.3 THESIS STRUCTURE

A field season was spent mapping soils in each of the lower, mid and upper Wright Valley regions resulting in lead authorship of published scientific papers for the mid and upper parts of the valley and co-authorship of a published paper on the lower Wright Valley.

Therefore, within this thesis, chapters 2, 3, 4 and 5 are published or submitted as scientific papers. Published papers are presented as they are published in the relevant journal, while submitted papers are formatted according to the relevant journal style. Chapter 6 is a stand-alone Soil Survey Report. Chapter 7 is synthesis of the research presented in this thesis.

Chapter 2 presents the spatial distribution of soils in the lower Wright Valley from the Lower Wright Glacier west to Bull Pass (Figure 1-4). New chemical analyses of the soils are presented and related to their soil development. The soil map is based both on new pit observations and historic soil observations of Bockheim (http://nsidc.org/data/ggd221.html) and Claridge and Campbell (http://soils.landcareresearch.co.nz/contents/SoilData_RossSeaSoils_Reports_v1.aspx?currentPage=SoilData_RossSeaSoils_Reports&menuItem=SoilData)

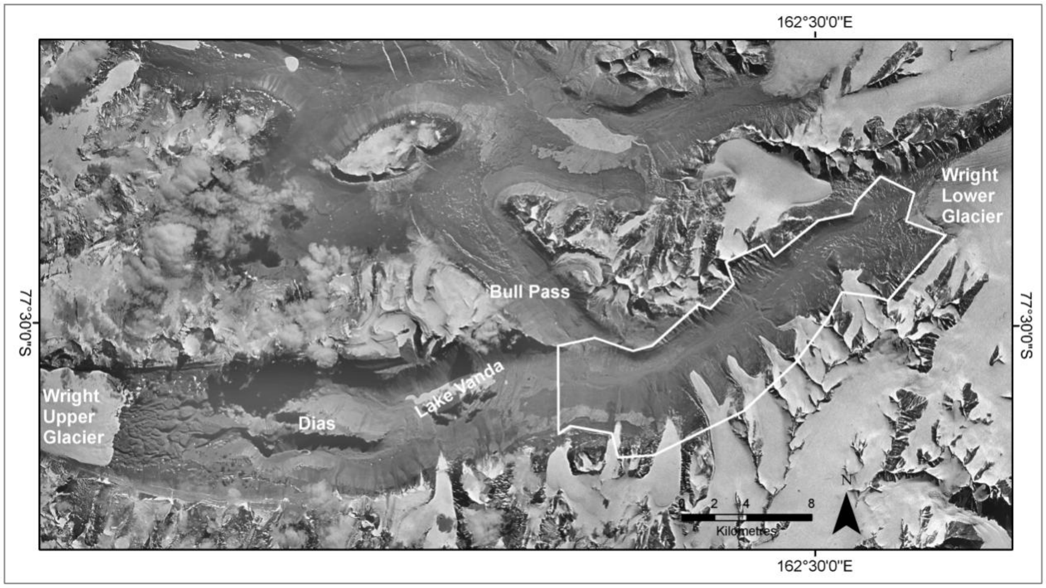

Figure 1-4. Study area in the lower Wright Valley.

Chapter 3 presents surficial deposits, soils and permafrost features in the central-western Wright Valley from Lake Vanda in the east to near the mid-part of the South Fork in the west. The study area is outlined in Figure 1-5, extracted from the published paper. This paper is published as:

McLeod M, Bockheim JG, Balks MR 2008. Glacial geomorphology, soil development and permafrost features in central-upper Wright Valley, Antarctica. *Geoderma* 144: 93–103.

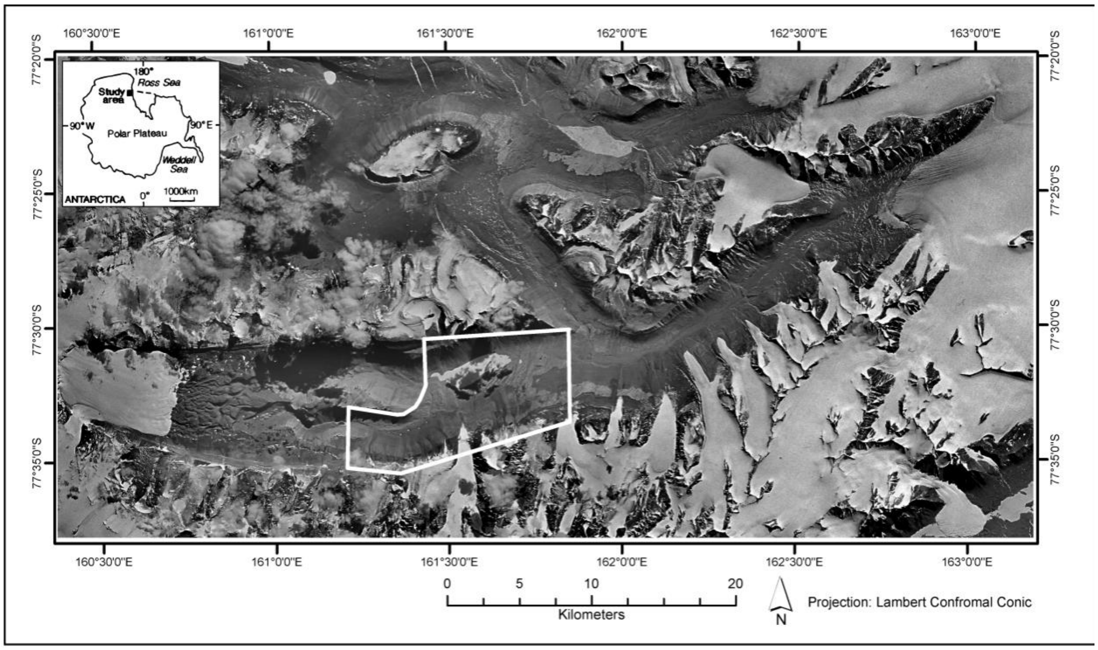

Figure 1-5. Study area in the central-upper Wright Valley outlined in white.

Chapter 4 examines soils of western Wright Valley, from Wright Upper Glacier to the western end of the Dais. The area is divided into three broad geomorphic regions: the elevated Labyrinth, the narrow Dais connected to the Labyrinth, and the North and South forks which are bifurcated by the Dais. The geomorphic units are shown in Figure 1-6 extracted from the published paper. This paper is published as:

McLeod M, Bockheim JG, Balks MR, Aislabie JM 2009. Soils of western Wright Valley, Antarctica. *Antarctic Science* 21: 355–365.

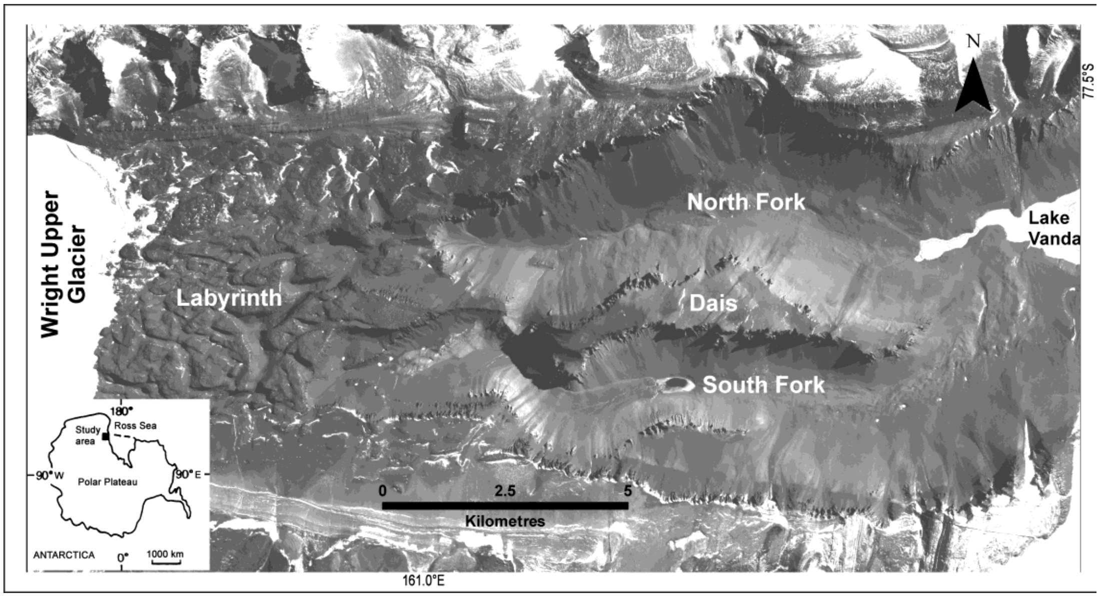

Figure 1-6. Study area in the upper Wright Valley showing the main geomorphic units.

Chapter 5 covers vulnerability of Wright Valley soils to human foot trampling. The spatial distribution of soils with high, moderate or low vulnerability to human foot trampling are shown on a map. Potentially, this map could be used by researchers to plan campsites or by tourists who wish to minimize their impact on the environment. This paper has been submitted to *Antarctic Science* as:

McLeod M, Balks MR, Hewitt AE, Bockheim JG. Vulnerability of soils to foot trampling in Wright Valley, Antarctica.

Chapter 6 is a stand-alone Soil Survey Report with 1:50 000 scale soil and permafrost maps of Wright Valley both as hard copy and as live GIS files with hyperlinks to nearly 200 soil descriptions, many of which contain chemical data as well as photographs of the soil and landscape.

Chapter 7 is a synthesis of the research presented in this thesis. Insights gained from this research will result initially in improved spatial depiction of soil and shallow permafrost properties of ice-free areas in the Ross Sea Region as part of ongoing research, and later over the whole ice-free area of the Transantarctic Mountains.

Appendix I gives the co-ordinates for soil pits used in this research. Pits identified with WV prefixes had their co-ordinates established by hand-held GPS while others were located from 1:50 000 topographic maps and may be of lower accuracy. Appendices II, III, IV, V and VI are co-authored published papers in international peer reviewed scientific journals where insights gained from the understanding of soil properties and processes in Wright Valley have assisted development of the paper.

1.4 CONTRIBUTION OF CO-AUTHORS

In the above published papers, or those prepared for submission to international peer-reviewed scientific journals, where I am the lead author the work is my own with input into review from the co-authors and anonymous external peer review. In the field, my supervisors Prof. Jim Bockheim and Dr Megan Balks introduced me to Antarctic soils and processes and took part in rigorous scientific debate and the formulation of new ideas commensurate with their role. Dr Jackie Aislabie, Landcare Research Programme Leader of the New Zealand Government Ministry of Science Innovation funded Environmental Domains Classification for the Ross Sea Region programme, provided internal peer review, consistent with Landcare Research standard operating procedures, of scientific papers before they were submitted to scientific journals.

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2 SOILS OF THE LOWER WRIGHT VALLEY, ANTARCTICA

2.1 ABSTRACT

Soils over approximately 16 000 ha of the lower Wright Valley, Antarctica from Lower Wright Glacier to Bull Pass have been mapped at a scale of 1:50 000. Soils were classified following the Gelisol order of Soil Taxonomy to subgroup level. More than half the area of soils mapped were a Typic Haplorthel/Haploturbel association where depth to permafrost with ice-cement was <70 cm. Over approximately one quarter of the area mapped the soils belonged to a Typic Anhyorthel/Anhyturbel association where depth to permafrost with ice-cement was >70 cm. Salic Anhyorthels, Petrosalic Anhyorthels and Glacic Haplorthels were also mapped but covered smaller areas. In the soils analysed, pH ranged between 7.1 and 9.5. Anions were generally dominated by chloride.

Keywords: Antarctica, Wright Valley, soil distribution, soil mapping, Gelisols

Submitted as:

McLeod M, Bockheim JG, Balks MR. Soils of the lower Wright Valley, Antarctica. Antarctic Science.

2.2 INTRODUCTION

Soils and surficial geology of lower Wright Valley have been studied extensively (Ugolini 1964, Ugolini & Bull 1965, Everett 1971, Bockheim 1978, Denton *et al*. 1991, Hall *et al*. 1993, Prentice *et al*. 1993, Hall & Denton 2005, Prentice & Krusic 2005), elucidating the glacial history and paleoclimate of Wright Valley. By studying progressive soil developmental sequences, soils in the lower Wright Valley have assisted in the prediction of ages on surfaces for which numerical ages were nonexistent (Bockheim 1978, Bockheim 1990). Soil studies have also identified where overriding of cold based glaciers has occurred with only minor deposition and where younger drift has not completely buried an older drift leaving a window of older soil material protruding (Bockheim 1982). Different soil development in the presence of ice cemented permafrost compared to dry cemented permafrost was demonstrated by Bockheim (1979) meaning that for comparative weathering studies, comparable sites must be used where maximum soil development occurs, e.g., on end moraines. For the purposes of soil mapping these sites may not be representative of the whole drift unit.

Comprehensive soil descriptions along with chemical and physical data for Alpine I, II and III soils associated with the Meserve Glacier area were presented by Everett (1971).

However, studies focusing on differentiating glacial drift units do not present a spatial coverage of the different soil classes over all the landscape. While both Prentice *et al*. (1993) and Hall & Denton (2005) have presented a spatial representation of surficial geology of landscape units, spatial soil class distribution was not prioritized.

Spatial representation of soil classes is required 1) to assist with more detailed Environmental Domains of Antarctica (Morgan *et al*. 2007), 2) to provide a spatial framework for environmental protection (Waterhouse 2001), and 3) to provide a basis for soil vulnerability classes and to guide site selection for other scientific research which requires soil development sequences or knowledge of soil conditions.

This paper presents an overview of soil distribution in the lower Wright Valley and chemical attributes of soils that have not been studied in relation to elucidating glacial chronology and paleoclimate.

2.3 STUDY AREA

The study area covers approximately 16 000 ha in lower-central Wright Valley from Lower Wright Glacier in the east to Bull Pass nearly 25 km to the west (Figure 2-1).

Figure 2-1. Study area in the lower Wright Valley outlined in white.

2.4 TOPOGRAPHY AND GLACIAL HISTORY

The lower Wright Valley lies at the eastern or coastal end of Wright Valley which is approximately 52 km long and 2–4 km wide, (Latitude 77.31S, Longitude 160.11E). The valley lies east–west and is part of the ice-free McMurdo Dry Valleys that were carved in the middle Miocene by an eastward flowing wet-based glacier from the East Antarctic Ice Sheet (EAIS) prior to 9±1.5 Ma (Prentice *et al.* 1993). At 5.5±0.4 Ma "Wright Valley" was a fjord in which the Prospect Mesa Gravels were deposited while prior to 3.9 Ma a wet-based glacier draining the EAIS filled the valley and deposited the Peleus till. (Prentice *et al.* 1993). In the lower Wright, during cool periods, dry-based glaciers from grounded ice of the Ross Sea embayment have advanced westward into Wright Valley on at least eight occasions between the late Quaternary and the Pliocene (Hall & Denton 2005). Furthermore, five alpine glaciers descend over the south wall of the eastern end of the valley and have advanced into the valley on at least four occasions (Hall *et al.* 1993). The alpine glacier advances are out of phase with the valley advances. During interglacial periods deep water warming raised high southern latitude sea surface temperature leading to an increase in water vapour in westerly flowing air masses which was precipitated over coastal mountains provoking advances of the alpine glaciers (Prentice & Matthews 1991).

The braided Onyx River flows — for about 3 months of the year — inland 30 km from the Lower Wright Glacier during the austral summer and discharges into Lake Vanda. Lake Vanda has a permanent ice cover except during the austral summer when marginal areas may become ice-free.

Valley walls are either bare rock in steeper areas or where there is only a minor colluvium source above or else they are covered with colluvium. In general, much of the wide colluvial slopes are relatively stable whereas small colluvial chutes are more active. During the austral summer small, often diurnally active, streams flow from the alpine glaciers, elevated snowfields, and alluvial chutes creating saturated and moist areas of soil on low-angle fans and the valley floor.

2.5 CLIMATE

Wright Valley is considered a cold desert (Bockheim & McLeod 2006). Precipitation is relatively low as a result of the effects of adiabatically-warmed highly turbulent easterly winds which flow down-valley off the Polar Plateau (Keys 1980). At Lake Brownworth, the pro-glacial lake to Wright Lower Glacier, Doran *et al*. (2002) report the average mean annual air temperature and the 0, 5 and 10 cm soil temperatures all to be approximately –20°C over the period 1986–2000, while average wind speed was 11 kph with a maximum of 115 kph.
(http://soils.usda.gov/survey/scan/antarctica/BullPass/).

Although comprehensive spatial precipitation data for the study area have not been published, Thompson *et al.* (1971) recorded an accumulated depth of snow of 8.2 cm and 0.7 cm for 1969 and 1970 respectively at Lake Vanda three kilometres to the west of the study area. More recently at Lake Vanda, Fountain *et al.* (2009) recorded accumulation values of 18 and 32 mm water equivalent for 2004 and 2005. At Lake Brownworth, closer to the coast and within the study area, values for the same years were 26 and 51 mm water equivalent.

2.6 METHOD

Soils

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 2005/06 austral summer, fieldwork was undertaken to validate the preliminary boundaries and determine the nature of soils, permafrost and surface geology. Approximately 120 small soil pits (approximately 0.4 m × 0.4 m × 0.7 m deep) were excavated, described, and classified following USDA Soil Taxonomy and located by a hand-held global positioning system unit. The soil pits were then backfilled. Soils were described following standard methods (Schoeneberger *et al.* 2002) and mapped at 1:50 000 scale using USDA Soil Taxonomy (Soil Survey Staff 2010) at subgroup level to differentiate soil polygons. All soils within the study site have permafrost conditions (Soil Survey Staff 2010) 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.

Horizon notations follow Schoeneberger et al. (2002) with the addition of “ox” and “n” horizon suffixes used in conjunction with “C” master horizons to represent oxidised and non-oxidised C horizon material. To distinguish between “Cox” and “Cn” horizons in the field the soil material was viewed under a 10× hand lens. Quartz grains in “Cox” material appear lightly stained while those in “Cn” material appear clean and unstained.

Colour-development equivalents (CDE) were calculated from classed soil colour hue multiplied by chroma (Buntley & Westin 1965). Under the CDE system, Antarctic soils from acidic parent rocks with higher CDE are redder with greater soil development than those with lower CDE. The soil relationship breaks down when comparing soils developed in acidic and basic parent rocks.

The six class weathering stage follows Campbell & Claridge (1975) while the seven class salt stage follows Bockheim (1990).

At 19 locations larger pits (approximately 1 m × 0.5 m × 1 m deep) 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 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.

To determine the presence of a salic horizon requires the EC of a saturated paste to be measured. However, we determined EC values from a 1:5 soil:water extract and multiplied by five as an approximation of the saturated paste method. 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 9.3© software, final soil polygon boundaries were plotted onto the 5th 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).

To determine the correlation of EC and CDE we conducted two-sample t-tests using GenStat 8.1©.

2.7 RESULTS

USDA Soil Taxonomy soil subgroups were mapped over approximately 16 600 ha (Figure 2-2). The soil association of Haplorthels and Haploturbels was commonly mapped on patterned ground, especially east of the prominent Loop moraine terminal deposit where precipitation is highest. Anhyorthels were mapped on older drifts predominantly in the west of the study area. A general description of each of the soil map units follows.

Soil chemical analyses of 19 profiles (Table 2-1) shows soil pH was always above neutral and ranges to extremely alkaline (pH>9), with TSS_{70} ranging from 7 to over 6000 mg/cm^2. High TSS_{70} values only occur in soils developed in older drifts. Low values may also occur in older drifts where there is leaching of salts but soils developed in young drifts always have low TSS_{70} values. Anions are generally dominated by chloride although predominantly in soils showing greater soil development sulphate may be the dominant anion. Cations are generally dominated by sodium although predominantly in soils showing greater soil development calcium may be the dominant cation.

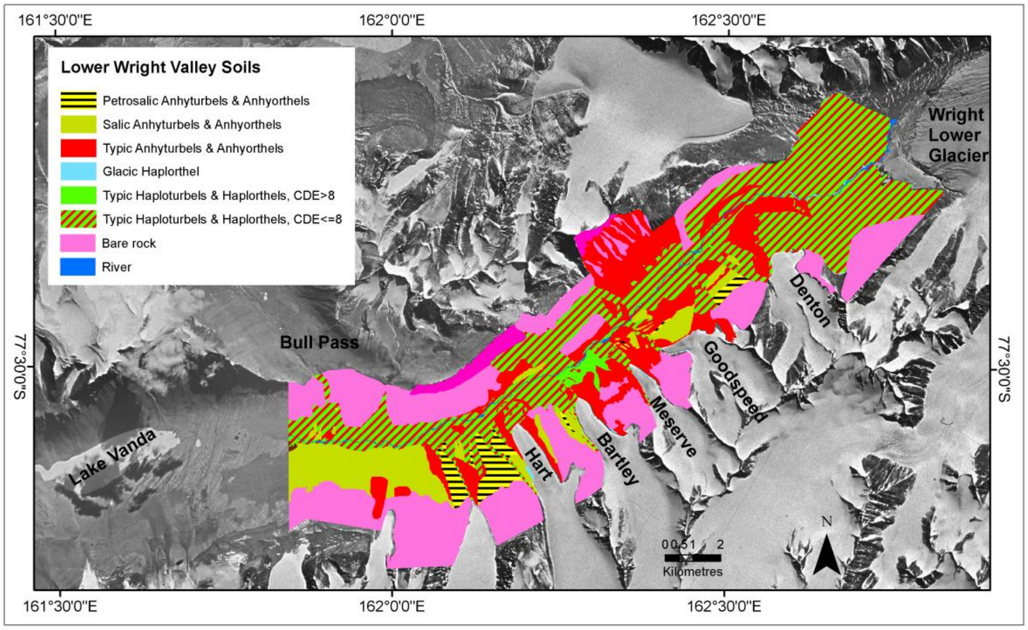

Figure 2-2. Soil map of lower Wright Valley showing the spatial distribution of USDA Soil Taxonomy soil subgroups.

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Table 2-1. Chemical properties of selected soils in lower Wright Valley.

Site	Sub-group	Depth (cm)	pH (water)	EC (1:5) (mS/cm)	TSS to 70 cm (mg/cm^2)	Water-soluble						
						Calcium mmol(+)/kg	Magnesium mmol(+)/kg	Sodium mmol(+)/kg	Potassium mmol(+)/kg	Chloride mmol(-)/kg	Nitrate-N mmol(-)/kg	Sulphate mmol(-)/kg
WV05-26	GHt	0–1	7.5	2.74	140	22	11	87	1.4	106	1	21
		1–4	8.4	2.64		46	13	66	1	63	1	68
		4–50	7.1	0.42		4.7	3.5	13	0.4	17	0.4	1
WV05-01	THo	0–1	8.9	0.13	40	0.3	0.9	4.5	0.5	2.6	0.4	1.2
		1–27	7.3	0.33		3.2	3.4	6.5	0.5	10	2.1	1.0
		27+	7.2	0.09		0.3	1.0	2.3	0.3	1.6	0.2	1.0
WV05-03	THo	0–1	7.9	0.54	60	8.5	3.8	9.6	0.7	12	0.6	7.8
		1–25	7.6	0.47		5.7	4.4	8.7	0.8	14	0.6	2.7
		25+	8.7	0.16		0.4	0.7	5.3	0.3	4.9	0.1	0.7
VW 05-08	THo	0–1	9.1	0.27	440	2.5	2.3	8.6	1.1	9.1	1.5	6.8
		1–21	7.6	2.56		70	12	49	1.7	52	7.2	85
		21–63	8.1	0.97		5.9	4.8	29	1.6	27	5.4	13
WV05-09	THt	0–1	8.5	0.11	7	0.5	0.9	3.1	0.6	2	0.1	1.6
		1–37	8.1	0.04		0.4	1.2	1.2	0.6	0.4	0.02	0.2
		37+	8.7	0.07		1.5	1.8	1.6	1	0.5	0.02	0.4
WV05-11	THo	0–1	9.2	0.24	375	1.1	1.9	8.1	1.4	5.1	0.4	1.8
		1–27	8.3	1.64		25	9.2	39	2.2	36	5.4	36
		27–46	8.0	1.50		16	8.5	40	3	35	5.2	30
		46–60	8.9	0.49		1.2	1.5	17	1.1	13	1.4	4.4

Table 2–1 ctd. Chemical properties of selected soils in lower Wright Valley.

						Water-soluble						
Site	**Sub-group**	**Depth (cm)**	**pH (water)**	**EC (1:5) (mS/cm)**	**TSS to 70 cm (mg/cm^2)**	**Calcium mmol(+)/kg**	**Magnesium mmol(+)/kg**	**Sodium mmol(+)/kg**	**Potassium mmol(+)/kg**	**Chloride mmol(-)/kg**	**Nitrate-N mmol(-)/kg**	**Sulphate mmol(-)/kg**
WV05-16	THo	0–1	8.2	5.91	135	76	28	173	2.6	228	3	67
		1–46	8.7	0.48		2.4	2.4	13	0.7	16	0.3	2.8
		46+	8.9	0.56		2	1.7	17	0.9	17	0.3	4.3
W05-27	THt	0–0.5	8.8	0.50	67	3.6	2.4	19	0.9	18	0.4	2.2
		0.5–24	8.6	0.58		7	2.4	20	0.9	14	0.2	10
		24+	7.5	0.08		0.5	0.5	2.9	0.3	2.3	0.02	0.7
WV05-28	THo	0–1	8.2	1.73	160	36	2.5	42	1.3	40	0.2	41
		1–29	8.2	1.11		12	9.7	28	1.9	34	1.2	14
		29+	9.5	0.27		0.6	1.3	15	0.9	8.2	0.2	1.8
WV05-33	THo	0–1	8.6	0.62	50	4.8	4.4	17	0.9	22	0.8	7.3
		1–20	9.0	0.51		2.1	2.9	13	1	18	0.6	1.4
		20+	8.9	0.19		1.2	1.2	5.8	0.6	5	0.1	2.3
WV05-34	THo	0–1	8.8	0.14	20	0.5	0.9	4.5	0.5	2.9	0.5	2.1
		1–6	8.9	0.09		0.3	0.9	3.0	0.3	1.6	0.3	0.8
		6–7	8.1	0.17		0.5	0.9	5.2	0.5	4.6	0.7	1.3
		7–28+	7.5	0.15		0.4	0.9	4.9	0.5	4.6	0.7	1.1
WV05-35	THo	0–1	8.7	0.33	450	2.8	0.8	8.8	0.8	7.9	0.5	5.1
		1–17	8.1	3.18		106	10	51	2.3	55	7.8	128
		17–51	7.8	1.23		28	5.2	21	1.9	20	4.2	37
		51+	9.4	0.24		0.5	1.1	7.7	0.8	6.7	0.8	1.3

Table 2–1 ctd. Chemical properties of selected soils in lower Wright Valley.

Site	Sub-group	Depth (cm)	pH (water)	EC (1:5) (mS/cm)	TSS to 70 cm (mg/cm^2)	Water-soluble						
						Calcium mmol(+)/kg	Magnesium mmol(+)/kg	Sodium mmol(+)/kg	Potassium mmol(+)/kg	Chloride mmol(-)/kg	Nitrate-N mmol(-)/kg	Sulphate mmol(-)/kg
WV06-27	THo	0–0.5	9.0	0.05	20	0.004	0.05	1.6	0.2	0.6	0.06	0.5
		0.5–12	9.1	0.06		<0.001	0.01	2.1	0.2	1.5	0.07	0.4
		12–34	8.7	0.04		0.06	0.2	1.7	0.2	0.1	0.05	0.2
WV06-28	THt	0–1	8.8	1.64	135	6.7	4.4	43	1	62	2.4	4.1
		1–13	8.7	1.28		24	5	17	0.9	26	2.3	28
		13–43	8.1	0.36		1.3	1.1	10	0.5	13	1.1	1.9
WV05-38	TAo	0–1	8.3	6.83	1820	56	30	205	13	205	82	68
		1–10	8.1	4.97		161	5.9	104	2.8	96	15	191
		10–29	8.4	7.81		33	17	275	8.8	344	23	64
		29–58	8.9	5.54		11	7.5	209	5.6	135	15	126
		58–80+	9.0	1.57		6.1	1.7	53	3.1	41	5.8	24
WV05-41	TAo	0–3	7.3	0.67	1060	3.5	2.2	21	0.2	21	3.9	11
		3–8	7.9	8.0		193	70	183	0.8	185	61	208
		8–18	7.9	6.6		182	82	116	0.8	136	51	219
		18–41	7.8	2.9		5.5	30	87	0.8	96	30	16
		41–70+	7.5	1.6		1.2	11	51	0.4	52	12	3.7

Table 2–1 ctd. Chemical properties of selected soils in lower Wright Valley.

Site	Sub-group	Depth (cm)	pH (water)	EC (1:5) (mS/cm)	TSS to 70 cm (mg/cm^2)	Water-soluble Calcium mmol(+)/kg	Magnesium mmol(+)/kg	Sodium mmol(+)/kg	Potassium mmol(+)/kg	Chloride mmol(-)/kg	Nitrate-N mmol(-)/kg	Sulphate mmol(-)/kg
WV05-02	PsAo	0–3	7.9	1.6	6270	33	9.3	32	1.3	42	1.5	31
		3–23	7.2	27		185	54	1050	7.5	1360	9.1	190
		23–63	7.1	19		42	54	721	8.7	914	8.8	23
		63–80	6.7	3.2		36	42	44	5.7	102	8.9	5.1
		80–100	7.1	4.6		42	48	108	5.1	160	8.6	14
WV05-20	SAo	0–1	8.5	10	6600	190	33	310	0.7	310	721	248
		1–7	8.5	44		57	217	2230	14	1350	69	1120
		7–13	7.9	34		24	97	1610	19	1480	63	377
		13–43	7.9	22		51	27	905	11	980	16	94
		43–67	7.8	9.4		110	25	331	9.9	253	12	102
		67–74+	8.3	6.3		173	24	138	16	142	27	183
WV05-37	SAo	0–1	8.5	0.92	2450	12	7.2	19	1.4	26	0.9	12
		1–29	8.0	9.90		185	39	266	10	328	8	191
		29–60	7.6	5.84		57	28	173	8.8	203	5	75
		60–70+	7.6	5.11		44	23	154	8.3	195	2.8	54

Glacic Haploturbels

Glacic Haploturbels (GHt) are the dominant soil subgroup on approximately 21 ha or less than 1% of the area.

Glacic Haploturbels are developed on the youngest Alpine drift (Alpine I) and drift associated with the most recent advance of the Lower Wright Glacier. Glacic Haploturbels are also developed in the recently identified Holocene age Brownworth lacustrine facies of Hall and Denton (2005). Glacic Haploturbels contain a layer of ice (>75% visible ice) at least 30 cm thick within the upper 100 cm of the soil profile.

A typical profile, developed in the center of diffuse high centered, non-sorted polygons (WV05-26), contains a weakly developed desert pavement over greyish brown gravelly sand material. Ice occurs at approximately 50 cm. Glacic Haploturbels are weathering stage 1 and salt stage 0 although occasionally thin carbonates have been observed under desert pavement gravels. The GHt have low TSS_{70} (Bockheim & McLeod 2006) dominated by sodium and chloride ions (Table 2-1). They have low (<8) CDE reflecting their young age, dominantly acidic parent rock and arrested soil development (Bockheim 1979).

Typic Haplorthel/Haploturbels

The Typic Haplorthel/Haploturbel associations (THo/THt) are mapped over approximately 5000 ha or 37% of the study area. While THo/THt are most common at the eastern, more humid end of the valley, they are not restricted to any climatic zone or parent material. Typic Haplorthel/Haploturbels are mapped on patterned ground where depth to ice-cemented permafrost (ICP) is less than 70 cm. Polygon centers are often Haplorthels with Haploturbels associated with cryoturbated margins of the polygon. Much of the lower Wright Valley contains patterned ground but where homogenisation of upper layers of the soil occurs by wind, water or slope movement, polygons fail to develop. In these areas of sand drifts, moist toe slopes or active colluvial slopes where depth to ICP is less than 70 cm, Typic Haplorthels are dominant.

Typic Haplorthel/Haploturbels have been described on aeolian deposits, alluvium, colluvium, Trilogy, Hummocky drift (H1), Brownworth and Loke drift. These deposits range in age from Recent to early-mid Quaternary. A number of these units have had their soil morphology and TSS_{70} summarised by Bockheim and McLeod (2006).

Typic Haplorthels/Haploturbels generally have a desert pavement underlain by Cn on Cnfm horizons. Cox horizons have been described infrequently. Bwz horizons were not observed; however, THo/THt exhibit a wide range of morphologies. Typic Haplorthels/Haploturbels with shallow depth (20 – 30 cm) to ICP show little soil development (e.g., profile W05-27), contain hue 2.5Y throughout with chroma ≤ 3, a low CDE of <8 and low electrical conductivity (EC) below the desert pavement. Typic Haplorthels/Haploturbels with greater depth to ICP often exhibit greater soil development (e.g., profile W05-11) because soil development is not being arrested by the ice cement. Where depth to ICP is greater Typic Haplorthels/Haploturbels commonly have chroma ≥ 4, CDE ≥ 8 and higher maximum EC below the desert pavement.

For THo/THt in the lower Wright Valley there is a significant difference ($p=0.002$) in maximum EC below the desert pavement, of soils with CDE<8 and those with CDE$\geq$ 8, the latter soils having greater EC. Map units to recognise the differences in THo/THt have been established *viz.*, THo/THt CDE$\leq$ 8 and THo/THt>8. In the study area THo/THt CDE$\leq$ 8 are dominant covering approximately 98% of the THo/THt association. However, there is no difference between soils with CDE <8 in the study area and those with CDE $\geq$8 in the western part of the valley. This is shown graphically in Figure 2-3.

Table 2-1 gives more detailed chemistry for the THo/THt. The pH is high or very high because of the soluble salt load in the profile. However, total soluble salts to 70 cm are less than 450 mg/cm^3 which is low for Antarctic soils. The low values are due to either young age or leaching. In Wright Valley, leaching occurs from direct snowmelt or melt water moving through the profile over the ICP, from higher elevation. Cations and anions are dominated by sodium and chloride respectively because in coastal environments most precipitation arises from marine influenced air masses (Campbell & Claridge 1987)

A pair of soils from the Trilogy drift was sampled from different landscape positions – one on a crest (WV05-33) and the other in the adjacent swale (WV05-34). Chemically the soils are similar but the soil in the swale has slightly lower TSS_{70} commensurate with lower values for cations and anions, which may reflect slightly greater leaching in the lower landscape position. A further Trilogy drift soil (WV05-09) was sampled on ground moraine where there was observable soil moisture throughout the profile. For a soil of early-mid Quaternary age the TSS_{70} of 7 mg/cm^3 is very low and gives insight into the difference in soil chemical properties associated with the leaching regime of moist Antarctic soils.

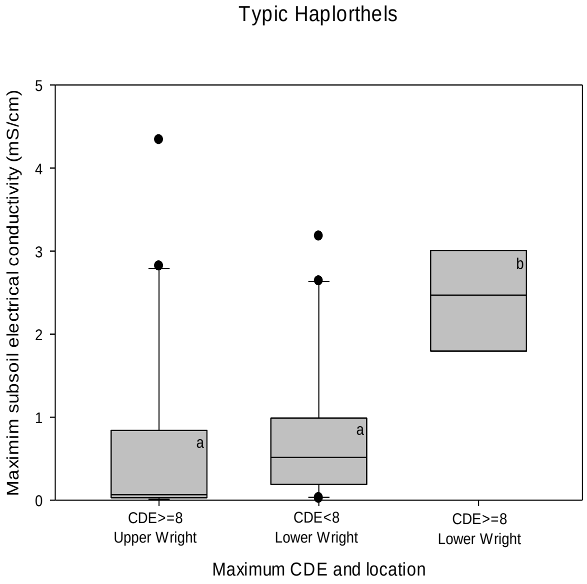

Figure 2-3. Box plot of EC and CDE for Typic Haplorthels in Wright Valley. Median, 10th , 25th, 75th and 90th percentiles are shown with dots representing outliers. There is a significant difference between boxes labelled a and b.

Soils on young surfaces, Onyx River alluvium (WV05-01) and active alluvial fan (WV05-03), have relatively low TSS_{70} and pH reflecting young age and (at least in the case of the alluvial fan) periodic leaching of salts by meltwater.

Typic Anhyorthel/Anhyturbels

The Typic Anhyorthel/Anhyturbel (TAo/TAt) association is dominant over approximately 2150 ha or approximately 16% of the study area. The subgroups occur where depth to ICP exceeds 70 cm and few salts have accumulated within the soil. Deepening of ICP to a depth exceeding 70 cm proceeds slowly under

Antarctic conditions and as a consequence, TAo/TAt predominantly occur on Alpine II or older geomorphic surfaces. Weathering stage averages 3.5 while the salt stage is only 1.5 (*n*=81, data not shown).

Typically TAo/TAt have a well-developed desert pavement over a Bw horizon with hue 10YR or 2.5Y. Visible salts may occur in the B horizon in which case they are given Bwz designation. (They do not meet the requirement for a salic horizon because they do not meet EC and/or EC × thickness requirements). A Cox horizon of light yellowish brown often transitions to the unoxidised Cn horizon.

Bockheim (1997) suggests a trend of sulphate anion dominance over chloride with distance from coastal precipitation influence. The Typic Anhyorthels sampled support this trend. At an altitude of approximately 750 m on the south wall between the Bartley and Conrow Glaciers, a Typic Anhyorthel (WV05-41) was developed in *in situ* Peleus till. Profile WV05-38 (Typic Anhyorthel) on the side of an Alpine III unit on a 22° slope also shows sulphate as the dominant anion in the upper subsoil. In both these profiles, although the soil had high EC, it did not satisfy the requirements of a salic horizon because the product of EC and horizon thickness was insufficient.

Petrosalic Anhyorthel/Anhyturbels

Petrosalic Anhyorthel/Anhyturbels (PsAo/PsAt) cover approximately 400 ha or 3% of the study area. They occur where depth to ICP is >70 cm and salts have accumulated within the profile to such an extent a cemented (predominantly NaCl) salt pan occurs. In Antarctica, such accumulation can only occur under very low precipitation on old geomorphic surfaces. We described PsAo/PsAt predominantly on Alpine IV, early Quaternary Onyx and Pliocene Valkyrie drifts, mainly in the west of the study area away from the more humid eastern coastal region. Weathering and salt stages both average 5 (n=46, data not presented).

An example of a Petrosalic Anhyorthel is profile VW05-02 developed in the Pliocene Valkyrie drift (Hall & Denton 2005) on a 20° slope on the north wall of the valley. The desert pavement was strongly ventifacted, with some boulders planed to surface, others fractured. The very gravelly loamy sand soil material had hue 10YR colours to over 60 cm. A strongly cemented Bwzm horizon, salt stage 5, extended from approximately 20 to 60 cm. Maximum electrical conductivity of the Bwzm horizon was 27 mS/cm with salts dominated by sodium and chloride ions.

Salic Anhyorthel/Anhyturbels

The Salic Anhyorthel/Anhyturbel association is dominant over approximately 1218 ha or about 9% of the study area. Salic Anhyorthel/Anhyturbels are mapped in patterned ground where depth to ICP exceeds 70 cm and salts (predominantly NaCl) have accumulated in the profile. Polygon centers are often Anhyorthel with Anhyturbels associated with the margins of the polygon. The polygonal ground may be relict or not clearly visible on the soil surface. In some profiles we observed only small (<25 cm deep) relict sand wedges. Salic Anhyorthel/Anhyturbels occur mainly on Alpine III and Trilogy drifts, or older and more commonly in the west of the study area away from the more humid eastern coastal region.

A typical profile (WV05-20) shows a strongly ventifacted desert pavement with, with some boulders planed to surface, others fractured. Oxidised salt enriched Bwz horizons (hue 2.5Y) approximately 15 cm thick lies on a Bw horizon (hue 2.5Y) extending to over 40 cm with oxidised hue 2.5Y Cox material extending a further 30 cm. Unoxidised Cn material extends to over 70 cm. Average weathering and salt stage equals 4 (n=31, data not presented).

Soils on the prominent horseshoe-shaped Pliocene or Miocene aged Loop moraine are mapped as Salic Anhyorthels. Profile WV05-37 on a 25° side slope is representative of the soils at 1:50 000 scale. In contrast, Bockheim & McLeod (2006) sampled a Petrosalic Anhyorthel in a ridge crest position nearby on the moraine in order to obtain maximum soil development to determine glacial chronology. In this map unit, Salic Anhyorthels better represents the spatial distribution of soil classes on the moraine at 1:50 000 scale. Petrosalic Anhyorthels on the ridge crest occupy only a small percentage of the map unit.

2.8 DISCUSSION

Petrosalic Anhyorthel/Anhyturbels have been described in the text but they are not recognised in USDA Soil Taxonomy (Soil Survey Staff 2010). We suggest the following definition:

Petrosalic Horizon

A petrosalic horizon is a horizon in which salts that are more soluble than gypsum in cold water have accumulated to the extent that the horizon is cemented or indurated. The horizon typically occurs as a subsurface horizon in cold desert soils.

Required Characteristics

A petrosalic horizon is 15 cm or more thick and, for 90 consecutive days or more in normal years, must have the following characteristics:

1. The horizon is cemented or indurated by salts that are more soluble than gypsum in cold water: *and*
2. The cumulative width of the horizon must exceed 50% of an exposed face: *and*
3. An electrical conductivity (EC) must be equal to or greater than 30 dS/m in the water extracted from a saturated paste; *and*
4. A product of the EC, in dS/m, and thickness, in cm, equal to 900 or more.

In petrocalcic and petrogypsic horizons there is a requirement for a minimum crack spacing indicating restricted root penetration. As PsAo/PsAt form exclusively in drier parts of Antarctica the requirement for a minimum crack spacing related to root extension is unwarranted. The petrosalic horizon is useful for interpretation of the soil profile as it shows a long period of soil development under an arid soil moisture regime.

Following the evolution of soil taxa proposed by Bockheim & McLeod (2006) Typic Anhyorthel/Anhyturbel subgroups occur on older drift units. Commonly, the older drifts occur further from the coast and consequently in drier climatic zones compared with younger drift units. Increased dryness may lead to greater depth to ICP. However, even within this drier zone there are many areas where the ice table is recharged on a recurring basis, e.g., hollows where snow accumulates cyclically, areas where melt water moves from higher elevations over ICP, hyperheic margins of streams. Thus, because a soil is developed in an older drift unit does not imply anhydrous soil conditions as the soils may not lose sufficient water to increase the depth to ICP.

Different USDA Soil Taxonomy great groups can develop on the same surficial geology unit. For example, soil profile WV05-28 (Table 2-1) is classified as a Typic Haplorthel with ice cemented soil at a depth of 29 cm. It occurs on the H1 (Hummocky 1 drift) surface (Bockheim 1979) situated in an inter-hummock position. Total soluble salts are low compared to the mean value quoted by Bockheim & McLeod (2006) but lie within one standard deviation. In contrast, on the same H1 surface Bockheim & McLeod (2006) describe a Typic Anhyorthel in a geomorphic position that does not receive soil water from upslope. Anhyorthels have anhydrous conditions. Part of the definition of anhydrous conditions states "the layer from 10 to 70 cm includes no ice-cemented permafrost" (Soil Survey Staff 2010, p. 16). This situation reinforces the difference between soil and surficial geology maps whereby the same surficial geology unit can have a range of soil subgroups.

The difference in soils on the Loop moraine described by Bockheim & McLeod (2006) and those exemplified by profile WV05-37 highlights three factors, which are peculiar to the way Antarctic cold-based glaciers move across the landscape without affecting existing soil materials. The factors are: a) the spatial variability of soils on a particular landform, b) differences in soils on drifts of the same age but in different locations, c) the difference in the thickness of younger drift over an older landform. In addition, the elucidation of soil properties to determine glacial history necessarily focuses on identifying maximum soil development. At the location of profile WV05-37 we hypothesise younger drift material overlies Loop drift.

The Salic Anhyorthel/Anhyturbel association must occur on older surfaces in order for there to be sufficient time for water to be removed from the profile and for salts to accumulate in significant quantities. In the Wright Valley they may occur on Onyx-age surfaces and older (Bockheim & McLeod 2006). In the lower Wright Valley Salic Anhyorthel/Anhyturbels were mapped at high elevation on the south wall near the Goodspeed Glacier and at both low and high altitudes in the west of the study area – presumably where precipitation is lower – associated with Peleus, Valkyrie and Alpine III and IV drifts. Under Antarctic ice-free conditions, our field observations map units of salic subgroups contain inclusions of typic subgroups because of the possibility of leaching associated with melting snow patches.

Comparison with soils in western parts of Wright Valley

Coastal soils in eastern Wright Valley are influenced by relatively high precipitation, which recharges the ice table and keeps ICP close to the soil surface thus limiting soil development and the build-up of salts within the profile. Thus even on some early Quaternary-aged Trilogy surfaces Haplothorthels are dominant 6 km west of Lower Wright Glacier.

In general, soils in parts of western Wright Valley tend to have relatively low TSS_{70} salt concentrations, perhaps due to a lack of deposition of salts from precipitation, leaching of salts by lateral flow of water or less likely by soil deflation from the strong katabatic winds (McLeod *et al.* 2009). Soils in parts of the eastern Wright Valley generally have low TSS_{70} salt concentration because of leaching under the relatively high (around 50 mm) precipitation. Thus maximum salt accumulation in soil tends to occur midway down the valley where removal of salts by leaching are lessened.

In the upper, western parts of the Wright Valley, Typic Haploturbels are frequently developed in material derived from a mixture of basic and acidic rocks including the Ferrar dolerite. As a consequence of the higher Fe content of basic rocks and hydrolysis of Fe^{2+} to Fe^{3+} oxides during weathering (Bockheim 1990), soils including Typic Haploturbels developed from basic parent rocks generally have a redder hue than those developed from acidic parent rocks. As CDE is highly correlated with dithionite-extractable Fe (Bockheim 1990), the CDE of these soils is often ≥ 8 irrespective of their soil development.

The lower Wright Valley tends not to have topographic depressions which accumulate saline seepage waters or reworked depositions of Peleus till, both of which are more common in western parts of the valley. Soils associated with these deposits have salic USDA subgroups.

2.9 CONCLUSIONS

Soils over approximately 16 000 ha of the lower Wright Valley, Antarctica from Lower Wright Glacier to Bull Pass have been mapped at a scale of 1:50 000.

Soils with a Glacic subgroup were confined to a young drift near the Lower Wright Glacier whereas soils with most soil development occurred further inland on older drifts under lower precipitation. Soils with ice-cemented permafrost at depth of <70 cm covered the majority of the area occurring where the ice table was recharged either from precipitation or surface/subsurface flow. A definition of a petrosalic horizon is suggested for soil layers – thought only to occur in Antarctica – cemented or indurated by salts more soluble than gypsum, with or without other cementing agents. Significant differences in the relationship between maximum colour development and electrical conductivity shown between the lower and upper reaches of Wright Valley are likely to be driven by differences in parent material.

2.10 ACKNOWLEDGEMENTS

This work was partially funded by the New Zealand Foundation for Research, Science and Technology under contract C09X0307. Antarctica New Zealand provided full logistical support. ALOS PRISM images were captured by JAXA and supplied through America’s ALOS Data Node. Jackie Aislabie contributed useful suggestions to an earlier draft.

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3 GLACIAL GEOMORPHOLOGY, SOIL DEVELOPMENT AND PERMAFROST FEATURES IN CENTRAL-UPPER WRIGHT VALLEY, ANTARCTICA

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Glacial geomorphology, soil development and permafrost features in central-upper Wright Valley, Antarctica

M. McLeod [a,]*, J.G. Bockheim [b], M.R. Balks [c]

[a] Landcare Research NZ Ltd, Private Bag 3127, Hamilton, New Zealand
[b] Department of Soil Science, University of Wisconsin, 1525 Observatory Drive, Madison, WI 53706-1299, USA
[c] Earth Sciences Department, Waikato University, Private Bag 3105, Hamilton, New Zealand

Abstract

We mapped surficial deposits, soils and permafrost features in the central-western Wright Valley, Antarctica, from Lake Vanda in the east to near the mid-part of the South Fork in the west. Outstanding features of the landscape include two large rock glaciers covering approximately 323 ha with a volume of 0.14 km^3, and the sinuous Upper Wright III moraine in the South Fork with typifying yellowish brown (10YR 5/6) subsoil colours. Soil morphology and weathering stage indicate the features are early Quaternary age and younger than Alpine III deposits. Soils are dominated by sodium and chloride ions, and the total salt content increases with age except where profile soil water is recharged either by subsurface flow from streams, melt water production at high elevation or sporadic surface flow. Ice-cemented permafrost at less than 70 cm depth is common, being associated with relatively young alluvial soils of the Onyx River, and with soils on the steep slopes of the south valley wall near the Dais where melt water from high elevation recharges soil water.

Keywords: Rock glaciers; Soil weathering salts; Soil chronosequence

1. Introduction

Although the surficial geology and soil development of the Wright Valley has been studied extensively since the late 1950s (Péwé, 1960; Ugolini 1963; Nichols, 1971; Calkin and Bull, 1972; Bockheim, 1979a; Denton et al., 1991; Hall et al., 1993; Prentice et al., 1993; Hall and Denton, 2005; Prentice and Krusic, 2005; Bockheim and McLeod, 2006), most of the research has been concentrated in the region east of the eastern end of Lake Vanda and especially east of Bull Pass where advances of ice from grounding in the Ross Embayment and alpine glaciers on the south wall have been mapped (Hall et al., 1993; Prentice et al., 1993) thereby providing an excellent field laboratory to determine the glacial chronology of Wright Valley (Hall et al., 1993; Prentice et al., 1993). In conjunction with the glacial chronology, Bockheim (1979a) developed relationships between soil morphology and age, later showing how this sequence would be arrested if soil water was recharged thus preventing depth to ice-cemented permafrost (ICP) increasing with age (Bockheim 1979b).

An early exception to study in the eastern Wright Valley was by Calkin and Bull (1972) who described deposits left by eastward advances of the Upper Wright Glacier–Upper Wright I, II, III, IV. Upper Wright IV is now generally referred to as Peleus till (Prentice et al., 1993), which was deposited during the Miocene (Hall et al., 1993). Prentice et al. (1993) later presented a comprehensive surficial geology map from the Dais in the west to Meserve Glacier in the east. However, in this study as a result of more detailed work we were able to re-interpret some of his colluvial deposits south east of the Dais as rock glaciers. A regional-scale geology map (Isaac et al., 1996) also identifies the features as rock glaciers.

Although soil descriptions have been made in the central Wright Valley, they have primarily been used to aid interpretation of surficial geologic deposits and assign ages/names to develop correct chronology. Renewed interest in environmental classification in a spatial framework (Waterhouse 2001) has led to the demand for soil and permafrost maps.

The objectives of this paper are to map the surficial geology, soils and permafrost in central-upper Wright Valley (Fig. 1) and

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* Corresponding author. Fax: +64 7 893701.
E-mail address: mcleodm@landcareresearch.co.nz (M. McLeod).

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doi:10.1016/j.geoderma.2007.10.017

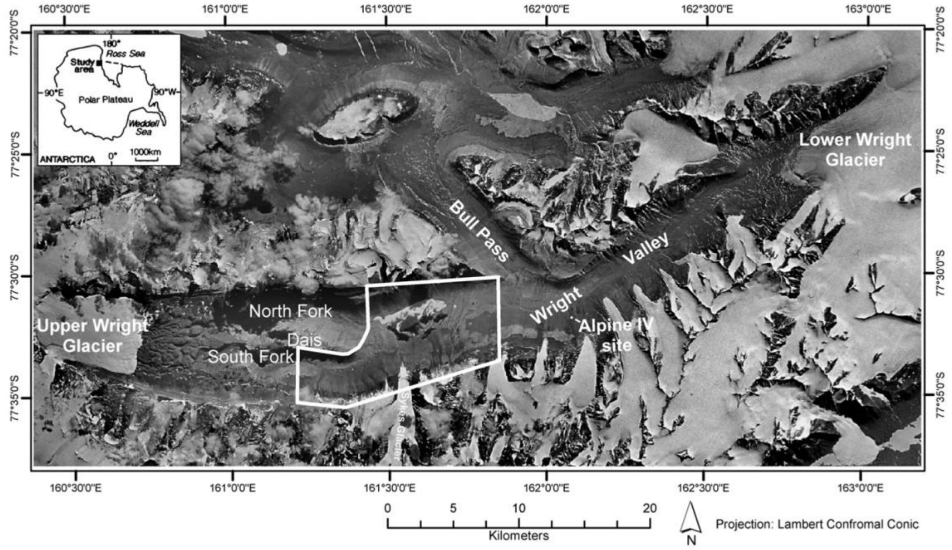

Fig. 1. Location diagram of study site and Alpine IV soil sample location to the east of the study site.

to interpret the results in the context of the glacial and climatic history and of Wright Valley.

2. Study site

Wright Valley (Fig. 1), lying east–west, forms part of the ice-free McMurdo Dry Valleys where precipitation is relatively low as a result of the effects of adiabatically warmed winds (relative humidity 2–5%; Bromley, 1986) that flow down-valley off the Polar Plateau (Keys, 1980). However, at low elevation (<100 m) east along the valley floor to the western end of Lake Vanda, the site lies at the limit of coastal Zone 1 (Marchant and Denton, 1996) where the climate is relatively mild with precipitation at Vanda station of approximately 80 mm yr^{-1} (Thompson et al., 1971).

However, in Zone 2, above 100 m, Marchant and Denton (1996) indicate cold, very dry conditions, with snowfall less than in Zone 1, and rare melt water except on snow banks and glaciers. During the 2006 summer field season (January) we observed many melt water surface flows and seepages along foot slopes of the south wall of the valley, i.e. north facing slopes, as anticipated by Marchant and Denton (1996).

Unconsolidated deposits in central-upper Wright Valley (Fig. 2) are dominated by: 1) two large rock glaciers, covering about 325 ha, that extend northwards from the southern wall (Isaac et al., 1996): 2) Peleus till (Prentice et al., 1993); 3) colluvium from north and south valley walls, and 4) alluvium from the Onyx River. For ease of discussion the two large rock glaciers have been termed Sykes West Rock Glacier (SWRG) for the larger and eastern-most rock glacier, and Plane Table Rock Glacier (PTRG) for the smaller western rock glacier. Deposits from alpine glaciers cover only a small area within the study site where Alpine II and III drifts (Calkin and Bull, 1972) are associated with Sykes Glacier. These drifts are likely of Quaternary and Pliocene age respectively (Hall et al., 1993). South east of Lake Vanda, where the valley floor is not covered in drift, mafic monzonite and felsic porphyry dikes (Turnbull et al., 1994) crop out, while at lower elevation on valley walls Jurassic Ferrar dolerite dykes intrude early Paleozoic orthogneiss (Isaac et al., 1996). Analyses from a profile of soil developed in Alpine IV drift, taken from outside the study area, about 1 km NNW of Conrow Glacier, is included in the dataset for comparison.

3. Methods

Stereo pair aerial photographs of 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) at a 1:50 000 scale. LIDAR data were used in conjunction with Spatial Analyst® (ESRI, ArcGis V9.1) to determine rock glacier volume.

During the 2005/06 austral summer, fieldwork was undertaken to validate the preliminary boundaries and determine the nature of surface geology, soils and permafrost. Eighty-five small test pits were excavated, described and classified following USDA *Soil Taxonomy* (Soil Survey Staff, 2003) and located by GPS. The soil

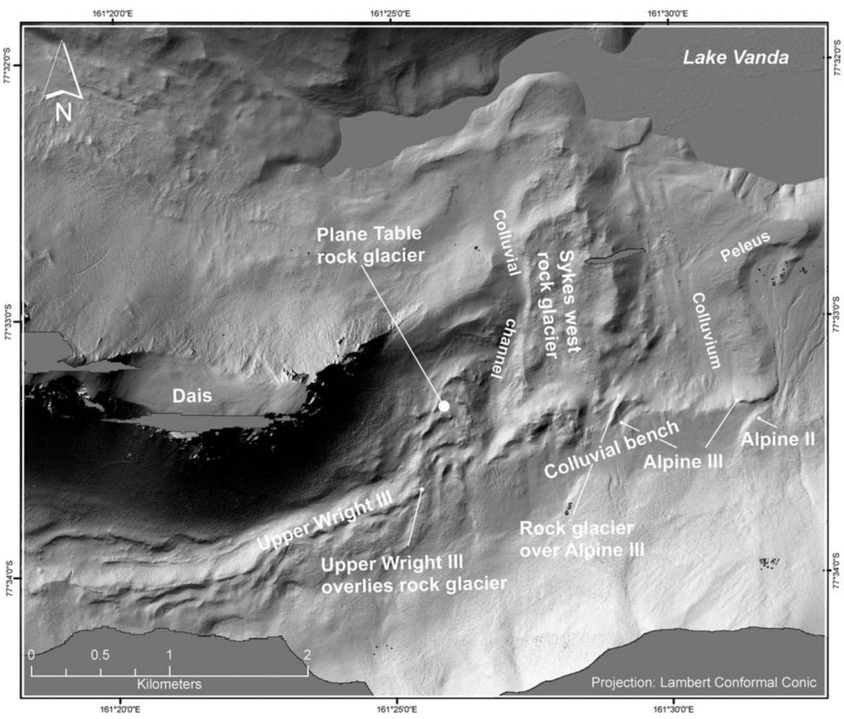

Fig. 2. LIDAR hillshade showing salient geomorphic features within the study site.

pits were then backfilled. Where pits on drift units were sampled to reveal maximum soil development they were located on convex, elevated sites to ensure that the potential for leaching from snow banks or periodic up-flux from free water lower in the soil profile was minimised. Descriptions of weathering stage and salt stage follow Campbell and Claridge (1975) (Table 1) and Bockheim (1990) (Table 2), respectively. Soil boundaries were upgraded daily at the research site using the GPS and soil pit information. At 34 locations larger pits were dug to at least 70 cm (unless ice-cemented permafrost or boulders were encountered), with the soil being sampled by horizon. Both <2- and >2-mm fractions were weighed, with the <2-mm fraction being retained for later analysis in New Zealand.

A 1:5 soil/water extract of subsamples was analysed for pH, EC, water soluble cations (Ca, Mg, K, Na) anions (Cl, nitrate–N, SO_4) 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 (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, 1979a).

Soil morphological properties were tabulated to determine relative age of deposits in the study area and to compare them with those in the eastern part of the valley (Bockheim 1979a).

4. Results

Soils were classified to subgroup level using *Soil Taxonomy* (Soil Survey Staff, 2003) and mapped (Fig. 3), as was permafrost form (Fig. 4). Soil associations of Orthels and Turbels were commonly mapped predominantly in areas of active patterned ground, but also in areas where relict sand wedges could be observed in soil pits.

Soil chemical attributes are within the range expected based on previous studies (Bockheim, 1978, 1979a) (Table 3), with total soluble salts ranging over four orders of magnitude from approximately 10 500 mg cm^{-2} on Alpine IV age soils (Profile 13) to about 5 mg cm^{-2} on soils developed on the active part of the Onyx flood plain (Profile 8). Soil pH ranges from near neutral (pH 7.04) (Profile 4) to extremely alkaline (pH 9.26) on weakly weathered rock likely to have little buffering capacity (Profile 7).

Morphological and salt concentration data for rock glaciers, UWIII, Alpine III and Alpine IV deposits (Table 4) indicate

Table 1
Soil weathering stage following Campbell and Claridge (1975)

Weathering stage	Surface rock characteristics	Soil colour	Horizon development	Soil salts	Soil depths	Other
1	Fresh, unstained, coarse and angular.	Pale olive to light grey (5Y 6/3–7/2).	Nil.	Absent.	Very shallow, underlain by ice.	Moderate patterned ground development
2	Light staining, slight rounding, some disintergration.	Pale brown to light brownish grey (10YR 6/3–2.5Y 6/2).	Weak.	Few flecks.	Shallow, underlain by ice.	Strong patterned ground development
3	Distinct polish, staining and rounding, some cavernous weathering, some ventifacts.	Light yellowish brown (10YR 5/3–2.5Y 6/4).	Distinct.	Many salt flecks in upper part of profile and beneath stones.	Moderately deep.	Some disintergration of boulders in the soil, slight increase in fine fraction.
4	Boulders much reduced by rounding, crumbling and ventifaction, strongly developed cavernous weathering, staining and polish well developed, some desert varnish.	Yellowish brown (10YR 5/4) in upper horizons, paler in lower horizons.	Very distinct.	In discontinuous or continuous horizon beneath surface.	Deep.	*(as for Stage 3).*
5	Few boulders, many pebbles forming pavement, extensive crumbling, staining, rounding, pitting and polish.	Dark yellowish brown to yellowish red (10YR 4/4–5YR 5/8).	Very distinct.	In horizon 20–30 cm from surface and scattered throughout profile.	Deep.	*(as for stage 3).*
6	Weathered and crumbled bedrock, very strongly stained, mainly residual.	Strong brown to yellowish red and dark red (7.5YR 5/6–5YR 4/8 to 2.5YR 3/6).	Very distinct.	*(as for stage 5).*	Shallow to deep.	Bedrock sometimes crumbled to 50 cm depth.

relative ages of the deposits but the less than optimal number of observations and chemical analyses means some caution is required during interpretation.

5. Discussion

5.1. Soils and geomorphology

Although there are many similarities between the surficial geology of the eastern Wright Valley and the central-western part of the valley (Peleus till, colluvium, alluvium), there are three broad differences. First, there are no deposits attributable to west-flowing ice from grounding in the Ross Embayment and/or expansion of the Wilson Piedmont Glacier. Second, fewer alpine glaciers extend down the southern valley wall in the study area compared with the eastern Wright Valley. This results in fewer alpine deposits on the valley floor and walls and as a consequence less of the intricate cross-cutting surficial geology patterns associated with the alpine glaciers of the eastern Wright Valley. Third, there are at least two large rock glaciers that dominate the landscape. While rock glaciers have been mapped in the eastern part of the valley (Hall et al., 1993) they are of smaller extent than the rock glaciers reported here, covering only a few hectares.

Table 2
Salt stages following Bockheim (1990)

Salt stage	Maximum salt morphology	EC (ds/m)*	Numerical age
0	None.	<0.6	<10 ka
I	Coatings on stone bottoms.	0.6–5.0	10–18 ka
II	Few flecks (<20% of surface area of horizon has accumulations that are about 1 or 2 mm in diameter).	5–18	18–90 ka
III	Many flecks (>20% of surface area has flecks as above).	18–25	90–200 ka
IV	Weakly cemented pan.	25–40	250–? Ka
V	Strongly cemented pan.	40–60	~1.7–2.5 Ma
VI	Indurated pan.	60–100+	~>2.5 Ma

* Electrical conductivity in the salt-enriched horizon.

The SWRG extends northwards from the valley wall approximately 2.2 km and is approximately 1.2 km wide. At its highest point it rises approximately 50 m above the surrounding colluvium. If the base of SWRG is set to the approximate height of adjacent ground the volume of material is approximately 0.1 km^3. The surface of the SWRG contains strongly weathered boulders and ventifacts and is classed as weathering stage 4 (Table 1) (Campbell and Claridge 1975). At this stage boulders are much reduced by rounding, crumbling and ventifaction with strongly developed cavernous weathering; staining and polish of surface rocks is well developed. Site surface morphology is characterised by many depressions 10–50 m wide within larger lobate structures of the rock glacier.

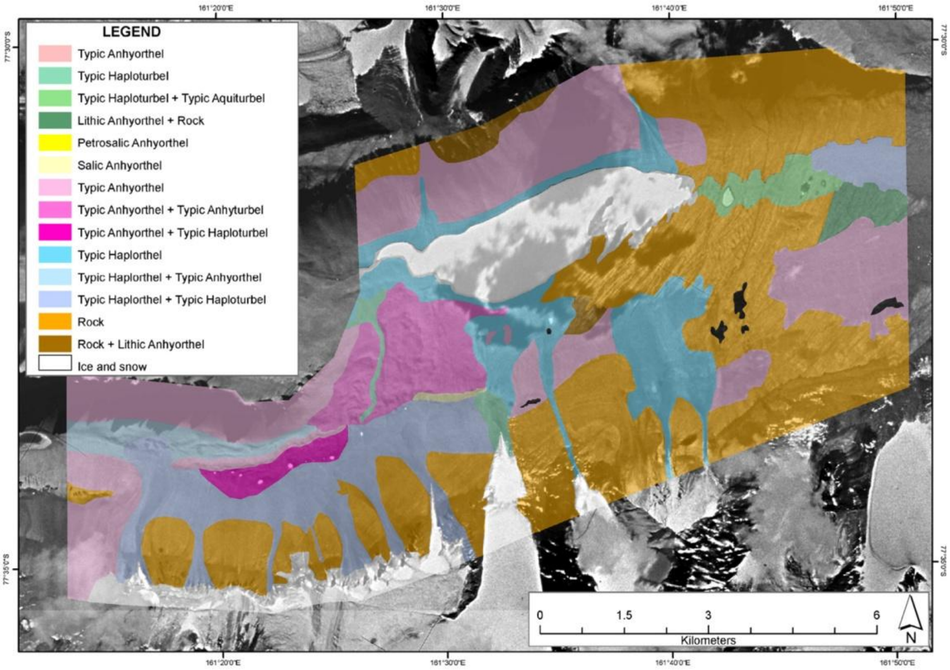

Fig. 3. Spatial distribution of USDA Soil Taxonomy Subgroups within the study site.

The second large rock glacier in central-western Wright Valley is the PTRG, which is approximately 2 km by 0.5 km and has a volume of about 0.04 km^3. The PTRG has a similar surface to SWRG, but the structural lobes of the rock glacier are even more pronounced. Both SWRG (10 observations) and PTRG (7 observations) have similar soil morphological features (Table 2). There are no consistent differences between weathering stage (approx. 4) (Table 1), salt stage (approx. 1.5) (Table 2), and depth of oxidation (approx. 32 cm). Judging from analyses by Bockheim and McLeod (2006), the rock glacier materials are of possible early Quaternary age. Total soluble salts to 70 cm (TSS_{70}) are also consistent with this age. Below the Sykes Glacier, an Alpine III deposit with age <3.5 Myr (Hall et al., 1993) was surrounded by rock glacier material. The feather edge of the rock glacier onto Alpine III indicates the rock glacier is younger than Alpine III.

The two rock glaciers are separated by a south–north trending channel that originates on the colluvial bench above and to the south of the rock glaciers. Ice-cemented permafrost occurs within 70 cm of the surface in this channel unlike the rock glaciers themselves, which have dry permafrost generally at depths greater than 70 cm. Ice-cemented permafrost at less than 70 cm occurs either because the channel is relatively young and based in the ice of the rock glaciers or is an older feature but receives melt water recharge, presumably from the colluvial bench and steep slopes to the south. On the basis of the degree of soil development, e.g., strong brown colours and rock ghosts to depth we favour the latter explanation.

The Upper Wright III moraine (UWIII) (Calkin and Bull, 1972) is a sinuous moraine in the South Fork extending from Don Juan pond to the eastern end of the Dais. Immediately east of Don Juan pond the UWIII moraine extends about 1 km along the north side of the fork about 50–60 m above the valley floor. Here a break occurs in the drift where a fan from the south wall discharges across the fork. East of this point the UWIII moraine occurs on the south side of the fork with a maximum height of about 70 m above the valley floor. The UWIII moraine roughly parallels colluviated rock glacier material from the south wall but is generally separated from it by a narrow gully system.

Soils developed on UWIII moraine often have yellowish brown (10YR 5/6) colour in the subsoil, presumably from doleritic grüss, and contain a greater fine earth (<2 mm) fraction (72%, $n=2$) than soils developed in the rock glaciers (59%, $n=3$). Calkin and Bull (1972) noted eastern terminal deposits were poorly marked. We observed similar yellowish brown (10YR 5/6) coloured material in parts of the PTRG and hypothesize that the maximum eastern extent of UWIII moraine is coeval with the PTRG and is now incorporated in PTRG material. While the UWIII moraine, PTRG and SWRG are all weathering stage 4, other age-related indicators such as depth to rock ghosts, depth of staining, and depth of coherence are not as

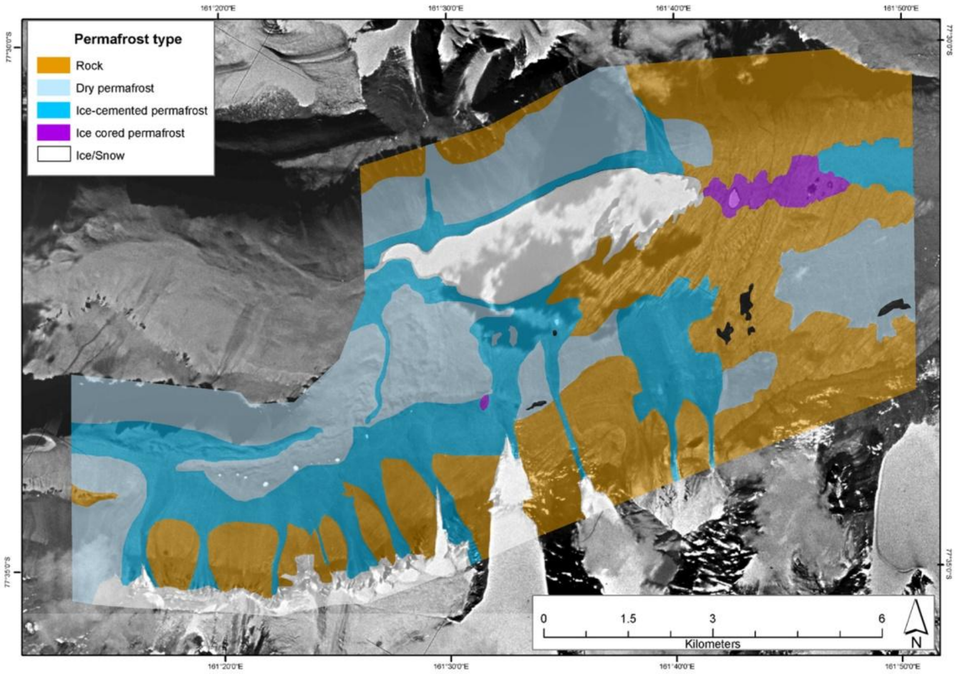

Fig. 4. Spatial distribution of permafrost types within the study site.

consistent and need field interpretation based on, for example, the nature of the parent material. Overall, the soil morphology and chemistry did not indicate consistently large age differences between the UWIII moraine and rock glacier deposits. Using similar published analyses (Bockheim and McLeod, 2006) we judge the rock glaciers and UWIII deposits to be of early Quaternary age and younger than Alpine III deposits.

Hall and others (2001) reported a high-level lake in the Wright Valley during the late glacial maximum and early Holocene. Our observations do not support an expanded Glacial Lake Wright in central-western Wright Valley. We see no evidence of lake deposits, deltas, or strandlines other than those up to 52 m above the 1977 level of Lake Vanda (Chinn 1993). At its highest extent (460 m a.s.l), Glacial Lake Wright (Hall et al., 2001) would have flooded the study area plus the South and North Forks to considerable depth.

Soil profile 13 (Table 1) developed on Alpine IV drift at 300 m elevation contained an indurated salic horizon with TSS_{70} of approximately 10 500 mg cm^{-2}, while a soil of Alpine III age at an elevation of 366 m contained TSS_{70} of approximately 3120 mg cm^{-2}. Under saturated conditions existing within the soil beneath a lake, soil salts would be rapidly dissolved by the lake water and widely redistributed, especially during the likely variability of soil–water saturation during a lake-filling episode. Any hypothesis for the existence of a high-level lake during the last glacial maximum and early Holocene needs to address the existence of soils with salic horizons that occur only in parts of the landscape and are associated with soils that exhibit other signs of age, e.g., greater depth of oxidation, greater depth of rock ghosts, greater surface weathering.

Low moisture inputs into the cold, dry soils of the Wright Valley mean that conceptually the soil pattern and development sequence are relatively straightforward and strongly related to landscape position. If initial soil parent materials contain ice and receive little input of moisture, the depth to ICP will progressively increase over time as will the depth of oxidation, the depth of rock ghosts and salt concentration within the profile (Bockheim, 1979a). The desert pavement is also a guide to soil development with relief decreasing with increasing age (Campbell and Claridge, 1975; Bockheim, 1979a). If soils are located in a moist part of the landscape, e.g., close to the coast where precipitation recharges soil water and ICP remains close to the surface, soil development is restricted (Bockheim, 1979a). Similarly, hyporheic zones of the Onyx River and melt water streams also recharge soil profile water, especially during midsummer when peak flow occurs. In both these more moist soil environments cryoturbation occurs and is reflected in the Turbel classification. Locally, another parent material in which the suite of soil development indicators is not coherent is Peleus till. Although Peleus till has a strongly developed desert pavement the pulverulent nature of the deposit means coherence, depth of

Table 3
Chemical properties of some soils from the central-western region of Wright Valley, Antarctica

Prifile number	Soil landscape	Relative age	Horizon designation	Depth (cm)	pH (water)	EC (1:5) (mS/cm)	TSS 70 cm (mg/cm^2)	Water soluble						
								Calcium (mg/kg)	Magnesuim (mg/kg)	Soduim (mg/kg)	Potassium (mg/kg)	Chloride (mg/L)	Nitrate–N (mg/L	Sulphate (mg/L
7	Weakly weathered rock	N/A	D	0–0.5	9.3	0.07	303	5.5	1.5	35	13	35	1.4	31
			Cox	0.5–19	8.1	0.96		331	77	360	40	975	38	496
			2CR	19+	8.1	0.89		339	76	319	39	901	33	505
8	Flood Plain	Active	D	0–0.5	9.5	0.13	5	25	8.6	59	15	59	5.7	73
			Cn	0.5–17	8.8	0.02		2.8	0.7	10	6.4	4.4	1.9	7.5
			Cg	17–19	8.5	0.01		1.7	0.5	7.0	3.9	4.7	0.5	2.7
3	Flood Plain	Young not active	D	0–2	7.8	0.51	60	381	18	57	16	48	5.4	907
			Cox	2–14	7.9	0.59		225	64	202	25	561	33	353
			2Cox	14–33	8.3	0.04		7.1	2.8	27	10	45	0.3	1.1
			2Cn	33–41	7.9	0.07		16	6.6	32	8.8	77	3.4	25
			2Cnfm	41+	7.9	0.10		22	9.4	41	11	114	4.5	34
4	Drift	Aphine III	D	0–1	8.3	1.54	1810	859	54	708	23	556	39	2820
			Bw	1–35	7.4	7.39		811	272	2550	54	5560	733	5390
			BC	35–90	7.0	3.53		302	270	2390	68	3510	362	1750
			Cox	90–100	7.6	1.87		133	100	1500	44	1480	187	1400
15	Drift	Alphine III	D	0–1	8.2	5.17	3130	1710	267	3380	70	4750	465	4890
			Bw	1–11	7.7	9.52		1720	524	3000	166	6980	2150	8970
			Bwz	11–26	7.5	24.9		952	1080	26600	324	23400	9380	939
			BC	26–58	6.9	4.36		464	916	2290	222	2560	1220	90
			Cox	58–80	7.1	3.17		388	689	1510	182	2720	571	154
5	Drift	Alphine III	D	0–1	7.5	3.06	4560	681	191	1420	45	2460	285	2630
			Bwz	1–.15	7.4	31.2		1220	202	9220	78	26600	6810	9050
			BC	10–63	7.5	10.1		718	668	7830	245	8260	1520	567
			Cox	63–90	6.8	3.50		424	183	1230	59	7260	522	4190
13	Drift	Upper Wright III	D	0–2	8.5	7.52	10500	1070	262	4890	13	7260	611	7960
			Bwzm1	2–13	8.6	38.9		2650	577	48200	72	48700	4490	38900
			Bwzm2	13–30	7.9	55.6		389	543	67400	260	81000	12800	22300
			Bw	30–70	7.5	20.1		725	1120	20600	308	31800	1150	4010
			Cox	70–85	7.1	7.09		586	442	6050	168	5450	1630	2360
21	Drift	Upper Wright III	D	0–1	8.9	0.61	679	88	25	200	14	699	81	177
			Bw1	1–6	8.4	1.87		298	79	427	37	1760	344	808
			Bw2	6–18	8.2	3.73		1700	170	563	47	1610	386	6350
			Bw3	18–34	7.9	2.31		256	80	718	29	2720	252	1530
			BC	34–71	7.7	1.38		146	38	363	20	1470	132	1120
			Cox	71–100	8.3	0.76		36	16	295	17	1010	77	178

(continued on next page)

Table 3 (*continued*)

Prifile number	Soil landscape	Relative age	Horizon designation	Depth (cm)	pH (water)	EC (1:5) (mS/cm)	TSS 70 cm (mg/cm^2)	Water soluble						
								Calcium (mg/kg)	Magnesuim (mg/kg)	Soduim (mg/kg)	Potassium (mg/kg)	Chloride (mg/L)	Nitrate–N (mg/L	Sulphate (mg/L
20	Drift	Upper Wright III	D	0–1	8.9	0.69	764	102	25	309	21	726	52	512
			Bw1	1–17	8.3	4.46		1290	51	391	33	2770	448	6440
			Bw2	17–33	8.2	2.85		406	77	450	47	2540	476	2670
			BC	33–57	7.9	1.18		41	27	289	26	1250	243	68
			Cox	57–100	7.7	1.02		46	25	334	22	1310	171	90
05–40	Drift	Peleus till	D	0–2	8.6	0.17	3470	20.1	14.0	109	25.3	149	12	69
			Bw1	2–16	7.6	14.4		4090	3360	5020	600	20100	2370	1150
			Bw2	16.42	7.5	10.3		3290	3190	1130	412	14000	2010	66
			BC	42–67	7.6	9.15		2860	2840	1110	335	12038	1740	34
			Cox	67–75	7.7	8.60		2630	2530	1240	347	12000	1550	107
16	Rock glacier	Young	D	0–1	8.5	2.35	127	2590	36	162	28	148	33	5080
			Bw	1–7	8.5	2.47		2570	60	321	32	130	26	4150
			BC	7–25	8.8	0.29		84	77	250	16	254	35	179
			Cox	25–45	8.9	0.09		5.6	6.7	57	10	52	5.3	59
17	Rock glacier	Intermediate	D	0–1	9.3	0.23	728	31	6.4	165	16	136	11	231
			Bw1	1–16	8.5	2.29		243	61	512	38	1820	353	2060
			Bw2	16–28	7.9	2.54		92	94	390	0.3	1560	390	3360
			BC	28–59	7.5	2.32		333	82	656	25	1570	306	2770
			Cox	59–70	7.6	1.33		72	99	1020	31	1280	241	567
24	Rock glacier	Intermediate	D	0–1	9.1	0.43	884	66	12	225	9.5	282	21	311
			Bw1	1–14	8.3	2.79		395	214	986	47	2250	646	525
			Bw2	14–24	7.7	5.62		435	84	911	131	3230	1430	4370
			BC	24–51	8.4	2.48		392	260	1500	55	2450	516	364
			Cox	51–100	8.7	1.28		130	116	716	47	545	135	17
18	Rock glacier	Intermediate	D	0–1	8.2	0.48	2110	93	15	245	14	343	20	472
			Bw1	1–13	8.3	4.42		996	95	700	29	2590	234	6310
			Bw2	13–25	7.9	11.5		161	185	3770	124	19900	677	2630
			BC	25–63	8.4	5.96		113	154	1850	96	8800	630	1010
			Cox	63–70	8.4	3.17		73	109	1290	82	3630	466	487
23	Colluvium	N/A	D	0–0.5	7.4	0.08	8	12	8.6	33	6.0	42	2.4	82
			Cox1	0.5–23	8.2	0.03		1.4	12.9	30	17	58	1.8	9.4
			Cox2	23–57	8.3	0.02		<0.03	0.6	21	3.6	16	0.8	11
22	Colluvium	N/A	D	0–1	8.5	0.39	1060	20	6.8	321	21	560	14	112
			Cox	1–11	8.1	6.51		1080	75	1370	73	7690	254	6490
			Coxb	11–32	8.2	3.34		1450	70	500	74	1750	126	6180
			Coxbb	32–50	8.5	2.22		419	78	602	107	2600	174	1600

Table 4
Morphological and salt concentration data for rock glaciers (PTRG and SWRG), UWIII, Alpine III and Alpine IV deposits in the central-western part of Wright Valley

Landform	Profile	Max. depth oxidation (cm)	Max. depth coherence (cm)	Max. depth visible salts (cm)	Max. depth rock ghosts (cm)	Depth of ICP* ~(cm)	Salt stage	Weathering stage	TSS# to 70 cm
UW III	185	40			9	>50	1	4.0	
UW III	20	82	57	70	15	>100	1	4.0	765
UW III	21	100	100	71	10	>100	2	4.0	679
Average		**75.0**	**78.0**	**70.5**	**11.3**		**1.3**	**4.0**	**721**
PTRG	183	11	40		11	>57	1	4.0	
PTRG	79–03	42		65		>100	4		1489
PTRG	152	56				56	1	4.0	
PTRG	153	>70				>70	1		
PTRG	149	28			18	>55	1	4.5	
PTRG	24	51		100+	10	100+	1	4.0	884
PTRG	150	11				>20	1	4.5	
Average		**33**		**65**	**13**	**>57**	**1.4**	**4.2**	**2373**
SWRG	179	14			14	>46	1	4.0	
SWRG	148	27		6	27	>48	2	4.0	
SWRG	147	34			34	>40	1	4.0	
SWRG	77–25	65		35		>110	1		
SWRG	178	25		23	10	>40	2	4.0	
SWRG	83–15	39		>100		>100	5		
SWRG	196	15		>63	18	>70	1	4.3	
SWRG	17	28	59	59	30	>70	1	4.0	728
SWRG	18	25		25	10	>70	1	4.0	2111
SWRG	177	36			21	>100	1	4.0	
Average		**31**		**29.6**	**21**	**>100**	**1.6**	**4.0**	**1419**
Alpine III	77–27	41		>93		>93	4		3057
Alpine III	15	58	>80	29	23	>80	3.5	5.0	3126
Average		**55**		**>28**	**23**	**>93**	**4**	**5**	**3091**
Alpine IV	13	85	70	70	51	>85	5	5.0	10500

* ICP = Ice-cemented permafrost.
# TSS = Total soluble salts mg cm^{-2}.
~> Indicates maximum depth of field observation.

oxidation and rock ghosts do not conform to the soil development progression discussed above (Prentice et al., 1993).

The definition of anhydrous conditions in *Soil Taxonomy* (Soil Survey Staff, 2003) include the following:

- The mean annual water-equivalent precipitation is less than 50 mm yr^{-1};
- Ice-cemented permafrost is not present in the upper 70 cm;
- The moisture content averaged over the 10–70 cm layer is <3% by weight; and
- The dry consistence of the 10–70 cm layer is loose to slightly hard except where a salt-cemented horizon is present.

Therefore, anhydrous conditions are restricted in western–central Wright Valley to soils in WU III, Alpine III, Alpine IV and Peleus drifts older rock glaciers and older colluvium that are not re-supplied with moisture.

Soil Landscape Models (SLM) can be constructed for soils in the central-western Wright Valley using a combination of understanding of soil development and fieldwork. The soil classification refers to the maximum soil development expected and observed. As in soil mapping exercises in more temperate climates, variation within map units can be expected. In the dry valleys of Antarctica, much soil variability can be attributed to small surface depressions that accumulate snow. The snow may remain only for short periods of time but results in increased soil moisture (Campbell and Claridge, 1982). As a consequence, salt distribution within the profile is altered. Table 5 shows the relationship between soil landscape unit and soil classification for salient landscape units of the central-western Wright Valley.

5.2. Soil chemistry

All soils sampled are from a similar climatic zone, thus removing the effect of different salt deposition rates under different climatic regimes (Bockheim, 1997). The soil chemistry follows expected trends of fewer salts in soils with a supply of soil moisture in the profile (Bockheim, 1997; Claridge and Campbell, 1977). Soils with lower salt content often occur in younger parts of the landscape but may also occur where there is a water supply up-slope. For example, at the mouth of the South Fork, a soil developed in scree material on a foot slope of the north wall of the Dais had dry soil conditions with TSS_{70} of 1055. In contrast, a soil developed in scree material on a foot slope of the south valley wall had TSS_{70} of 8. This latter soil, with elongated flat centered polygons 10 m by 6 m, was moist below 23 cm with subsurface water movement down slope above ICP at about 60 cm. The water was supplied from melting ice 1000 m up-slope.

Claridge and Campbell (1977) analysed 9 soils (32 horizons) from the Wright Valley to give average ionic ratios of water-

Table 5
Relationship between soil landscape unit and soil classification for salient landscape units of the central-western Wright Valley

Soil landscape	Relative age	Recharge*	Dominant classification	Profile number	Note
Weakly weathered rock	N/A	N/A	Lithic Anhyorthel	7	Both ridge and swale
Floodplain	Active	Yes	Typic Aquiturbel	8	High water table
	Young	Either	Typic Haplorthel/turbel association	3	
	Intermediate	Either	Typic Haplorthel/turbel association		
Drift	Intermediate	No	Salic Anhyorthel	4, 5, 15	Alpine III
	Intermediate	No	Petrosalic Anhyturbel	13	Alpine IV
	Old		Typic Anhyorthel	05–40	Peleus
Rock glacier	Young	Yes	Typic Haploturbel	16	Valley wall
	Intermediate	No	Typic Anhyorthel	17, 18, 24	Valley floor
Colluvium		Yes	Typic Haplorthel/turbel association	23	
		No	Typic Anhyorthel	22	

*Soil water recharge from ground/surface water rather than precipitation.
N/A — Not applicable.

soluble salts relative to potassium (Table 6). Calculating the ionic ratios relative to potassium overcame variation in salt content within a parent material. Using the same method we calculated values for soils from the central-western part of the valley. The latter values were considerably lower than those of Claridge and Campbell (1977) but are similar to those calculated from Bockheim (1979a) for the lower Wright Valley. Results presented here suggest a more granitic provenance for the soil parent material compared with those sampled by Claridge and Campbell (1977). The difference in ratios is plausible as Claridge and Campbell (1977) sampled soils from higher elevation developed on dolerite. At higher elevation, sulphates and nitrates are more common anions while doleritic material contains a greater proportion of weatherable minerals than the predominantly granitic material we sampled. Furthermore, in our study total salt concentration was not a good predictor of the calcium/magnesium ratio. Calcium and magnesium are liberated by rock weathering (Campbell and Claridge, 1982), which is weak in the relatively young soils of the low elevation parts of the Wright Valley.

There are two lines of evidence for a possible marine-aerosol origin for the majority of the salts in salt enriched horizons. First, soil salts in the salt-enriched horizons are dominated by Na^+ cations and Cl^- anions; as salt content increases with age there is a trend for the second dominant cation to move from Ca^{2+} to Mg^{2+}, which is consistent with accumulation of marine aerosols as the Na^+/Mg^{2+} ionic ratio by weight of seawater is 8.3 (Angino et al., 1964). Claridge and Campbell (1977) showed a Ca/Mg ratio decrease as salt content increased, and attributed the ratio decrease to precipitation of calcium sulphate as the concentration of the sulphate ion increased. Our analyses show a similar trend.

Second, from an age sequence of soils in the eastern Wright Valley Bockheim (1979a) reported consistent Na/Cl ratios for salt-enriched horizons suggesting enrichment from marine aerosols. Similarly, soils from the western Wright Valley have consistent but slightly lower Na/Cl ratios.

5.3. Permafrost

A notable feature of the permafrost map is the unexpected occurrence of large areas of soils with ice-cemented permafrost above 70 cm on the south valley wall associated with meltwater at high elevation. The distribution of permafrost type, dry or ice-cemented, is related to the age of the deposit and the modifying factor of soil water recharge. In the study area, especially at lower elevation, only minor recharge occurs from precipitation with most recharge occurring from subsurface flow — often along the ICP boundary. Streams or rivers contribute to the surface flow and may be channelised with a semi-permanent bed or may be areas of flow over a fan without the formation of an incised channel. Flow is often diurnal during the summer and may eventually develop into channelised flow. Eventually, surface flow supplies water to a soil by subsurface flow. In contrast, subsurface flow occurs from melt water zones at higher elevation where melting provides insufficient water to develop surface flow. The source may not be immediately obvious and the surface not necessarily moist. The supply of meltwater from high elevation and consequent down-slope effects may vary with season, and the surface flows we observed at the base of some slopes on the south wall may not occur every year. Alternatively, they may become more common as a response to unusual warming events such as that which occurred in December 2001–January 2002.

In the study area, soils with ICP at less than 70 cm ($ICP_{<70}$) are associated with the Onyx River and lake, colluvial fans, steep colluvial slopes with melt water supply at higher elevation. $ICP_{<70}$ within Peleus drift, Alpine III and Alpine IV was not observed although nivation hollows (10 m × 5 m × 1 m) and slumping was common along down-slope edges of thick deposits of Peleus till. Permafrost types in the central-western Wright Valley (Fig. 4) comprise of dry-cemented permafrost or ice-cemented permafrost within 70 cm. Within the study area, $ICP_{<70}$ occurs over approximately 2000 ha, 65% of which is on steeply sloping land.

Table 6
Average ionic ratios in water-soluble salts relative to potassium for soils from three regions in the Wright Valley

Data source	Average ionic ratios in water-soluble salts relative to potassium					
	Ca^{2+}	Mg^{2+}	Na^+	Cl^-	NO^{3-}	SO_4^{2-}
Claridge and Campbell (1977)	168	80	232	78	49	376
Bockheim (1979a)	6.4	4.2	38	37	N/A	5.4
This study	3.3	2.4	35	67	5.7	8.8

N/A = not assessed.

6. Conclusions

Two large rock glaciers extending from the south wall of the Wright Valley to Lake Vanda dominate the central-western part of the Valley. In the South Fork the sinuous Upper Wright III moraine parallels colluviated rock glacier material on the south side of the fork. Based on soil morphology and content of salts, both the rock glaciers and Upper Wright III are judged to be of early Quaternary age and considerably less developed and, therefore, younger than the Pliocene-age Alpine III drift. As with other soils in Antarctica, soils up to Alpine IV age show increasing salt content with age except where soil water content is recharged. In the central-western part of the Wright Valley the recharge is predominantly from subsurface flow associated with the Onyx River or melt water from higher elevation. The soil water recharge also affects the presence of ice-cemented permafrost, which occurs where there is soil water recharge. Small, isolated areas of relatively old soils with a high salt content that occur below the level of the hypothesized Glacial Lake Wright (Hall et al., 2001) require a mechanism to develop their high salt content as inundation by lake water should "re-set the clock" in respect of their salt content.

Acknowledgements

This work was partially funded by the New Zealand Foundation for Research, Science and Technology under contract C09X0307. Antarctica New Zealand provided logistical support. Jackie Aislabie contributed useful suggestions to an earlier draft. We appreciate comments from three anonymous reviewers.

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4 SOILS OF WESTERN WRIGHT VALLEY, ANTARCTICA

Antarctic Science 21(4), 355–365 (2009) © Antarctic Science Ltd 2009 doi:10.1017/S0954102009001965

Soils of western Wright Valley, Antarctica

MALCOLM MCLEOD[1]*, JAMES BOCKHEIM[2], MEGAN BALKS[3] and JACKIE AISLABIE[1]

[1]*Landcare Research, Private Bag 3127, Hamilton, New Zealand*
[2]*Department of Soil Science, University of Wisconsin, Madison, WI 53706-1299, USA*
[3]*Earth Sciences Department, University of Waikato, Private Bag 3105, Hamilton, New Zealand*
**mcleodm@landcareresearch.co.nz*

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.

Received 23 October 2008, accepted 22 January 2009

Key words: Dais, Gelisols, Labyrinth, soil chemical properties, soil map

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

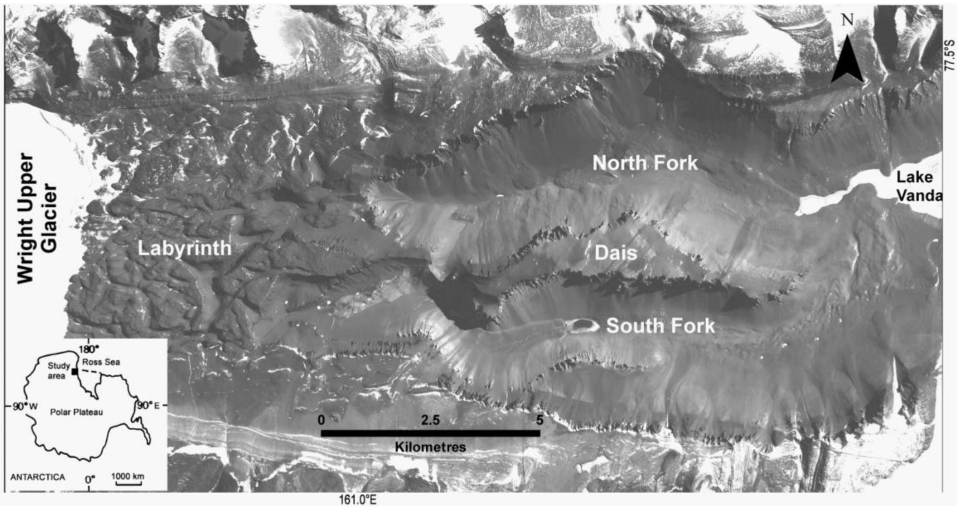

Fig. 1. Location and dominant geomorphic features of the western Wright Valley, Antarctica.

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 $1.6–2.2 \times 10^6$ 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

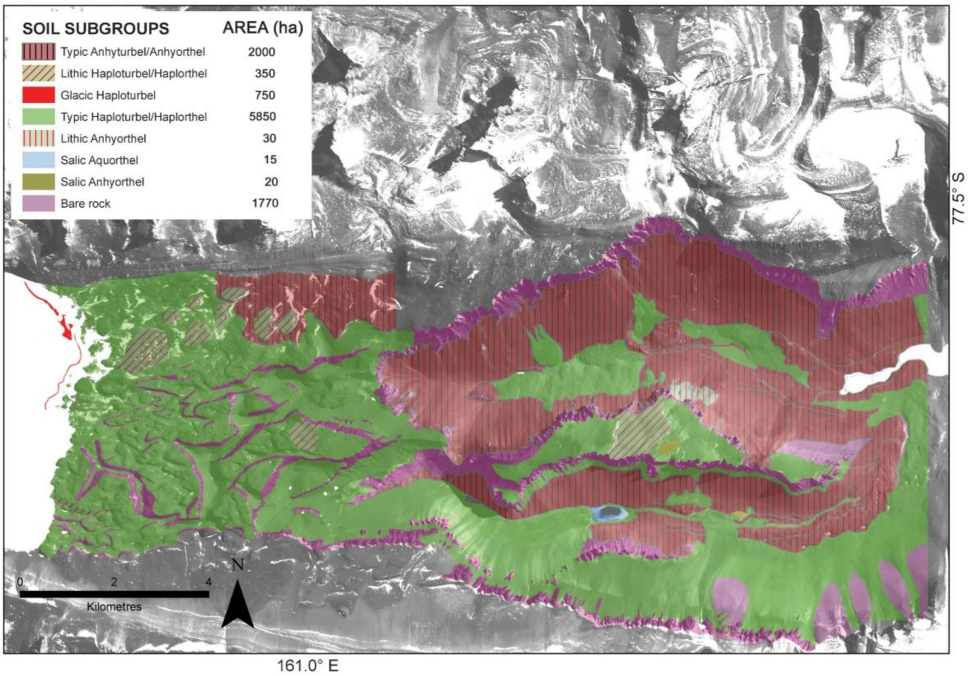

Fig. 2. Soil subgroup distribution within western Wright Valley, Antarctica.

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.

Acknowledgements

This work was partially funded by the New Zealand Foundation for Research, Science and Technology under contract C09X0307 Antarctica New Zealand provided full logistical support. One author (MM) was also supported by a Landcare Research NZ Ltd Capability Development Grant. ALOS PRISM images were captured by JAXA and supplied through America's ALOS Data Node.

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5 VULNERABILITY OF SOILS TO FOOT TRAMPLING IN WRIGHT VALLEY, ANTARCTICA

5.1 ABSTRACT:

Many soils in ice-free Wright Valley, Antarctica, are easily disturbed by foot trampling and rehabilitate slowly. Most rehabilitation processes, except for wind redistribution of finer particles, are slow in the prevailing cold desert conditions. When undisturbed for long periods some soils have developed a ventifacted and varnished desert pavement with salts under surface rocks. In contrast, many younger soils have not developed these features. A rapid method to assess the impact of foot trampling in Wright Valley has been developed that classifies the summed soil disturbance of ten boot prints. Soil vulnerability is the product of soil disturbance and soil rehabilitation values based on the nature of the soil material. Strongly weathered soils, as well as soil material with a high silt content in the layer below the desert pavement, are highly vulnerable, whereas aeolian soil material, while readily disturbed, is quickly rehabilitated and thus of low vulnerability. High, medium and low classes of soil vulnerability have been depicted on a 1:50 000 map that can aid selection of walking routes and campsites by visitors to the area.

Keywords: Antarctica, Wright Valley, soil disturbance, soil rehabilitation, Gelisols.

Submitted as:

McLeod M, Bockheim JG, Balks MR, Hewitt AE. Vulnerability of soils to foot trampling, Wright Valley, Antarctica. Antarctic Science.

5.2 INTRODUCTION

Soils in Wright Valley, Antarctica (Figure 5-1) lack many of the mechanisms for rehabilitation following disturbance that occur under a more temperate climate because of low precipitation, cold temperatures, and minimal biological inputs.

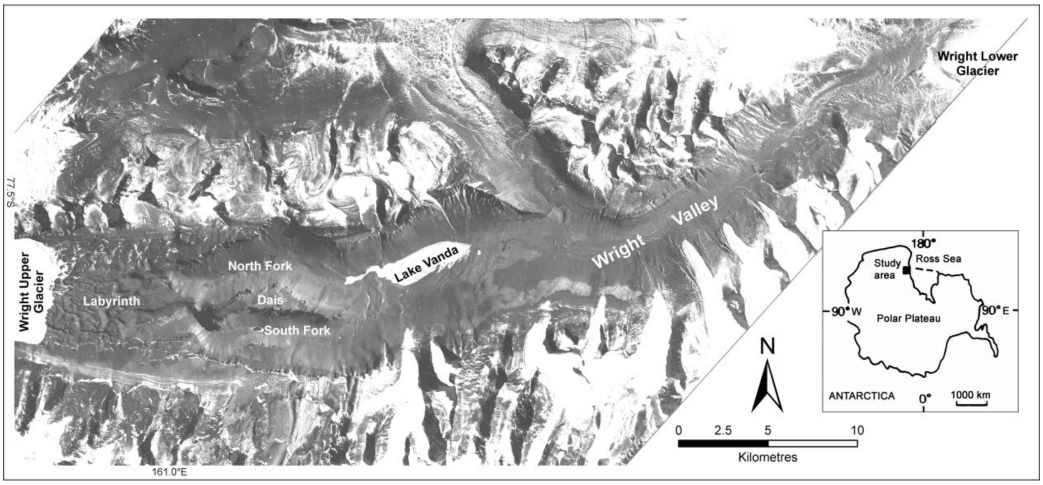

Figure 5-1. Location diagram of Wright Valley, Antarctica.

Wright Valley is part of the McMurdo Dry Valleys Antarctic Specially Managed Area No. 2 where the use of vehicles in the Area is restricted to lake ice (http://www.ats.aq/documents/recatt/Att208_e.pdf). However, trail formation and campsite disturbance, largely from science-based activities, is of concern in the relatively pristine environment. Tourism to the continent is increasing with the dry valleys presenting opportunities to view spectacular landscapes and fossilised biota.

There is therefore an increasing need to have soil vulnerability depicted within a spatial framework to help minimise the impact of human activities on the fragile soil in the Dry Valleys.

While there are many trail impact assessment and monitoring schemes detailed in the literature (Jewell & Hammitt 2000), most pertain to temperate climates with high trail usage where trail deepening and widening, often associated with moist soils, is of importance. In the dry valleys of Antarctica, however, trails are mainly non-existent, usage is low and disturbance, from a single passage on a soil surface that may be millions of years old, may be potentially large. In reviewing human impacts of trampling on Antarctic soils Tin *et al.* (2009) found very few studies on soils, although vulnerability to even low levels of disturbance was recognised. Furthermore, most studies of trampling impact on soil and/or vegetation were undertaken in moist areas with vegetation or under sub-Antarctic conditions. In contrast, there are no higher plants in Wright Valley. Huiskes *et al.* (2006) indicated that direct human impact on ecosystems is currently minor; however, some soil ecosystems cover < 100 m^2. Some of these small ecosystems are valuable to researchers and easily damaged. Thus general comments on human impacts on Antarctic terrestrial ecosystems may be misleading (Tin *et al.* 2009). Tin *et al.* (2009) noted that while the area affected by direct footfall was restricted, only about 0.34% of the continent is ice free and trampling effects are concentrated in these areas.

Campbell *et al.* (1998) investigated the rate of track formation at three sites in Antarctica on a limited range of surface lithologies, and concluded clearly defined tracks can occur after the passage of as few as 20 pairs of feet. Furthermore, greatest disturbance occurred on soils with sandy pebble-gravel textures and the least on soils with a high surface-boulder cover. This work has application in determining potential trampling impact in the vicinity of base camps or sites that are visited on a regular basis and gives insight into potential controlling mechanisms.

The nature of scientific research and a short 3-month window of opportunity each austral summer to work in Wright Valley means that in many locations single-passage new routes are often established. The requirements of trail assessment are therefore aligned to identifying vulnerable trampling conditions by observing the immediate effect of activities and having a simple assessment that can be imparted to field researchers in a short training session while recognising that soil disturbance from walking competes with other factors for researchers’ time and interest.

This paper presents a method for rapidly assessing the impact of foot trampling based on the disturbance of the desert pavement for all of the Wright Valley.

5.3 STUDY AREA

Wright Valley (160.11E 77.31S), 52 km long and approximately 2–4 km wide (Figure 5-1), lies east–west within the ice-free McMurdo Dry Valleys. The valley was carved in the middle Miocene by an eastward flowing wet-based outlet glacier from the East Antarctic Ice Sheet (EAIS) (Prentice *et al*. 1993). The valley is currently terminated at the upper, western end by the Upper Wright Glacier and at the eastern end by the Lower Wright Glacier. Since the Miocene, the EAIS has been relatively stable (Denton *et al.* 1993). However, there have been at least four eastward glacial advances (Calkin *et al.* 1970) of the Wright Upper Glacier and seven westward advances of the Wright Lower Glacier (Hall & Denton 2005). Furthermore, five alpine glaciers descend over the south wall of the eastern end of the valley and have advanced into the valley on at least four occasions (Hall *et al.* 1993). The alpine glacier advances are out of phase with the westward flowing valley advances. During interglacial periods deep water warming raised high southern latitude sea surface temperature leading to an increase in water vapour in westerly flowing air masses which was precipitated over coastal mountains provoking advances of the alpine glaciers (Prentice & Matthews 1991).

The Onyx River flows inland for 30 km from Wright Lower Glacier, for about 3 months of the year during the austral summer. It discharges into permanently frozen Lake Vanda. The Onyx River has created river terraces along its length and is, in places, braided. As a result, some older terraces suffer stream bank erosion and during rare periods in particularly warm summers, significant flood events alter river morphology. Small, often diurnally active, streams flow from the alpine glaciers creating saturated and moist areas of soil on low-angle fans close to the Onyx River.

Strong katabatic winds blowing almost daily down-valley to the coast, and frequent easterly winds in the coastal eastern end of the valley, constantly redistribute finer (up to ca 10 mm) particles. As a consequence, there are large areas of constantly rejuvenating sand sheets and some sand dunes while surface rocks become increasingly abraided and/or varnished with time. Wind-blown sand

and fine gravel also provide a ready source of material to infill contraction wedges in polygonated ground.

Where the floor of the valley is alluvium or aeolian material the surface is predominantly flat to undulating with low surface roughness and with the maximum clast size constrained by energy available from wind or water. Drift material has greater surface roughness, irregular topography and greater slopes. Maximum clast size can be up to several metres diameter. As drift material ages without rejuvenation, surface features become planed to surface through wind abrasion, cracking from large thermal gradients and slow chemical weathering.

5.4 CLIMATE

Wright Valley is considered a cold desert (Bockheim & McLeod 2006). Precipitation is low as a result of the effects of adiabatically warmed, highly turbulent westerly winds (relative humidity 1–10% (Bromley 1985)) that flow down-valley off the Polar Plateau (Keys 1980). At Lake Vanda, Fountain *et al.* (2009) recorded accumulation values of 18 and 32 mm water equivalent for 2004 and 2005 and at Lake Brownworth, closer to the coast values for the same years were 26 and 51 mm water equivalent. Meteorological observations at Lake Vanda Station (1969–1970) show a mean annual air temperature of –20°C (Thompson *et al.* 1971a) and an accumulated depth of snow of 82 mm and 7 mm for 1969 and 1970 respectively. Mean annual soil temperature at 46 cm depth was approximately –20°C (Thompson *et al.* 1971b). At Bull Pass (1999 – 2010), 4 km further east, the mean annual air and soil temperatures at 0, 15, 45 cm depth were all approximately –20°C (http://soils.usda.gov/survey/scan/antarctica/BullPass). At Lake Brownworth, the pro-glacial lake of Wright Lower Glacier, Doran *et al*. (2002) report the mean annual air temperature and the 0, 5 and 10 cm soil temperatures all to be approximately –20°C for the period 1986–2000.

Wind velocities are commonly high throughout much of the valley. For example, at Bull Pass in the base of Wright Valley consistent winds of up to 60 kph are common (http://soils.usda.gov/survey/smst/antarctica/BullPass/index.html), while at Mt Fleming, above Wright Valley to the west and close to the polar plateau, adiabatically driven winds with constant wind speeds of up to 80 kph are common (http://soils.usda.gov/survey/smst/antarctica/MtFleming/index.html). At Lake Brownworth average wind speed (1986–2000) was 11 km/h with a maximum of 115 km/h (Doran *et al*. 2002).

5.5 SOILS

Soils were described following standard methods (Schoeneberger *et al.* 2002) and mapped at 1:50 000 scale using USDA Soil Taxonomy (Soil Survey Staff 2010) at subgroup level to differentiate soil polygons. All soils within the study site have permafrost conditions (Soil Survey Staff 2006) 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.

The soils are typically non- to weakly consolidated stony to gravelly sands with approximately 5% silt and 5% clay.

The soils have no vegetation and very low organic carbon values (typically less than 0.03%), which are thought to be a legacy of organic carbon entrained in the glacial drifts and paleo-lacustrine systems (Burkins *et al*. 2000). As soil biological communities are sparse with low biomass (Hopkins *et al.* 2006) and soil temperatures are low, we conclude they have had a minor role in soil formation.

5.6 METHODS

Field assessment of particle-size distribution

Stone and cobble content (76–200 mm) was estimated with the assistance of visual percentage estimation charts (Folk 1951) while the percentage of gravel and <2 mm fractions were determined by sieving and weighing in the field.

Assessment of foot trampling disturbance

To assess the impact of foot trampling at any location the effects of 10 consecutive foot prints were scored for disturbance using the criteria in Table 5-1.

Table 5-1. Scores associated with four types of boot print disturbance

Boot print disturbance	Score
Nil	0
Imprint–boot print does not break through to 2nd soil layer	1
Partial–boot print partially breaks through to 2nd soil layer	2
Complete–boot print completely breaks through to 2nd soil layer	3

An example from each class is shown in the photographs in Figure 5-2.

Boot print disturbance scores incorporate the effects of operator weight, operator load, gait and boot size. While establishing the disturbance score method, two field-experienced pedologists independently scored 8 sets of the same set of 10 boot prints and arrived at the same total or within 1 point of each other, thus the scoring of the boot imprints is a robust part of the method.

Imprint: boot print does not break through to 2nd soil layer

Partial: boot print partially breaks through to 2nd soil layer

Complete: boot print completely breaks through to 2nd soil layer

Figure 5-2. Examples of boot print disturbance types.

The scores for the 10 foot prints are added and disturbance scores separated into three disturbance classes qualitatively (Table 5-2). To establish the classes, two field-experienced pedologists independently judged the total boot print score for each of eight sites to set disturbance class limits. It was important to separate soils that appeared to have a lot of disturbance and those that appeared to have minimal disturbance with the remainder falling into a middle class.

Table 5-2. Disturbance classes for scores of ten boot prints

Disturbance rating – 10 boot imprints		
Score for 10 imprints	**Disturbance class**	**Disturbance value**
0–10	Low	1
11–24	Medium	2
24–30	High	3

To determine the correlation of the disturbance value and readily observable soil properties we conducted two-sample t-tests (GenStat 8.1©) on disturbance class and the percentage of stones and cobbles (76–200 mm) in the desert pavement.

Assessment of relative rehabilitation rating

The relative rehabilitation value ranks different soil materials in terms of how quickly they return to near pre-disturbance states under Antarctic dry valley conditions. It is a qualitative ranking from field observation and assessment (Table 5-3) and is based on the soil weathering stage (Campbell & Claridge 1975) where the values are grouped as shown in Table 5-4.

Table 5-3. Soil weathering stage with surface rock characteristics (following Campbell & Claridge (1975)).

Weathering stage	**Surface rock characteristics**
1	Fresh, unstained, coarse and angular
2	Light sustaining slight rounding some disintegration
3	Distinct polish staining and rounding some cabinets weathering some ventifacts
4	Boulders much reduced by rounding crumbling and ventifaction strongly developed cabinets weathering staining and polish well developed some desert varnish
5	A few boulders many pebbles forming pavement extensive crumbling sustaining rounding pitting and polish
6	Weathered and crumbled bedrock very strongly stained many residual

Table 5-4. Rehabilitation ratings for soil parent materials of different weathering stage

Weathering stage	**Rehabilitation value**
1 or 2	1
3 or 4	5
5 or 6	25

Where soils show little soil development the soil is given a rehabilitation value of 1. In these areas, foot prints are rehabilitated by wind (sandy surfaces), free water (stream margins, fans, seepage areas) or active cryoturbation (high precipitation coastal margins). On the coarse gravelly to cobbly alluvial surfaces of an active flood plain, which show little soil or desert pavement development, foot prints are usually difficult to observe. Where soils show moderate soil development by having wind polished surfaces on the desert pavement, few salts under surface gravels and cobbles and reduced surface boulder frequency the soil is given a rehabilitation ranking of 5. Such soils are not influenced by coastal precipitation and belong, for example, to drift units of Wright Upper III, Alpine III and some rock glaciers.

Where the desert pavement is planed to the surface, and has intense reddish desert varnish and ubiquitous salts under surface gravels and cobbles, the soil is given a relative rehabilitation ranking of 25. Marked disturbance of this type of surface is visually obvious and in some circumstances may take generations to rehabilitate. Such soils are not influenced by coastal precipitation and belong, for example, to drift units of Alpine IV and some surfaces on the Dais and Labryinth.

Soil vulnerability

Vulnerability is the combined effect of two parts, i.e. a system’s ability to respond and recover from stress (Blaikie *et al*. 1994; Hewitt & Shepherd 1997). In this study we use the product of disturbance and rehabilitation values to gain a vulnerability value (Table 5-5). High-, medium-, and low-vulnerability classes are recognised to differentiate broad differences in the way different parent materials respond to human foot trampling. The highly vulnerable class is that with a vulnerability value ≥ 15. Of moderate vulnerability are those soils with a vulnerability value of 5 or 10, while low vulnerability soils have values of 1, 2 or 3. Soils with high boot print disturbance values and a high vulnerability values are the most vulnerable. In contrast, those soils with low boot print disturbance values and a low vulnerability values are the least vulnerable (Hewitt & Shepherd 1997).

Table 5-5. Soil vulnerability to trampling class based on the product of disturbance and rehabilitation values

Disturbance value	Rehabilitation value	Vulnerability Value	Vulnerability class
1	1	1	Low
1	5	5	Medium
1	25	25	High
2	1	2	Low
2	5	10	Medium
2	25	50	High
3	1	3	Low
3	5	15	High
3	25	75	High

5.7 RESULTS

Disturbance

Disturbance rating and field assessment of particle-size distribution was determined on 63 soils. Disturbance rating scores ranged from 0 to 30 but most occurred within the medium class with scores of 11–24. With experience, the very low scores and very high scores could be anticipated on approach to a site because of the nature of the parent material, e.g., stony/bouldery sites had low disturbance score while sites that were soft underfoot had high scores.

There was a significant difference ($p < 0.02$) between the desert pavement stone plus cobble (76–200 mm) content of soils with High and Low Disturbance Classes (Figure 5-3). This relationship confirms field experience where much disturbance occurs by walking on sandy soils but less on coarser soils. The strength of the relationship also indicates there are instances where this relationship breaks down. An example is where there is a desert pavement of cobbly material overlying finer material with few gravels or cobbles. In this scenario the desert pavement is pushed into the finer material below, resulting in much disturbance to the desert pavement.

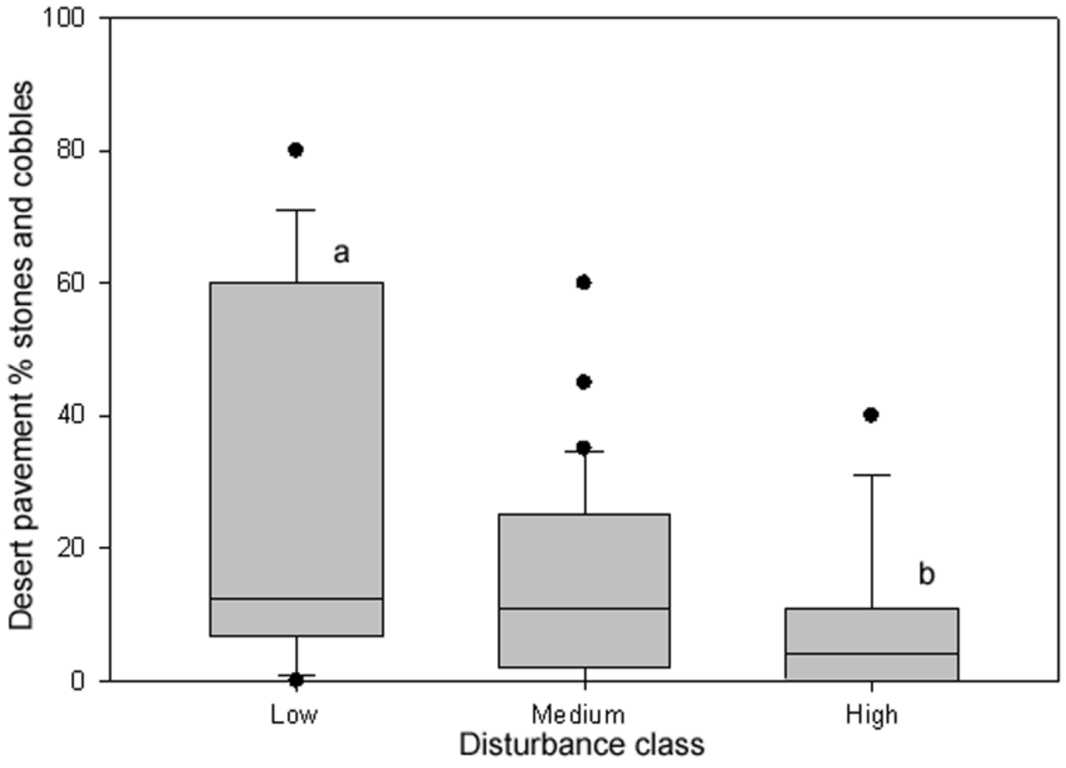

Figure 5-3. Box plot of disturbance classes and % stones and cobbles in the desert pavement. Median, 10th, 25th, 75th and 90th percentiles are shown with dots representing outliers. There is a significant difference between boxes labelled a and b.

Soil vulnerability classes

High-, medium-, and low-vulnerability classes are recognised to differentiate broad differences in the way different parent materials respond to human foot trampling. The highly vulnerable class is that with a vulnerability score ≥ 15. Of moderate vulnerability are those soils with a vulnerability score of 5 or 10, while low vulnerability soils have scores of 1, 2 or 3. While there are nine possible vulnerability scores our dataset, extending the length of Wright Valley, did not encompass soils with a high disturbance rating and a high rehabilitation value.

Soils with low vulnerability are often young surfaces or those subject to rejuvenation by cryoturbation, slope, water or aeolian processes. Within the low vulnerability group aeolian soils (>10 cm surficial aeolian material) rehabilitate most rapidly.

The spatial distribution of soil vulnerability classes (Figure 5-4) shows that soils with low vulnerability occur near the river and ephemeral streams as well as in the eastern end of the valley where precipitation is greater and soils have less soil development (Bockheim 1979). Highly vulnerable soils often occur on localized patches of Peleus Till (Prentice 1985), many of which are too small to identify at 1:50 000 scale, and on old surfaces such as Alpine IV (Bockheim & McLeod 2006) and older. High vulnerability soils also occur on the Dais and Labyrinth.

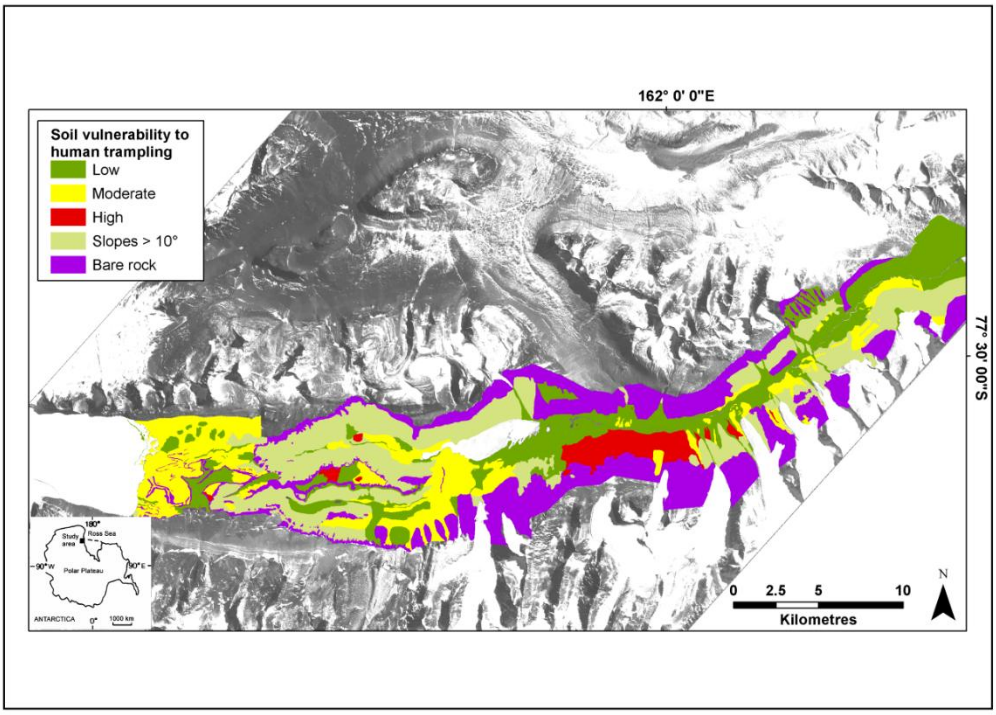

Figure 5-4. Spatial distribution of soil vulnerability to human foot trampling, Wright Valley, Antarctica.

We considered soils on slopes of <10° for our analysis. Under field conditions walkers tended to walk on their toes and ball of foot rather than have their foot flat on the slope when walking orthogonally up slopes of >10°. In the majority of cases “toe walking” resulted in full breakthrough to the second soil layer over the whole of the boot imprint area. For this reason soils on slopes >10° were not analysed further and their vulnerability set to high although this will overestimate vulnerability of some bouldery short steep slopes.

5.8 DISCUSSION

In this paper we describe a rapid method for assessing soil vulnerability to trampling where soil vulnerability is the product of a response (resistance) to, and recovery (resilience) from, stress. In soil science literature use of the terms resistance and resilience generally pertains to sustainability of a soil resource to combat soil degradation under agricultural or horticultural systems (Seybold *et al.* 1999). However, in Antarctica, the number of recovery processes is fewer and slower than in more temperate climates and recovery time frames tend to be longer (Campbell *et al.* 1993). For our purposes in the Antarctic, therefore, a narrower view is envisaged as agricultural use is currently not an option. Terminology applies here to a relatively pristine, cold desert environment with very low biological input, where soil-forming processes are slow and maintenance of the desert pavement is paramount.

Outliers in the box plot of desert pavement stone plus cobble content and Disturbance Class (Figure 5-3), result from the soil layer immediately beneath the desert pavement being developed in material with a high percentage of fines <2 mm or a very competent (firm and coherent desert pavement that is not easily disturbed) desert pavement. In our data set, a competent desert pavement was established either from cobbles settling due to moist soil conditions, receiving wind-blown sand in the interstices or weathering in situ over a long period of time. The rehabilitation rating distinguishes between each of these scenarios by allocating a high rehabilitation rating score to soil where fine material underlies the desert pavement and to soil material with strongly weathered surface cobbles. In contrast, a low rehabilitation rating score is allocated to material where moist soil conditions occur.

In the dry valleys of Antarctica reorganisation of soil material following disturbance is primarily by wind as precipitation is low and falls predominantly as snow that is removed largely by ablation rather than by melting and subsequent runoff (Chinn 1981). Wind velocities are commonly high throughout much of the valley and are responsible for most rehabilitation of disturbed sites. The long-term effects of high wind speed are seen in the natural environment as both desert varnish and ventifacts.

The reliance on wind reorganisation of soil material means that rehabilitation is very slow in coarse material. This is clearly demonstrated in Figure 5-5. The photo (left) of wheel tracks made no later than 1970 on a terrace of the Onyx

River, Wright Valley, was taken during the 2006 austral summer. Thirty-six years after they were made the wheel tracks are still clearly visible.

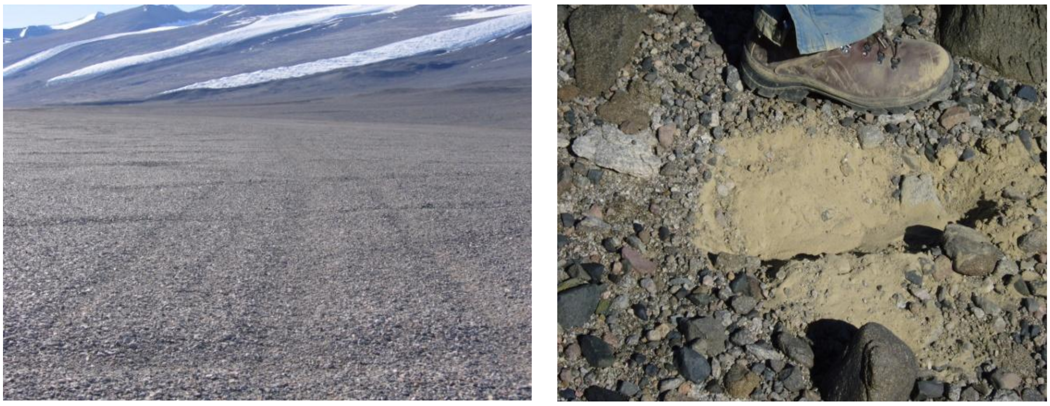

Figure 5-5. Wheel tracks (left) made no later than 1970 on a terrace of the Onyx River are still clearly visible in 2006 and (right) a single foot print in Peleus till. Photo Jim Bockheim.

While wind can have a rehabilitative effect in some settings, it can also exacerbate disturbance. For example, where soils are developed in some facies of the Peleus Till (Prentice *et al*. 1993) in which there is a desert pavement overlying loose “silt-rich” material, trampling of the desert pavement leads to a deep boot print (right, Figure 5-5). During our fieldwork in the Wright Valley we observed that such boot prints had widened considerably the following year as erosion of the silt-rich material continued until sufficient gravels were exposed, or had been contributed from side wall collapse, to form a new protective desert pavement in the rounded boot-print hollow. Similar principles are likely to apply to the small deposits of Hart Ash that occur in, e.g., Wright Valley between Goodspeed and Hart Glaciers.

Soil reorganisation by wind affects large areas within Wright Valley, whereas soil reorganisation by water affects smaller areas. However, water is potentially able to transport larger particles. Isolated areas marginal to periodically flowing water channels show the effect of differing amounts of surface recovery depending on the nature of the flow. Channels up to 1 m deep have been observed associated with alluvial fans that redistribute large volumes of sediment to low-angle toe slopes. Where flow on similar fans is less, only small amounts of debris are transported. For example, during the early stage of a melt-water event gravels up to 10 mm diameter were observed being transported in a narrow channel approximately 10 cm wide. Levy *et al.* (2008) suggest polygon troughs contribute to gully water transport and in the field we observed recently transported debris associated with the polygon troughs. Although Levy *et al.* (2008) investigated polygons close to gully systems we observed channelised flow and consequent debris transport extending for hundreds of metres. In places on low-angle fans and in small depressions where soils were damp we observed reorganization of the desert pavement where coarse gravel and cobbles formed a uniform, flat-lying densely packed layer with a smooth surface compared with surrounding areas. However, in the dry valley environment all these features combined cover only a small area.

With increasing age of Antarctic soils, surface boulder frequency decreases while depth of oxidation increases (Bockheim 1990). Disturbance of soil material of similar size distribution can have different rehabilitation requirements. For example, if a ventifacted and varnished desert pavement cobble with salts on the underside is displaced, it will take considerable time for rehabilitative processes to remove the salts and re-varnish the cobble. In contrast, a fresh cobble on a young alluvial surface will not show strong weathering features, hence any disturbance is less evident. Similarly, desert pavement disturbance on a weathered soil generally reveals a reddish coloured layer below, whereas on a young soil the desert pavement and the underlying layer have similar colour.

Young, active surfaces lack strong weathering or desert pavement features thus recover their “pre-disturbance” appearance more quickly. They also rejuvenate quickly, given that the fastest agents of rejuvenation are wind and water. Thus while areas of sand without coarse material are readily disturbed, their rejuvenation in the windy climate of the Wright Valley is rapid. Furthermore, as sandy material rejuvenates to a depth of at least 10 cm, contrasting soil colours do not develop within the foot print disturbance depth.

Some stony/cobbly surfaces are affected by cryoturbation, resulting in patterned ground with sand wedges between the polygons. Although the sand wedges show little colour change with depth, they may show signs of structural laminations. Upper parts of the wedge are rejuvenated by wind.

Spatial variability and spatial distribution

Short-range (5–20 m) spatial variability of soil vulnerability tends to be very high in the Wright Valley because of the numerous differing surficial geologies. An opposing process to reduce the spatial variability of vulnerability is the greater precipitation towards the eastern end of the valley, which maintains soil cryoturbation. Very weathered soils (weathering stage 6) have low surface boulder frequency (Bockheim 1990), while wind deflation has removed many fines from the desert pavement. The result is relatively large areas of a uniform desert pavement where cobbles and gravels interlock. Note that in the Antarctic older soils are not always the most weathered as in high precipitation coastal areas and areas of snow patches ice-cemented permafrost near the soil surface prevents weathering proceeding to depth and surface cryoturbation tends to rejuvenate the soil.

5.9 CONCLUSIONS

A rapid method to assess the impact of human foot trampling on ice-free areas of Wright Valley, Antarctica has been developed. The method is based on the impact score of 10 boot prints at each site whereby High-, Medium-, and Low-disturbance classes were established. Disturbance was related to the percentage of stones and cobbles in the desert pavement. Rehabilitation classes, based on soil weathering stage, were assigned to different soil materials and finally vulnerability classes (Disturbance × Rehabilitation) were established and applied to soil map units. While sandy aeolian soil material suffers high disturbance from trampling it is quickly rehabilitated by wind and thus has low vulnerability. Strongly weathered surfaces take a long time to re-establish their desert varnish, ventifaction, and accumulation of salts beneath the desert pavement so have high vulnerability even though they may suffer less damage during trampling.

Insights gained from this study could be introduced to science and tourism plans to protect vulnerable soils in the ice-free regions of Antarctica.

5.10 ACKNOWLEDGEMENTS

This work was partially funded by the New Zealand Foundation for Research, Science and Technology under contract C09X0307. Antarctica New Zealand provided full logistical support. ALOS PRISM images were captured by JAXA and supplied through America’s ALOS Data Node. Colleagues Jackie Aislabie and John Scott contributed useful suggestions to an earlier draft. We appreciate comments from anonymous reviewers.

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6 SOIL DISTRIBUTION, PERMAFROST DISTRIBUTION AND SOIL VULNERABILITY TO HUMAN FOOT TRAMPLING IN WRIGHT VALLEY, ANTARCTICA

6.1 INTRODUCTION

Soils and surficial geology of Wright Valley (Figure 6-1) have been studied extensively (Ugolini 1964; Ugolini & Bull 1965, Everett 1971; Calkin & Bull 1972; Bockheim 1978; Prentice et al. 1993; Hall et al. 1993; Hall & Denton 2005; Bockheim & McLeod 2006; Bockheim & McLeod 2008; McLeod et al. 2008; McLeod et al. 2009) explaining the glacial history and paleoclimate of Wright Valley. By studying progressive soil developmental sequences, Wright Valley soils have assisted in the prediction of ages on surfaces for which numerical ages were nonexistent (Bockheim 1978; Bockheim 1990). Soil studies have also identified where overriding of cold-based glaciers has occurred with only minor deposition and where younger drift has not completely buried an older drift, leaving a window of older soil material protruding (Bockheim 1982). The slowing of soil development in the presence of an ice core or ice cemented layer was demonstrated by Bockheim (1979), meaning that for comparative weathering studies, comparable sites must be used, e.g., on end moraines.

Comprehensive soil descriptions along with chemical and physical data for Alpine I, II and III soils associated with the Meserve Glacier area were presented by Everett (1971). However, these studies focus on differentiating glacial drift units and do not present a spatial coverage of the different soil classes over all the landscape. Both Prentice et al. (1993) and Hall and Denton (2005) have presented a spatial representation of surficial geology of all landscape units for the eastern portion of the valley but did not map soil class distribution.

Spatial representation of soil classes in Wright Valley is required to:

- assist with development of more detailed Environmental Domains of Antarctica (Morgan et al. 2007)

- provide a spatial framework for environmental protection (Waterhouse 2001)
- contribute to the Global Soil Map
- guide site selection for other scientific research that requires soil development sequences or knowledge of soil conditions.

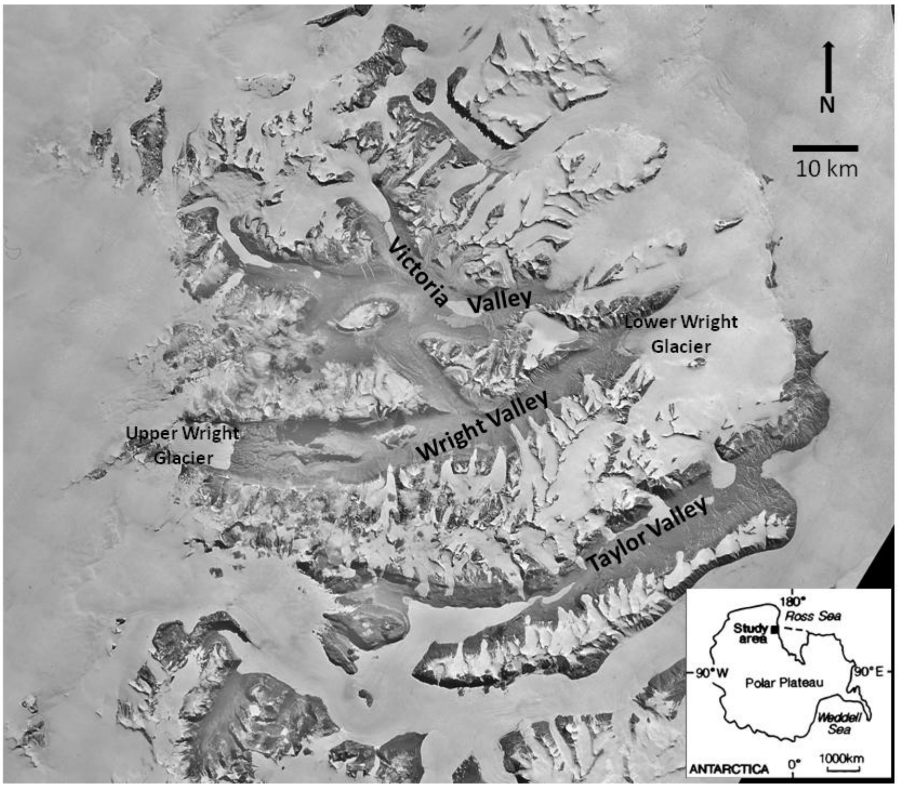

Figure 6-1. Location of Wright Valley within the dry valley system.

This soil survey combines over 185 soil profile descriptions made by Bockheim (2003) over the period 1976 to 1987 with 114 soil profile descriptions made by McLeod, Bockheim, Balks, Hewitt, Aislabie (unpub. data) over the period 2005–2008. Use was also made of soil descriptions by Campbell and Claridge contained within the Landcare Research database http://soils.landcareresearch.co.nz/contents/SoilData_RossSeaSoils_Reports_v1.aspx?currentPage=SoilData_RossSeaSoils_Reports&menuItem=SoilData). Surficial geology maps by Hall et al. (1993), Hall and Denton (2005), and Prentice et al. (1993) materially assisted with spatial representation of soil classes.

6.2 STUDY AREA

The study area covers approximately 40 000 ha of the Wright Valley from Lower Wright Glacier in the east to Upper Wright Glacier 52 km to the west (Figure 6-2).

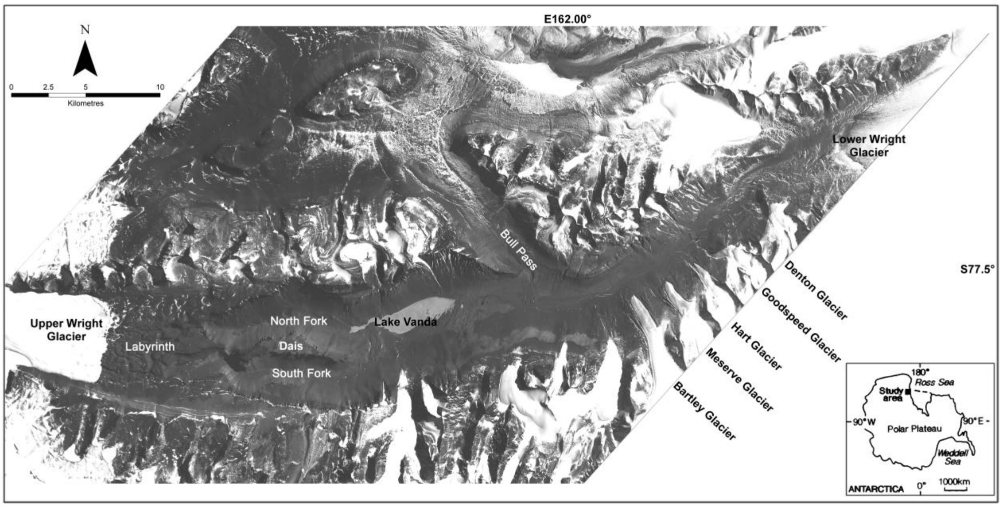

Figure 6-2. Wright Valley study area.

6.3 PHYSIOGRAPHY

Wright Valley is approximately 52 km long and 2–4 km wide, (160.11E 77.31S). The valley lies generally east–west and is part of the ice-free McMurdo Dry Valleys, which was carved in the middle Miocene by a westward flowing wet-based glacier from the East Antarctic Ice Sheet (EAIS) prior to 9±1.5 Ma (Prentice et al. 1993). Calkin and Bull (1972) recognized four major advances of the Wright Upper Glacier: Wright Upper IV, III, II, I. The Wright Upper IV advance has now been correlated with the Peleus till which according to Prentice et al (1993) is >3.9±0.3 Ma.

In the eastern or Lower Wright Valley during cool periods, dry-based glaciers from grounded ice of the Ross Sea Embayment, have advanced westward into Wright Valley on at least seven occasions (Hall & Denton 2005). Furthermore, five large alpine glaciers descend over the south wall of the eastern end of the valley and have advanced into the valley on at least four occasions (Hall et al. 1993). The alpine glacier advances are out of phase with advances of the Lower Wright Glacier because during interglacial periods warm water around Antarctica increases the amount of water vapour in the atmosphere. As air masses move over the cold continent the water vapour is precipitated over the mountains, eventually supplying ice to the alpine glaciers (Prentice & Matthews 1991). Table 6-1 summarises the advances of the different glaciers.

Table 6-1. Age of some surficial deposits in lower Wright Valley

Derivation	**Deposit**	**Age**
Alpine, south wall	Alpine I	[1]Recent
	Alpine II	[2]<3.3 Ma
	Alpine III	[2]<3.5 Ma
	Alpine IV	[2]>3.7 Ma
Lower Wright	Orange lacustrine sediments	[1]24-49k ^{14}C YBP
	Brownworth drift	[1]>49k ^{14}C YBP
	Loke drift	[1]Mid-late Quaternary
	Trilogy drift	[1]Early-mid Quaternary
	Onyx drift	[1]<3.3 Ma
	Wright drift	[1]<3.4 Ma
	Valkyrie drift	[1]Pliocene?
	Loop drift	[1]Pliocene or Miocene?
Upper Wright	Wright Upper I	Recent
	Wright Upper II	[3]70–120 ka
	Wright Upper III	[3]1.2–3.5 Ma
	Peleus till (Wright Upper IV)	[4]>3.9 Ma

[1]Hall and Denton (2005), [2]Hall et al. (1993), [3]Bockheim and McLeod (2008), [4]Prentice et al. (1993).

The braided Onyx River flows inland for 30 km from Lower Wright Glacier (Figure 6-3) for about 3 months of the year during the austral summer, and discharges into ice-covered Lake Vanda.

Figure 6-3. View inland along Wright Valley from Goodspeed Glacier. In the valley floor the braided Onyx River flows inland to Lake Vanda.

Figure 6-4. View east to Lake Vanda, which is frozen except for a narrow moat during summer.

Valley walls are either bare rock in steeper areas or where there is only a minor colluvium source above or they are covered with colluvium. In general much of the wide colluvial areas are relatively stable, whereas small colluvial chutes are more active. Small, often diurnally active, streams flow from the alpine glaciers and alluvial chutes creating saturated and moist areas of soil on low-angle fans close to the Onyx River.

6.4 CLIMATE

Wright Valley is considered a cold desert (Bockheim & McLeod 2006). Precipitation is relatively low as a result of the effects of adiabatically warmed, highly turbulent westerly winds that flow down-valley off the Polar Plateau (Keys 1980). At Lake Brownworth, the pro-glacial lake to Wright Lower Glacier, Doran et al. (2002) report the average mean annual air temperature and the 0, 5 and 10 cm soil temperatures all to be approximately –20°C over the period 1986–2000. In the central area of the valley, on the valley floor at Bull Pass, the mean annual air and soil temperatures at 0, 15, 45 cm depth were all approximately –20°C (1999 – 2010) while average wind speed was 11 km/h with a maximum of 115 km/h (http://soils.usda.gov/survey/scan/antarctica/BullPass/).

Although comprehensive precipitation data are not available, Thompson et al. (1971) recorded an estimated total snow depth of 82 mm and 7 mm for 1969 and 1970 respectively at Lake Vanda. More recently at Lake Vanda, Fountain *et al.* (2009) recorded accumulation values of 18 and 32 mm water equivalent for 2004 and 2005. At Lake Brownworth, closer to the coast, values for the same years were 26 and 51 mm water equivalent. Much of the snow that falls within the valley has been observed to sublimate within a few hours and thus often has relatively little impact on soil processes.

Marchant and Denton (1996) indicate three climatic zones within the area and surrounds (Table 6-2).

Table 6-2. Summary of climatic zones in the Wright Valley from Marchant & Denton (1996).

Zone	Location	Climate type	Landforms
Zone 1 Coastal.	Includes the area between sea level and about 1000 m at the coast and descends inland along valley bottoms to about 100 m elevation at Lake Vanda.	Relative humidity during summer months averages about 75%, reflecting the predominance of south-easterly winds. Precipitation probably exceeds 80 mm of water equivalent per year.	Gelifluction lobes, solifluction terraces, ice wedges, rills, channels, debris flows, levees, and ephemeral ponds, lakes, and rivers.
Zone 2. Intermediate zone	Moderate-to-low-elevation areas in the central Dry Valleys region and high-elevation areas near the coast. Extends from the floor of central Wright Valley to about 800 m elevation at the Dais/Labyrinth.	The predominance of katabatic winds ensure relatively cold and very dry climatic conditions. Relative humidity variable, ranging from about 10% to 70%, reflecting the influence of alternating westward-flowing katabatic winds and eastward- flowing winds from the Ross Sea.	Gelifluction lobes, debris flows, levees, and small streams are rare and are probably active only during extreme climatic events.
Zone 3. Inland zone	Includes all ice-free areas above 800 m elevation along the western rim of the Dry Valleys region.	Relative humidity probably averages less than 45% and reflects the predominance of dry, westerly katabatic winds. Precipitation is rare, but snow blown off the polar plateau accumulates on small glaciers and perennial snow banks in the lee of topographic obstacles.	Meltwater is absent. Glaciers and drifted snowbanks lose mass entirely by sublimation. There are no solifluction terraces. Active polygons are areally restricted to the margins of alpine glaciers and perennial snowbanks.

6.5 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).

Fieldwork was undertaken to validate the preliminary boundaries and determine the nature of soils, permafrost, and surface geology. Soils were described following standard methods (Schoeneberger et al. 2002) and mapped at 1:50 000 scale while using USDA Soil Taxonomy (Soil Survey Staff 2010) at Subgroup level to differentiate soil polygons. All soils within the study site have permafrost conditions (Soil Survey Staff 2010) 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. Colour-development equivalents (CDE) were calculated from classed soil colour hue multiplied by chroma (Buntley & Westin 1965).

Horizon notations follow Schoeneberger et al. (2002) with the addition of a "D" master horizon to describe the desert pavement at the soil surface and "ox" and "n" horizon suffixes used in conjunction with "C" master horizons to represent oxidised and non-oxidised C horizon material. To distinguish between "Cox" and "Cn" horizons in the field the soil material was viewed under a 10× hand lens. Quartz grains in "Cox" material appear lightly stained while those in "Cn" material appear clean and unstained.

Weathering stage follows Campbell and Claridge (1975) (Table 6-3).

Salt stage follows Bockheim (1990) and the morphology of soil salt accumulations is shown in Table 6-4.

The depth of staining is the maximum depth of the layers showing the strongest hue and chroma and is observed using a hand lens. In a soil pit, coherence refers to the thickness of the soil that does not collapse while digging the soil pit. The depth of ghosts refers to the depth to which highly weathered clasts or grüss can be observed in situ.

Table 6-3. Weathering stage following Campbell and Claridge (1975)

Weathering stage	Surface rock characteristics	Soil colour	Horizon development	Soil salts
1	Fresh, unstained, coarse and angular	Pale olive to light gray 5Y 6/3–7/2	Nil	Absent
2	Light staining, slight rounding, some disintegration	Pale brown to light brownish grey 10YR 6/3–2.5Y 6/2	Weak	Few flecks.
3	Distinct polish, staining and rounding, some cavernous weathering, some ventifacts	Light yellowish brown 10YR 5/3–2.5Y 6/4	Distinct	Many salts flecks in upper part of profile and beneath the surface
4	Boulders much reduced by rounding, crumbling and ventifaction, strongly developed cavernous weathering; staining and polish well developed; some desert varnish	Yellowish brown in upper horizons (10YR 5/4) paler in lower horizons	.Very distinct	In discontinuous or continuous horizon beneath surface
5	Few boulders, many pebbles forming pavement, extensive crumbling, staining, rounding, pitting and polish	Dark yellowish brown to yellowish red 10YR 4/4–5YR 5/8	Very distinct	In horizon 20 to 30 cm from surface and scattered throughout profile
6	Weathered and crumbled bedrock, very strongly stained mainly residual	Strong brown to yellowish red and dark red 7.5YR 5/6–2.5R 3/6	Very distinct	In horizon 20 to 30 cm from surface and scattered throughout profile

Table 6-4. Salt morphology following Bockheim (1990)

Salt stage	Maximum salt morphology
0	None
I	Coatings on stone bottoms
II	Few flecks < 20% of surface area of horizon has accumulations that are about 1 to 2 mm in diameter
III	Many flecks > 20% of surface area has flecks as above
IV	Weakly cemented pan
V	Strongly cemented pan
VI	Indurated pan

Using ArcGIS 9.3© software, final soil polygon boundaries were plotted onto the 5th 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).

6.6 CHEMICAL ANALYSES

For chemical analysis soils were sampled by horizon generally to at least 70 cm depth unless ice-cemented permafrost or boulders were encountered. Both <2- and >2-mm fractions were weighed, and the <2-mm fraction was retained for analysis in New Zealand.

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^-, NO_3^-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.

To determine the presence of a salic horizon requires the EC of a saturated paste to be measured. However, we determined EC values from a 1:5 soil:water extract and multiplied by five as an approximation of the saturated paste method.

Total soluble salts (mg/cm^2) to 70 cm depth (TSS_{70}) were calculated following Bockheim (1978) where horizon salts = EC (mS/cm) ×horizon thickness (cm) × 4.8. Furthermore, following Bockheim and McLeod (2006) no correction was made for coarse fragments >2 mm as they also readily accumulate salts. Salts are reported to a depth of 70 cm because this depth generally represents the maximum depth of staining.

6.7 SOIL PARENT MATERIALS AND SOIL EVOLUTION IN WRIGHT VALLEY

Predominant soil parent materials in Wright Valley are glacial drifts, alluvium, colluvium and rock glaciers (Table 6-5) with the larger rock glaciers being confined to the western part of the valley.

When soil parent material is first exposed as glacial drift it contains moisture in the form of ice. With time, interstitial ice is sublimated (Bockheim & McLeod 2006) leaving dry-frozen soil material that allows normal soil weathering and development processes to proceed. The degree of soil development in Wright

Valley can be expressed by salt stage (Bockheim 1990), weathering stage (Campbell & Claridge 1975), and morphological and chemical properties of the soil. For example, the depth of staining, depth of the coherence, and also maximum depth of rock ghosts or pseudomorphs generally increase with soil development (Appendix I – Bockheim & McLeod (2006)). Bockheim and McLeod (2006, 2008– Appendix II) provide salient soil morphology of maximum soil development for many of the drifts and these are augmented with non-drift materials in Table 6-5.

Bockheim and McLeod (2006) also show that 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. In environments where the the ice table is not being recharged, Typic Anhyorthels occur on drift of late to mid-Quaternary age, Salic Anhyorthels on drift of early Quaternary age, and Petrosalic Anhyorthels on drift of Pliocene age or older. This sequence is shown in Figure 6-5 modified from Bockheim and McLeod (2006) with pictorial examples in Figure 6-6. Salts originate primarily from marine aerosols (Bockheim 2002).

Table 6-5. Predominant soil parent materials and associated soil properties in Wright Valley after Bockheim and McLeod (2006, 2008)

	Typical		Typical maximum depth		
Parent material	**Weathering**	**Salt**	**Staining**	**Coherence**	**Ghosts**
Alpine I	1	0	0	5	0
Alpine II	3	2	15	35	4
Alpine III	6	4	>43	>56	21
Alpine IV	6	6	>55	>100	19
Lacustrine sediments	1	0	0	5	0
Brownworth drift	1	1	0	23	0
Loke drift	2	1	0	31	0
Trilogy drift	2	1	13	21	7
Onyx drift	4	3	29	5	13
Wright drift	4	3	>27	>30	16
Valkyrie drift	5	5	>44	>94	39
Loop drift	6	5	>60	>88	9
Wright Upper I	3	1	0	6	0
Wright Upper II	3	1	12	23	2
Wright Upper III	4	1	42	60	17
Peleus till	5	4	24	>100	10
Rock glacier	3	1	20	23	4
Alluvium	1–2	0–1	0	5	0
Colluvium	1–3	0–1	0–11	0–50	0–21

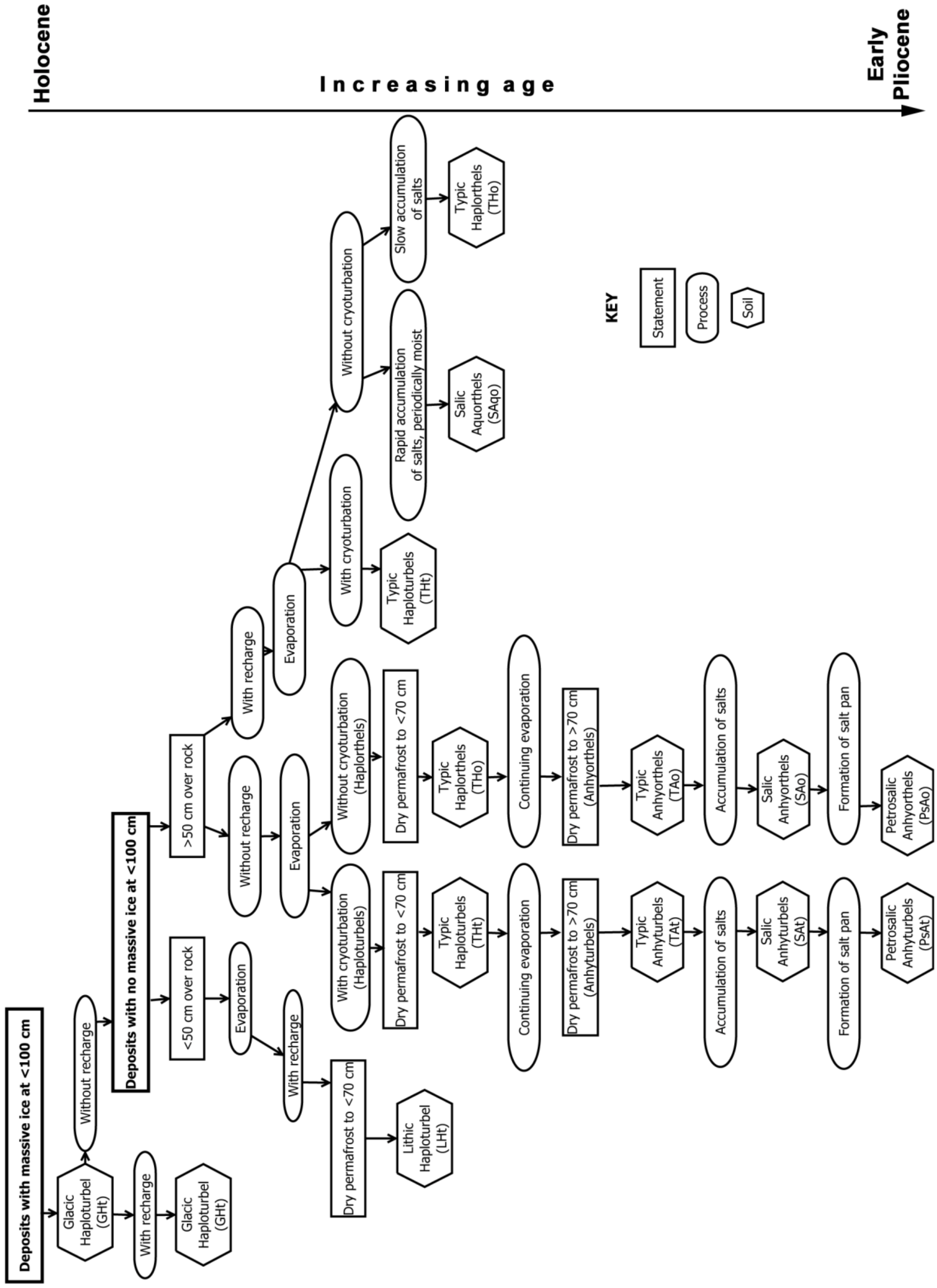

Figure 6-5. Evolution of soils in Wright Valley modified from Bockheim and McLeod (2006).

Glacic Haploturbel

Typic Haploturbel

Typic Anhyorthel

Petrosalic Anhyorthel

Figure 6-6. Typical soil subgroups occurring in Wright Valley.

There are, however, anomalies in the soil development sequence. Bockheim (1979) showed that in environments where the ice table was recharged, the continued presence of ice-cemented permafrost at shallow depth limited soil development. In Wright Valley, ice-cemented permafrost is common in recently deposited parent materials or where the ice cement table is recharged. The ice cement table can be recharged by precipitation in the higher precipitation coastal areas, regular snow patch melt, subsurface flow from higher altitudes over the ice-cemented permafrost interface or by surface flow of melt water. Landscape complexities mean that a range of soil taxa can occur over distances of tens of metres or less.

6.8 SOIL SUBGROUPS

Thirteen soil subgroups have been mapped. Soil Taxonomy (Soil Survey Staff 2010) does not recognise a petrosalic horizon. Therfore the subgroups of Petrosalic Anhyorthels and Petrosalic Anhyturbels are not recognized by Soil Taxonomy (Soil Survey Staff 2010). As these two subgroups likely only occur in the cold desert climate zones of Antarctica the following definition has been used.

Petrosalic Horizon

A petrosalic horizon is an horizon in which salts that are more soluble than gypsum in cold water have accumulated to the extent that the horizon is cemented or indurated. The horizon typically occurs as a subsurface horizon in cold desert soils.

Required Characteristics

A petrosalic horizon is 15 cm or more thick and has, for 90 consecutive days or more in normal years:

1. The horizon is cemented or indurated by salts that are more soluble than gypsum in cold water: *and*
2. The cumulative width of the horizon must exceed 50% of an exposed face: *and*
3. An electrical conductivity (EC) equal to or greater than 30 dS/m in the water extracted from a saturated paste; *and*
4. A product of the EC, in dS/m, and thickness, in cm, equal to 900 or more.

6.9 PERMAFROST

Permafrost is defined as a thermal condition in which a material (including soil material) remains below 0°C for 2 or more years in succession (Soil Survey Staff 2010).

Wright Valley is considered to be a cold dry desert and in areas where there is little soil moisture recharge interstitial ice sublimates with time (Bockheim & McLeod 2006) leaving dry permafrost. The term “dry permafrost” may not be commonly used by scientists working in the northern hemisphere (Bockheim & McLeod 2006) as dry permafrost may be restricted globally to the dry valleys of Antarctica (Bockheim & Tarnocai 1998).

6.10 VULNERABILITY TO HUMAN FOOT TRAMPLING

Soil vulnerability is the product of soil disturbance and soil rehabilitation values based on the nature of the soil material. A rapid method to assess the impact of foot trampling in Wright Valley has been developed and is described in Chapter 5 (McLeod at al. submitted).

6.11 MAP UNIT DESCRIPTIONS

In this soil survey, map units (Map 1) are defined on the basis of soil subgroups (Soil Survey Staff 2010) because the spatial depiction of the subgroups provides a unifying and understandable picture of the soils in the landscape.

In Wright Valley, and probably all ice-free areas, there are USDA Soil Taxonomy (Soil Survey Staff 2010) great group differences over short distances because soil development within the same parent material can be arrested where recharge of the ice table maintains ice-cemented permafrost at shallow depth (Bockheim 1979). Alternatively, salts may not build up in a profile because of leaching around a recurring snow patch. The snow patch may not be present every year or at the same time as the soil surveyor and may not leave surface indication. When the soil classification of a map unit is given on the soil map (Map 1) it is the maximum soil development and lesser developed soils should be expected as inclusions. As a guide, map units of more developed soils such as Petrosalic and Salic Anhyorthels are likely to contain a greater proportion of inclusions of lesser developed soils.

6.11.1 SALIC AQUORTHELS

Salic Aquorthels (SAqo) are mapped over a very small area (15 ha) associated with Don Juan pond in the South Fork. Salic Aquorthels require morphological evidence of reducing conditions in the form of redox segregations with chroma 2 or less and a high water table (Soil Survey Staff 2010). We recorded a water table at 32 cm and judging from the lack of change in soil morphology at this level we think it is at a low level, with 15 cm being a more typical level. The high concentration of calcium chloride in the soil water solution prevents it from freezing (Marion 1997). Currently we do not think low chroma colours (10YR 2/1) in the 2 – 15 cm horizon are evidence of reducing conditions. Nevertheless, we have assigned the classification of Salic Aquorthels based on the presence of the water table.

Range of morphological properties

We have insufficient data to give a range of properties but depth to ice-cement in the permafrost exceeds 50 cm. Weathering stage is between 3 and 4, salt stage is 4, and in January 2007 the water table was at 32 cm depth.

The Salic Aquorthel has a brownish yellow gravelly sand desert pavement underlain by Cz horizons. The upper Cz horizon contains black layers 1 – 3 cm thick in a very dark greyish brown sandy matrix.

Table 6-6 gives detailed chemistry for the Salic Aquorthel sampled. pH is slightly to moderately alkaline (range 7.6 – 7.9) because of the soluble salt load in the profile. Total soluble salts to 70 cm are approximately 3380 mg/cm^2. Anions are dominated by chloride while cations are dominated by sodium in the surface horizon and by calcium at lower concentrations in lower horizons.

Physiographic position

Salic Aquorthels occur in low-lying depressions of the South Fork.

Inclusions

None noted specifically because of the small area, but likely to be inclusions of Salic Haplorthels and Typic Haplorthels.

Figure 6-7. Profile WV07-04 (upper) and landscape view (lower) at Don Juan Pond, South Fork, Wright Valley.

Soil subgroup: Salic Aquorthel
Coordinates: S77.56409 E161.20024
Location: South Fork, Wright Valley
Profile Description
Landform: Saline pond margin
Parent material: Saline pond deposits
Weathering stage: 3–4
Salt stage: 4

Desig.	Depth (cm)	Description
D	0–2	Brownish yellow (10YR 6/6) gravelly sand, massive, slightly hard, weakly cemented, abrupt smooth boundary.
Cnz1	2–15	Very dark greyish brown 2.5Y 3/2 with black (10YR 2/1) layers 1–3 cm thick, sand, single grain, loose, abrupt smooth boundary.
Cnz2	15–32	Dark yellowish brown (10YR 3/6) sand, single grain, loose, abrupt wavy boundary.

Table 6-6. Chemical properties of a Salic Aquorthel.

Site	Feature	Depth (cm)	pH (water)	EC (1:5) (mS/cm)	TSS_{70} (mg/cm^2)	Water-Soluble Calcium mmol(+)/kg	Magnesium mmol(+)/kg	Sodium mmol(+)/kg	Potassium mmol(+)/kg	Chloride mmol(-)/kg	Nitrate-N mmol(-)/kg	Sulphate mmol(-)/kg
WV07-04	Don Juan	0–2	7.6	53.6	3380	669	16	1010	2.4	3170	2.5	43
	Pond	2–15	7.8	8.11		110	2.8	21	0.4	248	0.1	5.4
	sediments	15–32	7.6	8.93		142	3.7	21	0.5	326	0.1	0.9

6.11.2 GLACIC HAPLOTURBELS

Glacic Haploturbels (GHt) are the dominant soil subgroup over approximately 35 ha or less than 1% of the area. Glacic Haploturbels are developed on the youngest Alpine drift (Alpine I) as lateral moraines and drift associated with the most recent advance of Wright Lower and Wright Upper Glaciers. Glacic Haploturbels are also developed in Orange lacustrine sediments of Hall and Denton (2005). Glacic Haploturbels contain a layer of ice (75% visible ice) within one metre of the soil surface.

Range of morphological and chemical properties

There is little soil development within Glacic Haploturbels so the range of soil properties is limited. The profile consists of D over Cn horizons. B and Cox horizons were absent. A typical profile developed in the center of diffuse high centered, non-sorted polygons (WV05-26) contains a weakly developed desert pavement over gravelly sandy greyish brown material. Depth to ice ranges from 10 to 50 cm while colours range from 2.5Y 5/2 to 6/2. There is only one profile (WV05-26) with chemical analyses. Maximum EC is 2.7 mS/cm. Salt content in the profile to 70 cm is approximately 143 mg/cm^2. Chloride is the dominant anion with a maximum value in the surface horizon of 106 mmol$_{(-)}$/kg.

Glacic Haploturbels are weathering stage 1 and salt stage 1 or less, although thin carbonates may occur under desert pavement gravels. The GHt have low TSS$_{70}$ (Bockheim & McLeod (2006) dominated by sodium and chloride ions (Table 6-7). They generally have low (≤ 8) CDE, which reflects their young age, dominantly acidic parent rock and arrested soil development (Bockheim 1979). However, soils associated with Wright Upper I deposits may have CDE>8 because of the doleritic parent material.

Physiographic position

Glacic Haploturbels occur on the youngest drift of the alpine glaciers and Upper Wright Glacier as well as localised areas of lacustrine deposits on the valley floor.

Inclusions

None noted specifically because of the small area but likely to be inclusions of Typic Haplorthels.

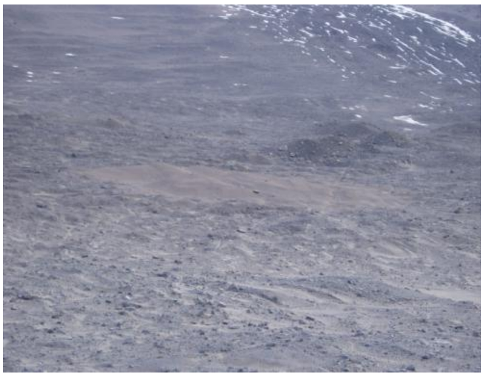

Figure 6-8. Profile WV05-26 (upper) and landscape view (lower) NNW over orange-colored lacustrine deposits in lower Wright Valley. Photo: Jim Bockheim.

Soil subgroup: Glacic Haploturbel
Coordinates: S77.42119 E162.68245
Location: Lower Wright Valley
Profile Description
Landform: Hummock of lacustrine sediments
Parent material: Orange lacustrine deposits
Weathering stage: 1
Salt stage: 1

Desig.	**Depth (cm)**	**Description**
D	0–1	Light brownish grey 2.5Y 6/2 very gravelly sand, single grain, loose, few carbonates under surface gravel, very abrupt smooth boundary.
Cn	1–4	Greyish brown 2.5Y 5/2 moist fine sand, single grain, loose, abrupt wavy boundary.
2Cn	40–50	Light brownish grey 2.5Y 6/2 gravelly coarse sand, single grain, loose, abrupt wavy boundary.
3Cwf	50+	Ice.

Figure 6-9. Glacic Haploturbel developed in Alpine I drift.

Figure 6-10. Marginal deposit of Alpine I drift on the west (left in photo) of Goodspeed Glacier, Lower Wright Valley.

Table 6-7. Chemical properties of a Glacic Haploturbel

				EC		Water-Soluble						
Site	**Feature**	**Depth (cm)**	**pH (water)**	**(1:5) (mS/cm)**	**TSS_{70} (mg/cm^2)**	**Calcium mmol(+)/kg**	**Magnesium mmol(+)/kg**	**Sodium mmol(+)/kg**	**Potassium mmol(+)/kg**	**Chloride mmol(-)/kg**	**Nitrate-N mmol(-)/kg**	**Sulphate mmol(-)/kg**
WV05-26	Orange	0–1	7.5	2.7	145	22	10.5	87.4	1.4	106	4.6	20.8
	lacustrine	1–4	8.4	2.6		46	13.2	65.6	1.0	63.4	4.5	68
	deposits	4–50	7.1	0.4		4.7	3.5	13.1	0.4	16.8	1.6	1.0

6.11.3 SALIC HAPLORTHELS

Salic Haplorthels (SHo) are mapped over a very small area (12 ha) associated with Don Juan pond in the South Fork and depressions in the North Fork as well as smaller unmapped depressions in the forks and main valley. Salic subgroups of Haplorthels are not recognized in USDA Soil Taxonomy (Soil Survey Staff 2010) probably because it was thought a salic horizon could not form in a moist soil environment. In Wright Valley Salic Haplorthels occur on the margin of saline ponds or in saline depressions.

Range of morphological properties

There are insufficient data to give a range of properties but depth to ice-cement within the permafrost exceeds 70 cm. The soil is moist and it is likely that the concentration of salts within the soil water prevents the soil from freezing (Marion 1997). The weathering stage is between 3 and 4 with salt stage 3.

The Salic Haplorthel has a light yellowish brown very gravelly sand desert pavement underlain by a Coxz horizon on dark greyish brown, gravelly sand Cn horizons.

Table 6-8 gives detailed chemistry for the Salic Haplorthel sampled. pH is slightly to moderately alkaline (range 7.4 – 7.9) because of the soluble salt load in the profile. Total soluble salts to 70 cm are approximately 4000 mg/cm^2. Anions are dominated by chloride while cations are dominated by sodium in the surface horizon and by calcium at lower concentrations in lower horizons.

Physiographic position

Salic Haplorthels occur in depressions on the valley floor, especially in western parts of the valley.

Inclusions

None noted specifically because of the small area but likely to be inclusions of Typic Haplorthels or Salic Aquorthols.

Figure 6-11. Profile WV07-05 (upper) and landscape view (lower) at Don Juan Pond, South Fork, Wright Valley.

Soil subgroup: Salic Haplorthel
Coordinates: S77.56436 E161.19810
Location: South Fork, Wright Valley
Profile Description
Landform: Saline pond margin
Parent material: Saline pond deposits
Weathering stage: 3–4
Salt stage: 3

Desig.	**Depth (cm)**	**Description**
D	0–4	Light yellowish brown (10YR 6/4) very gravelly sand, massive, slightly hard, weakly cemented in places, abrupt smooth boundary.
Coxz	4–26	Brown (10YR 5/3) sand, single grain, very friable, abrupt smooth boundary.
Cn1	26–40	Olive brown (2.5Y 4/3) gravelly sand, single grain, very friable, clear wavy boundary.
Cn2	40–100+	Dark greyish brown (2.5Y 4/2) gravelly sand, single grain, loose, clear wavy boundary.

Table 6-8. Chemical properties of a Salic Haplorthel.

				EC		**Water-Soluble**						
Site	**Feature**	**Depth (cm)**	**pH (water)**	**(1:5) (mS/cm)**	**TSS_{70} (mg/cm^2)**	**Calcium mmol(+)/kg**	**Magnesium mmol(+)/kg**	**Sodium mmol(+)/kg**	**Potassium mmol(+)/kg**	**Chloride mmol(-)/kg**	**Nitrate-N mmol(-)/kg**	**Sulphate mmol(-)/kg**
WV07-05	Saline	0–4	7.9	39.3	4000	189	2.9	413	0.9	2140	0.0	43
	sediments	4–26	7.9	8.1		121	2.3	49	0.4	224	0.1	5.4
		26–40	7.7	6.4		105	2.1	11	0.2	122	0.1	0.9
		40–60	7.4	13.6		188	4.8	27	0.5	382	0.0	

6.11.4 TYPIC HAPLORTHELS/HAPLOTURBELS

The Typic Haplorthels/Haploturbels soil association (THo/THt) is mapped over approximately 11 200 ha or 35% of the ice free study area. While THo/THt are common at the eastern, more humid end of the valley, they are not restricted to any climatic zone or parent material. Typic Haplorthels/Haploturbels are mapped on patterned ground where depth to permafrost with ice-cement (ICP) is less than 70 cm. The Typic Haplorthels/Haploturbels association is mapped as much of Wright Valley contains patterned ground. Polygon centers are often Haplorthels with Haploturbels associated with cryoturbated margins of the polygon. Where homogenisation of upper layers of the soil occurs by wind, water or slope movement, polygons fail to develop. In these areas of sand drifts, moist toe slopes or active colluvial slopes where depth to ICP is less than 70 cm, Typic Haplorthels are dominant.

Range of morphological properties

Average depth to ice-cement in the permafrost is 36 cm, range 12–68 cm. Average weathering stage is 1.9 and salt stage is 0.9. Maximum colour development equivalent (CDE) ranges from 2 in the eastern end of the valley to 30 in the Ferrar dolerite-rich drift in the Labyrinth. For THo/THt in the central-lower Wright Valley there is a significant difference (p=0.002) in maximum EC below the desert pavement, of soils with CDE$\leq$ 8 and those with CDE>8, the latter soils having greater EC. Map units to recognise the differences in THo/THt have been established *viz*, THo/THt CDE$\leq$ 8 and THo/THt>8. In Wright Valley, the two CDE classes cover approximately the same area but the soils with low CDE generally occur towards the eastern end of the valley. Higher CDE values are associated with Wright Upper II drift which has a high dolerite content and the weathering products impart a reddish hue to the soil.

Typic Haplorthels/Haploturbels generally have a desert pavement underlain by Cn on Cnfm horizons although Cox horizons have been described less frequently. Bwz horizons were not observed. Typic Haplorthels/Haploturbels exhibit a wide range of morphologies. Typic Haplorthels/Haploturbels with shallow depth (20 – 30 cm) to ICP show little soil development (e.g., profile W06-27) contain hue 2.5Y throughout with chroma $\leq$ 3, a low CDE of <8 and low EC below the desert pavement. Typic Haplorthels/Haploturbels with greater depth to ICP often exhibit greater soil development (e.g., profile W05-11) because soil development is not arrested by ice cement. Where depth to ICP is greater, Typic Haplorthels/Haploturbels commonly have chroma ≥ 4, CDE >8 and higher maximum EC below the desert pavement.

Typic Haplorthel/Haploturbels are ubiquitous and range in age from Recent to early-mid Quaternary. They have been described on aeolian deposits, alluvium, colluvium, Trilogy drift, Hummocky H1 drift (H1), Brownworth drift, Loke drift, Upper Wright II and III, Alpine II, III, and rock glaciers. Some of these deposits have had their soil morphology and TSS_{70} summarised by Bockheim and McLeod (2006).

Table 6-9 gives more detailed chemistry for the THo/THt. pH is predominantly alkaline (range 6.1 – 9.6) because of the soluble salt load in the profile. Although the salts increase pH, total soluble salts to 70 cm average 132 mg/cm^2 (range 3–898), which is low for Antarctic soils. The low salt values are due to either young age or leaching. In Wright Valley, leaching occurs from direct snow melt or melt water moving through the profile over the ICP, from higher elevation.

Anions are dominated by chloride but there are exceptions. In three soils analysed associated with rock glaciers in the western part of the valley (WV06-16, WV06-19, WV07-36, WV07-37) at least part of the profile is dominated by sulphate anions. However, other soils on rock glaciers (WV07-6, WV07-7) are dominated by chloride anions. Cations are dominated by sodium but if sulphate is the dominant anion it is likely calcium is the dominant cation.

Physiographic position

Because the Typic Haplorthel/Haploturbels soil association often occurs where there is recharge of the ice table, Typic Haplorthel/Haploturbels are ubiquitous occuring in most physiographic positions. For example, precipitation keeps the ice table recharged at the eastern end of the valley while subsurface flow from snow melt on the south valley wall keeps the ice table recharged in many locations to the west.

Inclusions

There may be inclusions of Glacic Haploturbels on the Brownworth drift.

Typifying profile with low maximum CDE.

Soil subgroup: Typic Haploturbel
Coordinates: S77.42462 E162.67898
Location: Lower Wright Valley
Profile Description
Landform: Conical knob
Parent material: Loke drift
Weathering stage: 2
Salt stage: 1

Desig.	Depth (cm)	Description
D	0–0.5	Near light brownish grey 2.5Y 6/1 very gravelly sand, 10% stones and 15% cobbles, single grain, loose, few carbonates under surface gravel, very abrupt smooth boundary.
Cn1	0.5–12	Light brownish grey 2.5Y 6/2 gravelly fine sand, 2% cobbles, single grain, loose, abrupt wavy boundary.
Cn2	12–34	Greyish brown 2.5Y 5/2 gravelly sand, 2% cobbles, single grain, friable, abrupt wavy boundary.
Cnfm	34+	Greyish brown 2.5Y 5/2 gravelly sand, strongly cemented.

Typifying profile with high maximum CDE.

Figure 6-12. Soil profile WV06-27 (upper) and WV07-18 (lower). Photos: Jim Bockheim.

Soil subgroup: Typic Haploturbel
Coordinates: S77.54382 E160.72659
Location: Labyrinth, western Wright Valley
Profile Description
Landform: Glaciated terrain with thin drift
Parent material: Mixed till
Weathering stage: 3
Salt stage: 1

Desig.	Depth (cm)	Description
D	0–1	Light yellowish brown 10YR 6/4 very gravelly sand, 25% stones and 20% cobbles, single grain, loose, few carbonates under surface gravel, very abrupt smooth boundary.
Cn	1–9	Light yellowish brown 10YR 6/4 gravelly sand, 5% cobbles, single grain, very friable, clear wavy boundary.
2Cox	9–38	Dark yellowish brown 10YR 4/4 gravelly sand, 5% cobbles, single grain, very friable, abrupt wavy boundary.
2Coxfm	38+	strongly cemented.

Table 6-9. Chemical properties for Typic Haplorthels/Haploturbels

				EC		**Water-soluble**						
Site	**Feature**	**Depth (cm)**	**pH (water)**	**(1:5) (mS/cm)**	**TSS_{70} (mg/cm^2)**	**Calcium mmol(+)/kg**	**Magnesium mmol(+)/kg**	**Sodium mmol(+)/kg**	**Potassium mmol(+)/kg**	**Chloride mmol(-)/kg**	**Nitrate-N mmol(-)/kg**	**Sulphate mmol(-)/kg**
WV05-1	Alluvium	0–1	8.5	0.1	40	0.3	0.9	4.5	0.5	2.6	0.4	1.2
		1–27	7.3	0.3		3.2	3.4	6.5	0.5	10	2.1	1.0
		27+	7.2	0.1		0.3	1.0	2.3	0.3	1.6	0.2	1.0
WV05-3	Colluvium	0-1	7.9	0.5	60	8.5	3.8	9.6	0.7	12	2.5	7.8
		1–25	7.6	0.5		5.7	4.4	8.7	0.8	14	2.7	2.7
		25+	8.7	0.2		0.4	0.7	5.3	0.3	4.9	0.6	0.7
WV05-8	Brownworth drift	0–1	9.1	0.3	440	2.5	2.3	8.6	1.1	9.1	1.5	6.8
		1-21	7.6	2.6		70	12	49	1.7	52	7.2	85
		21–63	8.1	1.0		5.9	4.8	29	1.6	27	5.4	13
WV05-9	Trilogy drift	0–1	8.5	0.1	10	0.5	0.9	3.1	0.6	2.0	0.1	1.6
		1–37	8.1	0.0		0.4	1.2	1.2	0.6	0.4	0.02	0.2
		37+	8.7	0.1		1.5	1.8	1.6	1.0	0.5	0.02	0.4
WV05-11	Brownworth drift	0–1	9.2	0.2	375	1.1	1.9	8.1	1.4	5.1	0.4	1.8
		1–27	8.3	1.6		25	9.2	39	2.2	36	5.4	36
		27–46	8.0	1.5		16	8.5	40	3.0	35	5.2	30
		46–60	8.9	0.5		1.2	1.5	17	1.1	13	1.4	4.4
		60+	8.9	0.6		2.0	1.7	17	0.9	17	1.5	4.3

Table 6–11 ctd. Chemical properties for Typic Haplorthels/Haploturbels

						Water-soluble						
Site	**Feature**	**Depth (cm)**	**pH (water)**	**EC (1:5) (mS/cm)**	**TSS$_{70}$ (mg/cm^2)**	**Calcium mmol(+)/kg**	**Magnesium mmol(+)/kg**	**Sodium mmol(+)/kg**	**Potassium mmol(+)/kg**	**Chloride mmol(-)/kg**	**Nitrate-N mmol(-)/kg**	**Sulphate mmol(-)/kg**
WV05-16	Alluvium	0–1	8.2	5.9	135	76	28	173	2.6	228	3	67
		1–46	8.7	0.5		2.4	2.4	13	0.7	16	0.3	2.8
		46+	8.9	0.6		2	1.7	17	0.9	17	0.3	4.3
W05-27	Brownworth	0–0.5	8.8	0.5	70	3.6	2.4	19	0.9	18	0.4	2.2
	drift	0.5–24	8.6	0.6		7	2.4	20	0.9	14	0.2	10
		24+	7.5	0.1		0.5	0.5	2.9	0.3	2.3	0.02	0.7
WV05-33	Trilogy	0–1	8.6	0.6	50	4.8	4.4	17	0.9	22	0.8	7.3
	drift	1–20	9.0	0.5		2.1	2.9	13	1	18	0.6	1.4
		20+	8.9	0.2		1.2	1.2	5.8	0.6	5	0.1	2.3
WV05-28	H1	0–1	8.2	1.7	160	36	2.5	42	1.3	40	0.7	41
	surface	1–29	8.2	1.1		12	9.7	28	1.9	34	5.5	14
		29+	9.5	0.3		0.6	1.3	15	0.9	8.2	0.8	1.8
WV05-29	H1	0–1	8.4	11	290	134	95	308	7.2	371	59	155
	surface	1–19	7.9	1.9		80	7.5	21	2.2	15	3.3	91
		19–48	8.8	0.5		3.8	3.4	15	1.1	12	2.3	8.3

Table 6–11 ctd. Chemical properties for Typic Haplorthels/Haploturbels

						Water-soluble						
Site	**Feature**	**Depth (cm)**	**pH (water)**	**EC (1:5) (mS/cm)**	**TSS_{70} (mg/cm^2)**	**Calcium mmol(+)/kg**	**Magnesium mmol(+)/kg**	**Sodium mmol(+)/kg**	**Potassium mmol(+)/kg**	**Chloride mmol(-)/kg**	**Nitrate-N mmol(-)/kg**	**Sulphate mmol(-)/kg**
WV05-31	Trilogy drift	0–1	8.6	0.6	50	4.8	4.4	17	0.9	22	3.7	7.3
		1–20	9.0	0.5		2.1	2.9	13	1	18	2.6	1.4
		20–21	8.9	0.2		1.2	1.2	5.8	0.6	5.0	0.6	2.3
WV05-34	Trilogy drift	0–1	8.8	0.1	20	0.5	0.9	4.5	0.5	2.9	0.5	2.1
		1–6	8.9	0.1		0.3	0.9	3.0	0.3	1.6	0.3	0.8
		6–7	8.1	0.2		0.5	0.9	5.2	0.5	4.6	0.7	1.3
		7–28+	7.5	0.2		0.4	0.9	4.9	0.5	4.6	0.7	1.1
WV05-35	Colluvium	0–1	8.7	0.3	450	2.8	0.8	8.8	0.8	7.9	0.5	5.1
		1–17	8.1	3.2		106	10	51	2.3	55	7.8	128
		17–51	7.8	1.2		28	5.2	21	1.9	20	4.2	37
		51+	9.4	0.2		0.5	1.1	7.7	0.8	6.7	0.8	1.3
WV06-1	Colluvium	0–1	8.6	2.0	340	19	15	50	1.2	78	7.4	7.4
		1–21	8.0	2.6		32	23	52	1.7	86	8.4	12
		21–52	8.9	0.5		4.9	3.6	9.4	0.7	15	1.3	3.2
		52+	9.7	0.2		<0.01	0.02	5.6	0.3	3.6	0.2	1.2

Table 6–11 ctd. Chemical properties for Typic Haplorthels/Haploturbels

						Water-soluble						
Site	**Feature**	**Depth (cm)**	**pH (water)**	**EC (1:5) (mS/cm)**	**TSS_{70} (mg/cm^2)**	**Calcium mmol(+)/kg**	**Magnesium mmol(+)/kg**	**Sodium mmol(+)/kg**	**Potassium mmol(+)/kg**	**Chloride mmol(-)/kg**	**Nitrate-N mmol(-)/kg**	**Sulphate mmol(-)/kg**
WV06-3	Alluvium	0–2	7.8	0.5	60	19	1.5	2.5	0.4	1.4	0.4	19
		2–14	7.9	0.6		11	5.3	8.8	0.6	16	2.3	7.3
		19–33	8.3	0.0		0.4	0.2	1.2	0.2	1.3	0.02	0.02
		33–41	7.9	0.1		0.8	0.5	1.4	0.2	2.2	0.2	0.5
		41+	7.9	0.1		1.1	0.8	1.8	0.3	3.2	0.3	0.7
WV06-10	Colluvium	0–0.5	9.2	0.2	30	3.6	1.0	5.0	0.4	5.2	0.4	4.9
		0.5–24	7.8	0.1		0.9	0.5	2.6	0.4	4.5	0.3	0.4
		24+	9.4	0.1		0.05	0.03	1.8	0.2	1.1	0.08	0.4
WV06-12	Aeolian sand	0–1	8.9	0.0	125	<0.01	0.01	1.3	0.08	0.8	0.1	1.2
		1–22	8.6	0.6		13	2.3	7.4	0.5	8.3	0.6	18
		22–37	8.6	0.6		6.0	4.9	6.1	0.8	25	1.6	2.3
		37+	8.9	0.1		0.8	0.5	1.9	0.3	2.8	0.2	1.3
WV06-14	Alluvium	0–1	9.2	0.1	5	0.7	0.2	1.9	0.2	1.1	0.1	1.3
		1–18	8.0	0.0		<0.01	0.004	0.3	0.1	0.3	0.03	0.2
		18+	7.5	0.0		<0.01	0.003	0.3	0.2	0.2	0.02	0.2

Table 6–11 ctd. Chemical properties for Typic Haplorthels/Haploturbels

						Water-Soluble						
Site	**Feature**	**Depth (cm)**	**pH (water)**	**EC (1:5) (mS/cm)**	**TSS_{70} (mg/cm^2)**	**Calcium mmol(+)/kg**	**Magnesium mmol(+)/kg**	**Sodium mmol(+)/kg**	**Potassium mmol(+)/kg**	**Chloride mmol(-)/kg**	**Nitrate-N mmol(-)/kg**	**Sulphate mmol(-)/kg**
WV06-16	Rock glacier	0–1	8.5	2.3	130	129	3.0	7.1	0.7	4.2	2.4	106
		1–7	8.5	2.5		128	5.0	14	0.8	3.7	1.9	86
		7–25	8.8	0.3		4.2	6.4	11	0.4	7.2	2.5	3.7
		25+	8.9	0.1		0.3	0.6	2.5	0.3	1.5	0.4	1.2
WV06-19	Melt water channel	0–0.5	8.3	0.6	605	16	1.2	3.7	0.5	2.4	0.9	28
		0.5–9	8.5	3.4		54	3.2	20	1	35	9.2	137
		9–26	8.1	3.5		60	6.8	19	1.6	36	17	151
		26+	8.2	1.0		17	2.8	9.0	1.1	7.8	2.5	39
WV06-23	Colluvium	0–0.5	7.4	0.1	10	0.6	0.7	1.5	0.2	1.2	0.2	1.7
		0.5–23	8.2	0.0		0.07	1.1	1.3	0.4	1.6	0.1	0.2
		23+	8.3	0.0		<0.01	0.05	0.9	0.09	0.4	0.06	0.2
WV06-25	Colluvium	0–1	9.4	0.2	25	1.5	1.1	6.0	0.4	2.5	0.8	4.4
		1–7	9.4	0.2		1	1.1	3.9	0.4	1.1	0.4	3.5
		7–26	8.9	0.1		0.1	0.4	2.8	0.3	1.7	0.4	0.8
		26–38	8.7	0.0		0.04	0.2	0.5	0.2	0.3	0.07	0.05
		38+	9.5	0.1		0.3	0.4	1.8	0.3	0.4	0.09	0.2

Table 6–11 ctd. Chemical properties for Typic Haplorthels/Haploturbels

Site	Feature	Depth (cm)	pH (water)	EC (1:5) (mS/cm)	TSS_{70} (mg/cm^2)	Water-soluble						
						Calcium mmol(+)/kg	**Magnesium mmol(+)/kg**	**Sodium mmol(+)/kg**	**Potassium mmol(+)/kg**	**Chloride mmol(-)/kg**	**Nitrate-N mmol(-)/kg**	**Sulphate mmol(-)/kg**
WV06-26	Colluvium	0–1	8.8	0.2	35	2.1	1.1	4.7	0.3	1.7	0.5	4.6
		1–12	9.0	0.5		5.9	4.4	9.4	0.4	4.5	1.2	12
		12–43	8.5	0.0		0.02	0.3	0.4	0.2	0.2	0.04	0.09
		43+	8.3	0.1		0.3	0.5	1.3	0.2	0.7	0.2	0.6
WV06-27	Loke drift	0–0.5	8.9	0.1	20	0.004	0.05	1.6	0.2	0.6	0.06	0.5
		0.5–12	9.2	0.1		<0.001	0.01	2.1	0.2	1.5	0.07	0.4
		12–34	8.7	0.0		0.06	0.2	1.7	0.2	0.1	0.05	0.2
		34+	9.6	0.1		0.7	0.4	1.9	0.3	0.9	0.06	0.5
WV06-28	Brownworth drift	0–1	8.8	1.6	135	6.7	4.4	43	1.0	62	2.4	4.1
		1–13	8.7	1.3		24	5.0	17	0.9	26	2.3	28
		13+	8.2	0.4		1.3	1.1	10	0.5	13	1.1	1.9
WV07-1	Colluvium	0–1	8.0	0.0	10	0.2	0.2	0.4	0.4	0.9	0.06	0.3
		1–22	8.2	0.0		0.2	0.3	0.4	0.2	0.5	0	0.3
		22+	7.9	0.0		0.4	0.4	0.7	0.5	1.9	0	0.3

Table 6–11 ctd. Chemical properties for Typic Haplorthels/Haploturbels

				EC		Water-soluble						
Site	Feature	Depth (cm)	pH (water)	(1:5) (mS/cm)	TSS_{70} (mg/cm^2)	Calcium mmol(+)/kg	Magnesium mmol(+)/kg	Sodium mmol(+)/kg	Potassium mmol(+)/kg	Chloride mmol(-)/kg	Nitrate-N mmol(-)/kg	Sulphate mmol(-)/kg
WV07-6	Rock	0–0.5	9.2	0.3	360	4.1	0.5	7.3	0.7	16	0.5	2.7
	glacier	0.5–7	8.7	1.5		8.8	2.7	17	0.3	69	2.2	11
		7–33	8.4	1.8		20	5.3	20	0.5	72	3.9	20
		33+	8.8	0.5		11	0.9	4.2	0.3	18	0.8	3.6
WV07-7	Rock	0–0.5	8.6	0.8	5	9.6	2.3	5.5	0.5	33	0.5	2.8
	glacier	0.5–16	9.0	0.0		0.2	1.3	0.7	0.5	0.6	0	0.2
		16+	8.4	0.0		0.3	2.1	0.5	0.6	0.5	0	0.3
WV07-9	Upper	0–1	9.1	0.7	20	9.9	3.2	9.2	0.7	21	3.3	10
	Wright	1–14	8.8	0.1		0.4	0.4	2.4	0.3	2.4	0.3	0.8
	III drift	14+	8.7	0.0		2.3	1.2	2.3	0.5	1.8	0.08	0.7
WV07-10	Upper	0–1	9.1	0.3	380	3.4	1	6.7	16	30	1	1
	Wright	1–22	8.4	2.8		81	6.1	15	1.9	33	6.2	68
	III drift	22+	8.9	0.4		5.5	1.4	6.9	0.8	7.5	1.4	2.5
WV07-12	Colluvium	1–1	8.9	0.1	10	0.3	0.2	3.2	0.2	2.0	0.2	2.3
		1–15	8.9	0.1		0.5	0.5	2.2	0.3	1.4	0.09	1.5
		15–22	8.4	0.0		0.3	0.9	0.6	0.5	0.7	0.04	0.2
		22+	8.7	0.0		1.4	0.6	0.8	0.3	0.9	0.1	0.5

Table 6–11 ctd. Chemical properties for Typic Haplorthels/Haploturbels

						Water-soluble						
Site	**Feature**	**Depth (cm)**	**pH (water)**	**EC (1:5) (mS/cm)**	**TSS$_{70}$ (mg/cm^2)**	**Calcium mmol(+)/kg**	**Magnesium mmol(+)/kg**	**Sodium mmol(+)/kg**	**Potassium mmol(+)/kg**	**Chloride mmol(-)/kg**	**Nitrate-N mmol(-)/kg**	**Sulphate mmol(-)/kg**
WV07-13	Colluvium	0–1	9.4	0.3	15	1.9	0.8	7.7	0.2	4.9	1.1	6.0
		1–14	9.4	0.2		1	1.1	4.9	0.9	5.1	0.6	3.5
		14–22	9.1	0.0		0.5	0.7	1.4	0.5	1	0.04	0.5
		22+	8.5	0.0		0.2	0.2	0.6	0.2	0.5	0	0.2
			8.7	0.0		0.3	0.5	0.9	0.5	0.7	0.05	0.3
WV07-14	Colluvium	0–1	7.5	0.0	5	0.2	0.2	0.4	0.4	0.7	0.03	0.4
		1–22	8.1	0.0		0.2	0.6	0.4	0.5	0.5	0	0.2
		22+	8.1	0.0		0.2	0.8	0.4	0.6	0.6	0	0.3
WV07-17	Upper	0–1	6.7	0.0	10	0.1	0.1	0.5	0.7	1.0	0.09	0.2
	Wright	1–9	6.2	0.0		0.1	0.1	0.4	1.1	1.6	0.05	0.3
	II drift	9+	6.1	0.0		0.05	0.1	0.3	1.1	1.6	0.06	0.3
WV07-18	Upper	0–1	7.7	0.1	5	0.5	0.4	6.6	0.6	2.0	0.4	2.2
	Wright	1–8	7.5	0.1		0.09	0.08	1.5	0.8	1.2	0.1	0.3
	II drift	8+	8.6	0.0		0.6	0.7	0.8	0.4	1.9	0	0.3

Table 6–11 ctd. Chemical properties for Typic Haplorthels/Haploturbels

						Water-soluble						
Site	**Feature**	**Depth (cm)**	**pH (water)**	**EC (1:5) (mS/cm)**	**TSS_{70} (mg/cm^2)**	**Calcium mmol(+)/kg**	**Magnesium mmol(+)/kg**	**Sodium mmol(+)/kg**	**Potassium mmol(+)/kg**	**Chloride mmol(-)/kg**	**Nitrate-N mmol(-)/kg**	**Sulphate mmol(-)/kg**
WV07-19	Upper	0–1	6.4	1.2	40	12	15	10	0.9	11	7.3	3.3
	Wright	1–14	6.6	0.3		0.2	0.8	7.7	0.9	5.0	1.8	3.2
	II drift	14+	6.8	0.1		0.04	0.2	1.1	1.2	1.9	0.09	0.4
WV07-21	Upper	0–1	6.6	0.0	10	0.1	0.09	1.3	0.8	1.0	0.09	0.7
	Wright I drift	1-13	6.7	0.0		0.1	0.08	0.6	1.2	1.6	0.09	0.3
WV07-23	Upper	0–1	9.3	0.2	10	0.4	0.3	5.4	0.4	2.8	0.8	2.9
	Wright	1–10	8.8	0.0		0.0001	0.09	0.7	0.09	0.9	0.2	0.7
	II drift	10–22	8.8	0.0		0.5	0.7	1.7	0.3	1.5	0	1.0
		22+	8.7	0.0		0.2	0.5	1.3	0.2	1.2	0.1	0.6
WV07-24	Upper	0–1	8.2	0.0	5	0.1	0.4	1.4	0.3	1.2	0.2	1.1
	Wright	1–9	8.2	0.0		0.06	0.2	0.7	0.3	0.8	0.09	0.3
	II drift	9–20	8.3	0.0		0.05	0.2	0.5	0.4	0.9	0	0.3
		20+	8.2	0.0		0.1	0.3	0.7	0.8	2.0	0	0.5

Table 6–11 ctd. Chemical properties for Typic Haplorthels/Haploturbels.

						Water-soluble						
Site	**Feature**	**Depth (cm)**	**pH (water)**	**EC (1:5) (mS/cm)**	**TSS$_{70}$ (mg/cm^2)**	**Calcium mmol(+)/kg**	**Magnesium mmol(+)/kg**	**Sodium mmol(+)/kg**	**Potassium mmol(+)/kg**	**Chloride mmol(-)/kg**	**Nitrate-N mmol(-)/kg**	**Sulphate mmol(-)/kg**
WV07-25	Upper	0–1	9.6	0.3	10	0.2	0.6	9.8	0.4	4.0	1.4	6.0
	Wright	1–3	9.2	0.1		0.2	0.6	4.4	0.3	2.2	0.6	2.2
	II drift	3–22	8.9	0.0		0.002	0.6	0.9	0.3	0.9	0.06	0.4
		22+	8.9	0.0		0.0002	1.2	1	0.5	1	0.06	0.6
WV07-26	Upper	0–1	7.4	4.2	130	54	8.1	62	1	8.1	7.3	174
	Wright I drift	1–15	7.5	1.7		64	7.9	6.0	1	1.3	0.6	24
WV07-27	Upper	0–1	7.9	0.0	5	0.5	0.4	0.6	0.2	0.4	0.05	1.2
	Wright	1–25	8.3	0.0		0.09	0.09	0.5	0.4	0.8	0.05	0.3
	II drift	25+	8.1	0.0		0.1	0.08	0.6	0.4	1.3	0.05	0.6
WV07-28	Upper	0–1	8.7	0.1	5	0.5	0.9	2.1	0.6	2.0	0.5	1.1
	Wright	1–8	9.0	0.0		0.2	0.1	1.6	0.4	1.5	0.2	1.0
	II drift	8–16	7.6	0.0		0.009	0.07	0.6	0.8	1.5	0.06	0.3
		16+	7.9	0.0		0.2	0.2	0.5	0.9	1.5	0.05	0.3

Table 6–11 ctd. Chemical properties for Typic Haplorthels/Haploturbels.

Site	Feature	Depth (cm)	pH (water)	EC (1:5) (mS/cm)	TSS$_{70}$ (mg/cm^2)	Water-soluble						
						Calcium mmol(+)/kg	Magnesium mmol(+)/kg	Sodium mmol(+)/kg	Potassium mmol(+)/kg	Chloride mmol(-)/kg	Nitrate-N mmol(-)/kg	Sulphate mmol(-)/kg
WV07-29	Upper	0–1	9.3	0.0	5	0.05	0.06	1.5	0.5	1.0	0.06	0.4
	Wright	1–8	8.6	0.0		0.3	0.09	1.2	0.9	2.2	0.09	0.6
	II drift	8–29	7.9	0.0		0.1	0.7	0.6	0.6	1.6	0.08	0.5
		29+	8.4	0.0		0.3	0.2	0.9	0.3	0.8	0.1	0.4
WV07-30	Former	0–1	6.3	0.1	80	0.1	0.04	0.7	1.4	2.2	0.1	0.9
	Vanda	1–10	7.3	0.2		0.9	0.2	3.0	1.5	3.0	0.2	2.6
	Lake	10–36	7.4	0.4		7.6	2.5	3.0	1.7	12	2.4	0.9
		33	6.3	0.2		0.9	0.5	1.5	2.1	5.7	0.4	1
WV07-36	Rock	0–1	7.7	0.8	390	8.8	12	12	0.7	17	6.3	13
	glacier	1–11	7.8	4.3		150	51	47	5.9	62	29	174
		11+	8.6	0.6		1.5	6.31	16.4	1.2	19.1	7.3	3.31
WV07-37	Rock	0–1	9.0	0.7	155	10	3.4	16	0.7	9.4	3.7	16
	glacier	1–10	8.4	2.8		92	11	17	1.4	17	8.2	133
		10–26	9.4	0.1		1.9	0.7	1.6	0.5	1.9	0.4	1.5
		26+	9.4	0.1		3.4	1.1	2.1	0.4	1.8	0.4	2.5

Table 6–11 ctd. Chemical properties for Typic Haplorthels/Haploturbels

						Water-soluble						
Site	**Feature**	**Depth (cm)**	**pH (water)**	**EC (1:5) (mS/cm)**	**TSS$_{70}$ (mg/cm^2)**	**Calcium mmol(+)/kg**	**Magnesium mmol(+)/kg**	**Sodium mmol(+)/kg**	**Potassium mmol(+)/kg**	**Chloride mmol(-)/kg**	**Nitrate-N mmol(-)/kg**	**Sulphate mmol(-)/kg**
WV07-42	Colluvium	0–1	8.9	0.1	230	1.0	0.3	1.5	2.0	6.3	0.1	2.7
		1–29	8.6	1.7		53	2.4	2.4	0.3	3.7	1.5	105
		29–39	7.8	0.0		0.2	0.3	0.8	0.5	0.8	0.06	1.4
		39+	7.9	0.0		0.1	0.2	1.0	0.3	0.7	0.08	0.9
WV07-43	Colluvium	0–0.5	7.7	0.1	55	0.07	0.05	1.8	0.6	1.8	0.2	1.6
		0.5–16	9.1	0.5		5.1	1.6	6.4	0.3	7.0	3.8	9.0
		16+	7.8	0.1		0.2	0.2	1.7	0.3	2.9	0.8	1.1
WV07-45	Dais	0–1	8.5	7.9	900	136	11	127	1	107	66	37
		1–11	8.2	8.8		96	24	96	1.0	72	35	44
		11–28	8.5	2.5		41	2.7	16	0.3	14	5.5	19
		28–68	9.6	1.1		0.4	0.3	18	0.2	30	11	1.4

6.11.5 PETROSALIC ANHYORTHELS/ANHYTURBELS

Petrosalic Anhyorthel/Anhyturbels (PsAo/PsAt) cover approximately 622 ha or <2% of the ice-free study area. They occur where dry permafrost extends to >70 cm and salts have accumulated within the profile to such an extent a cemented (predominantly NaCl) salt pan occurs. In Antarctica, such accumulation can only occur under very low precipitation on old geomorphic surfaces with no recharge of the ice table by snow patch melt or subsurface flow of melt water. Petrosalic Anhyorthel/Anhyturbels are predominantly described on Alpine IV, early Quaternary Onyx and Pliocene Valkyrie drifts, mainly in the west of the study area away from the more humid eastern coastal region. Weathering and salt stages both average 5 (n=46).

Range of morphological and chemical properties

An example of a Petrosalic Anhyorthel is profile VW05-02 developed in the Pliocene Valkyrie drift (Hall & Denton 2005) on a 20° slope on the north wall of the valley. The desert pavement was strongly ventifacted, with some boulders planed to surface, others fractured. The very gravelly loamy sand soil material had hue 10YR colours to over 60 cm. A strongly cemented Bwzm horizon, salt stage 5, extended from approximately 20 to 60 cm. Maximum electrical conductivity of the Bwzm horizon was approximately 27 mS/cm with salts dominated by sodium and chloride ions.

As PsAo/PsAt are Anhyorthels depth to ICP must exceed 70 cm but the average depth to ICP has not been investigated although it is known to exceed 120 cm at some sites. Average weathering and salt stage are 5.5 and 5.3 respectively, both with range 4–6. Maximum CDE ranges from 6 to 24 with an average of 11.8. All contain a hue of 10YR or redder.

Maximum EC within the soil profiles analysed ranges from approximately 14 to 62 with an average of 53 mS/cm. Average salt content in the profile to 70 cm is 7440 mg/cm^2, and ranges from about 3500 to 10 000. While chloride is generally the dominant anion, averaging approximately 2000 mmol$_{(-)}$/kg it ranges from 565 to 3930 mmol$_{(-)}$/kg. Sulphate is generally the next most dominant anion and ranges from 24 to 810 mmol$_{(-)}$/kg. Interestingly, profile WV05-40 where there is more nitrate-N than sulphate, is in a toe-slope position and is thought to be developed in reworked Peleus till. Magnesium is the dominant cation in this soil.

Physiographic position

Petrosalic Anhyorthel/Anhyturbels form where water has been sublimated from the soil profile and salts have accumulated in the form of a cemented horizon. This process requires time and a lack of recharge from precipitation or surface/subsurface flow. Thus the soils occur on older surfaces and where the ice table is not recharged such as the Valkyrie, Loop, Onyx or Alpine IV drifts in low precipitation areas. Petrosalic Anhyorthel/Anhyturbels do not occur on young drifts such as Brownworth, Hummocky (H1) or Alpine I – III drifts.

Inclusions

There are inclusions of Salic Anhyorthel/Anhyturbels where the salt enriched horizon is not cemented; Typic Anhyorthel/Anhyturbels where the soil contains sufficient salts for a salic horizon; Typic Haplorthels/Haploturbels where the permafrost is ice-cemented within 70 cm of the soil surface.

Figure 6-13. Soil profile WV05-27 (upper) and Weathering stage 5 surface of a Petrosalic Anhyturbel, central Wright Valley (lower).

Soil subgroup: Petrosalic Anhyturbel
Coordinates: S77.52673 E162.13899
Location: Central Wright Valley
Profile Description
Landform: Dissected moraine
Parent material: Mixed till of Valkyrie age
Weathering stage: 5
Salt stage: 5

Desig.	**Depth (cm)**	**Description**
D	0–2	Greyish brown 2.5Y 5/2 very gravelly sand, 10% cobbles, single grain, loose, few salts under surface gravel, very abrupt smooth boundary.
Bw1	2–25	Yellowish brown 10YR 5/4 very gravelly sand, 20% cobbles, single grain, soft, salt stage 2, clear wavy boundary.
Bwzm	25–46	Greyish brown 2.5Y 5/2 very gravelly sand, 20% cobbles, massive, very hard, strongly cemented, salt stage 5, clear wavy boundary.
Bw2	46–70	Brown 10YR 5/3 very gravelly sand, 20% cobbles, single grain, soft, salt stage 1, clear wavy boundary.
BC	70–75	Brown 10YR 5/3 very gravelly sand, 10% cobbles, single grain, loose, salt stage 1, clear wavy boundary.

Table 6-10. Chemical properties for Petrosalic Anhyorthels/Anhyturbels.

Site	Feature	Depth (cm)	pH (water)	EC (1:5) (mS/cm)	TSS_{70} mg/cm^2	Water-Soluble Calcium mmol(+)/kg	Magnesium mmol(+)/kg	Sodium mmol(+)/kg	Potassium mmol(+)/kg	Chloride mmol(-)/kg	Nitrate-N mmol(-)/kg	Sulphate mmol(-)/kg
WV05-2	Valkyrie drift	0–3	7.9	1.6	6230	33	9.3	32	1.3	42	6.5	31
		3–23	7.2	26.6		185	54	1050	7.5	1360	40	190
		23–63	7.1	18.7		42	54	721	8.7	914	39	23
		63–80	6.7	3.2		36	52	44	5.7	102	39	5.1
		80–100	7.1	4.6		42	48	108	5.1	160	38	14
VW05-7	Valkyrie drift	0–2	7.4	0.7	9550	8.2	1.7	21	0.5	14	1.7	16
		2–25	7.4	10.5		163	31	353	1.8	361	18	268
		25–46	6.7	62.2		16	57	3060	2.7	3930	30	115
		46–70	6.8	18.4		10	73	754	3.9	842	79	62
		70–75	6.8	7.4		17	52	264	3.0	243	75	57
VW05-40	Peleus drift	0–2	8.6	0.2	3470	1.0	1.2	4.7	0.6	4.2	0.8	1.4
		2–16	7.6	14.4		204	280	218	15	565	169	24
		16–42	7.5	10.3		164	265	49	11	394	144	1.4
		42–67	7.6	9.2		143	237	48	8.6	339	124	0.7
		67+	7.7	8.6		131	211	54	8.9	326	111	2.2

Table 6–12 ctd. Chemical properties for Petrosalic Anhyorthels/Anhyturbels.

				EC		**Water-soluble**						
		Depth	**pH**	**(1:5)**	**TSS$_{70}$**	**Calcium**	**Magnesium**	**Sodium**	**Potassium**	**Chloride**	**Nitrate-N**	**Sulphate**
Site	**Feature**	**(cm)**	**(water)**	**(mS/cm)**	**mg/cm^2**	**mmol(+)/kg**	**mmol(+)/kg**	**mmol(+)/kg**	**mmol(+)/kg**	**mmol(-)/kg**	**mmol(-)/kg**	**mmol(-)/kg**
WV06-13	Alpine IV	0–2	8.5	7.5	10520	53	22	212	0.3	204	44	166
		2–13	8.6	38.9		132	48	2100	1.9	1370	321	810
		13–30	7.9	55.6		19	45	2930	6.7	2280	914	465
		30–70	7.5	20.1		36	93	894	7.9	897	82	84
		70–85	7.1	7.1		29	37	263	4.3	153	116	49

6.11.6 SALIC ANHYORTHELS/ANHYTURBELS

The Salic Anhyorthel/Anhyturbel association is dominant over approximately 2000 ha or about 6% of the ice-free study area. Salic Anhyorthel/Anhyturbels are mapped in relict or weakly expressed patterned ground where depth of dry permafrost exceeds 70 cm and salts (predominantly NaCl) have accumulated in the profile but do not form a cemented pan. Polygon centers are often Anhyorthel with Anhyturbels associated with the margins of the polygon. In some profiles we observed only small (<25 cm deep) relict sand wedges. Salic Anhyorthel/Anhyturbels occur mainly on Alpine III and Trilogy or older drifts, and more commonly in the west of the study area away from the humid eastern coastal region.

Range of morphological and chemical properties

A typical profile shows a strongly ventifacted desert pavement, with some boulders planed to surface, others fractured. An oxidised Bw horizon (hue 2.5Y or 10YR) approximately 10 cm thick lies on a salt enriched Bwz horizon (hue 2.5Y or 10YR) extending to about 20 cm with oxidised hue 2.5Y, Cox material extending a further 10 cm. Non-oxidised Cn material extends to over 70 cm. Average weathering and salt stage both equal 4 (n=31).

Maximum profile EC ranges from approximately 7 to 74 (Table 6-11) with an average of 26 mS/cm. Average salt content in the profile to 70 cm is 3883 mg/cm^2 and ranges from about 1000 to 11800. While chloride is the dominant anion, averaging approximately 1344 mmol$_{(-)}$/kg it ranges from about 200 to 5100 mmol$_{(-)}$/kg. Rarely is sulphate the dominant ion but when dominant it ranges from 145 to 219 mmol$_{(-)}$/kg. Nitrate-N was not the dominant anion in any of the Salic Anhyorthels/Anhyturbels analysed. While sodium is the dominant cation, averaging approximately 970 mmol$_{(-)}$/kg, it ranges from approximately 125 to 3660 mmol$_{(-)}$/kg.

Physiographic position

Salic Anhyorthel/Anhyturbels form where water has been sublimated from the soil profile and salts have accumulated in a layer generally close to the soil surface. This process requires time and a lack of recharge from precipitation or surface/subsurface flow. Thus the soils occur on older surfaces and where the ice table is not recharged such as the Valkyrie, Loop, Onyx or Alpine III drifts in low precipitation areas. Salic Anhyorthel/Anhyturbels cannot occur on young drifts such as Brownworth, Hummocky (H1) or Alpine I – II drifts.

Inclusions

There are inclusions of Petrosalic Anhyorthel/Anhyturbels where the salt enriched horizon is cemented; Typic Anhyorthel/Anhyturbels where the soil contains insufficient salts for a salic horizon; Typic Haplorthels/Haploturbels where the permafrost is ice-cemented within 70 cm of the soil surface.

Figure 6-14. Soil profile WV05-23 (upper) and landscape position (lower).

Soil subgroup: Salic Anhyorthel
Coordinates: S77.48649 E162.41328
Location: South wall, lower-central WrightValley
Profile Description: WV05-23
Landform: Midslope south valley wall
Parent material: Colluvium
Weathering stage: 5
Salt stage: 5

Desig.	Depth (cm)	Description
D	0–1	Light brownish grey 10YR 6/2 very gravelly sand, 10% cobbles, single grain, loose, few salts under surface gravel, very abrupt smooth boundary.
Bwz	1–22	Light yellowish brown 2.5Y 6/4, very stony sand, 45% stones, 10% cobbles, single grain, soft but slightly hard in places, salt stage 2 with 4 in places, abrupt wavy boundary.
Bw	22–48	Light yellowish brown 2.5Y 6/4, very stony sand, 45% stones, 10% cobbles, single grain, soft, salt stage 1, clear wavy boundary.
BC	46–70+	Light yellowish brown 2.5Y 6/4, very gravelly sand, single grain, soft, salt stage 1.

Table 6-11. Chemical properties for Salic Anhyorthels/Anhyturbels

				EC		Water-Soluble						
		Depth	**pH**	**(1:5)**	**TSS_{70}**	**Calcium**	**Magnesium**	**Sodium**	**Potassium**	**Chloride**	**Nitrate-N**	**Sulphate**
Site	**Feature**	**(cm)**	**(water)**	**(mS/cm)**	**(mg/cm^2)**	**mmol(+)/kg**	**mmol(+)/kg**	**mmol(+)/kg**	**mmol(+)/kg**	**mmol(-)/kg**	**mmol(-)/kg**	**mmol(-)/kg**
WV05-5	Hart Ash	0–2	7.7	2.5	4630	17	11	79	2.7	93	6.4	15
		2–14	7.9	50		192	111	2120	15	2500	45	178
		14–36	8.1	13		27	47	498	8.7	601	20	21
		36–47	8.1	2.9		26	17	83	4.7	90	11	28
		47–72	8.4	2.2		11	3.0	76	4.3	68	3.9	19
WV05-18	Loop drift	0–1	8.2	3.1	11775	33	4.5	99	1.2	118	1.9	38
		1–17	8.1	74		57	190	3660	15	5130	51	599
		17–31	7.5	47		161	211	2040	72	2170	228	1070
		31–58	8.0	21		57	197	760	19	896	92	344
		58–70+	7.8	4.5		73	20	129	9.1	134	22	92
WV05-19	Onyx drift	0–1	7.8	2.9	6565	152	4.7	22	1.5	19	3.8	168
		1–9	8.1	4.1		157	14	75	2.0	63	5.8	207
		9–19	8.3	53		178	91	2510	18	2780	79	368
		19–30	8.4	19		129	56	710	9.2	945	38	209
		30–70+	8.3	15		49	30	571	0.7	641	25	89

Table 6–9 ctd. Chemical properties for Salic Anhyorthels/Anhyturbels

				EC		**Water-Soluble**						
Site	**Feature**	**Depth (cm)**	**pH (water)**	**(1:5) (mS/cm)**	**TSS_{70} (mg/cm^2)**	**Calcium mmol(+)/kg**	**Magnesium mmol(+)/kg**	**Sodium mmol(+)/kg**	**Potassium mmol(+)/kg**	**Chloride mmol(-)/kg**	**Nitrate-N mmol(-)/kg**	**Sulphate mmol(-)/kg**
WV05-20	Wright drift	0–1	8.5	10	6600	190	33	310	0.7	310	721	248
		1–7	8.5	44		57	217	2230	14	1350	69	1120
		7–13	7.9	34		24	97	1610	19	1480	63	377
		13–43	7.9	22		51	27	905	11	980	16	94
		43–67	7.8	9.4		110	25	331	9.9	253	12	102
		67–70+	8.3	6.3		173	24	138	16	142	27	183
WV05-23	Colluvium	0–1	8.1	0.82	7145	21	1.3	14	0.9	14	0.7	24
		1–22	8.3	4.9		157	14	115	2.3	85	1.8	189
		22–48	8.3	41		205	129	1760	21	1510	61	341
		61+	8.5	25		155	79	819	31	862	73	208
WV05-37	Loop drift	0–1	8.5	0.92	2450	12	7.2	19	1.4	26	4.1	12
		1–29	8.0	9.9		185	39	266	10	328	36	191
		29–60	7.6	5.8		57	28	173	8.8	203	22	75
		60–70+	7.6	5.1		44	23	154	8.3	195	12	54
WV05-39	Alpine II drift	0–1	7.9	1.1	1910	16	5.6	25	1.5	30	4.4	15
		1–14	7.6	4.7		108	35	89	4.6	125	31	112
		14–34	8.0	9.8		190	34	269	5.0	332	31	197
		34–70+	8.1	3.9		43	20	101	4.1	126	14	55

Table 6–9 ctd. Chemical properties for Salic Anhyorthels/Anhyturbels.

				EC		Water-Soluble						
Site	**Feature**	**Depth (cm)**	**pH (water)**	**(1:5) (mS/cm)**	**TSS$_{70}$ (mg/cm^2)**	**Calcium mmol(+)/kg**	**Magnesium mmol(+)/kg**	**Sodium mmol(+)/kg**	**Potassium mmol(+)/kg**	**Chloride mmol(-)/kg**	**Nitrate-N mmol(-)/kg**	**Sulphate mmol(-)/kg**
WV06-4	Alpine III drift	0–11	8.3	1.5	1805	43	4.5	31	0.6	16	2.8	59
		11–35	7.4	7.4		41	23	111	1.4	157	52	112
		35–70	7.0	3.5		15	22	104	1.7	99	26	36
			7.6	1.9		6.7	8.3	65	1.1	42	13	29
WV06-5	Alpine III drift	0–1	7.5	3.1	4555	34	16	62	1.1	69	20	55
		1–15	7.4	31		61	17	401	2.0	750	487	189
		15–63	7.2	10		36	56	340	6.3	233	109	12
		63–70+	6.8	3.5		21	15	53	1.5	205	37	87
WV06-11	Colluvium	0–1	9.1	0.37	1485	4.1	1.5	5.0	0.5	11	0.8	3.7
		1–10	8.3	3.8		87	8.4	8.7	1.0	64	8.9	145
		10–30	8.6	9.1		51	23	158	2.8	81	13	26
		30–64	8.5	2.5		38	23	51	2.3	106	6.2	17
		64–70+	8.7	1.2		25	14	14	1.4	43	3.0	12
WV06-15	Alpine III drift	0–1	8.2	5.2	3130	86	22	147	1.8	134	33	102
		1–11	7.7	9.5		86	44	130	4.3	197	153	187
		11–26	7.5	25		48	90	1150	8.3	659	670	20
		26–58	6.9	4.4		23	76	100	5.7	72	87	1.9
		58–70+	7.1	3.2		19	57	66	4.7	77	41	3.2

Table 6–9 ctd. Chemical properties for Salic Anhyorthels/Anhyturbels.

				EC		Water-Soluble						
Site	Feature	Depth (cm)	pH (water)	(1:5) (mS/cm)	TSS_{70} (mg/cm^2)	Calcium mmol(+)/kg	Magnesium mmol(+)/kg	Sodium mmol(+)/kg	Potassium mmol(+)/kg	Chloride mmol(-)/kg	Nitrate-N mmol(-)/kg	Sulphate mmol(-)/kg
WV07-3	Upper	0–1	8.9	0.60	1460	12	0.7	4.9	0.3	28	1.8	1.0
	Wright	1–24	7.8	10		145	8.5	100	1.5	258	10	14
	III	24–43	8.1	2.3		11	3.5	36	1.2	128	6.1	0.9
		43–70+	8.2	1.1		11	0.8	10	0.7	60	3.2	0.3
WV07-4	DJ Pond	0–2	7.6	54	3380	669	16	1010	2.4	3170	11	43
	margin	2–15	7.8	8.1		110	2.8	21	0.4	248	0.4	5.4
		15–32+	7.6	8.9		142	3.7	21	0.5	326	0.4	0.9
WV07-5	DJ Pond	0–4	7.9	39	4000	189	2.9	413	0.9	2140	0	84
	outer	4–26	7.9	8.1		121	2.3	49	0.4	224	0.3	23
		26–40	7.7	6.4		105	2.1	11	0.2	122	0.3	16
		40+	7.4	14		188	4.8	27	0.5	382	0	3.5
WV07-11	Upper	0–1	9.1	0.37	1690	9.6	0.6	3.3	0.4	5.1	0.7	4.5
	Wright	1–20	8.4	15		52	8.2	618	1.2	667	8.0	49
	III	20–47	8.8	1.9		17	2.3	21	0.7	67	6.0	4.1
		47–81	9.0	0.83		5.6	1.3	14	0.9	30	4.0	1.4

Table 6–9 ctd. Chemical properties for Salic Anhyorthels/Anhyturbels

						Water-Soluble						
Site	Feature	Depth (cm)	pH (water)	EC (1:5) (mS/cm)	TSS$_{70}$ (mg/cm^2)	Calcium mmol(+)/kg	Magnesium mmol(+)/kg	Sodium mmol(+)/kg	Potassium mmol(+)/kg	Chloride mmol(-)/kg	Nitrate-N mmol(-)/kg	Sulphate mmol(-)/kg
WV07-35	Upper	0–1	6.9	0.85	2490	28	3.1	9.9	1	4.6	2.4	24
	Wright	1–8	6.8	5.1		162	28	68	2.8	40	35	127
	III	8–34	6.7	14		197	31	460	3.6	448	87	173
		34–70	6.9	6.1		75	9.7	179	2.8	210	27	69
WV07-38	Colluvium	0–1	8.5	1.8	2270	84	9.8	28	2.1	32	11	64
		1–13	8.4	8.2		165	58	201	6.6	264	118	202
		13–40	8.4	8.9		108	85	232	26	246	113	55
		40–70+	8.5	4.3		159	45	99	14	123	59	26
WV07-46	Dais	0–1	8.4	3.0	2565	69	6.2	33	0.9	79	16	18
		1–9	8.2	5.9		55	9.8	42	1.0	126	20	49
		9–28	8.3	11		56	11	125	1.6	282	23	45
		28–70+	8.4	6.5		35	11	103	1.5	281	22	21

6.11.7 TYPIC ANHYORTHELS/ANHYTURBELS

The Typic Anhyorthel/Anhyturbel (TAo/TAt) association is dominant over approximately 7257 ha or approximately 23% of the ice-free area. The Subgroups occur where the depth of dry frozen permafrost exceeds 70 cm and few salts have accumulated within the soil. Deepening of ICP to a depth exceeding 70 cm proceeds slowly under Antarctic conditions and as a consequence, TAo/TAt occur predominantly on Alpine II or older geomorphic surfaces.

Range of morphological and chemical properties

Typically, TAo/TAt have a well-developed desert pavement over a Bw horizon with hue 10YR or 2.5Y. While visible salts may occur in the B horizon, in which case they are given Bwz designation, the horizon does not qualify as a salic horizon. A Cox horizon of light yellowish brown often transitions to the unoxidised Cn horizon. Weathering stage averages 3.5 while the salt stage is only 1.5 (n=81).

At an altitude of approximately 750 m on the south wall between the Bartley and Conrow Glaciers, Typic Anhyorthels (WV05-41), were developed in in-situ Peleus till. In the upper subsoil the dominant anion was sulphate, which is consistent with a trend of dominance with distance from coastal precipitation influence (Bockheim 1997). Although the salt-rich horizons met the requirements for thickness and EC, the product of thickness and EC was insufficient to satisfy the requirements of a salic horizon as defined in Soil Taxonomy (Soil Survey Staff 2010).

Maximum profile EC ranges from approximately 2 to 16 (Table 6-12) with an average of 11 mS/cm. Average salt content in the profile to 70 cm is 1185 mg/cm^2 and ranges from about 370 to 3000 mg/cm^2. Interestingly, in the salt-rich horizon, chloride is the dominant anion in half the profiles analysed while sulphate is the dominant anion in the other profiles analysed. Chloride anions average approximately 291 mmol$_{(-)}$/kg (range 62–719 mmol$_{(-)}$/kg) with sulphate anions averaging 158 mmol$_{(-)}$/kg (range 70–219 mmol$_{(-)}$/kg. Nitrate-N is never the dominant anion.

Similarly, in the salt-rich horizon, sodium is the dominant cation in nearly half the profiles analysed while calcium is the dominant cation in the other profiles analysed. Sodium cations average approximately 159 mmol$_{(-)}$/kg (range 36–599 mmol$_{(-)}$/kg) with calcium cations averaging 125 mmol$_{(-)}$/kg (range 64–161 mmol$_{(-)}$/kg.

Physiographic position

Typic Anhyorthel/Anhyturbels form where water has been sublimated from the soil profile but salts have not accumulated in a layer. This process requires time and a lack of recharge from precipitation or surface/subsurface flow. Thus the soils occur on older surfaces and where the ice table is not recharged such as the Alpine II or Alpine III drifts in low precipitation areas. Typic Anhyorthel/Anhyturbels cannot occur on young drifts such as Brownworth, Hummocky (H1) or Alpine I – II drifts.

Inclusions

There are inclusions of Salic Anhyorthel/Anhyturbels where there is sufficient salts within the soil to form a salic horizon and Typic Haplorthels/Haploturbels where the permafrost is ice-cemented within 70 cm of the soil surface – generally in recharge zones.

Figure 6-15. Soil profile WV05-38.

Soil subgroup: Typic Anhyorthel
Coordinates: S77.49541 E162.38976
Location: South wall lower-central Wright Valley
Profile Description
Landform: Distal side of lateral moraine
Parent material: Mixed granite and dolerite till, Alpine III? age
Weathering stage: 5
Salt stage: 2

Desig.	**Depth (cm)**	**Description**
D	0–1	Light brownish grey 2.5Y 6/2 extremely gravelly sand, 10% cobbles, single grain, loose, few salts under surface gravel, very abrupt smooth boundary.
Bw1	1–10	Light yellowish brown 2.5Y 6/4, extremely gravelly sand, 10% cobbles, single grain, soft, salt stage 1, abrupt wavy boundary.
Bwz	10–29	Light olive brown 2.5Y 5/6, very gravelly sand, 10% stones, 15% cobbles, single grain, soft, salt stage 2, clear wavy boundary.
Bw2	29–58	Light yellowish brown 2.5Y 6/4, extremely gravelly sand, 10% stones, 15% cobbles, single grain, soft, salt stage 1, clear wavy boundary..
Cox	58–80	Near light yellowish brown 2.5Y 6/3, very gravelly sand, 10% cobbles, single grain, loose.

Table 6-12. Chemical properties for Typic Anhyorthels/Anhyturbels

				EC		**Water-Soluble**						
Site	**Feature**	**Depth (cm)**	**pH (water)**	**(1:5) (mS/cm)**	**TSS_{70} (mg/cm^2)**	**Calcium mmol(+)/kg**	**Magnesium mmol(+)/kg**	**Sodium mmol(+)/kg**	**Potassium mmol(+)/kg**	**Chloride mmol(-)/kg**	**Nitrate-N mmol(-)/kg**	**Sulphate mmol(-)/kg**
WV05-6	Sand plain	0–1	8.9	0.09	730	0.3	0.8	4.5	0.6	1.9	0.3	1.3
		1–12	7.7	1.3		8.8	9.5	38	1.4	48	7.0	4.2
		12–30	7.6	3.6		131	17	56	2.2	67	11	161
		30–44	7.4	3.5		150	8.3	51	1.9	49	5.5	166
		44–72	8.8	0.96		1.5	1.5	36	1.4	29	3.3	8.7
		72+	9.2	0.81		0.9	0.7	33	1.3	23	2.3	6.7
WV05-18	Hummocky (H1) drift	0–1	7.8	2.1	1350	63	2.0	43	1.8	43	3.7	70
		1–17	8.4	5.2		107	35	131	8.5	125	18	168
		17–31	8.5	2.3		28	14	58	6.6	56	13	51
		70+	8.0	4.2		136	9.0	97	8.3	41	9.5	225
WV05-31	Colluvium	0–1	8.2	2.4	1210	37	17	56	2.3	54	22	39
		1–19	8.0	4.1		154	36	49	1.2	62	28	168
		19–70+	7.8	3.4		157	22	31	3.0	34	11	169
WV05-38	Alpine III drift	0–1	8.3	6.8	1820	56	30	205	13	205	82	68
		1–10	8.1	4.9		161	5.9	104	2.8	96	15	191
		10–29	8.4	7.1		33	17	275	8.8	344	23	64
		29–58	8.9	5.5		11	7.5	209	5.6	135	15	126
		58–70+	8.9	1.6		6.1	1.7	53	3.1	41	5.8	24

Table 6–10 ctd. Chemical properties for Typic Anhyorthels/Anhyturbels

				EC		Water-soluble						
Site	**Feature**	**Depth (cm)**	**pH (water)**	**(1:5) (mS/cm)**	**TSS_{70} (mg/cm^2)**	**Calcium mmol(+)/kg**	**Magnesium mmol(+)/kg**	**Sodium mmol(+)/kg**	**Potassium mmol(+)/kg**	**Chloride mmol(-)/kg**	**Nitrate-N mmol(-)/kg**	**Sulphate mmol(-)/kg**
WV05-41	Peleus drift	0–3	7.3	0.67	1060	3.5	2.2	21	0.2	21	3.9	11
		3–8	7.9	8.0		193	70	183	0.8	185	61	208
		8–18	7.9	6.6		182	82	116	0.8	136	51	219
		18–41	7.8	2.9		5.5	30	87	0.8	96	30	16
		41–70+	7.5	1.6		1.2	11	51	0.4	52	12	3.7
WV05-42	Alpine III drift	0–1	7.9	0.80	755	20	1.6	12	0.8	14	1.7	21
		1–22	7.6	2.6		143	3.6	15	1.6	7.2	1.3	170
		22–45	7.6	2.4		84	6.8	36	2.1	33	4.8	100
		45–56	8.3	2.4		58	4.3	47	2.2	25	3.8	110
		56–70+	8.2	1.4		35	2.0	27	1.7	12	1.8	66
WV06-17	Rock glacier	0–1	9.3	0.23	730	1.5	0.5	7.2	0.4	3.8	0.8	4.8
		1–16	8.5	2.3		12	5.1	22	1	51	25	43
		16–28	7.9	2.5		4.6	7.8	17	0.008	44	28	70
		28–59	7.5	2.3		17	6.8	29	0.6	44	22	58
		59–70+	7.6	1.3		3.6	8.3	44	0.8	36	17	12

Table 6–10 ctd. Chemical properties for Typic Anhyorthels/Anhyturbels

				EC		**Water-soluble**						
Site	**Feature**	**Depth (cm)**	**pH (water)**	**(1:5) (mS/cm)**	**TSS_{70} (mg/cm^2)**	**Calcium mmol(+)/kg**	**Magnesium mmol(+)/kg**	**Sodium mmol(+)/kg**	**Potassium mmol(+)/kg**	**Chloride mmol(-)/kg**	**Nitrate-N mmol(-)/kg**	**Sulphate mmol(-)/kg**
WV06-18	Rock	0–1	8.2	0.48	2110	4.7	1.2	11	0.4	9.7	1.4	9.8
	glacier	1–13	8.3	4.4		50	7.9	30	0.8	73	17	131
		13–25	7.9	11.5		8.0	15	164	3.2	561	48	55
		25–63	8.4	5.9		5.6	13	81	2.4	248	45	21
		63–70+	8.4	3.2		3.6	9.1	56	2.1	102	33	10
WV06-20	Upper	0–1	8.9	0.69	765	5.1	2.1	13	0.5	20	3.7	11
	Wright	1–17	8.3	4.5		64	4.3	17	0.8	78	32	134
	III drift	17–33	8.2	2.8		20	6.5	20	1.2	72	34	56
		33–54	7.9	1.2		2.1	2.2	13	0.7	35	17	1.4
		54–68+	7.7	1.0		2.3	2.1	15	0.6	37	12	1.9
WV06-21	Upper	0–1	8.9	0.61	680	4.4	2.1	8.7	0.4	20	5.8	3.7
	Wright	1–6	8.4	1.9		15	6.6	19	0.9	49	25	17
	III drift	6–18	8.2	3.7		85	14	24	1.2	45	28	132
		18–34	7.9	2.3		13	6.7	31	0.7	77	18	32
		34–70	7.7	1.4		7.3	3.2	16	0.5	41	9.4	23
		70–99	8.3	0.76		1.8	1.3	13	0.4	28	5.5	3.7

Table 6–10 ctd. Chemical properties for Typic Anhyorthels/Anhyturbels

				EC		**Water-Soluble**						
Site	**Feature**	**Depth (cm)**	**pH (water)**	**(1:5) (mS/cm)**	**TSS$_{70}$ (mg/cm^2)**	**Calcium mmol(+)/kg**	**Magnesium mmol(+)/kg**	**Sodium mmol(+)/kg**	**Potassium mmol(+)/kg**	**Chloride mmol(-)/kg**	**Nitrate-N mmol(-)/kg**	**Sulphate mmol(-)/kg**
WV06-22	Colluvium	0–1	8.5	0.39	1055	1	0.6	14	0.5	16	1.0	2.3
		1–11	8.1	6.5		54	6.3	59	1.9	217	18	135
		11–32	8.2	3.3		73	5.8	22	1.9	49	9.0	129
		32–70+	8.5	2.2		21	6.5	26	2.7	73	12	33
WV06-24	Rock glacier	0–1	9.1	0.43	885	3.3	1	9.8	0.2	8.0	1.5	6.9
		1–14	8.3	2.8		20	18	43	1.2	63	46	11
		14–24	7.7	5.6		22	7.0	40	3.3	91	102	91
		24–51	8.4	2.5		20	22	65	1.4	69	37	7.6
		51–70+	8.7	1.3		6.5	9.7	31	1.2	15	9.7	0.3
WV06-29	Trilogy drift	0–1	9.6	0.23	370	1.2	0.6	6.4	0.6	5.9	0.5	2.4
		1-11	8.9	1.2		9.2	3.8	28	1.2	37	3.4	15
		11–27	8.8	1.8		9.2	4.0	37	1.5	62	4.9	14
		27–70+	8.9	0.85		10	2.8	19	1.5	18	2.9	16
WV06-30	H1over Trilogy over Loop drift	0-1	8.8	1.1	1080	15	2.1	21	1.0	29	2.3	22
		1-12	8.3	3.2		72	5.9	26	1.7	30	4.1	121
		12–38	7.9	4.1		72	9.8	72	2.2	75	5.8	95
		38–54	7.9	2.9		40	7.8	63	3.2	73	6.4	60
		54–70+	8.4	2.24		12	4.9	58	2.3	39	5.3	62

Table 6–10 ctd. Chemical properties for Typic Anhyorthels/Anhyturbels

				EC		**Water-soluble**						
Site	**Feature**	**Depth (cm)**	**pH (water)**	**(1:5) (mS/cm)**	**TSS_{70} (mg/cm^2)**	**Calcium mmol(+)/kg**	**Magnesium mmol(+)/kg**	**Sodium mmol(+)/kg**	**Potassium mmol(+)/kg**	**Chloride mmol(-)/kg**	**Nitrate-N mmol(-)/kg**	**Sulphate mmol(-)/kg**
WV07-22	Asgard	0–1	5.9	1.9	940	8.0	29	19	0.9	38	18	0.8
	Till?	1–7	5.9	4.5		94	54	55	0.9	44	27	126
		7–17	5.8	3.9		100	53	53	1.1	30	23	177
		17–30	5.4	1.9		27	15	20	1	17	24	27
		30–53	5.6	2.2		19	24	26	0.8	23	13	40
		53–70+	5.8	3.1		25	23	42	1	27	13	99
WV07-31	Upper	0–1	6.9	2.1	2970	92	3.6	13	1.1	7.3	1.7	106
	Wright III	1–24	6.9	5.2		84	36	114	4.3	83	40	16
	drift	24–50	6.0	16.2		50	35	599	4.8	719	56	5.9
		50–70+	6.2	3.9		37	23	101	3.1	139	28	2.2
WV07-33	Colluvium	0–1	6.9	0.44	1800	2.9	2.2	11	0.9	11	2.9	3.5
		1–10	6.7	6.8		169	59	111	2.3	149	48	156
		10–26	6.1	12		14	40	418	2.7	473	63	49
		26–50+	6.1	5.1		12	27	167	2.8	159	53	4.6
WV07-34	Upper	0–1	7.2	0.76	770	13	4.2	15	1.7	13	4.9	11
	Wright III	1–19	6.8	2.5		27	18	36	3.2	31	28	37
	drift	19–48	6.4	2.5		29	20	52	4.0	73	28	6.5
		48–70+	6.1	1.9		16	16	45	2.7	63	23	3.0

Table 6–10 ctd. Chemical properties for Typic Anhyorthels/Anhyturbels

				EC	**Water-soluble**							
Site	**Feature**	**Depth (cm)**	**pH (water)**	**(1:5) (mS/cm)**	**TSS$_{70}$ (mg/cm^2)**	**Calcium mmol(+)/kg**	**Magnesium mmol(+)/kg**	**Sodium mmol(+)/kg**	**Potassium mmol(+)/kg**	**Chloride mmol(-)/kg**	**Nitrate-N mmol(-)/kg**	**Sulphate mmol(-)/kg**
WV07-35A	Upper Wright III drift	0–1	6.4	2.9	1100	88	20	40	1.2	26	8.7	112
		1–12	8.0	7.6		75	44	123	2.5	150	69	211
		12–36	8.0	2.7		1.5	21	59	2.6	68	48	13
		36–59	7.7	2.8		26	31	64	2.3	52	39	44
		59–70+	8.7	1.2		4.6	11	35	1.3	29	13	12
WV07-40	Peleus drift	0–1	7.8	2.2	1520	38	3.8	7.4	0.6	6.9	2.8	34
		1–6	8.1	3.6		45	22	39	1.6	23	10	7.0
		6–29	8.5	6.8		51	24	57	1.5	82	37	11
		29–50	8.7	4.8		9.2	9.2	37	0.9	66	23	0.6
		50–100	9.0	1.9		5.4	3.4	27	0.8	27	7.5	2.9
		100–110	8.5	1.3		2.6	1.8	11	0.5	21	5.8	18

6.11.8 LITHIC HAPLORTHELS/HAPLOTURBELS

Lithic Haplorthels/Haplorthels (LHo/LHt) are the dominant soil subgroup over approximately 350 ha or less than 1% of the area. Lithic Haplorthels are developed predominantly on dykes east-south east of Lake Vanda and lower slopes of the valley walls. As Lithic Haplorthels/Haploturbels must have some soil development, many areas of the valley walls on steep slopes or upper slopes, are mapped as bare rock where soil formation has not progressed sufficiently.

Range of morphological and chemical properties

A typical profile developed in a mafic dyke in the Bonny Pluton near Lake Vanda (WV06-07) contains a thin, weakly developed desert pavement with 70% gravels and stones over cobbly greyish brown sand of granitic grüss (Figure 6-16). Below, the largely unaltered gravel with cobbles is shattered rock. Lithic Haplorthels have moderately to extremely alkaline pH and low levels of cations and anions (Table 6-13).

There is little soil development within this subgroup so the range of soil properties is limited. The profile consists of D over Cox horizons. pH (Table 6-13) is moderately to extremely alkaline (8.1–9.3). Maximum profile EC ranges from 1.0 to 1.1 mS/cm with an average of 1 mS/cm. Average salt content in the profile to 70 cm is 195 mg/cm^2 and ranges from about 90 to 300 mg/cm^2. Chloride is the dominant anion in the salt-rich horizon, averaging approximately 30 mmol$_{(-)}$/kg (range 27–33 mmol$_{(-)}$/kg). Sulphate is predominantly the next most dominant ion and ranges from approximately 9 to 12 mmol$_{(-)}$/kg. The concentration of nitrate-N never exceeds that of sulphate. Sodium is generally the dominant cation in the salt-rich horizon, and when dominant ranges from 16–17 mmol$_{(-)}$/kg.

Physiographic position

In Wright Valley, lithic soils occur where bedrock occurs within 50 cm of the soil surface. Thus the soils occur on the valley walls where there is only thin glacial drift, colluvium or in-situ residuum. Lithic soils also occur on the valley floor in some locations where glacial action has planed bedrock without deposition but there has been sufficient time for rudimentary soils to develop.

Inclusions

There are inclusions of bare rock Typic Haplorthels/Haploturbels where the soils are deeper than 50 cm and the permafrost is ice-cemented within 70 cm of the soil surface – generally in recharge zones.

Figure 6-16. Soil profile WV06-07 (upper) and landscape position (lower) of dyke rock intruded into the Bonny Pluton.

Soil subgroup: Lithic Haploturbel
Coordinates: S77.51902 E161.74530
Location: ESE end Lake Vanda
Profile Description
Landform: Crest of narrow dyke
Parent material: Mafic dyke in Bonny Pluton
Weathering stage: 4
Salt stage: 1

Desig.	**Depth (cm)**	**Description**
D	0–0.5	Light brownish grey 2.5Y 6/2, very cobbly sand, single grain, loose, abrupt boundary.
Cox	0.5–19	Light yellowish brown 2.5Y 6/3, gravelly sand, single grain, loose, abrupt wavy boundary.
2CR	19+	Light yellowish brown 2.5Y 6/3, very gravelly sand, single grain, loose, abrupt wavy boundary.

Table 6-13. Chemical properties for Lithic Haplorthels/Haploturbels–

Site	Feature	Depth (cm)	pH (water)	EC (1:5) (mS/cm)	TSS$_{70}$ (mg/cm^2)	Water-Soluble						
						Calcium mmol(+)/kg	Magnesium mmol(+)/kg	Sodium mmol(+)/kg	Potassium mmol(+)/kg	Chloride mmol(-)/kg	Nitrate-N mmol(-)/kg	Sulphate mmol(-)/kg
WV06-6	Swale in dyke country	0–0.5	9.3	0.10	190	0.67	0.28	2.2	0.42	1.2	0.146	1.8
		0.5–20	8.7	1.1		11	5.1	17	0.738	33	2.1	9.3
		20–22	8.9	0.4		6.8	3.5	4.1	0.511	12	0.994	1.9
WV06-7	Basalt dyke	0–0.5	9.3	0.1	300	0.27	0.12	1.51	0.35	0.99	0.097	0.65
		0.5–19	8.1	1.0		16	6.4	16	1.0	27	2.7	10
		19-22	8.1	0.9		17	6.3	14	1.0	25	2.4	10
WV06-9	Aeolian over bedrock	0–0.5	8.5	0.1	90	0.52	0.226	1.13	0.21	1.04	0.09	0.64
		0.5–20	8.3	1.0		23	8.1	9.6	0.81	33	1.9	12

6.12 PERMAFROST

The permafrost materials are defined as follows:

- Ice cemented permafrost is material with temperatures <0°C, for at least two consecutive years, that contains enough frozen water to cement the soil materials.

- Dry permafrost is material with temperatures <0°C, for at least two consecutive years, that has insufficient water to form ice-cement.

- Ice cored permafrost is material with temperatures <0°C, for at least two consecutive years, with >75% visible ice.

Permafrost map units that we have used in the Wright Valley (Map 2) are:

Ice-cemented permafrost

- where ice-cemented permafrost occurs within 70 cm of the ground surface ($ICP_{<70}$).

Dry permafrost

- where dry permafrost occurs to a depth of at least 70 cm from the ground surface.

Ice cored permafrost

- where ice-cored permafrost occurs within 100 cm of the ground surface.

The depth of dry permafrost to at least 70 cm coincides with the minimum depth requirement for anhydrous conditions (Soil Survey Staff 2010) and forms the cut-off between Anhy- and Haplo- great groups of Soil Taxonomy.

Within the study area, $ICP_{<70}$ occurs over approximately 12 000 ha or 75% of the mapped ice-free area. A notable feature of the permafrost map is the unexpected occurrence of large areas of soils with ice-cemented permafrost shallower than 70 cm depth on the south valley wall associated with melt water inputs from higher elevation.

The distribution of permafrost type (dry or ice-cemented), is related to the age of the deposit as in general dry-frozen permafrost is formed over time as interstitial ice is sublimated from Antarctic soils (Ugolini, 1964; Bockheim, 1990, 2002; Bockheim & Wilson, 1989). However, there is a modifying factor of soil water recharge. In the study area, especially at lower elevation away from the coast, only minor recharge occurs from precipitation with most recharge occurring from subsurface flow – often along the ICP boundary. Streams or rivers contribute to the surface flow and may be channelised with a semi-permanent bed or may be areas of flow over a fan without the formation of an incised channel. Flow is often diurnal during the summer. Eventually, surface flow supplies water to a soil by subsurface flow. In contrast, subsurface flow may also occur from melt water zones at higher elevation where melting provides insufficient water to develop surface flow. The source may not be immediately obvious and the surface not necessarily moist. The supply of melt water from high elevation and consequent down-slope effects may vary with season, and the surface flows we observed at the base of some slopes on the south wall may not occur every year. Alternatively, surface or subsurface flow may become more common as a response to unusual warming events such as that which occurred in December 2001/January 2002. During this event water was initially released from increased melting of ice and snow and perhaps later from melting of upper parts of ice-cemented permafrost.

In Wright Valley, soils with ICP at less than 70 cm are associated with the Onyx River and Lake Vanda, colluvial fans, steep colluvial slopes with melt water supply at higher elevation. $\text{ICP}_{<70}$ was not observed within Peleus drift, Alpine III and Alpine IV although nivation hollows (10 m ×5 m ×1 m) and slumping was common along down-slope edges of thick deposits of Peleus till.

6.13 VULNERABILITY TO HUMAN FOOT TRAMPLING

Soil vulnerability in Wright Valley (Map 3), is ranked High, Medium or Low. Many soils in ice-free Wright Valley, Antarctica, are easily disturbed by foot trampling and rehabilitate slowly. Most rehabilitation processes, except for wind redistribution of finer particles, are slow in the prevailing cold desert conditions. When undisturbed for long periods some soils have developed a ventifacted and varnished desert pavement with salts under surface rocks. In contrast, many young soils have not developed these features.

Generally, the disturbance scores indicate that walking on finer textured material produces more disturbance. This is similar to the findings of Campbell et al. (1993). Exceptions occur where the smaller diameter coarse material, e.g., coarse gravels and fine cobbles are well rounded and deeply set into a matrix of fines. Old surfaces have developed desert varnish, surface pitting and salt encrustations under gravels/cobbles over a long period of non-disturbance. Once disturbed, based on a chronosequence of soils on alpine drift and drift from fluctuations of the Wilson Peidmont Glacier the soil may take thousands of years to return to pre-disturbance appearance.

Where a coarse desert pavement overlies fine material such as silty Peleus till, trampling will result in immediate disruption of the protective desert pavement exposing readily wind-erodible material. Trampling on this material is done only as a last resort.

We recommend that strongly weathered surfaces with cobbles that can be dislodged and surfaces with coarse desert pavement overlying fine material are least trampled.

Young, active surfaces rejuvenate quickly as the fastest agents of rejuvenation are wind and water. Thus, while areas of sand without coarse material are readily disturbed their rejuvenation in the windy climate of the Wright Valley is rapid, often less than one year. Furthermore, sandy material often rejuvenates to a depth of at least 10 cm and layers of contrasting soil colour do not develop within the foot print disturbance depth. We recommend that, where possible, human activities be concentrated on active surfaces.

Some gravelly/cobbly surfaces are affected by cryoturbation, resulting in patterned ground with sand wedges between the polygons. In many cases the sand wedges show little colour change with depth, whereas they may show signs of structural laminations. However, upper parts of the wedge are often rejuvenated by wind. We recommend that where patterned ground must be traversed, walking in the most active part of the surface, which is the sandy areas of the patterned ground cracks, minimizes impacts and allows most rapid rejuvenation of the surface.

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7 SYNTHESIS

7.1 DISCUSSION

In this research, Chapters 2, 3 and 4 describe the spatial distribution of soils and some of their chemical properties in the lower, central and upper Wright Valley, Antarctica. Chapter 6 amalgamates the soil spatial and chemical data into a stand-alone soil survey report with live GIS files hot linked to the soil profile descriptions, soil chemical analyses and soil photographs. Chapter 5 presents a rapid method to determine the vulnerability of soils to human foot trampling and depiction of soil vulnerability in Wright Valley at a scale of 1:50 000.

Soil spatial distribution

The soil subgroup spatial distribution (Chapters 2, 3, 4 and 6) forms a pattern of Glacic Haploturbels predominantly on young drift with Typic Haplorthels/Haploturbels in the higher precipitation coastal region or where there is recharge of the permafrost by visible water movement or by subsurface seepage from higher ground. Subsurface seepage is not always evident at the surface but during the Austral summer flow may be seen over the ice-cemented permafrost. Subsurface water movement leads to the situation where Haplorthel and Anhyorthel soils can occur as adjacent map units within a previously defined climatic zone based on precipitation. Typic and Salic Anhyorthels/Anhyturbels occur on drier, inland, older surfaces where dry permafrost extends to below 70 cm. Finally, Petrosalic Anhyorthels/Anhyturbels occur on old surfaces predominantly of Pliocene age such as the Valkyrie drift where dry permafrost extends to below 70 cm. On the Dais and Labyrinth are the oldest soils possibly developed in Asgard Till of Pliocene or Miocene age. They have low salt content for their age and are classified as Typic or Salic Anhyorthels. Figure 7-1 summarises the development pathways of soils in Wright Valley.

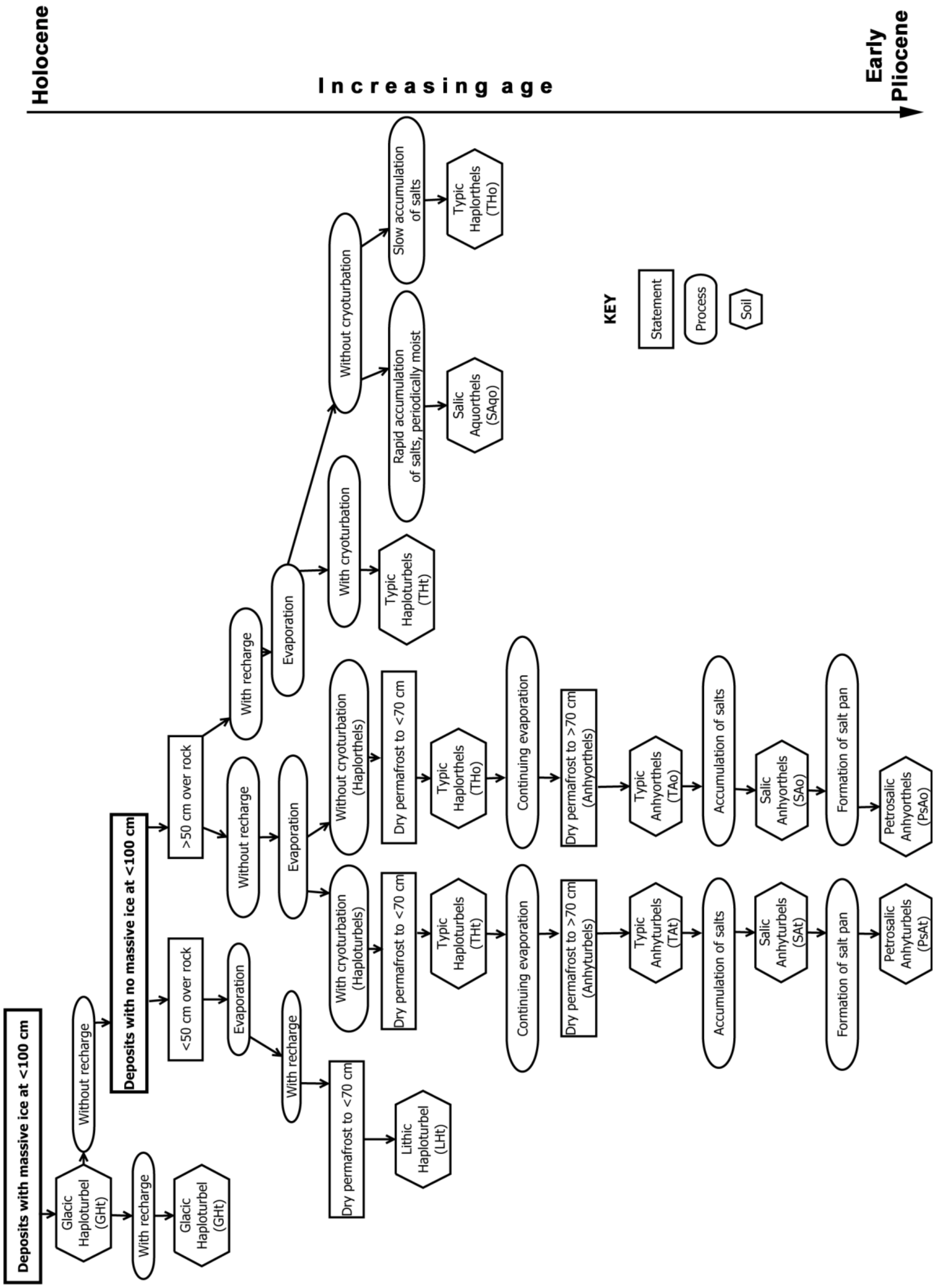

Figure 7-1. Flow diagram showing development pathways of soils in Wright Valley, following Bockheim and McLeod (2006).

Soil maps and surficial geology maps are now distinctly different due in part to the development of the Gelisol Order within USDA Soil Taxonomy (Soil Survey Staff 2010). Similar surficial geologies can have a range of soil subgroups, each with distinctly different soil morphological and soil chemical attributes, over a short distance. In contrast, early soil maps (e.g. McCraw 1967) used soil separations based largely on differences in topography and parent materials (Campbell & Claridge 1987).

A notable feature of the soil map is the high proportion of Typic Haplorthels/Haploturbels especially on the south wall of the western part of the valley where there are large areas of gelifluction deposits, many of which receive seepage water from snow and ice deposits upslope. As a rule-of-thumb, Typic Haplorthels/Haploturbels can be mapped where patterned ground or gelifluction deposits are observed.

Chemical properties of the soils

Generally, the soils of Wright Valley are dominated by chloride anions with some, generally older, soils dominated by sulphate anions. In contrast to observations by Bockheim (1982) where gypsic horizons (dominated by sulphate anions) are observed inland in soils on older surfaces, gypsic horizons have not been observed in Wright Valley, possibly because the whole valley system is influenced by chloride dominated marine air masses.

Application of USDA Soil Taxonomy Subgroups

Delineation of soil map units at USDA Soil Taxonomy subgroup level (Soil Survey Staff 2010) was appropriate because Soil Taxonomy identified the main morphological differences within the soil which allows the soils to be placed in a developmental sequence as water is sublimated from the soils and salts accumulate (Chapter 6). Using USDA Soil Taxonomy family level would provide little further information about the map units as most of the soils have a sandy-skeletal particle size group. Family-level mineralogy would distinguish between soils developed in predominantly granitic drift and those developed in drift or residuum from Ferrar dolerite. However, further subdivision of the Haplorthels/Haploturbels subgroup based on colour development equivalents would be easier in the field and would capture the morphological differences.

Subdivision of Haplorthels/Haploturbels

Typic Haplorthels/Haploturbels are the most common soil subgroup throughout the Wright Valley and possibly throughout the ice-free areas of the Ross Sea Region as well. Bockheim (1979) recognised the overall limited development of these soils but pedologically, it is useful to distinguish between the weakly developed and more developed Typic Haplorthels/Haplorthels. As a consequence map units to recognise the differences in THo/THt in Wright Valley have been established on the basis of maximum colour development equivalent (Buntley & Westin 1965). Other possibilities for the subdivision of Haplorthels/Haploturbels include subgroups of soils with no developmental horizons i.e., desert pavement over Cn horizons and subgroups of soils with salic horizons.

Proposal for a petrosalic horizon

While petrocalcic and petrogypsic soil horisons have been defined in USDA Soil Taxonomy (Soil Survey Staff 2010) a petrosalic soil horizon has not been defined. The definition may have been overlooked possibly because in temperate climates the salic horizon would not become cemented. A definition for a salt-rich cemented petrosalic horizon, which commonly occurs in the dry valleys of Antarctica but is not reported elsewhere in the world, is proposed in Chapter 6.

Permafrost

Depth to shallow permafrost was recorded as part of the soil mapping programme. Permafrost types in the Wright Valley include dry permafrost or permafrost with ice cement within 70 cm with minor (<0.5%) amounts of ice-cored permafrost. We observed unexpectedly large areas of soils with permafrost with ice cement above 70 cm on the south valley wall which was associated with melt water from up-slope. The supply of melt water from high elevation and consequent down-slope effects may vary with season, and may not occur every year. Alternatively, soils with permafrost containing ice-cement at less than 70 cm may become more common as a response to particularly warm summers such as that which occurred in December 2001/January 2002. In Wright Valley, permafrost with ice-cement at less than 70 cm is associated with most geomorphic features including the Onyx River and lake, drift of various ages at the high precipitation eastern end of the valley, drift in the Labyrinth, colluvial fans, and steep colluvial slopes with melt water supply at higher elevation. Within the study area, soils with permafrost and ice-cement at <70 cm occur over approximately 50% of the area.

Soil vulnerability to human foot trampling

Vulnerability of Wright Valley soils to human foot trampling (Chapter 1) suggests that many soils in ice-free Wright Valley, Antarctica, are easily disturbed by foot trampling and rehabilitate slowly because the rehabilitation processes, except for wind redistribution of finer particles, are slow in the prevailing cold desert conditions.

Generally, the vulnerability ratings indicate that young, active surfaces rejuvenate quickly as the fastest agents of rejuvenation are wind and water. Thus, while areas of sand, without coarse material, are readily disturbed, their rejuvenation in the windy climate of the Wright Valley is rapid, leading to low vulnerability. In contrast, old surfaces have developed desert varnish, surface pitting and salt encrustations under gravels/cobbles over a long period of non-disturbance. Once disturbed the older soils may take thousands of years to return to pre-disturbance appearance and thus are highly vulnerable.

Similarly, highly vulnerable are soils where a coarse desert pavement overlies fine material such as Peleus till. Trampling will result in disruption of the protective desert pavement exposing the readily wind-erodible Peleus till. A single pass of foot prints in this material remains for long periods as regularly spaced depressions in-filled with a contrasting desert pavement.

Using the simple methods presented in Chapter 5 to determine soil vulnerability combined with the map showing the spatial distribution of vulnerability classes, visitors to Wright Valley can select areas to camp or traverse which minimize soil damage. Furthermore, visitors can be forewarned of vulnerable soils and avoid them if possible.

Immediate use of the research

Insights gained from this research will result initially in improved spatial depiction of soil and shallow permafrost properties of ice-free areas in the Ross Sea Region as part of ongoing research, and later over the whole ice-free area of the TransAntarctic Mountains. Both these regions have low-resolution interim soil maps in which Anhyorthels have been allocated predominantly on the basis of climate.

Potentially, AntarcticaNZ could use the soil vulnerability map to alert visitors to the Dry Valleys of differences in vulnerability of soils to trampling and, where possible, tailor work to avoid highly vulnerable soils. Campsites are often located near water and soils at these locations often have low vulnerability.

Review of related publications included in appendices

Published papers, related to the McMurdo dry valleys, in the appendices are included where McLeod is a co-author. The papers reflect on-going collegial field discussions and the role of the authors in preparing the manuscripts.

Appendix II (Bockheim & McLeod 2006) uses the extensive historic database of Bockheim (http://nsidc.org/data/ggd221.html) to conclude that 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 be readily distinguished on the basis of morphological properties, particularly the amount and distribution of soluble salts, and the degree of chemical weathering. The morphological and chemical changes are reflected in the USDA Soil Taxonomy soil classification.

In Appendix III Bockheim and McLeod (2008a) conclude that they observed deposits reflective of four advances of the Wright Upper Glacier, confirming and considerably amplifying the earlier work of Calkin et al. (1970). Based on surface weathering and soil properties, they correlated WU I and II drifts with Taylor I and II drifts, extensive rock glacier activity with Taylor III drift, and WU III drift with Taylor IVa and Alpine III drifts in central Taylor and Wright Valleys, respectively. The WU IV drift was correlative with the Peleus till dated in central Wright Valley at >3.9 Ma. These correlations imply that the Wright Upper Glacier advanced into upper Wright Valley depositing WU III drift during the early Pliocene. These interpretations are consistent with advances of the Ferrar and Taylor Glaciers during the early Pliocene. The presence of wet margin ice features, such as kame moraines, esker-like features, kames, and melt water channels, suggests that wetter and possibly warmer conditions occurred during the WU III Glaciation.

In Appendix VI, Bockheim et al. (2008a) conclude there was no field evidence for the existence of high-level lakes in central Wright and Taylor Valley, although they did find evidence for fluctuations of modern lakes by ca. 50 m. There were few significant differences in soil properties above and below the proposed lake high-water-level contours, causing them to reject hypotheses that salt-related soil properties and other physical and chemical soil properties would be less in soils below the highest paleo-lake level than in soils above this level. In contrast, there were significant age-related trends in soil properties both above and below these lake levels with no significant differences in rates of change in soil properties. There were few differences in slopes of regression lines relating soil property to time of exposure, causing them to reject the hypothesis that age-related trends in soil development rates will be dampened below the highest paleo-lake level. These data cast doubt on whether high-level lakes existed in the McMurdo Dry Valleys as recently as the early Holocene.

In Appendix V Bockheim et al. (2008b) conclude that at least one of the bulky alpine drifts in Taylor Valley is probably early Pleistocene to late Pliocene in age. Soil development is comparable to that on Alpine III drift in central Wright Valley (Bockheim & McLeod 2006) for which only a maximum date, 3.5 My BP, currently exists (Hall et al. 1993). If correct, this indicates that part of the Alpine III drift in Wright Valley, suggested by Prentice and Krusic (2005) as being multiple, dates to the late Pliocene. The soils of Taylor Valley follow the evolutionary sequence observed in Wright Valley immediately to the north (Bockheim & McLeod, 2006). Holocene-aged surfaces contain Glacic Haploturbels; surfaces of late Quaternary age contain Typic Haploturbels; surfaces of late to mid-Quaternary age contain Typic Anhyorthels; surfaces of early Quaternary to late Pliocene age contain Salic Anhyorthels; and surfaces of mid- to early Pliocene age contain Petrosalic Anhyorthels. In Taylor Valley, ice-cemented permafrost is common within 28 km west of the coast and in Alpine II moraines; most of the remaining area to the upper Taylor Glacier contains dry-frozen permafrost. Ground ice is restricted to Holocene-aged Alpine I moraines.

Appendix VI (Bockheim and McLeod 2008b) is a reconnaissance 1:2 000 000 scale map of the McMurdo Dry Valleys region, the largest ice-free region in Antarctica, using published and unpublished data. The new definition of anhydrous conditions linked to soil properties rather than climatic zones was incorporated into the map following early experience in Wright Valley. Improvements to the map could now be made to recognize the role snow patches and subsurface flow of meltwater have on ice table recharge. These improvements have been incorporated into the current Wright Valley soil map.

7.2 FURTHER RESEARCH

This research has identified the following areas for further investigation:

Identification of anhydrous conditions

The distinction at Great Group level of USDA Soil Taxonomy (Soil Survey Staff 2010) between Anhyorthels and Haplorthels depends on the identification of Anhydrous conditions. Because for Anhydrous conditions the required soil characteristics of the 10 – 70 cm layer include no ice-cemented permafrost, the condition is not directly related to climatic regime.

In Wright Valley, Haplorthels were on occasion associated with ground that contained snow patches or snow trapped in the margins of polygons. McKay (2009) demonstrated that the recurrence of snow can explain the depth of dry permafrost at high elevation in the Dry Valleys. This approach could assist soil mapping over much ice-free ground as only sequential air photos are required.

The hypothesis requiring testing is: Presence of permanent discrete snow patches in a soil map polygon equates to soil Haplorthel or Haploturbel Great Groups.

Use of soil classes to predict soil microbial structure

The utility of soil classes to predict soil microbial and soil animal community structure needs to be investigated in Antarctic soils. USDA Soil Taxonomy Subgroups (Soil Survey Staff 2010) likely contain sufficient information, especially on soil moisture, salt species and content, to be able to extrapolate results of site specific studies.

The hypothesis requiring testing is: Do soil classes predict soil microbial or soil fauna community structure over long distances?

Nature of remotely sensed soil layers

There is sufficient evidence in the literature to suggest quad-polarisation synthetic aperture radar (Quad-pol SAR) may work well under Antarctic conditions to spatially depict surface roughness, soil salts and soil moisture. These parameters would significantly assist in assigning soil subgroup. Wright Valley, where there is now a spatial depiction of soil subgroups, could be a trial site.

The hypothesis requiring testing is: Does Quad-pol SAR spatially depict soil salts and soil moisture under Antarctic conditions?

7.3 CONCLUSIONS

The spatial distribution of soils in Wright Valley, Antarctica have been depicted at a scale of 1:50 000. A rapid method to determine soil vulnerability to human foot trampling has been developed and the soil map used as a basis to extrapolate soil vulnerability classes. The soil map has also been used to create a map of shallow permafrost types in Wright Valley. Soil mapping also revealed the need for a Petrosalic subgroup of Anhyorthels/Anhyoturbels. A definition for Petrosalic subgroups has been proposed.

Concerning the soil map:

- Glacic Haplorthels/Haploturbels must have >75% visible ice within 100 cm of the soil surface and are confined to the most recent deposits associated with Upper and Lower Wright Glaciers and the alpine glaciers.
- Typic Haplorthels/Haploturbels are the dominant subgroups which in Wright Valley have permafrost in which ice cement occurs within 70 cm of the soil surface. Ice cement often occurs within 70 cm of the soil surface if the soils are young or the ice cement is recharged by free water. Thus Typic Haplorthels/Haploturbels predominantly occur at both ends of the Wright Valley on a range of surficial geologies, as well as marginal to the Onyx River. Typic Haplorthels/Haploturbels also occur downslope of water sources on a range of surficial geologies and on young alpine moraines.
- Anhyorthels/Anhyturbels have dry permafrost extending to at least 70 cm from the soil surface. Anhyorthels/Anhyturbels predominantly occur in the central part of the Wright Valley and also towards the eastern end of Wright Valley at high elevation. When Anhyorthels/Anhyturbels are developed in moraine, water must have been progressively evaporated out of the soil thus the great groups are constrained to older moraines in positions of little soil water recharge.
- In areas affected by recharge of soil water (other than recharge by precipitation), Haplorthels and Anhyorthels can occur as adjacent map units on the same surficial geology.

- Differences between maximum color development equivalent and electrical conductivity shown between the lower and upper reaches of Wright Valley are likely to be driven by differences in parent material – granitic compared to doleritic
- The central-western part of Wright Valley is dominated by two large rock glaciers extending from the south wall and are considered early Quaternary in age.
- Extracts of water soluble cations and anions are generally dominated by sodium and chloride respectively.

Concerning soil vulnerability:

- Disturbance can be evaluated from 10 boot prints at each site.
- Rehabilitation was related to soil weathering stage.
- Wind is the fastest, most widespread agent of rehabilitation which constrains rapid rehabilitation to finer (less than about 10 mm) particles. However, soils developed in this type of parent material are easily disturbed by trampling.
- It is preferable to establish walking routes and campsites on soils with a parent material which can be readily rehabilitated by wind rather than on smooth, desert varnished surfaces with salts under surface gravels and stones.

Concerning the permafrost map:

- Three types of shallow permafrost were recognized in Wright Valley:
    - ice-cored permafrost occurs within 100 cm of the ground surface
    - ice-cemented permafrost occurs within 70 cm of the ground surface
    - dry permafrost occurs to a depth of at least 70 cm from the ground surface.
- Massive ice was associated with young moraines of Upper and Lower Wright Glaciers and alpine glaciers.

- Permafrost with ice cement at less than 70 cm was the dominant (75% of the ice-free area mapped) form of permafrost and was associated with the Onyx River, Lake Vanda, and areas with high precipitation (coastal) or blowing snow. Notably, large areas of permafrost with ice cement at less than 70 cm were observed on colluvial fans and steep colluvial slopes, on the south valley wall, with melt water supply from higher elevation.
- Dry permafrost to >70 cm was observed in in-situ Peleus drift, Alpine III and Alpine IV materials.

Many insights gained from pedological investigations within this study of the Wright Valley have application to other dry valleys in the Ross Sea region.

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8 APPENDIX I

Location of soil pits used in the study.

Pit number	Latitude	Longitude
76-50	-77.48453	162.36214
77-01	-77.51412	162.31285
77-02	-77.50605	162.29684
77-03	-77.513	162.30345
77-04	-77.51334	162.30002
77-05	-77.5221	162.22332
77-06	-77.52217	162.21704
77-07	-77.52001	162.28035
77-08	-77.5015	162.21075
77-09	-77.51327	162.26407
77-10	-77.52409	162.16418
77-11	-77.50714	162.30129
77-12	-77.50175	162.26689
77-13	-77.52926	162.13628
77-14	-77.48378	162.34621
77-15	-77.48872	162.35792
77-16	-77.44306	162.44191
77-17	-77.46065	162.47772
77-18	-77.50142	162.33456
77-19	-77.50067	162.33907
77-20	-77.48909	162.32306
77-21	-77.50072	162.33504
77-22	-77.48798	162.37076
77-23	-77.49732	162.35609
77-24	-77.49385	162.28433
77-25	-77.54676	161.48911
77-26	-77.54456	161.53625
77-27	-77.55557	161.52575
77-28	-77.51846	161.65666
77-29	-77.5163	161.65626
77-30	-77.54877	161.51476
77-31	-77.55856	161.52677
77-32	-77.52225	161.91251
77-33	-77.52013	161.91284
77-34	-77.53091	161.96047
77-35	-77.52251	161.8781
77-36	-77.4957	162.41171
77-37	-77.4889	162.3921
77-38	-77.48098	162.35998
77-39	-77.48062	162.36169
77-40	-77.50124	162.20796
77-41	-77.50681	162.3112
77-42	-77.54843	162.19747
77-43	-77.41673	162.54691
77-44	-77.43533	162.79969
77-45	-77.42888	162.69825
77-46	-77.4607	162.471
78-01	-77.59516	161.15533
78-02	-77.59194	161.18256
78-03	-77.59727	161.21396
78-06	-77.53397	161.3659
79-01	-77.54725	161.76977
79-01jl	-77.52321	162.34698
79-02	-77.51674	161.6838
79-02jl	-77.51139	162.38313
79-03	-77.55401	161.42715
79-06	-77.52631	162.10582
79-07	-77.51416	160.9953
79-08	-77.52897	161.00047
79-09	-77.53917	162.06077
79-10	-77.53947	162.08036
79-11	-77.539	162.09157
79-12	-77.53205	162.1216
79-13	-77.53514	162.12059
79-14	-77.53575	162.1108
80-26	-77.51132	162.14514
80-27	-77.5111	162.19102
82-18	-77.49183	162.40089
83-14	-77.53997	161.6799
83-15	-77.54072	161.46511
83-16	-77.53782	161.37148
83-17	-77.59385	161.21258
83-18	-77.59375	161.13959
83-19	-77.59489	161.13951
83-20	-77.59507	161.12678
83-21	-77.59806	161.13875
83-22	-77.60222	161.15912
83-23	-77.52452	162.16433
83-24	-77.61558	161.10096
83-25	-77.61796	161.06737
83-26	-77.60053	161.1624
83-27	-77.60991	161.10825
83-28	-77.4608	162.47073
83-29	-77.46079	162.47555
83-30	-77.49336	162.28066
83-31	-77.49374	162.28014
83-32	-77.48486	162.3495
83-33	-77.48384	162.38207
83-34	-77.47126	162.37028
83-35	-77.48126	162.32345

Pit number	Latitude	Longitude
83-36	-77.53123	162.09678
83-37	-77.53296	162.11181
83-38	-77.53032	162.0908
83-39	-77.53713	162.05482
83-40	-77.53607	162.06984
83-41	-77.53956	162.03487
84-22	-77.52829	162.16769
84-23	-77.5256	162.16209
84-24	-77.52499	162.16838
84-25	-77.52912	162.17277
84-26	-77.53781	162.20914
84-27	-77.5388	162.2036
84-28	-77.53601	162.19804
84-29	-77.53303	162.18436
84-30	-77.51993	162.13336
84-31	-77.51865	162.13091
84-32	-77.51944	162.13022
84-33	-77.52997	162.18558
84-34	-77.52937	162.1786
84-35	-77.53412	162.19722
84-36	-77.52923	162.23515
84-37	-77.52955	162.2359
84-38	-77.52286	162.22461
84-39	-77.52441	162.21763
84-40	-77.52166	162.22134
84-41	-77.51656	162.26506
84-42	-77.51735	162.26632
84-43	-77.51545	162.26955
84-44	-77.51677	162.2615
84-45	-77.5174	162.26292
84-46	-77.51844	162.26241
84-47	-77.51759	162.2609
84-48	-77.51675	162.25943
84-49	-77.52101	162.22482
84-50	-77.50021	162.33396
84-51	-77.50049	162.33717
84-52	-77.50116	162.33055
84-53	-77.4983	162.32645
84-54	-77.49622	162.32376
84-55	-77.49548	162.36144
84-56	-77.49583	162.36224
84-57	-77.4956	162.36091
84-58	-77.49785	162.2885
84-59	-77.49389	162.30959
84-60	-77.50427	162.28054
84-61	-77.5014	162.27735
84-62	-77.51398	162.30193
84-63	-77.51344	162.30394
84-64	-77.51356	162.3043
84-65	-77.51161	162.29907
84-66	-77.51121	162.29498
84-67	-77.51372	162.30133
84-68	-77.50435	162.26956
84-69	-77.50682	162.29918
84-70	-77.50218	162.33947
84-71	-77.50395	162.26328
84-72	-77.47744	162.34563
84-73	-77.47099	162.52036
84-74	-77.50093	162.25694
84-75	-77.49762	162.22048
84-76	-77.52423	161.9648
84-77	-77.52515	161.96144
84-78	-77.54759	161.61104
84-79	-77.54878	161.57815
84-80	-77.54306	161.69078
84-81	-77.53943	161.75658
84-82	-77.47305	161.03927
84-83	-77.47181	161.04795
84-84	-77.49809	162.26891
84-85	-77.53388	161.93619
84-90	-77.59357	161.15703
84-91	-77.59412	161.15119
84-92	-77.5931	161.15018
84-93	-77.59254	161.15288
84-94	-77.60613	161.17263
84-95	-77.5335	162.08875
84-96	-77.53448	162.08946
84-97	-77.53454	162.0893
84-98	-77.53576	162.08594
84-99	-77.53388	162.0366
86-04	-77.49461	162.38679
86-05	-77.49375	162.38747
86-06	-77.48945	162.38999
86-07	-77.49517	162.39155
86-08	-77.48754	162.38966
86-09	-77.49553	162.40723
86-10	-77.48849	162.33531
86-11	-77.48815	162.36841
86-12	-77.48368	162.37014
86-13	-77.48381	162.38001
86-14	-77.48711	162.35482
86-15	-77.49478	162.39271
86-16	-77.49516	162.36515
86-17	-77.49348	162.35433

Pit number	Latitude	Longitude
86-18	-77.49379	162.38022
87-29	-77.49471	162.37554
05-1	-77.48858	162.33327
05-2	-77.50283	162.16237
05-3	-77.48673	162.33037
05-5	-77.49336	162.36771
05-6	-77.4904	162.31501
05-7	-77.52673	162.13899
05-8	-77.44701	162.64075
05-9	-77.45168	162.6385
05-11	-77.44187	162.65519
05-12	-77.48766	162.37427
05-13	-77.48848	162.38483
05-14	-77.48881	162.38629
05-15	-77.48812	162.38201
05-16	-77.49358	162.31377
05-17	-77.48432	162.35221
05-21	-77.47438	162.44997
05-22	-77.47582	162.45943
05-18t	-77.47578	162.46549
05-19	-77.4762	162.4763
05-20	-77.47838	162.48669
05-23	-77.48649	162.41328
05-24	-77.49109	162.32937
05-25	-77.49705	162.40431
05-26	-77.42119	162.68245
05-27	-77.421	162.67894
05-28	-77.47967	162.36239
05-29	-77.47089	162.38325
05-30	-77.50472	162.24403
05-31	-77.47181	162.30747
05-33	-77.44724	162.51046
05-34	-77.44666	162.50941
05-35	-77.44332	162.49717
05-36	-77.4758	162.45934
05-40	-77.50596	162.16643
05-37	-77.4853	162.36547
05-38	-77.49541	162.38976
05-39	-77.50112	162.33133
05-41	-77.54252	162.17272
05-42	-77.49359	162.38437
06-9	-77.51662	161.80024
06-8	-77.51902	161.75721
06-1	-77.51945	161.97429
06-2	-77.52312	161.96728
06-3	-77.52306	161.96849
06-4	-77.54137	161.98405

Pit number	Latitude	Longitude
06-5	-77.54258	161.83408
06-6	-77.51887	161.7471
06-7	-77.51902	161.7453
06-10	-77.52097	161.90471
06-11	-77.51192	161.90139
06-12	-77.50924	161.90238
06-13	-77.53343	162.07617
06-14	-77.52685	162.00691
06-15	-77.55542	161.52564
06-16	-77.5576	161.52459
06-17	-77.54641	161.46601
06-18	-77.542	161.46354
06-19	-77.54764	161.4546
06-20	-77.56727	161.3313
06-21	-77.56738	161.30818
06-22	-77.56102	161.32534
06-23	-77.57172	161.41994
06-24	-77.55522	161.4355
06-26	-77.56541	161.44182
06-25	-77.56188	161.45152
06-27	-77.42465	162.67898
06-28	-77.41716	162.66273
06-29	-77.45226	162.47385
06-30	-77.45042	162.52639
07-1	-77.56131	160.96999
07-2	-77.56458	161.10079
07-3	-77.56223	161.26385
07-4	-77.56409	161.20024
07-5	-77.56436	161.1981
07-6	-77.56416	161.16977
07-7	-77.56415	161.14313
07-8	-77.56752	161.30836
07-9	-77.56781	161.30842
07-10	-77.56434	161.33974
07-11	-77.56385	161.32204
07-12	-77.57068	161.30293
07-13	-77.57187	161.32406
07-14	-77.57662	161.32891
07-15	-77.56897	161.3439
07-16	-77.56342	161.30674
07-23	-77.55649	160.73212
07-24	-77.54441	160.77361
07-25	-77.53668	160.80619
07-26	-77.52418	160.7291
07-27	-77.55684	160.84395
07-28	-77.53844	160.86995
07-29	-77.54637	160.9232

Pit number	Latitude	Longitude
07-38	-77.53243	161.23195
07-30	-77.53938	161.38551
07-31	-77.53392	161.32601
07-33	-77.53677	161.32957
07-34	-77.53894	161.3276
07-35	-77.53049	161.27825
07-35A	-77.53531	161.12895
07-36	-77.53297	161.13163
07-37	-77.52659	161.23612
07-40	-77.53128	161.21528
07-41	-77.52978	161.23953
07-42	-77.53398	161.24016
07-44	-77.53263	161.19384
07-45	-77.54919	161.18368
07-46	-77.54969	161.24763
07-32	-77.53782	161.32922
07-43	-77.52672	161.20944
07-17	-77.56374	160.72011
07-18	-77.54382	160.72659
07-19	-77.52019	160.76303
07-20	-77.5237	160.72902
07-21	-77.5519	160.80214
07-22	-77.52193	160.88235

9 APPENDIX II

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Geoderma 137 (2006) 109 – 116
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Soil formation in Wright Valley, Antarctica since the late Neogene

J.G. Bockheim [a,*], M. McLeod [b]

[a] *Department of Soil Science, University of Wisconsin, 1525 Observatory Drive, Madison, WI 53706-1299, USA*
[b] *Landcare Research, Private Bag 3127, Hamilton, New Zealand*

Received 8 March 2005; received in revised form 3 August 2006; accepted 16 August 2006

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

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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* Corresponding author.
E-mail address: bockheim@wisc.edu (J.G. Bockheim).

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doi:10.1016/j.geoderma.2006.08.028

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

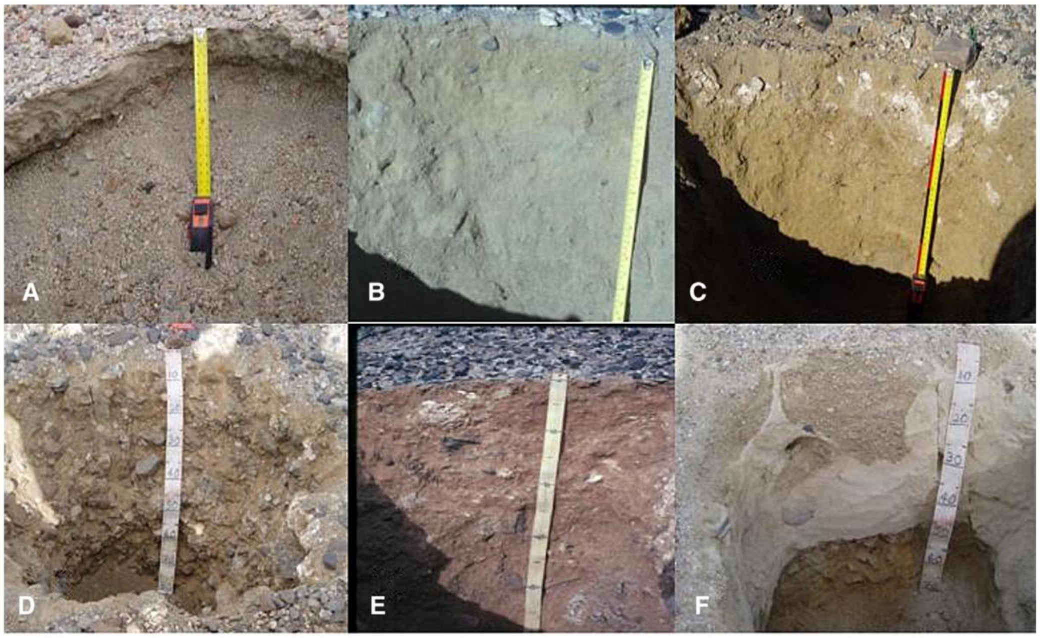

Fig. 2. Representative soils in Wright Valley, including (A) a soil on a Late Glacial Maximum surface, (B) a soil on mid to late Quaternary (H1) aged hummocky drift, (C) a soil on early Quaternary (Wright) drift, (D) a soil on the Pliocene-aged Valkyrie drift, (E) a soil on the Pliocene or older Alpine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

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

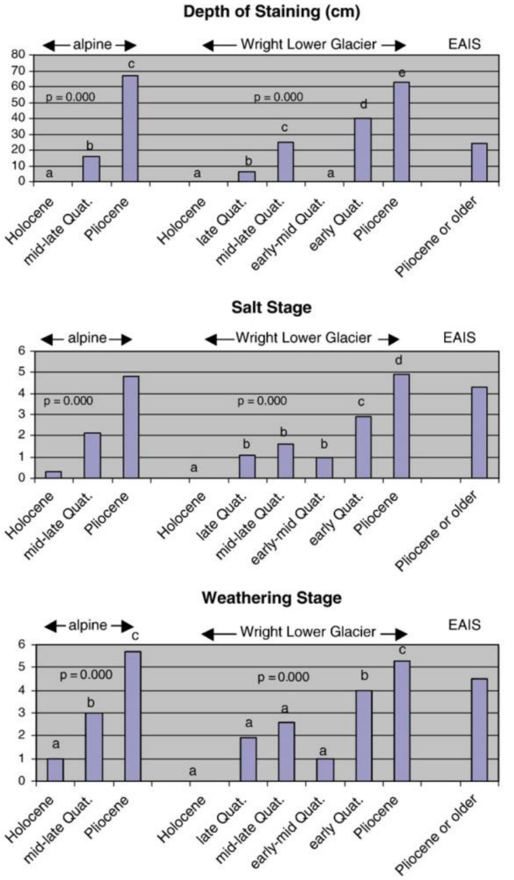

Fig. 3. Relations between (A) depth of oxidation, (B) salt stage, and (C) weathering stage for soils of on alpine drifts and drifts from the Wright Lower Glacier. Differences in small-case letters imply statistically significant differences in mean values at $p<0.05$. Specific drift units within an age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

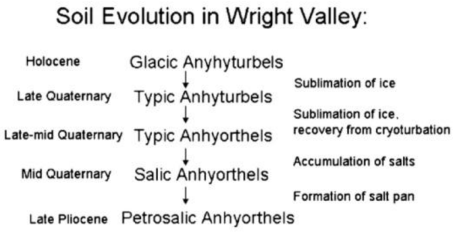

Fig. 4. Proposed evolution of soil taxa in Wright Valley.

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).

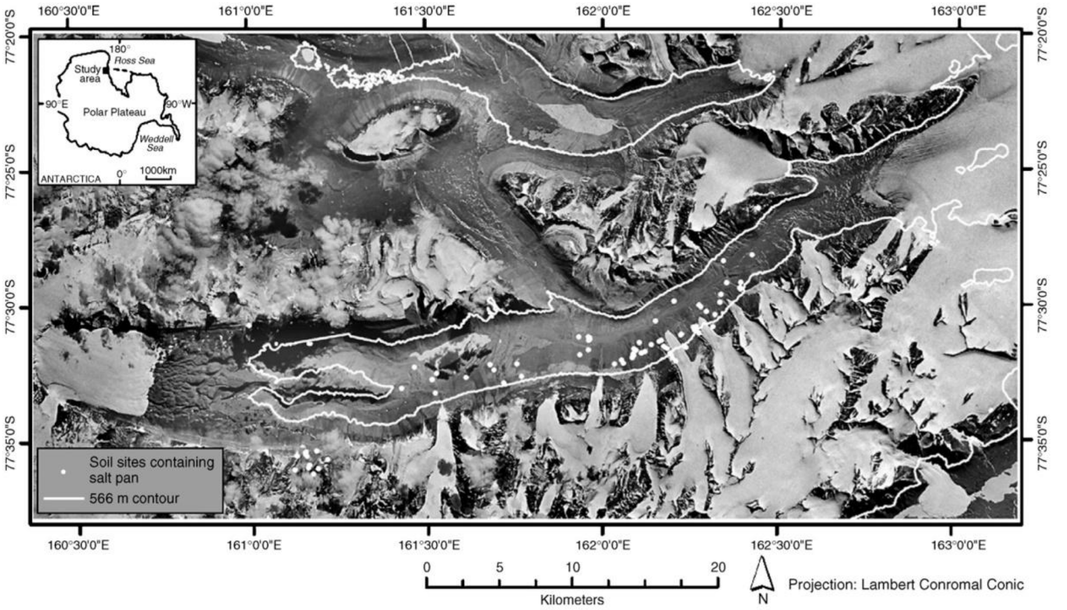

Fig. 5. Location of soils with saltpans in Wright Valley along with the 566-m contour line that represents the maximum level of the proposed Glacial Lake Wright.

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.

Acknowledgments

The USA National Science Foundation Office of Polar Programs, and the New Zealand Foundation for Research, Science and Technology (contract C09X0307), supported this research. Antarctic New Zealand provided logistical support in 2005 and 2006. M.L. Prentice and C. McKay provided insightful reviews of this manuscript.

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10 APPENDIX III

EARLY PLIOCENE EXPANSION OF THE EAST ANTARCTIC ICE SHEET, UPPER WRIGHT VALLEY, ANTARCTICA

BY
JAMES BOCKHEIM[1] AND MALCOLM MCLEOD[2]

[1] Department of Soil Science and Gaylord Nelson Institute for Environmental Studies,
University of Wisconsin, USA
[2] Landcare Research, Hamilton, New Zealand

Bockheim, J. and McLeod, M., 2008: Early Pliocene Expansion of the East Antarctic Ice Sheet, Upper Wright Valley, Antarctica. *Geogr. Ann.*, 90 A (3): 187–199.

Abstract. Whereas the glacial geomorphology of lower and central Wright Valley is reasonably well understood, the upper valley region, including the North and South Forks and the Dais, has received little attention. Our studies suggest that a wet-based glacier overrode the area and deposited what has been mapped elsewhere as the Peleus till. While we did not observe this silt-rich till in the Labyrinth, it occurs on the Dais and in protected areas of the North and South Forks. Most importantly, our findings imply that the Wright Upper Glacier, an outlet glacier of the East Antarctic Ice Sheet, deposited lateral moraines and lateral-moraine segments along the north and south walls of both the North and South Forks following deposition of the Peleus till. We argue that this drift is correlative with Taylor IVa drift in central Taylor Valley and Alpine III drift in central Wright Valley, based on landscape features, surface-boulder weathering, soil development, and stratigraphy. The presence of meltwater channels, outwash, kame moraines, esker-like features, and kames suggests that ice-marginal or supraglacial water may have accompanied this glaciation.

Key words: glacial geomorphology, Peleus till, wet-based glacier, Labyrinth, North Fork, South Fork

Background

Wright Valley has played a key role in reconstructing the glacial and climatic history of the McMurdo Dry Valleys, Antarctica. The valley has undergone a complex series of glaciations involving expansion of the Wright Upper Glacier, an outlet glacier of the East Antarctic Ice Sheet (i.e. glacial advances from the west), grounding of ice in the Ross Embayment and expansion of the Wilson Piedmont Glacier (i.e. glacial advances from the east), and fluctuations of local alpine glaciers (Nichols 1971; Calkin and Bull 1972; Prentice *et al*. 1993; Hall *et al*. 1997; Hall and Denton 2005). The glacial deposits of Wright Valley have been mapped from the easternmost part of the valley to the Dais (Hall *et al*. 1993, 1997; Prentice *et al*. 1993; Hall and Denton 2005; Prentice and Krusic 2005). However, the westernmost 16 km of the valley have not been mapped, other than a sketch map by Calkin and co-workers (Calkin *et al*. 1970; Calkin and Bull 1972).

Calkin and Bull (1972) recognized four major advances of the Wright Upper Glacier, which is fed by ice from the Taylor Dome on the **East Antarctic Ice Sheet (EAIS)**. These glaciations, from oldest to youngest, include the **Wright Upper (WU)** IV, WU III, WU II, and WU I. Deposits of the WU IV Glaciation have since been identified as Peleus till. This till was dated at >3.8 Ma from dating of basalt in Alpine III drift and stratigraphic relations (Hall *et al*. 1993). However, Hall *et al*. (1997) later revised their estimates from stratigraphic analyses at Prospect Mesa to suggest that the till is *c*. 5.1 Ma. Calkin and Bull (1972) showed WU IV drift terminating at the eastern end of Lake Vanda. They also mapped the Wright Lower IV ('Pecten drift') from Bull Pass eastward. Since the work of Calkin and his co-workers, the two tills have been viewed as contemporaneous and identified as a single body, the Peleus till (Prentice *et al*. 1993). The Peleus till is silt-rich and was deposited by an eastward-flowing wet-based glacier when the climate was warmer than at present (Prentice *et al*. 1993).

The WU III drift is something of an enigma. Based on correlation with radiometrically dated drifts in the adjacent Taylor Valley, Calkin *et al*. (1970) suggested that the WU III drift was deposited between 0.5 and 2.1 Ma. Wright Upper II drift was mapped from the distribution of cavernously weathered sandstone erratics extending 2 km east

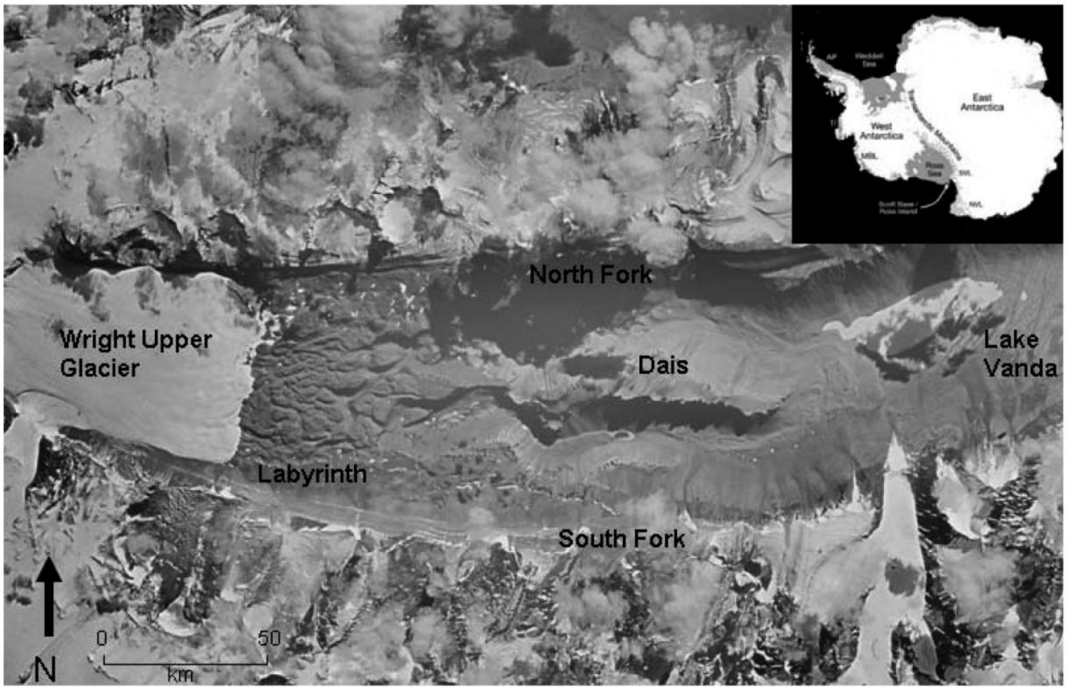

Fig. 1. Satellite image of the study area showing key features. The scale is approximately 1:140 000

of the present terminus of the Wright Upper Glacier. The WU I Glaciation pertains to the ice-cored drift at the margin of the Wright Upper Glacier.

Wright Valley has been a focal point of a debate as to whether the EAIS underwent extensive deglaciation during the Pliocene Climatic Optimum, *c*. 3 Ma (Webb *et al*. 1984; Barrett *et al*. 1992), or whether the EAIS has been relatively stable since the middle Miocene, *c*. 15 Ma (Denton *et al*. 1993; Marchant *et al*. 1993a; Marchant and Denton 1996; Lewis *et al*. 2006). According to the latter group, a wet-based glacier advanced over the Transantarctic Mountains sometime during the middle Miocene and through Wright Valley.

At 2 km deep and up to 9 km wide, Wright Valley was described by Prentice *et al*. (1993, p. 208) as 'overdeepened with a minimum elevation of 3 **metres above sea level (m a.s.l.)** in the central Lake Vanda basin, a valley-mouth threshold at about 270 m a.s.l. and a two-step headwall with 1900 m of relief'. The wet-based glacier previously described incised a network of bedrock channels and scoured terrain into a 300-m thick sill of Ferrar dolerite at the head of Wright Valley, creating or restructuring the Labyrinth. Lewis *et al*. (2006) estimated the discharge of subglacial meltwater to have been of catastrophic proportions and that the source of the water was likely from subglacial lakes in East Antarctica. ^{40}Ar/^{39}Ar ages on volcanic tephra from the Labyrinth suggested that channel incision pre-dated 12.4 Ma. This radiometric date not only constrains the timing of the last subglacial flood, but also indicates that all wet-based advances of Wright Upper Glacier (that extended across the Labyrinth to the North and South Forks) must pre-date 12.4 Ma. Based on the geometric relations of dated drift sheets (discussed below), Denton *et al*. (1993) proposed that the upper Dry Valley region has not experienced a major glaciation from expansion of the EAIS since the middle Miocene. Recently, Lewis *et al*. (2007) presented a glacial record from the western Olympus Range and proposed a permanent shift in the thermal regime of local glaciers from wet- to cold-based more than 13.9 Ma ago.

In contrast to these findings, Wilch *et al*. (1993) mapped and dated glacial drifts that record at least four Pliocene–Pleistocene expansions of Taylor Glacier, which like the Wright Upper Glacier is a major outlet glacier of the EAIS. Similar expansions were recorded in Arena Valley (Brook *et al*. 1993; Marchant *et al*. 1993b; Bockheim 2007) and in the upper Ferrar Glacier area (Staiger *et al*.

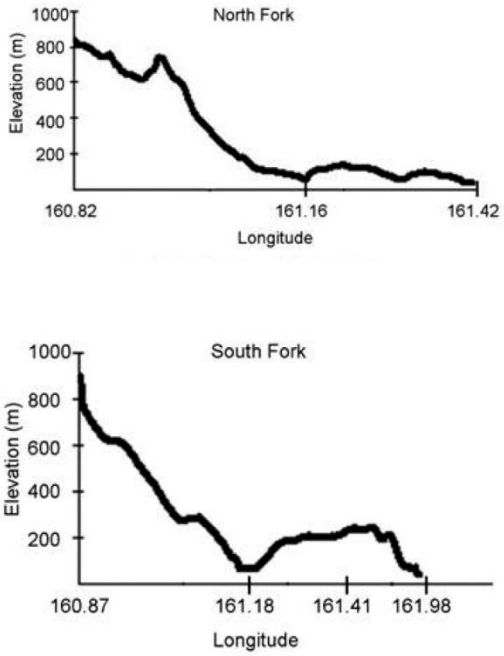

Fig. 2. Longitudinal profiles of the North and South Forks constructed from LIDAR imagery using ArcGIS 9.2

2006). Prentice and Krusic (2005) studied the massive, Pliocene-aged Alpine III and IV moraines in Wright Valley and their proximity to the Wright Fjord grounding line, and suggested that based on the work of Wilch *et al*. (1993) in Taylor Valley, some expansion of the Wright Upper Glacier into Wright Valley was plausible.

While mapping the soils of Wright Valley, we undertook an investigation of the surficial geology of upper Wright Valley, including the Labyrinth, the Dais, and the North and South Forks. In this paper, we report the results of that investigation. Our results will corroborate the exploratory mapping of Calkin and co-workers (Calkin *et al*. 1970; Calkin and Bull 1972), provide details of the landforms and soils in upper Wright Valley, propose a correlation of glacial deposits and their chronology, and discuss the implications of the chronology on palaeoclimate reconstruction.

Setting

The study area extends from the margin of the Wright Upper Glacier (1000 m a.s.l.) to the east end of the Dais and includes the Labyrinth, the Dais and the North and South Forks (Fig. 1). The Labyrinth consists of a 5-km long network of bedrock channels up to 200 m deep, and scoured terrain in the Wright Upper Glacier region. The Labyrinth has been studied in detail (Calkin 1974; Shaw and Healy 1977; Lewis *et al*. 2006). According to Lewis *et al*. (2006), the Labyrinth extends an additional 45 km to the west beneath the Wright Upper Glacier and was carved by subglacial meltwater from a wet-based glacier during the middle Miocene. Lewis *et al*. (2006) distinguished three separate erosion surfaces within the Labyrinth.

A sill of highly resistant Ferrar dolerite caps the Dais. The Dais comprises 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. Although there have been no reports of glacial drift on the Dais, a geological map of the region shows three patches of Peleus till (Turnbull *et al*. 1994) on the Dais that were identified from an aerial reconnaissance.

The North and South Forks represent the first step of the two-step valley profile reported by Prentice *et al*. (1993). The forks have nearly identical longitudinal profiles, starting at an elevation of *c*. 800 m a.s.l. and reaching a depression of 82 m a.s.l. in the North Fork and 117 m a.s.l. in South Fork, *c*. 15 km from the west ends of the forks with thresholds at 200 to 350 m 19 km down-valley (Fig. 2). There have been no reports of glacial deposits in the North and South Forks other than the general occurrence of WU III and IV by Calkin *et al*. (1970).

Methods

We mapped surficial deposits in upper Wright Valley from the eastern end of the Dais westward to the Wright Upper Glacier during the austral summers of 2005–2006 and 2006–2007 (Fig. 1). As base maps we used both georeferenced satellite and **light detection and ranging (LIDAR)** imagery (USARC 2007). In the field we walked the boundaries of each geomorphic feature, taking readings with a **global positioning system (GPS)**. These were downloaded onto a laptop computer powered by a solar panel in the field and superimposed onto the satellite and LIDAR images.

As part of a soil-mapping study, we dug approximately 120 test pits on 19 major geomorphic features that we identified in the region. Following an analysis of the data, we dug 52 soil pits on key surfaces and recorded surface-boulder weathering and

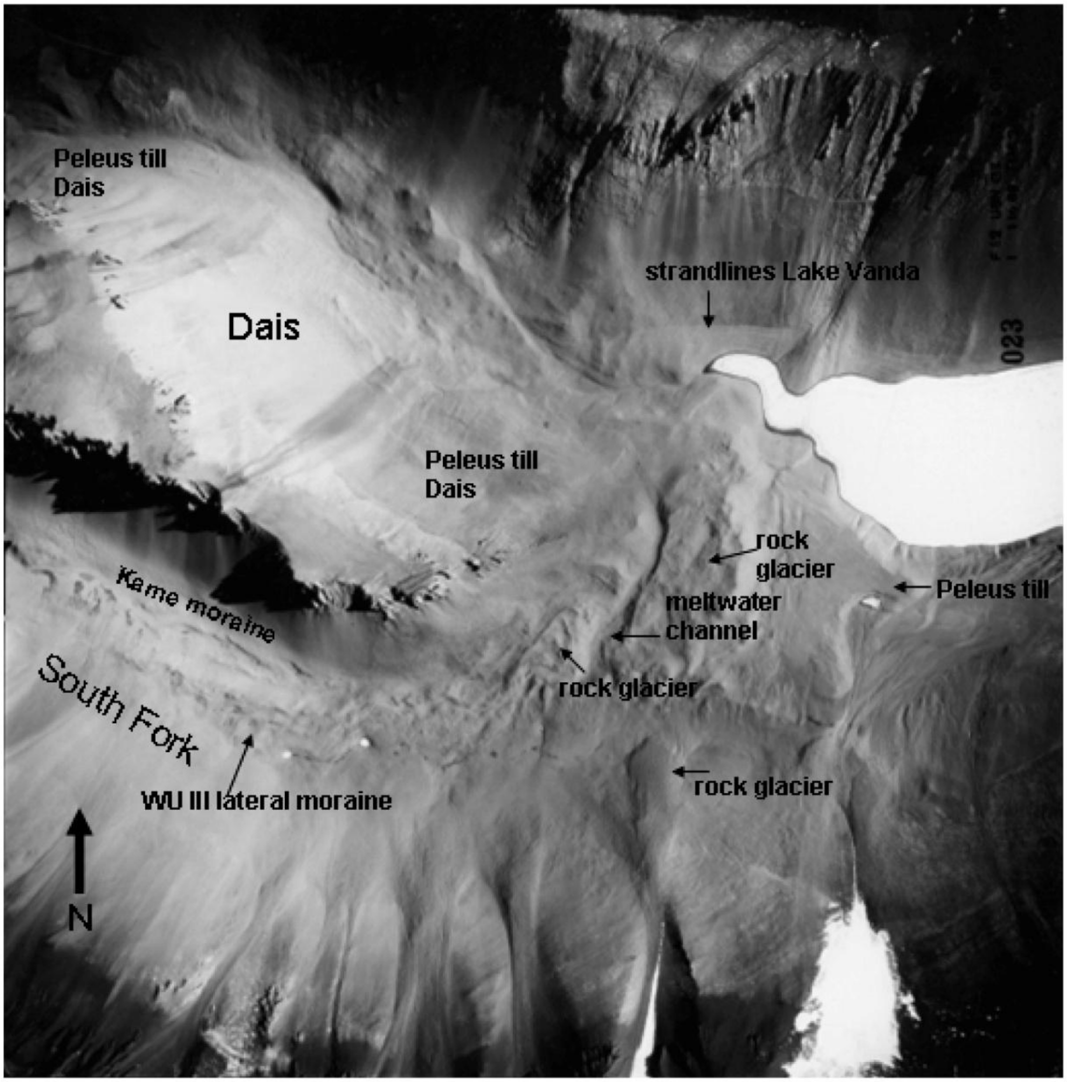

Fig. 3. Surficial geology of the North Fork and Dais superimposed onto TMA 2194, F32, image 27 (US Navy photograph)

soil morphological features following criteria described by Bockheim (2007).

Results

Lateral moraines

Lateral moraines occur on both walls of the North and South Forks of Wright Valley. In the South Fork a pronounced lateral moraine extends for 3.5 km along the south wall and swings northward at the eastern end of the Dais, merging with a large rock glacier (Figs 3 and 4). In the North Fork a lateral moraine extends continuously for 2.5 km along the south wall (Fig. 5). Segments of these lateral moraines exist in both forks and on both walls. The lateral moraines range from 10 to 50 m in height, 100 to 150 m in width, occur at elevations ranging from 262 to 320 m a.s.l. in the South Fork and 139 to 234 m a.s.l. in the North Fork, and descend eastward. Calkin *et al*. (1970) assigned these moraines to the Wright Upper III Glaciation.

We examined soils at 19 locations on the lateral moraines in both forks. On a scale of 1 to 6, the weathering stage averaged 4 (Table 1). The WU III

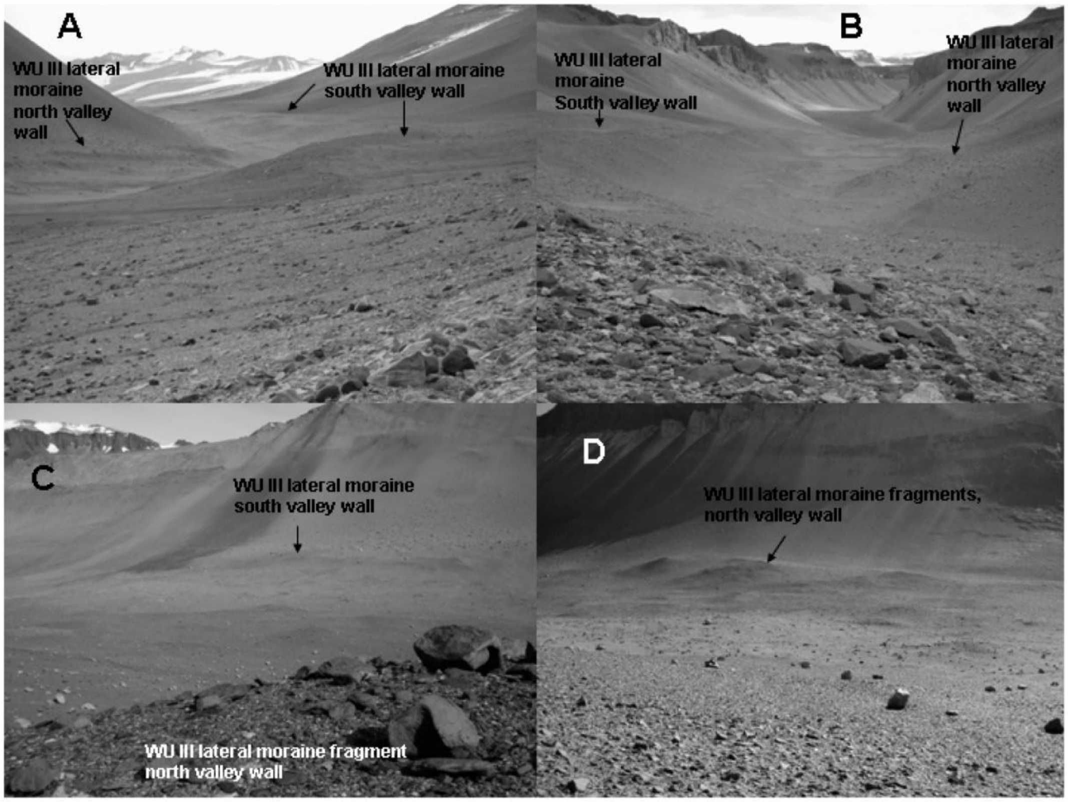

Fig. 4. Key glacial features in the North and South Forks: (A) WU III lateral moraine along the south wall of the South Fork; (B) WU III lateral moraine along the south wall of the North Fork; (C) WU III lateral moraine segment along the north wall of the South Fork; (D) WU III lateral moraine fragments along the north wall of the North Fork

lateral moraine surface has a moderately low surface-boulder frequency, well-developed staining and polish, strong cavernous weathering, and some ventification. Ice-cemented permafrost commonly occurs at depths of 65 to 70 cm. Although the salt stage was only 1 (salt encrustations beneath clasts), salts were visible in the profiles to depths of 35 cm, and the depth of staining averaged 42 cm. The soils are classified as Typic Anhyorthels.

Drift sheets

We observed several patches of drift in the Labyrinth, on the Dais, in the North and South Forks, and immediately east of the Dais. Drift previously identified as Peleus or Wright Upper IV was observed at four locations, including two patches on the Dais (Turnbull *et al*. 1994), one south of the western end of Lake Vanda (Prentice *et al*. 1993), and a fourth below the north wall of the North Fork (Figs 3 and 5). These drift patches are <3 km^2, subdued, and have an extremely low surface boulder frequency and a strongly developed desert pavement. The Peleus drift commonly is 1 m or less in thickness. Soils on the Peleus drift, classified as Typic Anhyorthels, are strongly developed and have a mean weathering stage of 5.5, a salt stage of 1.7, and an average depth of staining of 33 cm (Fig. 6A and B, Table 1).

During a reconnaissance of the Labyrinth, we identified a strongly developed soil on till (Fig. 6C; 77.52193°S, 160.88235°E) that resembles soils on Asgard till in the Asgard Range (Marchant *et al*. 1993; Bockheim and Ackert 2007). The landform has a weathering stage of 5, and the soil has a salt stage of 2 and is stained to at least 80 cm (Table 1). Although the soil horizons were strongly cryoturbated (Typic Anhyturbel), there was no sign of ice-cemented permafrost in the upper 80 cm.

We also observed drift sheets at seven locations

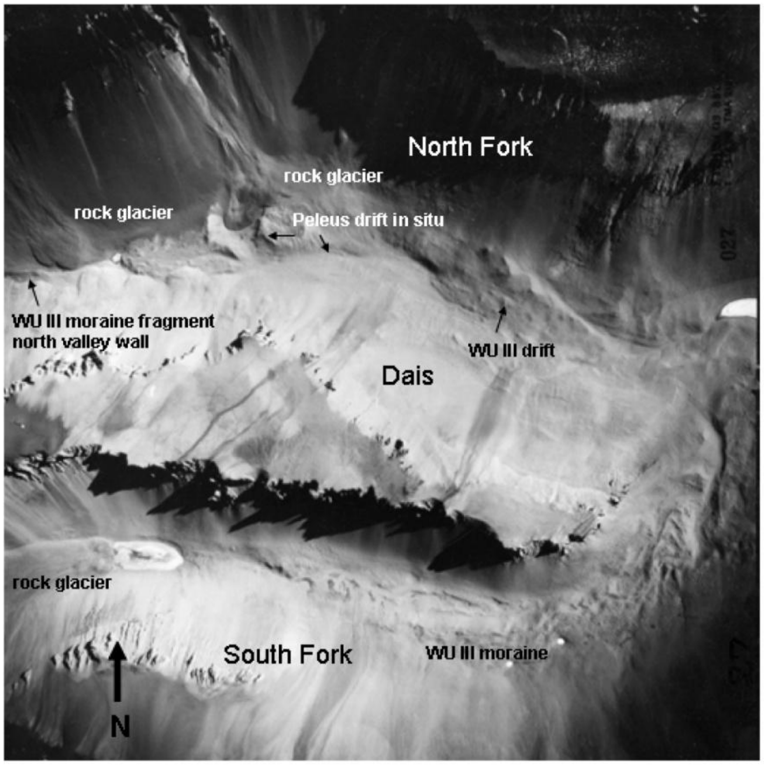

Fig. 5. Surficial geology of the South Fork and Dais superimposed onto TMA 2194, F32, image 23 (US Navy photograph)

in the Labyrinth within 2 km of the Wright Upper Glacier that was mapped by Calkin *et al.* (1970) as representing the Wright Upper II Glaciation. The drift patches are moderately weathered (weathering stage 3) and contain somewhat poorly developed soils (Table 1). Ice cement occurs within 25 cm of the surface, and the soils are stained to an average depth of 12 cm. The soils contain minimal salts and are classified as Typic Haploturbels.

Kames, kame-moraines, and esker-like features

We observed kame moraines, esker-like features, and kames in both the North and South Forks (Fig. 7). For example, a kame-moraine segment on the north wall of the South Fork is 250 m long and contains highly stratified sand and gravel throughout. Small esker-like features that contain stratified sand and gravel occur to the east of this feature. These features range from 100 to 300 m long and 15 to 30 m wide. Kames, which are present in both forks, are 3 to 10 m high, 10 to 35 m wide, and contain well-stratified materials. These features are dissimilar to hummocky drift or lake-ice conveyor sediments observed in lower Taylor Valley (Hall *et al.* 2000). We did not observe evidence of former lakes, nor did we find algae in the sediments.

Rock glaciers

Rock glaciers are the most prevalent feature in the North and South Forks. In the North Fork there are two pronounced rock glaciers below the north wall. These rock glaciers are 630 to 670 m wide, 470 to 990 m long, and about 30 m high; they have areas of 0.25 and 0.45 km^2. In the South Fork a large rock glacier (7 km long, 0.5 km wide, 45 m high, and 3.75 km^2 area) plugs the valley and terminates immediately to the west of Don Juan Pond. In addition, there are three rock glaciers along the outer portion of the South Fork extending from the south wall. The two larger rock glaciers (Fig. 3) vary from 2.0 to 2.2 km long, 0.5 to 1.2 km wide, are about 50 m high, and have areas from 1.3 to 2.2 km^2.

Table 1. Comparison of weathering features and soil morphological properties on geomorphic surfaces in upper Wright Valley and moraines in Tayor Valley

Geomorphic feature	Weathering stage[5]	Salt stage[6]	Depth of ghosts (cm)	Minimum depth to ice-cement (cm)	Depth of visible salts (cm)	Depth of coherence (cm)	Depth of staining (cm)	Dominant soil subgroup[7]
Upper Wright Valley								
WUII, Labyrinth (7 sites)	3,1	1,0	2	23	12	23	12	THo
WUIII, South Fork (9 sites)	4,2	1,7	17	65	32	49	43	TAo
WUIII, North Fork (10 sites)	4,1	1,2	17	71	38	71	42	TAo
Peleus till (3 sites)	5,5	1,7	20	72	44	69	33	TAo
Asgard till (1 site)	5,0	2	8	>80	24	>80	>80	TAt
Rock glaciers (6 sites)	3,1	1,0	4	36	14	23	20	THo, THt
Meltwater channels (6 sites)	2,5	1,0	14	43	nd	38	34	THt
Gelifluction lobes (2 sites)	3,0	1,0	0	28	1	17	11	THt
Talus (3 sites)	2,3	1,0	7	38	14	42	19	THo, TAo
Taylor Valley[1]								
Taylor II	2,1	1	6	45	3	18	3	TAo, TAt
Taylor III	2,7	2	9	85	21	46	18	TAo
Taylor IVa	4,2	3,4	15	44	33	48	38	TAo
Taylor IVb	4,0	2,8	15	46	29	49	33	TAo
Central Wright Valley[2]								
Alpine III (15 sites)	5,5	4,4	21	>103	48	56	43	PsAo
Alpine IV (18 sites)	5,8	5,6	19	>100	62	>100	55	PsAo
Miocene-aged drifts								
Arena till (6 sites)[3]	4,2	3,2	6	>76	10	69	26	TAo
Altar till (12 sites)[3]	4,6	3,8	37	>74	27	62	41	TAo, TAt
Quartermain II till (2 sites)[3]	5,5	4,5	0	>90	24	>90	43	PnAt
Asgard till (14 sites)[4]	4,6	3,5	9	>73	23	60	33	THt, TAt
Average	4,7	3,8	13	>78	21	>64	36	

1 Bockheim *et al*. (2008).
2 Bockheim and McLeod (2007).
3 Bockheim (2007).
4 Bockheim and Ackert (2007).
5 Campbell and Claridge (1975).
6 Bockheim (1990).
7 THo, Typic Haplorthel; THt, Typic Haploturbel; TAo, Typic Anhyorthel; TAt, Typic Anhyturbel; PnAt, Petronitric Anhyturbel; PsAo, Petrosalic Anhyorthel.

McLeod *et al*. (2007) described these features in detail. All of the rock glaciers have a lobate form, concentric ridges, and a steeply ramped front. Landforms on the rock glaciers have a weathering stage of 3 to 4, and the soils have a salt stage of 1 to 2 and an average depth of staining of 20 to 30 cm (Table 1; McLeod *et al*. 2007).

Talus and gelifluction lobes

Talus and gelifluction lobes are common, particularly on the south walls of both the North and South Forks. These features have a moderate weathering stage (2.3 and 3, respectively) and poorly developed soils (Table 1).

Meltwater channels and strandlines

Although an extensive meltwater system occurs in the region, there are two predominant, abandoned meltwater channels in the study area (Fig. 3), including a channel in the North Fork that extends from the north wall 3.8 km to the western lobe of Lake Vanda. A second meltwater channel occurs between two rock glaciers to the east of the Dais and extends 2.3 km downward to Lake Vanda. These channels are 10 to 15 m deep and 10 to 50 m wide. The weathering stage of meltwater channels averages 2.5, ice-cemented permafrost occurs at a shallow depth (43 cm), and the soils are stained to about 34 cm (Table 1).

A series of strandlines occur along the north wall of the outer North Fork reflecting former levels of Lake Vanda. These strandlines occur 50 m above the present lake surface and have been dated at 3.0–1.9 ka (Yoshida *et al*. 1975). The level of Lake Vanda has risen more than 10 m since the late 1960s (Chinn 1993).

Discussion

Glacial correlations and chronology

We recognize four advances of the Wright Upper Glacier in western Wright Valley, confirming earlier findings of Calkin *et al*. (1970) and Calkin and Bull

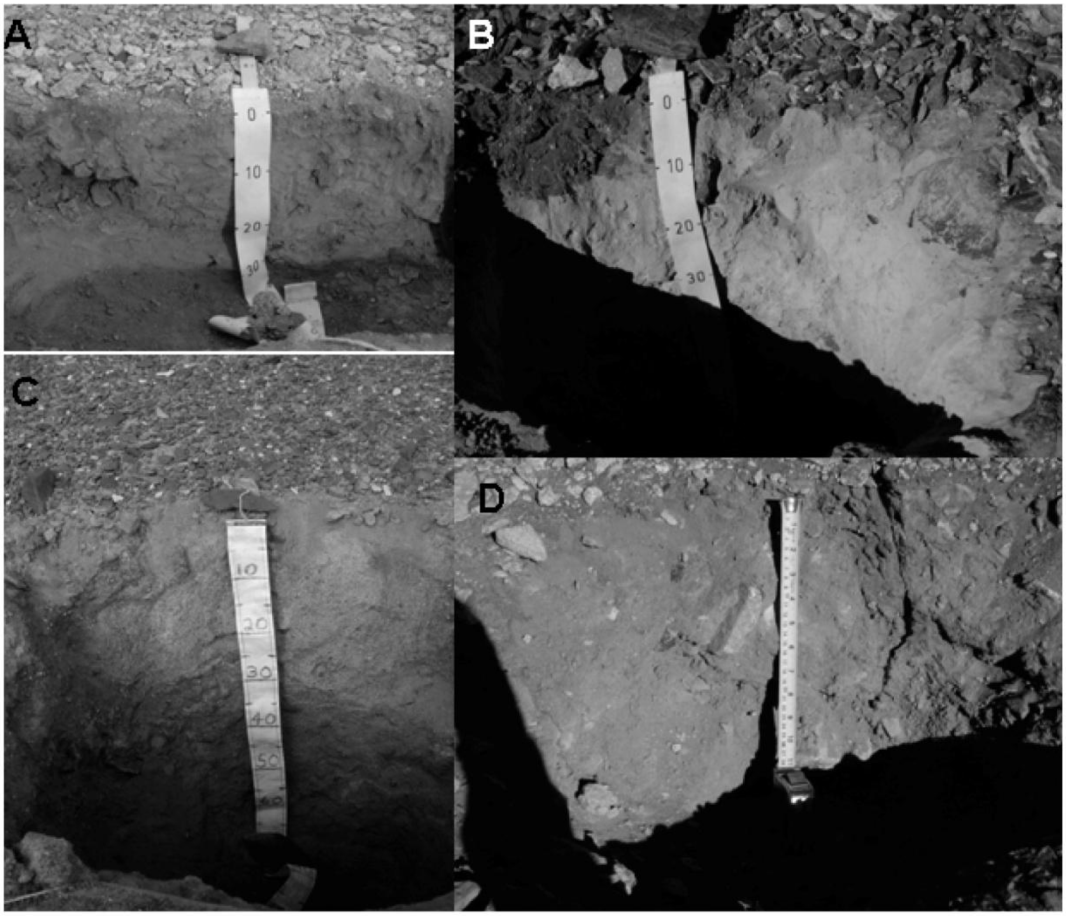

Fig. 6. Selected soils in upper Wright Valley: (A) a soil from Peleus till at 700 m on the Dais (S77.54951°, E161.27852°); (B) a soil from Peleus till on a glacially moulded ridge with bedrock at 110 cm in the North Fork (S77.53128°, E161.21528°); (C) a soil on Asgard-like drift in the Labyrinth (S77.52193°, E160.88235°); (D) a soil on Wright Upper III till in the North Fork below the Dais (S77.53408°, E161.26399°) (note sand-wedge cast to the right of the measuring tape)

(1972). Calkin designated these advances as the Wright Upper I, II, III, and IV. Now recognized as the Peleus Glaciation, the WU IV Glaciation left patches of ground moraine along the south valley floor from Lake Canopus east to the Bartley Glacier (Prentice *et al*. 1993; Hall and Denton 2005). Peleus drift and reworked Peleus drift have been observed in easternmost Wright Valley (Hall and Denton 2005).

We observed a thin mantle of Peleus drift over glacially moulded bedrock, particularly in the lee of differentially weathered, upstanding dykes, in the North Fork, in meltwater channels of the North and South Forks, and at elevations between 700 and 800 m a.s.l. on the eastern end of the Dais (Fig. 3). We did not find Peleus till in the Labyrinth at 12 selected locations during a close-support helicopter campaign on 15 January, 2007, but this does not rule out its existence there.

There is considerable debate about the age of the Peleus drift, and this debate is germane to this study. Based on radiometric dates of basalt in the overlying Alpine III drift and stratigraphic arguments, Hall *et al*. (1993) suggested that it is >3.8 Ma in age. Hall *et al*. (1997) later revised their age estimate for Peleus till to *c*. 5.1 Ma and suggested that the Peleus till was in place when the *Pecten* shells grew on the floor of the fjord and that the unstable sediment slumped over the top of the shell bed. Marchant *et al*. (1993) correlated the Peleus till with the Asgard till found in north-facing valley mouths in the Asgard Range. This unit is derived predominantly from sandstone, ranges from 1.0 to 1.5 m in thickness, occurs at ele-

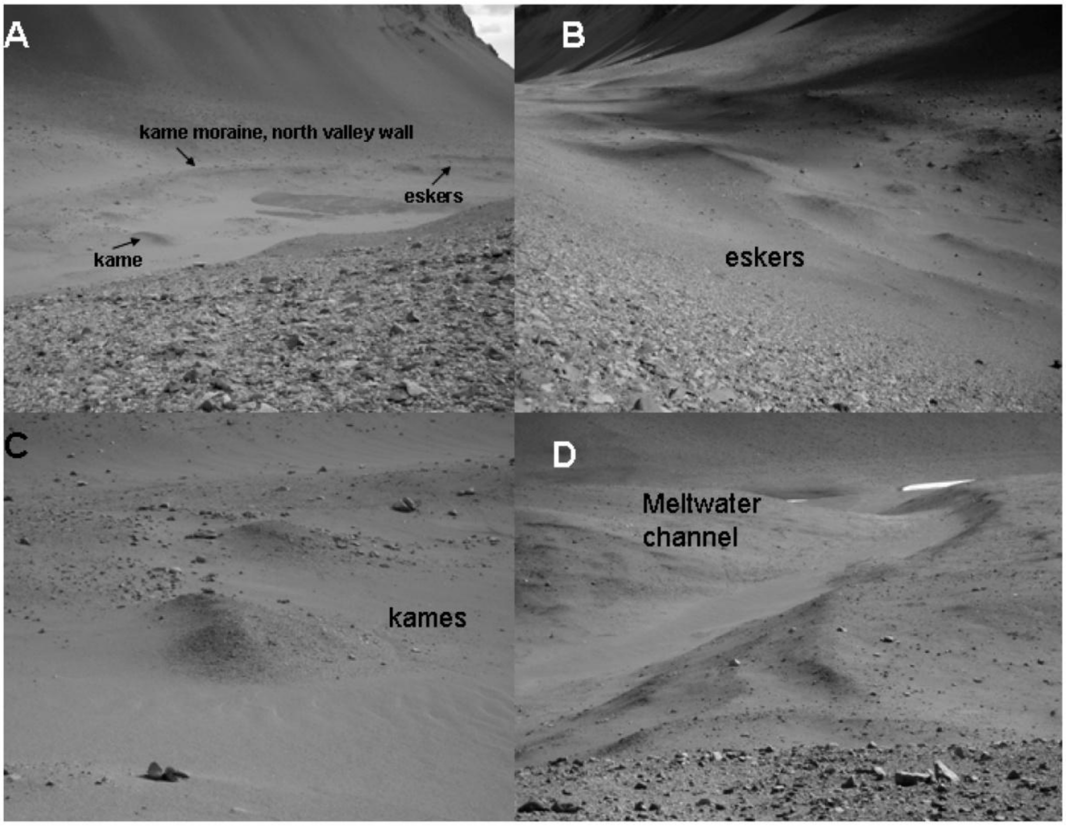

Fig. 7. Stagnant-ice and meltwater features associated with the WU III Glaciation in the South Fork: (A) a kame moraine measuring about 10 m high and 10 m in width and a meltwater channel; (B) esker-like features measuring 100–300 m long and 15–30 m in width; (C) kames measuring 3–10 m high and 10–35 m in width; (D) a meltwater channel from the South Fork to Lake Vanda measuring 10–15 m deep and about 50 m in width

vations above 1500 m a.s.l., and is bracketed by ages of <15.2 and >13.6 Ma. Denton *et al*. (1993) proposed that the Peleus, Asgard, and Quartermain II (from Arena Valley in the Quartermain Mountains) tills are contemporaneous and of middle Miocene age, and represent the last drift sheet originating from major expansion of the EAIS. From stratigraphic relations involving alpine drift and fjord deposits, Prentice and Krusic (2005) proposed that the Prospect fjord episode in Wright Valley was about 5.5 Ma ago. These contrasting results suggest that the Peleus till is either *c*. 5.1 to <15 Ma (Marchant *et al*. 1993; Hall *et al*. 1997) or <5.5 Ma (Prentice and Krusic 2005).

Calkin *et al*. (1970) depicted WU III drift as occurring throughout the Labyrinth and North and South Forks. They reported that terminal deposits of WU III were 'poorly marked' at the eastern end of the Dais. We observed distinct lateral moraines and moraine segments on the north and south walls of both the North and South Forks. The moraines are located primarily in the eastern parts of the forks, as the western parts contain rock glacier deposits and colluvium.

Wright Upper II drift occurs within 2.5 km of the Wright Upper Glacier and is recognized by sandstone erratic boulders and a thin drift mantle over residuum and colluvium. Ice-cored Wright Upper I drift occurs along the present margin of the Wright Upper Glacier. These two drifts do not contain clear evidence of liquid water; the Wright Upper II may have been cold-based. The distribution of surficial

Table 2. Suggested correlations of Pleistocene and Pliocene drifts in central Wright Valley, upper Wright Valley and Taylor Valley, along with approximate ages in parentheses

Taylor Valley[1]	Central Wright Valley[2]	Upper Wright Valley[3]	Vernier Valley (Ferrar)[4]
Taylor I (2.5–3.5 ka)	Alpine I drift (3.7 ka)	Wright Upper I drift	
Taylor II (Bonney) drift (70–120 ka)	Alpine IIa drift	Wright Upper II drift	Ferrar 1 (50 ka)
Taylor III drift (208–335 ka)	Alpine IIb drift	[rock glacier advance]	Ferrar 2 (0.7 Ma)
Taylor IVa drift (<2.7 Ma)	Alpine III drift (<3.5 Ma)	Wright Upper III drift	Ferrar 3 (1.2 Ma)
Taylor IVb drift (2.7–3.0 Ma)	Alpine IV drift (>3.7 Ma)	Ferrar 4 (*c.* 3.4 Ma)	
	Peleus till (>3.8 Ma)	Wright Upper IV drift	

[1] Denton *et al*. (1971); Brook *et al*. (1993); Wilch *et al*. (1993); Higgins *et al*. (2000b).
[2] Hall *et al*. (1993); Hall and Denton (2005); Prentice and Krusic (2006).
[3] Calkin and Bull (1972); this study.
[4] Staiger *et al*. (2006).

deposits in the North and South Fork is shown in Figs 3 and 5, respectively.

Calkin *et al*. (1970) were uncertain of the ages of the four drifts they mapped in western Wright Valley. They correlated the WU IV (i.e. Peleus) with Alpine III moraines of alpine glaciers in Wright Valley, suggesting that the WU IV Glaciation occurred between 2.1 and 3.5 Ma. However, Prentice *et al*. (1993) have shown that the WU IV drift is analogous to the Peleus till and is >3.8 Ma. Denton *et al*. (1993) tentatively correlated Alpine III and IV drifts with Taylor IVb and Quartermain I drifts in Arena Valley. Taylor IVa and IVb drifts on the Rhone Platform are of Pliocene age, *c*. <2.7 and 2.71–2.97 Ma, respectively (Wilch *et al*. 1993). Recently, Staiger *et al*. (2006) distinguished four drifts in Vernier Valley from fluctuations of the Ferrar Glacier, which along with the Taylor Glacier is a major outlet glacier from the EAIS. Ferrar 1, 2, 3, and 4 drifts were dated using ^{21}Ne cosmogenic-nuclide analyses at 50 ka, 0.7 Ma, 1.2 Ma, and *c*. 3.4 Ma, respectively.

Wright Upper III drift overlies Peleus till in the North Fork; therefore, it is younger than Peleus till. In addition, Peleus till has been incorporated in WU III drift in places in both forks. There were no readily observable differences in properties of WU III soils with and without the admixture of Peleus material. Based on surface boulder and soil weathering features and stratigraphy, we correlate the WU III drift with Taylor IVa drift in central Taylor Valley and Alpine III drift in central Wright Valley (Table 2). Weathering features of the WU III drift in the North and South Forks are not significantly different from each other. They have a weathering stage of 4.1–4.2, a salt stage of 1–2, and nearly equivalent depths of ghosts (17 cm), visible salts (32 vs. 38 cm), and staining (42 vs. 43 cm) (Table 1). Taylor IVa drift in central Taylor Valley has a comparable weathering stage (4.0), depth of ghosts (15 cm), depth of visible salts (29 cm), and staining (33 cm) (Bockheim *et al*. 2008). Soils on Alpine III drift appear to be more strongly developed than those on WU III drift, partly because of the large amount of salts.

One difference between soils on WU III and Taylor IVa and Alpine III drifts is that the former have substantially lower amounts of salt. In general the soils of upper Wright Valley have fewer salts than soils of comparable age elsewhere in the McMurdo Dry Valleys. This may relate to the extreme aridity of the region in which there is insufficient snow to contribute salts from marine aerosols and katabatic winds from the polar plateau.

Based on surface boulder and soil weathering characteristics, we correlate WU I and II drifts with Taylor I and II drifts in Taylor Valley and Alpine I and IIa drifts in central Wright Valley (Tables 1, 2). Taylor III drift, dated at 208–335 ka (Brook *et al*. 1993), is a distinct drift in Taylor Valley and in Arena Valley in the Quartermain Range. While we do not recognize Taylor III-equivalent drift in western Wright Valley, we do observe several rock glaciers that bear surface weathering characteristics comparable to Taylor III drift elsewhere in the region (Table 1). We recognize that our inter-valley comparisons are limited by the differences between Taylor and Ferrar Glaciers and the Wright Upper Glacier. Not only do they have significantly more East Antarctic ice flow, but also the threshold for significant ice flow is much lower in Taylor and Ferrar Valleys than in upper Wright Valley.

Moreover, our interpretations are strongly dependent on the ages of the Peleus till and the younger WU III deposits. Based on comparative studies with drifts elsewhere in the McMurdo Dry Valleys, we favour an early Pliocene age for the last expansion of the Wright Upper Glacier that deposited WU III drift into upper Wright Valley. This interpretation is consistent with the glacial chronology in the upper Ferrar and Taylor Glacier regions. While it is difficult to evaluate the 'robustness' of our approach, we have successfully used soils as a relative-age dating tool (e.g. Bockheim 1990). The technique involves a comparison of landforms, surface-boulder weathering features, soil development, and stratigraphy.

Implications of chronology on palaeoclimate reconstruction

We observed several features that provide information about the nature of the WU III advance, including meltwater channels, outwash, esker-like features, kames, and kame moraines in both forks (Fig. 3, 7). In all cases these features comprised loose, well-stratified sand and gravel materials. However, we did not find hummocky drift/lake-ice conveyor deposits (Hall and Denton 2005), lacustrine materials, or substantial bodies of ground ice. These features could imply ice-marginal, supraglacial, or wet-based (temperate) glacial conditions.

Our reporting of drift in the North and South Forks is consistent with **Dry Valley Drilling Project (DVDP)** borehole logs for sites 13 (Don Juan Pond, South Fork) and 14 (North Fork). The sediments in the Don Juan Pond vicinity included sorted sands and silt to a depth of 12.67 m that represent 'reworked morainal material' (Mudrey *et al.* 1975). Sediments in North Fork borehole include poorly sorted, quartz-rich silt, 'mud,' and very fine sand to a depth of 29 m (Chapman-Smith 1975). These materials may represent the Peleus till.

Our correlation of WU III drift with Taylor IVa drift is inconsistent with the interpretations of Denton and co-workers. According to them (Denton *et al.* 1993; Marchant *et al.* 1993a, b; Marchant and Denton 1996; Lewis *et al.* 2006, 2007), the Peleus till and its associated deposits represent the last overriding of the Transantarctic Mountains by a wet-based glacier around 15 Ma.

However, there can be little doubt that the lateral moraines and wet-margin ice features observed in the North and South Forks were deposited after the Peleus till. This allows for the possibility of a significant expansion of the EAIS in the early Pliocene, an option that was proposed by Prentice and Krusic (2005) in their study of early Pliocene alpine glaciations in Wright Valley. Likewise, the occurrence of esker-like features, kames and other features indicative of ice-marginal or wet-based glacial conditions supports the idea that the Pliocene climate of the upper Dry Valleys was wetter and possibly warmer than the present climate (Prentice and Krusic 2005; Raymo *et al.* 2006). However, the warming would not have approached the 2–5°C increase suggested by those favouring the Pliocene deglaciation hypothesis (Barrett *et al.* 1992).

Further evidence of a warmer and/or moister early Pliocene climate than at present includes the presence of strongly cryoturbated soils in Peleus drift, which implies the availability of liquid water. Moreover, sand-wedge casts are common in both WU III and Peleus soils within the upper 25 cm (Fig. 6D), implying the presence of ice-cemented permafrost since deposition of these sediments. Soils on these drifts contain dry-frozen permafrost in the upper 70–100 cm today.

Conclusions

We observed deposits reflective of four advances of the Wright Upper Glacier, confirming and considerably amplifying the earlier work of Calkin *et al.* (1970, 1972). Based on surface weathering and soil properties, we correlate WU I and II drifts with Taylor I and II drifts, extensive rock glacier activity with Taylor III drift, and WU III drift with Taylor IVa and Alpine III drifts in central Taylor and Wright Valleys, respectively. The WU IV drift is correlative with the Peleus till dated in central Wright Valley at >3.8 Ma. These correlations imply that the Wright Upper Glacier advanced into upper Wright Valley depositing WU III drift during the early Pliocene. These interpretations are consistent with advances of the Ferrar and Taylor Glaciers during the early Pliocene. The presence of wet-margin ice features, such as kame moraines, esker-like features, kames, and meltwater channels, suggests that wetter and possibly warmer conditions occurred during the WU III Glaciation.

Acknowledgements

We appreciate the field assistance provided by M.R. Balks and J. Aislabie. The New Zealand Foundation for Research, Science and Technology under C09X0307 supported this project, with logistic support by Antarctica New Zealand. We appreciate the assistance of the staff at Scott Base. B.L. Hall, R.A. Ackert and an anonymous reviewer offered insightful comments on an earlier draft of this manuscript.

J.G. Bockheim, Department of Soil Science, University of Wisconsin, 1525 Observatory Drive, Madison, WI 53706-1299, USA
E-mail: bockheim@wisc.edu

Malcolm McLeod, Landcare Research, Hamilton, New Zealand
E-mail: mcleodm@landcareresearch.co.nz

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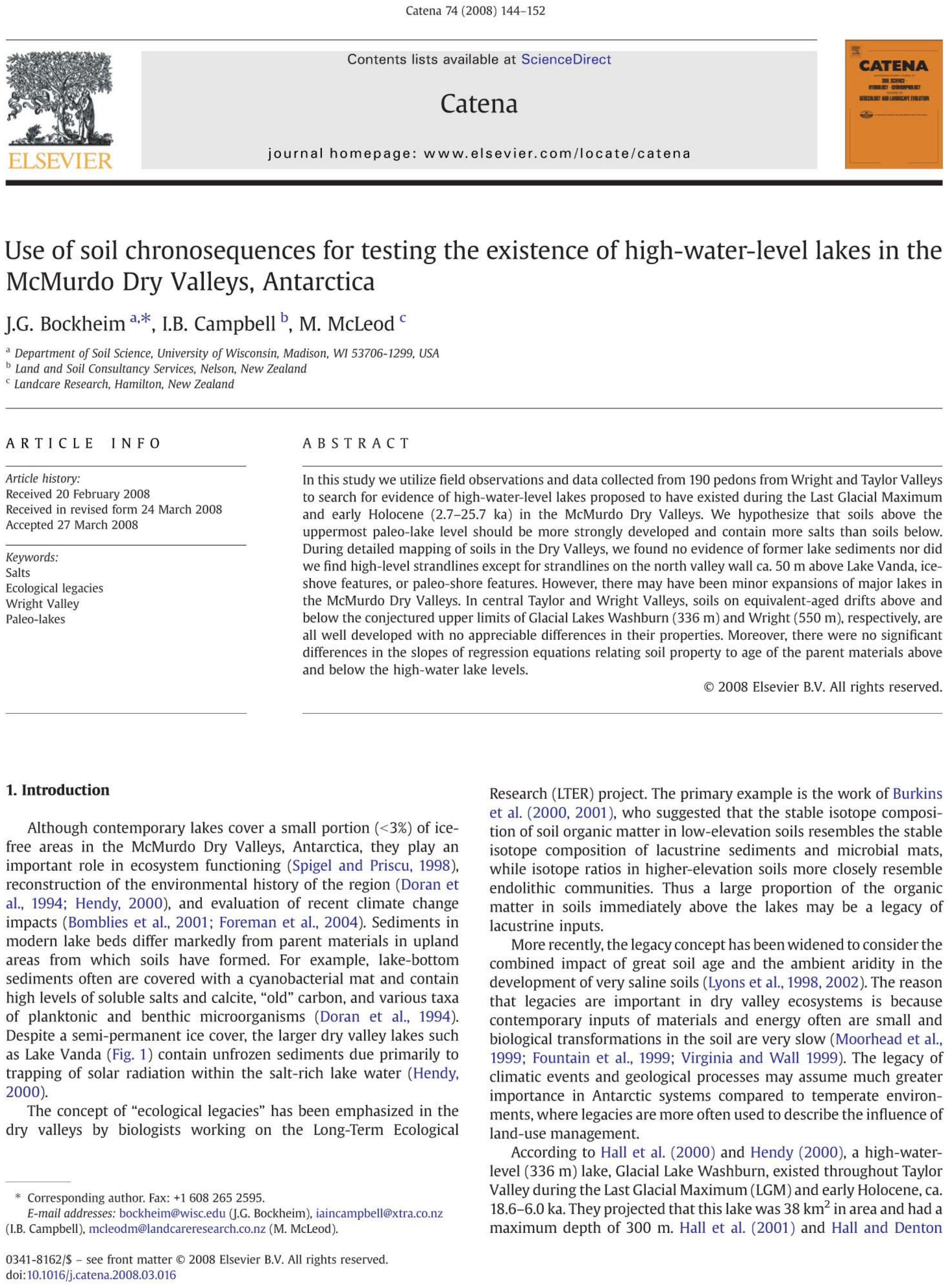
11 APPENDIX VI



Catena 74 (2008) 144–152

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Use of soil chronosequences for testing the existence of high-water-level lakes in the McMurdo Dry Valleys, Antarctica

J.G. Bockheim [a,*], I.B. Campbell [b], M. McLeod [c]

[a] Department of Soil Science, University of Wisconsin, Madison, WI 53706-1299, USA
[b] Land and Soil Consultancy Services, Nelson, New Zealand
[c] Landcare Research, Hamilton, New Zealand

ARTICLE INFO

Article history:
Received 20 February 2008
Received in revised form 24 March 2008
Accepted 27 March 2008

Keywords:
Salts
Ecological legacies
Wright Valley
Paleo-lakes

ABSTRACT

In this study we utilize field observations and data collected from 190 pedons from Wright and Taylor Valleys to search for evidence of high-water-level lakes proposed to have existed during the Last Glacial Maximum and early Holocene (2.7–25.7 ka) in the McMurdo Dry Valleys. We hypothesize that soils above the uppermost paleo-lake level should be more strongly developed and contain more salts than soils below. During detailed mapping of soils in the Dry Valleys, we found no evidence of former lake sediments nor did we find high-level strandlines except for strandlines on the north valley wall ca. 50 m above Lake Vanda, ice-shove features, or paleo-shore features. However, there may have been minor expansions of major lakes in the McMurdo Dry Valleys. In central Taylor and Wright Valleys, soils on equivalent-aged drifts above and below the conjectured upper limits of Glacial Lakes Washburn (336 m) and Wright (550 m), respectively, are all well developed with no appreciable differences in their properties. Moreover, there were no significant differences in the slopes of regression equations relating soil property to age of the parent materials above and below the high-water lake levels.

1. Introduction

Although contemporary lakes cover a small portion (<3%) of ice-free areas in the McMurdo Dry Valleys, Antarctica, they play an important role in ecosystem functioning (Spigel and Priscu, 1998), reconstruction of the environmental history of the region (Doran et al., 1994; Hendy, 2000), and evaluation of recent climate change impacts (Bomblies et al., 2001; Foreman et al., 2004). Sediments in modern lake beds differ markedly from parent materials in upland areas from which soils have formed. For example, lake-bottom sediments often are covered with a cyanobacterial mat and contain high levels of soluble salts and calcite, "old" carbon, and various taxa of planktonic and benthic microorganisms (Doran et al., 1994). Despite a semi-permanent ice cover, the larger dry valley lakes such as Lake Vanda (Fig. 1) contain unfrozen sediments due primarily to trapping of solar radiation within the salt-rich lake water (Hendy, 2000).

The concept of "ecological legacies" has been emphasized in the dry valleys by biologists working on the Long-Term Ecological Research (LTER) project. The primary example is the work of Burkins et al. (2000, 2001), who suggested that the stable isotope composition of soil organic matter in low-elevation soils resembles the stable isotope composition of lacustrine sediments and microbial mats, while isotope ratios in higher-elevation soils more closely resemble endolithic communities. Thus a large proportion of the organic matter in soils immediately above the lakes may be a legacy of lacustrine inputs.

More recently, the legacy concept has been widened to consider the combined impact of great soil age and the ambient aridity in the development of very saline soils (Lyons et al., 1998, 2002). The reason that legacies are important in dry valley ecosystems is because contemporary inputs of materials and energy often are small and biological transformations in the soil are very slow (Moorhead et al., 1999; Fountain et al., 1999; Virginia and Wall 1999). The legacy of climatic events and geological processes may assume much greater importance in Antarctic systems compared to temperate environments, where legacies are more often used to describe the influence of land-use management.

According to Hall et al. (2000) and Hendy (2000), a high-water-level (336 m) lake, Glacial Lake Washburn, existed throughout Taylor Valley during the Last Glacial Maximum (LGM) and early Holocene, ca. 18.6–6.0 ka. They projected that this lake was 38 km^2 in area and had a maximum depth of 300 m. Hall et al. (2001) and Hall and Denton

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[*] Corresponding author. Fax: +1 608 265 2595.
E-mail addresses: bockheim@wisc.edu (J.G. Bockheim), iaincampbell@xtra.co.nz (I.B. Campbell), mcleodm@landcareresearch.co.nz (M. McLeod).

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doi:10.1016/j.catena.2008.03.016

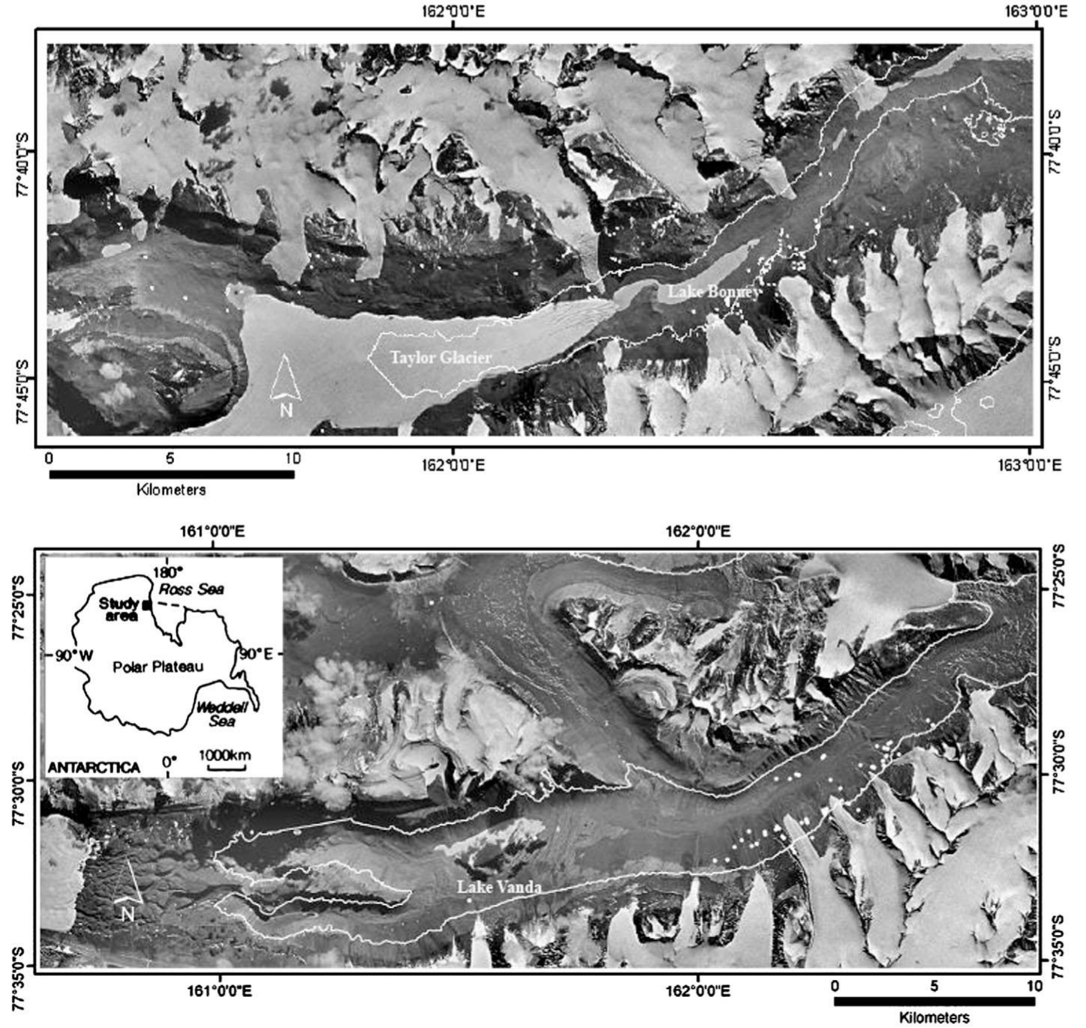

Fig. 1. The locations of the uppermost presumed paleo-lake levels in Taylor Valley (336 m) and Wright Valley (550 m), along with soil sampling locations (note: one point may represent more than one sampling site because of scale).

(2005) proposed the existence of Glacial Lake Wright, a high-water-level (550 m) lake, during the LGM and early Holocene, ca. 2.7–25.7 ka. They proposed that this lake was 212 km^2 in area and had a maximum depth of 470 m. The primary evidence for high-water-level lakes is the presence of deltas containing cyanobacterial mats that have been radiocarbon dated.

While we do not dispute that lake levels have varied in the geologic past and continue to vary at the present time (Bomblies et al., 2001; Foreman et al., 2004), we will demonstrate that except in a few isolated instances dry valley soils within the proposed lake basins contain no record of these high-water-level lakes. Small proglacial lakes commonly occur at various elevations, but their mere existence does not provide a basis for extrapolation as regional events. Moreover, the amount, distribution and composition of soluble salts in dry valley soils largely reflect differences in age of soils affected by continuous marine aerosol inputs and have not been impacted by lakes as recent as the LGM or late Holocene.

The primary aim of this paper is to utilize soils data to test the hypothesis that high-level lakes have existed in the McMurdo Dry Valleys as recently as the early Holocene. In this study we use data from soil chronosequences, i.e., an array of soils that owe their properties chiefly to the passage of time (Bockheim, 1990; Schaetzl et al., 1994). Three hypotheses were tested:

(i) Depth of visible salts, salt stage, thickness of the salt pan (on old surfaces only), maximum electrical conductivity, and quantities of profile salts to 70 cm will be significantly less in soils below

Table 1
Mean soil properties (standard deviations in parentheses) on drifts in Taylor Valley collected above and below the 336-metre contour (nd = insufficient data for analysis)

Property	Glaciation (age)				
	Alpine II (113–120 ka)	Taylor II (113–120 ka)	Taylor III (208–375 ka)	Taylor IVa (1.6–2.1 Ma)	Taylor IVb (2.7–3.5 Ma)
Number of sites					
Above	29	7	19	26	18
Below	7	7	11	2	0
Dominant soil subgroup[a]					
Above	TAt-TAo	TAo	TAo	TAo-TAt-SAo	TAo
Below	TAo	TAo	TAo	TAo-TAt	
Depth of staining (cm)					
Above	11 (.5)	3 (4)	17 (11)	39 (18)	33 (21)
Below	16 (9.9)	4 (5)	30 (18)	25 (14)	
p value	0.23	0.68	0.02	0.28	
Depth of coherence (cm)					
Above	27 (24)	26 (24)	70 (41)	70 (37)	71 (21)
Below	30 (24)	25 (22)	82 (34)	78 (53)	
p value	0.73	0.89	0.42	0.80	
Depth of visible salts (cm)					
Above	10 (11)	5 (7)	21 (19)	34 (20)	29 (20)
Below	10 (13)	0 (0)	31 (21)	25 (14)	
p value	0.93	0.07	0.18	0.55	
Depth of ghosts (cm)					
Above	9 (14)	8 (7)	8 (6)	15 (20)	15 (10)
Below	9 (7)	3 (5)	9 (13)	4 (6)	
p value	0.88	0.16	0.81	0.46	
Depth to ice-cemented permafrost (cm)					
Above	56 (24)	79 (25)	94 (17)	83 (37)	75 (28)
Below	93 (13)	56 (12)	94 (18)	78 (53)	
p value	0.00	0.05	0.99	0.85	
Maximum color-development equivalence					
Above	11 (4.5)	9.7 (2.1)	11 (5)	13 (7)	15 (8)
Below	8.7 (1.5)	7.8 (0.9)	9.1 (2)	9 (0)	
p value	0.20	0.06	0.18	0.38	
Salt stage					
Above	1.7 (0.7)	1.3 (0.5)	1.8 (0.5)	3.4 (1.4)	2.8 (0.9)
Below	1.3 (0.5)	0.7 (0.5)	1.9 (0.5)	3.0 (1.4)	
p value	0.21	0.05	0.56	0.72	
Thickness of salt pan (cm)					
Above	0	0	0	6 (6)	3 (6)
Below	0	0	1 (3)	4 (5)	
p value			0.19	0.53	
Weathering stage					
Above	2.1 (1.5)	2.1 (0.4)	2.6 (0.6)	4.2 (1.1)	4.0 (0.9)
Below	2.6 (0.5)	2.0 (0)	3.4 (0.8)	4.5 (0.7)	
p value	0.03	0.34	0.01	0.71	
Maximum EC (dS/m)					
Above	4.4 (3.0)	5.3 (1.0)	15 (11)	25 (24)	15 (19)
Below	3.3	1.8	4.5	22	
p value					
Profile salts to 70 cm (mg/cm^2)					
Above	670 (440)	1220 (205)	1460 (910)	2080	1600 (1500)
Below	590	440	1080	970	
p value	nd	nd	nd	nd	nd
Proportion of Cl in 1:5 soil:water extracts (%)					
Above	67 (26)	46 (23)	79 (19)	70 (30)	46 (38)
Below					
p value	nd	nd	nd	nd	nd

[a] Soil subgroup: TAo = Typic Anhyorthels; SAo = Salic Anhyorthels; TAt = Typic Anhyturbels.

the highest paleo-lake level, because of leaching of salts during lake recession;

(ii) Other properties, such as depths of staining, coherence, and ghosts, depth to ice-cemented permafrost, maximum color color-development equivalence, and weathering stage, will be slightly less below the highest paleo-lake level, because of interruption of soil/landscape formation during lake occupation.

(iii) Age-related trends in soil development rates will be dampened below the highest paleo-lake level, because of leaching of salts during lake recession and interruption of soil/landscape formation during lake occupation.

2. Study sites

We limited our study to the central portions of two major ice-free valleys in the McMurdo Dry Valley system, Wright Valley and Taylor Valley (Fig. 1). The drift sheets in both areas reflect a complex interplay of outlet glaciers, such as the Upper Wright Glacier and the Taylor Glacier, alpine glaciers along the valley walls, and grounding of ice in the Ross Embayment.

In Wright Valley we concentrated on alpine moraines differentiated as Alpine I, II, III, and IV (Prentice and Krusic, 2005). Whereas Alpine I drift is of mid-Holocene age, Alpine II is late Quaternary, and Alpine III (<3.5 Ma) and IV (>3.7 Ma) are of Pliocene age (Hall and Denton, 2005). In Taylor Valley we focused on a sequence of moraines associated with fluctuations of the Taylor Glacier margin. Whereas the Taylor II and Taylor III drifts are of late Quaternary age, Taylor IVa drift is of early Quaternary age and Taylor IVb is of Pliocene age. More specifically, Taylor II drift is 113–120 ka, Taylor III 208–375 ka (Higgins et al., 2000), Taylor IVa is 1.6–2.1 Ma, and Taylor IVb is 2.7–3.5 Ma (Wilch et al., 1993). We also sampled Alpine II moraines adjacent to alpine glacier on both valley walls in central Taylor Valley which may be comparable in age to Taylor III drift (Denton et al., 1971).

3. Methods

Our sampling concentrated on sediments of uniform age that cross the uppermost levels of Glacial Lake Wright (550 m) and Glacial Lake Washburn (336 m). In Wright Valley, we sampled nested moraines of alpine glaciers along the south valley wall and across strandlines along the north valley wall above Lake Vanda.

Replicate soils were described and sampled on the following drifts: Alpine II, Alpine III, and Alpine IV in Wright Valley and Alpine II, Taylor II, Taylor III, Taylor IVa, and Taylor IVb in Taylor Valley. The dataset includes 190 pedons. We successfully sampled soils above and below the uppermost paleo-lake levels on Alpine II, Alpine III, and Alpine IV drifts in Wright Valley and Alpine II, Taylor II, Taylor III, and Taylor IVa drifts in Taylor Valley. We also examined an altitudinal sequence of soils above Lake Vanda (Fig. 1) at elevations of 185, 250, 500, and 600 m, which is 144 m above the uppermost raised shoreline that was dated as mid-Holocene (3.0 ka) by Yoshida et al. (1975).

The following parameters were evaluated in the field (Bockheim and McLeod, 2006). 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; soil readily caves into the pit below the depth of coherence. The depth of "ghosts" (pseudomorphs) refers to the depth to which highly weathered clasts can be observed *in situ*; this parameter varies with rock type as well as soil age.

Table 2
Probability values for the relation between soil property and soil age and position relative to the uppermost lake level from General Linear Models (GLM) (values significant at <0.05 are highlighted in bold face; nd = insufficient data for analysis)

Property	Taylor Valley		Wright Valley	
	Soil age	Lake level	Soil age	Lake level
Depth of staining (cm)	**0.000**	**0.044**	**0.039**	0.268
Depth of coherence (cm)	**0.000**	0.363	0.633	0.604
Depth of visible salts (cm)	**0.000**	0.513	**0.000**	0.662
Depth of ghosts (cm)	0.204	0.550	0.651	0.258
Depth to ice-cemented permafrost (cm)	**0.000**	0.297	0.305	0.423
Maximum color-development equivalents	0.097	**0.027**		
Salt stage	**0.000**	0.239	**0.000**	0.266
Thickness of salt pan (cm)	**0.000**	0.971	**0.028**	0.322
Weathering stage	**0.000**	**0.006**	**0.001**	0.862
Profile salts to 70 cm (mg/cm^2)	nd	nd	0.169	0.340

The depth of visible salts refers to the maximum depth at which salts can be observed in a soil pit. We used a six-stage salt sequence developed by Bockheim (1990) that includes encrustations, flecks, and salt cementation. We also determined the depth to buried or ground ice or ice-cemented permafrost. The active (seasonal thaw) layer in the two study areas varies between 20 and 75 cm; material below this depth that is not cemented by ice contains "dry-frozen" permafrost, i.e., perennially frozen materials lacking sufficient interstitial water to cause cementation. The weathering stage, an overall representation of the landscape/material based on criteria derived from Campbell and Claridge (1975), includes the degree of surface boulder weathering, soil morphology, and the development of patterned ground.

Profile salts to a depth of 70 cm were estimated from measurements of electrical conductivity (U.S. Soil Salinity Staff, 1954) and the equation of Bockheim (1979). Soils were classified into the Gelisol order to the subgroup level (Soil Survey Staff, 2006). Mineral soils showing cryoturbation are classified as Turbels, whereas mineral soils without obvious cryoturbation are Orthels. Both suborders are divided into great groups on the basis of soil climate and other soil properties. In central Taylor and Wright Valleys, soils have anhydrous conditions (i.e., the mean water-equivalent precipitation is less than 50 mm/yr; ice-cemented permafrost is not present in the upper 70 cm; the moisture content averaged over the 10–70 cm layer is <3% by weight; and the dry consistence of the 10–70 cm layer is loose to slightly hard except where a salt-cemented horizon is present). These soils are classified into the Anhyturbel or Anhyorthel great groups. The soils are further subdivided into subgroups on the basis of presence or absence of soluble salts (e.g., salic) and other features.

Three statistical approaches were used to test the hypotheses. One-way Analysis of Variance (ANOVA) was used to compare soil properties above and below the highest lake-level contour (i.e., hypotheses 1 and 2), using Minitab Release 13 (Minitab, Inc., 2000). Two important assumptions underlying the use of any ANOVA procedure are that the data are normally distributed, and there is no direct relationship between variances and the mean (i.e., there is

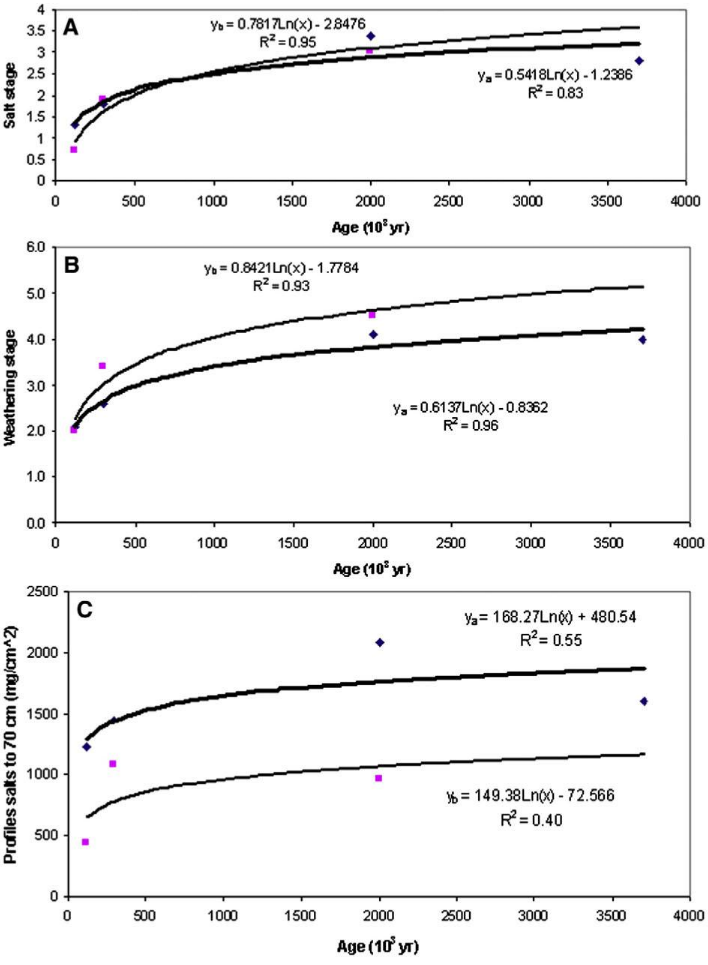

Fig. 2. Soil chronosequences above and below the 366-metre contour representing the highest level of Glacial Lake Washburn in Taylor Valley, including (A) salt stage, (B) weathering stage, and (C) profile salts to 70 cm. Note: Y_a = above paleo-lake level; Y_b = below paleo-lake level.

homogeneity of variances). The first assumption was verified by a Kolmogorov–Smirnov normality test, and the second assumption was tested using Levene's test for equal variances. Our data generally satisfied the requirements of both tests for using ANOVA.

To test hypothesis 3 regression models, or soil chronofunctions, were prepared that relate the soil property to the age of the soil parent material above and below the uppermost projected lake level. Several transformations were tested, including linear, logarithmic, power, exponential, and polynomial functions. The choice of the equation form was based not only on its ability to explain the most variance, but also on its contribution to a process-based understanding of pedogenic theory (Schaetzl et al., 1994). In accordance with recommendations of Schaetzl et al. (1994), we did not extrapolate chronofunctions to time zero because the soil parent materials may contain some weathering products from previous cycles of soil development.

There are four assumptions regarding regression analysis: (i) the values are normally distributed, (ii) the dependent variables are mutually independent, (iii) the relation between dependent and independent variables is linear, and (iv) there is constant variance between the variables, i.e., they exhibit homoskedasticity. We have already addressed the issue of normality. A linear relationship was achieved through the selection of a model with a high correlation coefficient (R^2). The last assumption was most difficult to achieve because of the age-distribution of the drifts, e.g., Taylor III is 208–375 ka and Taylor IVa is 1.6–2.1 Ma. However, the standard errors about the mean values were generally comparable.

We used a General Linear Models (GLM) to test the relative importance of parent material age and position relative to the highest lake-water-level contour (Minitab, Inc., 2000). Calculations for this model are done using a regression approach.

4. Results

4.1. General field observations

Our examination of soils immediately above modern lakes such as Lakes Bonney and Vanda (Fig. 1) yielded the following. Strandlines readily apparent from afar that are within 50 m of the current lake levels are not always visible on the ground. Salts generally are absent adjacent to modern lakes except as encrustations below surface clasts. Cyanobacterial crusts or flakes are very common. These observations suggest the salts are flushed out of the lake sediments as the lake levels fall. We did simple experiments by taking pieces of saltpan from older soils and placing them in saturated sediments within the modern-day hyporheic zone. Within an hour, the salts had slaked and the saltpan had disintegrated with few traces of the salts.

Lake-bottom sediments of the McMurdo Dry Valleys are distinctly different from the adjacent soils. Larger lakes such as Lake Vanda (Fig. 1) and Lake Fryxell (S77°37′, E163°07.5′) contain bottom sediments with a cyanobacterial mat and high levels of soluble salts and calcite, "old" carbon, and various taxa of planktonic and benthic microorganisms (Doran et al., 1994). Most importantly, these sediments are layered and often feature oxic and anoxic zones. In contrast, soils unaffected by lacustrine processes do not contain a cyanobacterial mat unless they are located in the hyporheic zone, which is typically limited to within several metres on each side of meltwater streams and along lake margins (Gooseff et al., 2003). Soils also contrast with lake sediments by containing a distinct layer of staining, and the oldest soils have a saltpan.

4.2. Taylor Valley

There were few consistent differences in soil development and salt accumulation above and below the uppermost water level (336 m) of Glacial Lake Washburn in central Taylor Valley (Table 1). Of the 10 parameters measured on four drift sheets, a total of 32 comparisons, there were significant differences ($p < 0.05$) above and below the 336-metre contour for only four comparisons: depth to ice-cemented permafrost on Alpine II drift, depth of staining on Taylor III drift, and weathering stage on Alpine II and Taylor III drifts. Because of insufficient comparisons, we were unable to do statistical analyses for profile salts to 70 cm and the proportion of Cl^- in soil:water extracts.

In contrast, there were significant age-related differences in soils for most soil properties, including depths of staining, coherence, visible salts, and to ice-cemented permafrost, the thickness of the salt pan, and salt and weathering stages (Table 2). Therefore, soil

Table 3
Mean soil properties (standard deviations in parentheses) on drift sampled in Wright Valley above and below the 550-metre contour (nd = insufficient data for analysis)

Property	Glaciation (age)		
	Alpine II (115 ka)	Alpine III (<3.5 Ma)	Alpine IV (>3.7 Ma)
Number of sites			
Above	1	8	6
Below	3	7	12
Dominant soil subgroup[a]			
Above	TAo	PsAo	PsAo
Below	TAo	PsAo	PsAo
Depth of staining (cm)			
Above	9	69 (29)	85 (15)
Below	17 (9)	47 (26)	73 (25)
p value	0.48	0.16	0.32
Depth of coherence (cm)			
Above	100	96 (21)	91 (12)
Below	71 (49)	72 (23)	78 (23)
p value	0.63	0.06	0.16
Depth of visible salts (cm)			
Above	36	64 (28)	84 (21)
Below	35 (31)	44 (8.0)	78 (23)
p value	0.97	0.08	0.57
Depth of ghosts (cm)			
Above	9	26 (22)	25 (18)
Below	5.8 (6.6)	16 (13)	14 (8)
p value	0.69	0.32	0.19
Depth to ice-cemented permafrost (cm)			
Above	100	107 (11)	94 (7.4)
Below	95 (20)	102 (12)	101 (14)
p value	0.84	0.40	0.24
Maximum color-development equivalence			
Above	18	13 (4)	14 (34)
Below	15 (3.5)	9 (2)	12 (2.7)
p value	0.50	0.07	0.16
Salt stage			
Above	2.0	4.4 (0.7)	5.3 (0.5)
Below	2.2 (1.2)	4.4 (1.1)	5.7 (0.6)
p value	0.87	0.91	0.29
Thickness of salt pan (cm)			
Above	0	20 (10)	22 (8)
Below	0	14 (11)	21 (9)
p value		0.31	0.95
Weathering stage			
Above	3.0	5.8 (0.7)	5.8 (0.4)
Below	4.0 (1.4)	5.3 (1.0)	5.8 (0.4)
p value	0.57	0.30	1.0
Maximum EC (dS/m)			
Above	16 (5.4)	36 (13)	65 (27)
Below	5.4	48 (21)	42 (24)
p value	nd	nd	nd
Profile salts to 70 cm (mg/cm^2)			
Above	3950 (1600)	5380 (1600)	7890 (2800)
Below	713	8100 (5800)	5750 (2470)
p value	nd	nd	nd
Proportion of Cl in 1:5 soil:water extracts (%)			
Above	87 (17)	76 (10)	71 (10)
Below	13	85 (6)	83 (5)
p value	nd	nd	nd

[a] Soil subgroup: TAo = Typic Anhyorthels; SAo = Salic Anhyorthels; PsAo = Petrosalic Anhyorthels.

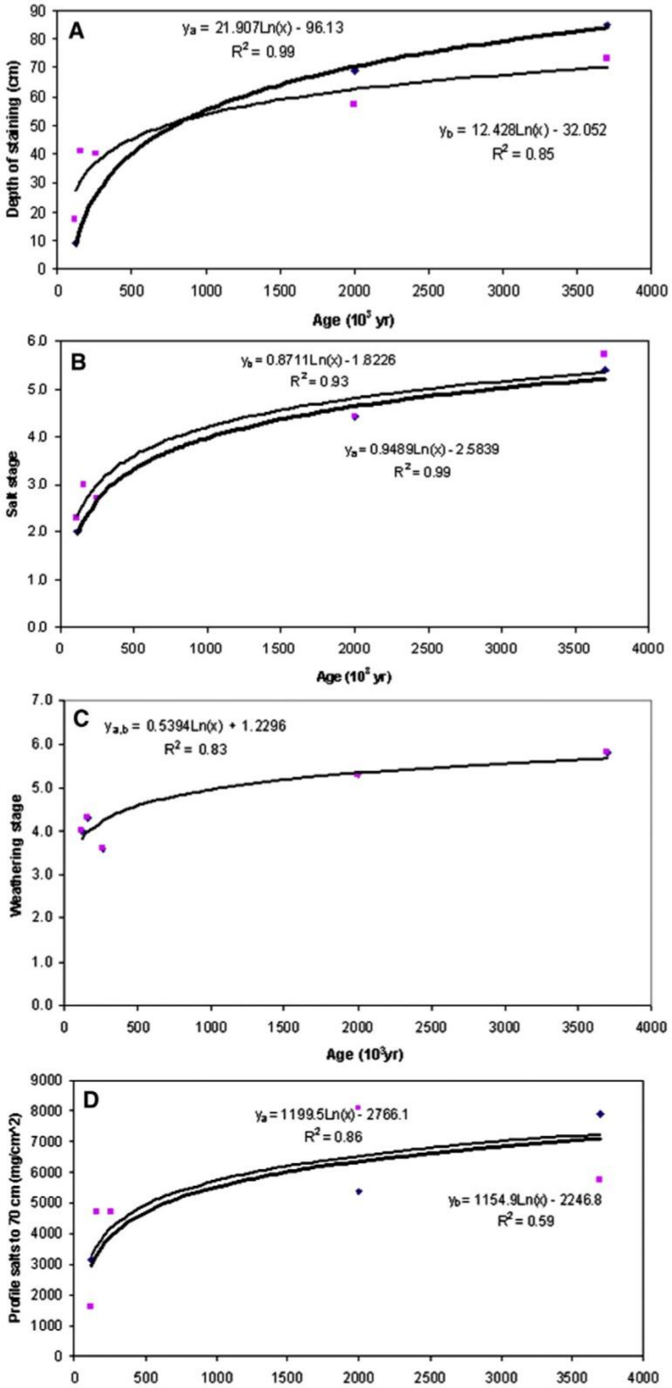

Fig. 3. Soil chronosequences above and below the 550-metre contour representing the highest level of Glacial Lake Wright in Wright Valley, (A) depth of staining, (B) salt stage, (C) weathering stage, and (D) profile salts to 70 cm. Note: Y_a = above paleo-lake level; Y_b = below paleo-lake level.

properties, particularly those related to salt accumulation, do not vary significantly above and below the uppermost projected lake level. Rather, the soil properties reflect progressive changes during soil evolution.

A logarithmic model explained a greater amount of variance in soil properties in relation to age of parent material than linear, power, exponential, or polynomial functions. Based on the soil chronofunction literature, the logarithmic model is the most commonly applied function globally (Barrett and Schaetzl, 1992) and in Antarctica (Bockheim, 1990). The logarithmic model embraces soil-formation theory of a rapid initial development, followed by a decelerating development and possibly eventually equilibrium depending on the particular soil property and the nature of the soil system. There were no major differences in the slopes of the linear regression lines relating soil property to time above and below the 336-metre contour, with the exception of depth of staining, maximum CDE, weathering stage, and profile salts (Fig. 2). These results imply that soil formation has progressed similarly above and below the projected uppermost lake level.

Based on the GLM, there were seven significant correlations between soil properties and soil age and three correlations between soil properties and lake level (Table 3).

4.3. Wright Valley

There were no significant differences in soil development and salt accumulation between soils above and below the uppermost lake level (550 m) of Glacial Lake Wright in central Wright Valley (Table 3). However, there were significant age-related trends in several soil properties, including depths of staining and visible salts, thickness of the saltpan, and salt and weathering stages (Table 2). Based on the GLM, there were five significant correlations between soil properties and soil age and none between soil properties and lake level (Table 2). Because of insufficient comparisons, we were unable to do statistical analyses for profile salts to 70 cm and the proportion of Cl^- in soil: water extracts.

As with soils from Taylor Valley, a logarithmic model explained the greatest amount of variance in soil properties in relation to age of parent material. Further, there were no major differences in the slopes of the linear regression lines relating soil property to time above and below the 550-metre contour (Fig. 3).

A specific example that highlights major soil and weathering differences within the fluctuating lake-level zone is provided by a comparison of two soils adjacent to Lake Vanda: soil 704 at 98 m and soil 705 at 500 m that are below the purported 550 m paleo-lake level. Based on soil morphological properties, the soil at the higher level is classed as weathering stage 3, while the soil at the lower level is classed as weathering stage 1. The differences in soil morphological properties are accompanied by significant differences in soil salt chemistry (Table 4) which taken together are strongly suggestive of a stable environment for a considerable period for the soil at 500 m and an absence of modification in a fluvial or lacustrine environment.

5. Discussion

We provide four lines of arguments disfavoring the former existence of high-water-level lakes during the LGM and early Holocene period in Taylor and Wright Valleys, including (i) field observations, (ii) a comparison of analytical data above and below the proposed uppermost former lake levels, and (iii) evidence supporting a steady-state accumulation of salts in profiles above and below the presumed uppermost former lake levels.

5.1. Field observations

We observed no field evidence for the existence of high-water-level lakes other than localized deltas and strandlines above Lake Vanda. We did not observe relict lake sediments, bedding, or cyanobacterial fragments in soils. Nor did we observe ice-shove features and paleo-shore features such as indentations and ridges that are common to ice-covered lakes. Soils adjacent to modern lakes such as Bonney and Vanda that have experienced fluctuations in lake levels since the mid-Holocene are poorly developed and contain few salts.

We consider it highly unlikely that the morphological features distinguishing Antarctic soils and delineating soil chronosequences could have survived the impact of the sedimentary and hydrological processes in an unstable or fluctuating lake-edge environment.

5.2. Comparison of analytical soil properties above and below the uppermost lake levels

The existence of former high-water-level lakes should be readily detectable by the distribution of salts in the soils above and below the uppermost lake level. There should be significant differences in depth of visible salts, thickness of the salt pan, salt stage, and profiles salts to a depth of 70 cm in soils above and below the uppermost lake levels. However, our data showed few significant differences in soil properties from samples collected above and below the uppermost lake levels in Taylor and Wright Valleys (Tables 1 and 3), forcing us to reject hypotheses 1 and 2.

Age-related trends in soil development in Taylor and Wright Valley generally are comparable above and below the 336-metre and 550-metre upper lake levels, respectively (Figs. 2 and 3), forcing us to reject hypothesis 3. Based on our General Linear Models, there were 12 significant correlations between soil property and soil age and three between soil property and position relative to the uppermost lake level in central Taylor and Wright Valleys (Table 3). Moreover the probability values for two of the three correlations between soil property and position relative to the paleo-lake levels were lower than

Table 4

Chemistry of soil:water extracts from soil 704 along the valley floor (98 m a.s.l.) near Lake Vanda and soil 705 at 500 m a.s.l. that is below the postulated uppermost lake level of Glacial Lake Wright

Pedon no.	Depth (cm)	EC (dS/m)	$\mu mol_c/kg$								
			Na	K	Ca	Mg	F	Cl	NO_3–N	PO_4–P	SO_4
704	0–7	0.25	0.36	0.01	0.75	0.14	0.014	0.21	0.7	0.01	1.02
	7–13	0.40	0.6	0.06	0.99	0.25	0.025	0.62	1.5	0.01	1.06
	13–40	0.24	0.19	0.06	0.49	0.22	0.012	0.9	0.9	0.15	0.039
	40–70	0.06	0.13	0.02	0.12	0.06	0.018	0.18	0.06	0.02	0.016
705	0–3	2.7	0.87	0.06	14	1.7	0.017	3.3	5.0	1.8	14
	3–15	6.0	15	0.07	15	2.1	0.014	18	8.0	17	13
	15–20	10.6	60	3.3	18	7.2	0.066	59	28	3.4	10
	20–32	13.0	61	3.2	8.8	7.2	0.031	57	24	20	1.5
	32–55	5.0	8.4	2.0	7.0	6.2	0.008	2.2	27.0	0.1	0.5
	55–85	5.0	8.6	1.8	7.2	6.8		23		3.6	0.44

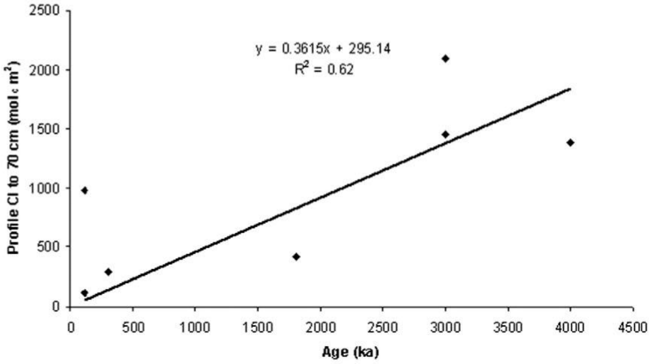

Fig. 4. Profile accumulation rate of Cl^- in relation to amount contributed by snowfall.

those between soil property and soil age. These data suggest the age-related differences are more important that position relative to lake level, which would not be the case if former lakes influenced soil development. Presumably, if high-water-level lakes had existed in these valleys, they would have arrested soil development during their existence, and would have obliterated some vestiges of soil formation such as accumulation of soluble salts.

5.3. Evidence for steady-state salt accumulation

Chloride is the dominant anion in soil:water extracts of soils in central Taylor and Wright Valleys (Tables 1 and 3). We plotted the mean Cl^- content of the soils against age of the 8 moraines studied in the two valleys, obtaining an R^2 of 0.63 and a probability value of 0.02 (Fig. 4). Assuming that the salts originate primarily from marine aerosols (Claridge and Campbell, 1977), we calculated the annual input of Cl^- in snow by assuming 10 mm of water-equivalent precipitation per year and a Cl^- concentration of snowfall of 0.033 mmol_c Cl/L (Bockheim, unpublished) (Eq. (1)).

$$10\text{L}/\text{m}^2/\text{yr} \times 0.033\text{mmol}_c\text{Cl}^-/\text{L} = 0.33\text{mmol}_c/\text{m}^2/\text{yr} \qquad (1)$$

The slope of the regression line, 0.36 $\text{mmol}_c/\text{m}^2/\text{yr}$, is consistent with current inputs of salts from water-equivalent precipitation, which from Eq. (1) is 0.33 $\text{mmol}_c/\text{m}^2/\text{yr}$.

Based on these data, the annual accumulation of Cl^- in the soil is comparable to that contributed by precipitation over the long term (Fig. 4). Therefore, salt input does not appear to have been arrested by the persistence of high-level lakes. Moreover, the highly mobile Cl^- anion would have been leached following lake recession. Claridge et al. (1999) conducted experiments using lithium chloride to monitor movement of salts in Antarctic soils. In the coastal soils of Ross Island, melting snow caused vertical movement of salts to depths of 10 to 25 cm and lateral movement of salts up to 5 m. In contrast on a dry site near Lake Vanda, only trace amounts of salt moved vertically or laterally. If the salts had leached out following lake recession, the rate of Cl^- input from snowfall would have had to be 145 $\text{mmol}_c/\text{m}^2/\text{yr}$, or more than two orders of magnitude greater than the rate shown in Fig. 4.

5.4. Climatic requirements for high-level lakes

Finally, we believe that the existence of several high-level lakes in Taylor and Wright Valleys implies dramatically warmer and moister conditions, particularly during the austral summer, in the McMurdo Dry Valleys. However, evidence for such conditions in soils is singularly lacking. Rather, the soil properties here point to a legacy derived from a period of prolonged arid conditions.

6. Conclusions

We found no field evidence for the existence of high-level lakes in central Wright and Taylor Valley, although we did find evidence fluctuations of modern lakes by ca. 50 m. Based on statistical analysis (ANOVA, GLM and regressions), there were few significant differences in soil properties above and below the proposed lake high-water-level contours, causing us to reject hypotheses that salt-related soil properties (hypothesis 1) and other physical and chemical soil properties (hypothesis 2) will be less in soils below the highest paleo-lake level than in soils above this level. In contrast, there were significant age-related trends in soil properties both above and below these lake levels with no significant differences in rates of change in soil properties. There were few differences in slopes of regression lines relating soil property to time of exposure, causing us to reject hypothesis 3, i.e., that age-related trends in soil development rates will be dampened below the highest paleo-lake level. These data cast doubt as to whether high-level lakes existed in the McMurdo Dry Valleys as recently as the early Holocene. An alternative explanation is that the former lakes had no effects on soils other than depositing deltas with cyanobacteria along meltwater streams, which does not appear likely.

Acknowledgments

The New Zealand Foundation for Research Science and Technology (contract C09X0307) supported this research. Antarctic New Zealand provided logistical support in 2005 and 2006. We appreciate the thoughtful insights of K.M. Hinkel and reviews by two anonymous persons.

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12 APPENDIX V

Arctic, Antarctic, and Alpine Research, Vol. 40, No. 2, 2008, pp. 279–286

Distribution of Glacial Deposits, Soils, and Permafrost in Taylor Valley, Antarctica

*J. G. Bockheim**
M. L. Prentice† and
M. McLeod‡

*Corresponding author: Department of Soil Science, University of Wisconsin, Madison, 1525 Observatory Drive, Madison, Wisconsin 53706, U.S.A.
bockheim@wisc.edu
†Indiana Geological Survey, Indiana University, 611 North Walnut Grove, Bloomington, Indiana 47405, U.S.A.
‡Soil Services, Landcare Research, Private Bag 3127, Hamilton 2001, New Zealand

Abstract

We provide a map of lower and central Taylor Valley, Antarctica, that shows deposits from Taylor Glacier, local alpine glaciers, and grounded ice in the Ross Embayment. From our electronic database, which includes 153 sites from the coast 50 km upvalley to Pearse Valley, we show the distribution of permafrost type and soil subgroups according to *Soil Taxonomy*. Soils in eastern Taylor Valley are of late Pleistocene age, cryoturbated due to the presence of ground ice or ice-cemented permafrost within 70 cm of the surface, and classified as Glacic and Typic Haploturbels. In central Taylor Valley, soils are dominantly Typic Anhyorthels of mid-Pleistocene age that have dry-frozen permafrost within the upper 70 cm. Salt-enriched soils (Salic Anhyorthels and Petrosalic Anhyorthels) are of limited extent in Taylor Valley and occur primarily on drifts of early Pleistocene and Pliocene age. Soils are less developed in Taylor Valley than in nearby Wright Valley, because of lesser salt input from atmospheric deposition and salt weathering. Ice-cemented permafrost is ubiquitous on Ross Sea, pre–Ross Sea, and Bonney drifts that occur within 28 km of the McMurdo coast. In contrast, dry-frozen permafrost is prevalent on older (≥115 ky) surfaces to the west.

DOI: 10.1657/1523-0430(06-057)[BOCKHEIM]2.0.CO;2

Introduction

Taylor Valley has been the focus of the McMurdo Dry Valleys Long-Term Ecological Research (LTER) in Antarctica since 1992 (http://www.mcmlter.org). The valley contains perennially ice-covered lakes, ephemeral streams, and extensive areas of exposed soils and has played an important role in understanding biodiversity, ecosystem functioning, and biogeochemical cycling (Barrett et al., 2006).

The surficial geology of Taylor Valley has received considerable attention over the past 50 years and has yielded a wealth of information regarding the long-term history of the Antarctic ice sheets and climate (e.g., Péwé, 1960; Denton et al., 1971, 1991, 1993; Stuiver et al., 1981). Eastern Taylor Valley has provided much of the surficial geologic evidence that a marine-based Ross Sea Ice Sheet, an extension of the West Antarctic Ice Sheet, filled the Ross Sea during past global glaciations. Past fluctuations in Taylor Glacier, which presently occupies the western and central portions of the valley, have provided a significant record of fluctuations of the Taylor Dome, a peripheral dome of the East Antarctic Ice Sheet west of Taylor Valley (Hendy et al., 1979; Denton et al., 1989). Alpine glaciers on the sides of Taylor Valley have been regarded as fluctuating in-phase with Taylor Glacier, with both systems being driven by regional climate change (Denton et al., 1989). However, glacial-geomorphologic maps exist for only portions of the valley, and a comprehensive summary of the glacial chronology is not available.

During the period 1975–1987, Bockheim (http://nsidc.org/data/ggd221.html) compiled an extensive database for Antarctic soils, including surface boulder weathering, soil morphology, and soil chemical and physical properties. The database includes 153 pedons from Taylor Valley. Data from the early stages of the study were used to relate soil development in central Taylor Valley to glacial geomorphology (Pastor and Bockheim, 1980). Soils of Taylor Valley have been studied in some detail as part of the McMurdo LTER (Campbell et al., 1997; Campbell, 2000; http://www.mcmlter.org).

There has been minimal soil mapping in Antarctica. McCraw (1967) prepared one of the few such maps, a third-order (1:63,500) soil map of Taylor Valley based primarily on geomorphological features, including topography and parent material. A modern soil map based on *Soil Taxonomy* (Soil Survey Staff, 1999) is lacking and would be useful for understanding biodiversity (Barrett et al., 2006) and predicting human impacts on soils in the region (Campbell et al., 1994). Permafrost-affected soils such as those occurring in Antarctica are incorporated into the Gelisol order (Soil Survey Staff, 1999, 2006). Two primary suborders in Taylor Valley include Turbels (one or more horizons featuring frost-stirring, or cryoturbation) and Orthels (cryoturbation not apparent). To date, there have been few efforts to classify soils of Antarctica according to *Soil Taxonomy*. In Wright Valley, Bockheim and McLeod (2006) identified an evolutionary sequence of soils that included, from youngest to oldest, Glacic Haploturbels (cryoturbated soils in coastal areas with soil moisture contents >3% and ground ice), Typic Haploturbels (cryoturbated soils in coastal areas with soil moisture contents >3%), Typic Anhyorthels (soils without cryoturbation and occurring in regions away from the coast with <3% soil moisture content), Salic Anhyorthels (soils with abundant salts enriched in sodium chloride), and Petrosalic Anhyorthels (soils with a strongly cemented or induration horizon from accumulation of sodium chloride).

The distribution of permafrost and ground-ice features in the McMurdo Dry Valleys (MDVs) and elsewhere in Antarctica is poorly understood (Bockheim, 1995). While ice-cemented permafrost is common in coastal areas of the MDVs, dry-frozen permafrost occurs on older inland surfaces where the interstitial ice in ice-cemented permafrost has sublimated (Bockheim, 2002; Bockheim and McLeod, 2006).

1523-0430/08 $7.00

The objectives of this research are to present preliminary maps of glacial deposits, soils, and permafrost/ground ice in central and lower Taylor Valley, a key valley in the McMurdo Oasis.

Study Area

Taylor Valley is the southernmost and smallest of the three main valleys that comprise a large part of the McMurdo Oasis (4800 km^2), which constitutes the largest ice-free region in Antarctica. Three types of glaciations have occurred in Taylor Valley: advances of outlet glaciers from the East Antarctic Ice Sheet, advances from grounding of ice in the Ross Embayment, and advance of alpine glaciers along the valley walls. Unlike Victoria and Wright Valleys, Taylor Valley contains an active outlet glacier, the Taylor Glacier, which drains the Taylor Dome. Dating of the drift sheets is from $^{40}Ar/^{39}Ar$ and K-Ar dates of cinder cones intercalated with drifts, reworked basalt clasts, and volcanic ash crystals in upper Taylor Valley and ^{14}C dating in lower Taylor Valley. Uncertainties of ages are given in Denton et al. (1989, 1993), Marchant et al. (1993), Wilch et al. (1993), and Higgins et al. (2000b).

Fluctuations of Taylor Glacier during the Plio–Pleistocene are recorded by at least four drift sheets, in order of decreasing age and extent, Taylor IVb, IVa, III, and II (Denton et al., 1989, 1993). The oldest advance of Taylor Glacier yet known in central Taylor Valley occurred prior to 3.5 My BP, based on isotopically dated volcanic rocks intercalated with glacier drifts (Wilch et al., 1993). Taylor IVb drift is commonly considered mid–late Pliocene in age (<3.5 My BP), and Taylor IVa drift is regarded as Pleistocene in age. Tills in the upper Taylor Glacier region, dated by volcanic ash at 7–15 My BP, indicate still older and larger-scale advances of Taylor Glacier, some of which culminated in complete overriding of the valley by ice (Marchant et al., 1993). Taylor III drift dates to ca. 208–335 ky BP, whereas Taylor II/Bonney drift dates to 113–120 ky BP (Higgins et al., 2000a). Taylor Glacier is advancing today, and this advance is referred to as TI.

Ross Sea drift deposited from the marine-based Ross Sea Ice Sheet mantles much of lower Taylor Valley. Alpine glaciers in western Taylor Valley may have advanced in phase with Taylor Glacier advances (Denton et al., 1991). Ross Sea I drift consists mainly of sediments deposited in a large proglacial lake, Glacial Lake Washburn, which existed ca. 12.4–23.8 ka (Denton et al., 1989; Hall and Denton, 2000a, 2000b).

Taylor Valley has a cold desert climate with a mean annual air temperature ranging from $-15°C$ near the coast to ca. $-20°C$ further inland and at the higher elevations (Doran et al., 2002). The mean annual water-equivalent precipitation is approximately 100 mm near the coast and declines upvalley. There is a strong interaction between moist easterly winds and dry katabatic winds from the west. Physical obstacles, such as the Nussbaum Riegel, create isolated weather systems in Taylor Valley (Doran et al., 2002).

Methods

We sampled 153 pedons in Taylor Valley from the northeast part of the study area near the coast to Pearse Valley in the southwest. Although we have sampled extensively in the upper Taylor Glacier region, including Beacon and Arena Valleys, these sites are not included in the present study. Details of plot location, site and soil description, and soil sampling procedures are given in Bockheim (2002).

We assigned each soil a morphogenetic salt stage (Bockheim, 1990). According to this system, the form of soluble salts reflects soil age and is related to total dissolved salts from electrical conductivity measurements. Salt stage 0 contains no visible salts; salt stage 1 has coatings on the bottom of stones; salt stage 2 has salt flecks 1–2 mm in diameter that cover $<20\%$ of the surface area of the horizon; salt stage 3 has salt flecks 1–2 mm in diameter that cover $>20\%$ of the surface area of the horizon; salt stage 4 has a weakly cemented salt pan; salt stage 5 has a strongly cemented salt pan; and salt stage 6 has an indurated salt pan.

The weathering stages assigned in this study represent the overall age of the landscape/material based on the degree of surface boulder weathering and soil morphology and has been adapted from Campbell and Claridge (1975). Weathering stage 1 has fresh, unstained, and angular boulders; 5Y soil colors; minimal horizon development; stage 0 salts; very shallow ice-cemented permafrost; and moderate patterned ground development. Weathering stage 2 has light staining of boulders with some disintegration; 10YR 6/3–2.5Y 6/2 soil colors; weak horizon development; stage 2 salts; shallow ice-cemented permafrost; weak soil horizon development; and strong patterned ground development. Weathering stage 3 has boulders with distinct polish, staining, and rounding; some cavernous weathering and ventifacts; 10YR 5/3–2.5Y 6/4 soil colors; distinct horizon development; stage 3 salts; moderately deep soil depth; and some ghosts. Weathering stage 4 has boulders much reduced by rounding, crumbling, and ventifaction; strongly developed cavernous weathering; well developed staining and polish, and some desert varnish; 10YR 5/4 soil colors; very distinct soil horizons; salt stage 4; deep soil profiles; and some ghosts. Weathering stage 5 has few boulders; a well developed desert pavement with extensive crumbling, rounding, pitting, and polish; 10YR 4/4–5YR 5/8 soil colors; very distinct soil horizon development; stage 5 salts; deep soil profiles; and some ghosts. Weathering stage 6 has weathered and crumbled bedrock; very strongly stained residual materials; 7.5YR 5/6–5YR 4/8 or 2.5YR 3/6 soil colors; very distinct soil horizon development; stage 6 salts; shallow to deep profiles; and bedrock sometimes crumbled to 50 cm in depth.

A glacial geomorphology map of Taylor Valley was constructed from published maps of eastern (Hall and Denton, 2000b) and central Taylor Valley (Higgins et al., 2000a, 2000b) and detailed maps of selected alpine glaciers compiled by one of us (MLP).

Soils data contained in the National Snow and Ice Data Center database (http://nsidc.org/data/ggd221.html) were used to determine the distribution of soils and permafrost features at a 1:250,000-scale. Soils were delineated at the subgroup level. Soil map units included Glacic Haploturbels, Typic Haploturbels, Salic Anhyturbels, Typic Anhyorthels, Salic Anhyorthels and Petrosalic Anhyorthels. The following permafrost categories were used: (1) ground ice within 70 cm of the surface; (2) ice-cemented permafrost within 70 cm of the surface; and (3) dry-frozen permafrost within the upper 70 cm. A depth of 70 cm was chosen because our observations suggest that cryoturbation becomes unimportant when ground ice or ice-cemented permafrost is below this depth.

Results

GLACIAL DRIFTS IN LOWER AND CENTRAL TAYLOR VALLEY

Taylor II or Bonney drift forms a nearly continuous drift sheet on the floor and sides of central Taylor Valley from Canada

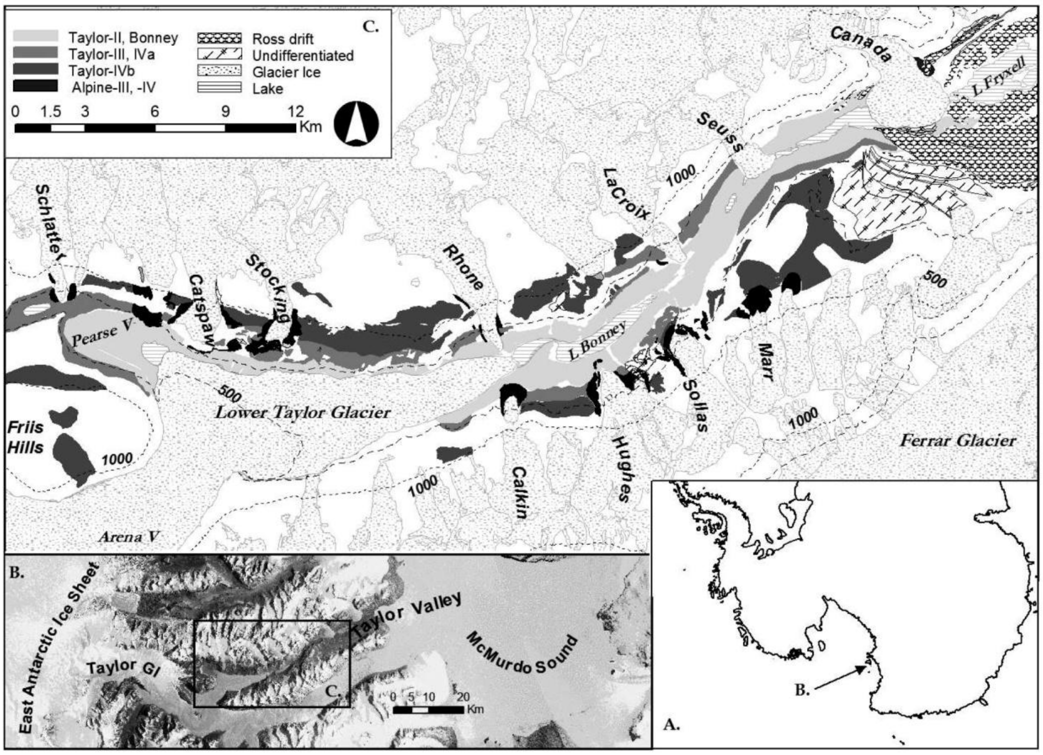

FIGURE 1. Generalized distribution of glacial deposits in Taylor Valley (compiled from Wilch et al., 1993; Hall and Denton, 2000b; Higgins et al., 2000a, 2000b; and unpublished data of Prentice and Bockheim). Colluvial, lacustrine, eolian, Alpine II, and Alpine I deposits are not shown. Blank patches are either the latter, bedrock, or snow.

Glacier to the Taylor Glacier snout (Higgins et al., 2000a, 2000b), along the margin of Taylor Glacier, and on the floor of Pearse Valley (Fig. 1). TII drift outcrops up to 300 m a.s.l. by Sollas Glacier and up to ~600 m a.s.l. at Stocking Glacier. In the central valley, TII drift consists of matrix-rich water-lain and melt-out till as well glaciolacustrine and glaciofluvial sediment, all of which contain fragments of inorganic lake carbonates. These sediments were deposited from cold-based Taylor ice where the ice overran, froze on, and reworked proglacial lake sediments (Higgins et al., 2000a). More weathered and eroded lateral moraines and ice-marginal features parallel the upper TII limit about 100 m upslope throughout much of the central valley. We assigned these features to TIII drift.

Still older matrix-rich drift and boulder-belt moraines mantle the valley sides above TIII drift up to at least 1000 m a.s.l. Over this vertical range, these sediments are characterized by numerous sets of ice-marginal features that become more discontinuous and influenced by gelifluction with increasing elevation. This drift clearly comprised multiple units of different age but, with insufficient evidence to subdivide it, we assigned it to TIV drift. Within TIV drift, we group boulder-belt moraines mapped by Wilch et al. (1993) as well as the silty tills found on Rhone platform beneath boulder-belt moraines. The ages of the silty tills at Rhone platform range from younger than 2.71 ± 0.24 My BP to older than 3.47 ± 0.05 My BP (Wilch et al., 1993).

Narrow, ice-cored moraines at the margins of many alpine glaciers today reflect the ongoing alpine glacier advance, referred to as AI. Ringing the margins of most alpine glaciers and extending outward a few hundred meters are narrow boulder-belt moraines and thin, discontinuous sandy gravel sheets. The gravel is varnished, ventifacted, and shows no sign of subglacial processing. This boulder-belt drift has been assigned to the AII glacial episode (Denton et al., 1971; Leide, 1980). Alpine II drift is draped over and distributed proximal to massive, 10–20 m high, rounded, and discontinuous alpine-glacier moraines. Commonly, two different generations of "bulky" (as opposed to boulder-belt moraines) alpine moraine remnants are present as indicated by crosscutting moraines or different stratigraphic relations to Taylor drift. The inner bulky moraine has traditionally been assigned to AIII drift; the outer, to AIV drift. They are shown in Figure 1 as combined AIII/IV drift.

The orientation of the remnant bulky moraines, approximately perpendicular to contour lines, implies that the associated advances of the alpine glaciers were largely out-of-phase with Taylor IV glacier advances (Fig. 1). Perhaps the bulky alpine moraines below 1000 m a.s.l. are younger than the Taylor boulder belts and silt-rich tills outcropping up to 1000 m a.s.l. on the Rhone platform, which would negate this interpretation. However, we do favor this explanation, because soil development is comparable on alpine and Taylor drifts (Table 1). Not only do the bulky Alpine III/IV drifts occur below 1000 m a.s.l., but also their distribution implies no blocking interference from Taylor Glacier.

Ross I drift mantles the floor and sides of lower Taylor Valley (Fig. 1). This drift is draped over TII drift in front of Canada

TABLE 1

Properties of soils of Taylor Valley, Antarctica.

Drift unit	Approx. age[1]	No. of pedons	Depth (cm) Staining	Coherence	Vis. Salts	Ghosts	Ice cement	Salt stage	Weathering stage	Thickness salt pan (cm)	Profile salts to 70 cm (mg cm^{-2})	Soil subgroup[2]
Alpine I	<3.7 ky	3	0	11	0	0	16 (core)	0	1	0	213	GHt-THt
Ross Sea	12.4–23.8 ky	7	0	28	5	0	34	1.1	1.6	0	180	THt
pre-Ross	>12.4–23.8 ky	3	0	23	0	0	25	1.0	1.7	0	32	THt
Alpine II	113–120 ky	32	10	21	7	8	>40	1.5	2.1	0	591	THt-TAo
Taylor II	113–120 ky	14	3	18	3	6	>45	1.2	2.1	0	1029	TAo-TAt
Taylor III	208–375 ky	27	18	>46	21	9	>85	2.0	2.7	0	1494	TAo
Taylor IVa	1.6–2.1 My	28	38	>48	33	15	>44	3.4	4.2	4	1988	TAo-SAo
Taylor IVb	2.7–3.5 My	18	33	>49	29	15	>46	2.8	4.0	4	1600	TAo
Alpine III–IV	2.7–3.5 My	4	41	>47	41	14	>47	3.3	3.5	7	4393	TAo
Silty till	?	6	19	>100	11	23	>56	1.0	1.0	1	1317	TAo
Lava/undiff. Till or scree	?	4	18	>120	44	46	>120	1.0	4.0	2	nd	TAo
Undiff. Till	?	6	42	>85	43	10	>85	2.5	4.0	6	nd	TAo

[1] Dating from Denton et al. (1971; 1991); Hall and Denton (2000b); Higgins et al. (2000b); Marchant et al. (1993); Wilch et al. (1993).

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

Glacier. Older generations of Ross drift crop out higher on the valley walls and also are draped onto the eastern face of Nussbaum Reigel. These are not well differentiated and so all Ross units are mapped as a single Ross drift category.

PERMAFROST DISTRIBUTION IN TAYLOR VALLEY

More than half of lower and central Taylor Valley contains ice-cemented permafrost (Fig. 2). Deposits containing ice-cemented permafrost include Ross and Bonney drift in the easternmost 28 km of the valley (Fig. 2). Ice-cemented permafrost is also present in Alpine II drift throughout the valley. Ice-cored drift is of limited extent in Taylor Valley and appears to be restricted to Holocene-aged Alpine I moraines along the north and south valley walls. Dry-frozen permafrost is prevalent in central and upper Taylor Valley, primarily in Taylor III and older drift and in Alpine III and IV drifts (Fig. 2).

SOIL DISTRIBUTION IN TAYLOR VALLEY

The youngest soils in Taylor Valley contain ground ice and are classified as Glacic Haploturbels. These soils occur on ice-cored Alpine I drift of Holocene age (Fig. 3). Soils in eastern Taylor Valley contain ice-cemented permafrost in the upper 70 cm of the solum and are strongly cryoturbated (Typic Haploturbels). The ice-cement results from melting of snow in the eastern part of the valley and the comparatively young geomorphic surfaces such as the Ross Sea (Fig. 4A) and Bonney (Fig. 4B) and Alpine II drifts. Typic Anhyorthels occur on Taylor III drift further upvalley in areas of dry-frozen permafrost (Fig. 4C). These soils often have sand-wedge casts and presumably once contained ice-cemented permafrost.

Salt-enriched soils (Salic Anhorthels) are common on Taylor IV drift on Andrews Ridge, above 1000 m along the LaCroix, Matterhorn, Stocking, and Catspaw Glaciers on the north valley wall, and in Pearse Valley (Fig. 3). Salic Anhyorthels also occur on Alpine III and IV drifts near the Marr, Sollas, Hughes, and Stocking Glaciers. Soils with salt-cemented horizons (Petrosalic Anyhyorthels) are of limited extent in Taylor Valley and are restricted to Taylor IV drift on the Rhone Platform and in Pearse Valley (Fig. 4D) and on Alpine IV surfaces near the Sollas and Stocking Glaciers.

Discussion

GLACIAL HISTORY OF TAYLOR VALLEY

Taylor IV drift appears to contain multiple drift sheets, but we were unable to distinguish among these sheets. It is plausible that TIVa and TIVb drifts, which occur as boulder belts where defined in upper Taylor Valley, consist solely of boulder-belt moraines throughout Taylor Valley. The presence of Taylor boulder-belt moraines draped over silty Taylor basal till on Rhone platform constitutes positive evidence of multiple Taylor IV drifts. If this interpretation is correct, then these and similar silty tills high on central valley walls would likely reflect substantially different and older Taylor glaciations not appropriate for inclusion in TIVb drift. Boulder-belt moraines indicate cold-based ice and an absence of ice-marginal lakes. On the other hand, silty basal till often indicates active subglacial deposition by wet-based ice in the McMurdo Dry Valleys (Prentice et al., 1993). We draw a distinction between silty basal till described by Wilch et al. (1993) and stratified glacial lake sediments contorted and reworked by cold-based ice, which is typical of TII drift.

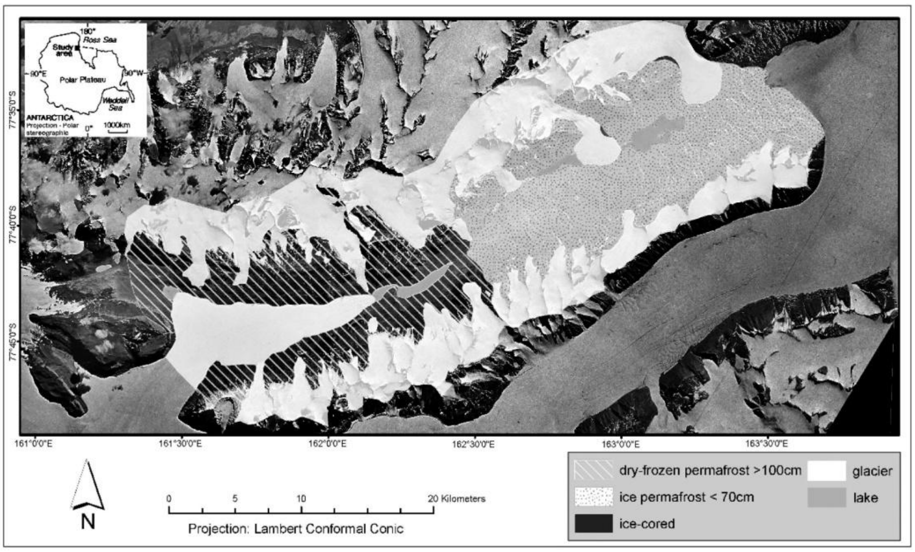

FIGURE 2. Preliminary permafrost map of Taylor Valley. Place names referred to in the text are given in the caption of Figure 1.

Many issues regarding the bulky alpine glacier drift sheets in central Taylor Valley remain unresolved. These include the extent and number of Alpine III and IV drifts as well as their stratigraphic relations with Taylor Glacier drifts. Wilch et al. (1993) suggested that, in the Pliocene, alpine glaciers were, for the most part, no more extensive than they are today. However, we see at least two generations of bulky drift sheets that are modestly extensive.

The bulky moraine loops appear to be crosscut by Taylor Glacier drifts. This implies that the alpine glaciers were significantly expanded relative to their present positions at times in the Pliocene and that these expansions were out-of-phase with Taylor Glacier advances. According to Higgins et al. (2000b), alpine glaciers in central Taylor Valley fluctuated in-phase with Taylor Glacier during the TII and TI advances. We think that the lateral boulder-belt moraines of Hughes, Lacroix, and Suess

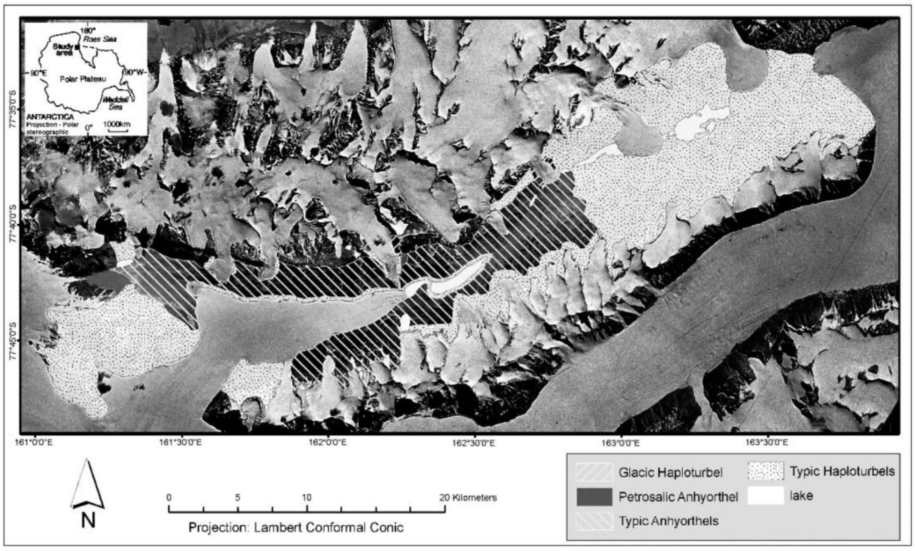

FIGURE 3. Preliminary soils map of Taylor Valley. Place names referred to in the text are given in the caption of Figure 1.

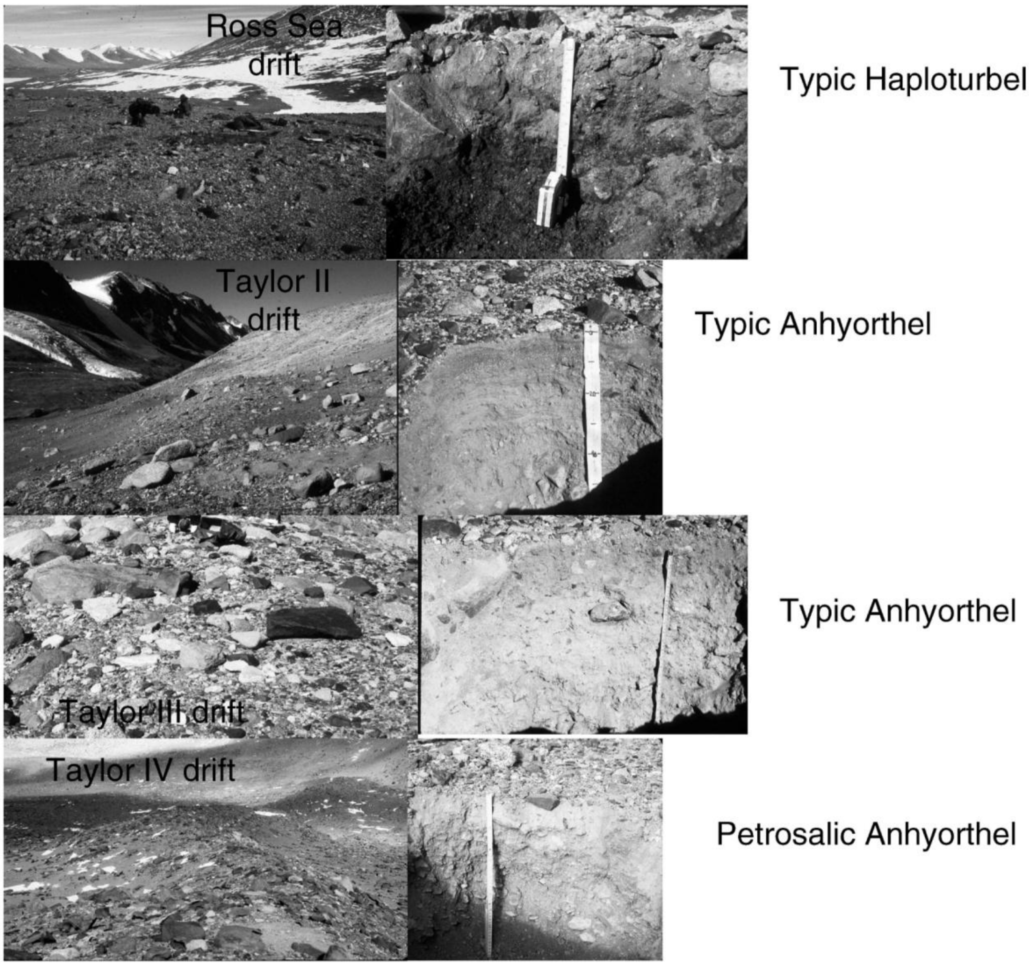

FIGURE 4. Landforms and soils on key drifts in Taylor Valley, including (A) a Typic Haploturbel on Ross Sea drift in eastern Taylor Valley, (B) a Typic Anhyorthel on Taylor II drift between the Sollas and Hughes Glaciers, (C) a Typic Anhyorthel on Taylor III drift below the Hughes Glacier, and (D) a Petrosalic Anhyorthel on Taylor IVa drift in Pearse Valley.

Glaciers crosscut Bonney drift. Higgins et al. (2000b) proposed that the alpine glacier moraines merged with TII lateral moraines in central Taylor Valley.

SOIL PROPERTIES IN RELATION TO DRIFT AGE IN TAYLOR VALLEY

Soil properties in Taylor Valley are strongly related to drift age. For example, the depths of staining (primarily oxidation of iron-bearing minerals), coherence (consolidation from salts, iron oxides, or other soil constituents), visible salts, and ghosts (pseudomorphs of weathered rocks) and depth to ice-cemented permafrost increase with age (Table 1). Similarly, the salt and weathering stages and quantity of salts in the upper 70 cm of soil profile increase with drift age. Salt and weathering stages can readily be used to differentiate soils according to relative age. Surfaces from the Holocene and last glacial maximum lack staining, have minimal salts in the profile, and have salt and weathering stages of 1 (Table 2). Late Pleistocene soils are stained from 8 to 15 cm, contain visible salts from 6 to 18 cm, and have salt and weathering stages of 1.4–2.0 and 2.1–3.0, respectively. Early Pleistocene and Pliocene soils are deeply stained (≥33 cm) and have salt stages of 4.0–4.4 and weathering stages of 4.0–5.5.

Except on the mid-Holocene–aged Alpine I moraines, soil development is less in Taylor Valley than on roughly equivalent-aged surfaces in nearby Wright Valley (Table 2). These differences are primarily related to the threefold greater salt accumulation in soils of Wright Valley, which is important in weathering processes (Bockheim and McLeod, 2006). The greater amount of salts in Wright Valley is difficult to explain but may be due to a lower amount of precipitation (Doran et al., 2002) and lesser leaching than in soils of similar age in Taylor Valley. Moreover, Wright

TABLE 2

Comparison of soil development on approximately equivalent-aged drifts in Taylor Valley (TV) and Wright Valley (WV).[1]

	Staining[2] (cm)		Vis. salts (cm)		Salt stage[3]		Salt pan (cm)		Profile salts (mg/cm^2)		Weath. Stage[4]		Dominant soil taxa[5]	
Drift	TV	WV[2]	TV	WV	TV	WV	TV	WV	TV	WV	TV	WV	TV	WV
Alpine I	0	0	0	0	0.0	0.0	0	0	210	75	1.3	1.0	GHt-THt	GHt
Alpine II (T II)	8	15	6	18	1.4	2.0	0	0	1105	1700	2.1	3.0	THt-TAo	TAo
Alpine III (T IVa)	38	>43	33	48	3.4	4.4	6	17	2000	7100	4.2	5.5	TAo-SAo	PsAo
Alpine IV (T IVb)	33	>55	30	>63	4.0	5.6	4	22	1600	6100	4.0	5.8	TAo	PsAo
Peleus ("silty till")	19	24	16	17	2.8	4.3	1	8	1300	3900	3.8	4.5	TAo	TAt

[1] Data for Wright Valley from Bockheim and McLeod (2006).

[2] Staining refers to coatings on soil particles primarily of iron oxides.

[3] Salt stage was assigned using criteria by Bockheim (1990).

[4] The weathering stage was assigned using criteria by Campbell and Claridge (1975).

[5] Soil taxa: GHt = Glacic Haploturbel; THt = Typic Haploturbel, TAt = Typic Anhyturbel, TAo = Typic Anhyorthel, SAo = Salic Anhyorthel, PsAo = Petrosalic Anhyorthel.

Valley is broader than Taylor Valley in its upper reaches and more directly receives katabatic winds from the polar plateau, resulting in more arid conditions.

PERMAFROST DISTRIBUTION IN TAYLOR VALLEY

Unlike the upper Taylor Glacier region (Beacon Valley), ground ice is of limited extent in Taylor Valley and is restricted to ice-cored Alpine I drift of Holocene age.

Ice-cemented permafrost is dominant in Taylor Valley, particularly in the eastern half of the valley and adjacent to alpine glaciers. Dry-frozen permafrost results from sublimation of interstitial ice over time (Bockheim and Tarnocai, 1998; Bockheim and McLeod, 2006) and is manifested by the presence of fossil sand wedges (Bockheim, 2002). The maximum depth of dry-frozen permafrost in central and upper Taylor Valley is uncertain.

Conclusions

We draw several conclusions from our compilation of the surficial geology and soil development in lower and central Taylor Valley. The first is that at least one of the bulky alpine drifts in Taylor Valley is probably early Pleistocene to late Pliocene in age. Soils developed on this drift make it pre–late Pleistocene while incorporated volcanic clasts indicate that it is younger than 2.5 My BP. Soil development is comparable to that on Alpine III drift in central Wright Valley (Bockheim and McLeod, 2006) for which only a maximum date, 3.5 My BP, currently exists (Hall et al., 1993). If correct, this indicates that part of the Alpine III drift in Wright Valley, suggested by Prentice and Krusic (2005) as being multiple, dates to the late Pliocene.

Another conclusion is that the morphology of the Taylor Alpine III/IV drift sheets, symmetrical in plan view, implies that these advances were largely out-of-phase with advances of Taylor Glacier. This contradicts the prevailing view of in-phase fluctuations (Denton et al., 1993). Assuming both alpine and axial glacier systems are significantly influenced by regional climate change, an out-of-phase behavior implies that regional climate change has a spatial gradient and a causal influence. One possibility is that, in the Pliocene, Taylor Glacier was moderately restricted by the presence of Taylor Fjord, whereas the fjord may have enhanced alpine glacier advances.

The soils of Taylor Valley follow the evolutionary sequence observed in Wright Valley immediately to the north (Bockheim and McLeod, 2006). Holocene-aged surfaces contain Glacic Haploturbels; surfaces of late Quaternary age contain Typic Haploturbels; surfaces of late to mid-Quaternary age contain Typic Anhyorthels; surfaces of early Quaternary to late Pliocene age contain Salic Anhyorthels; and surfaces of mid- to early Pliocene age contain Petrosalic Anhyorthels. In Taylor Valley, ice-cemented permafrost is common within 28 km west of the coast and in Alpine II moraines; most of the remaining area to the upper Taylor Glacier contains dry-frozen permafrost. Ground ice is restricted to Holocene-aged Alpine I moraines.

The maps contained herein will be of use in understanding biodiversity and predicting the impacts of human activities on soils in Taylor Valley.

Acknowledgments

Funding from the OPP-NSF is gratefully acknowledged. We appreciate the opportunity to have worked with G. H. Denton over the years. D. Muhs offered many suggestions for improving the manuscript.

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Ms accepted June 2007

13 APPENDIX VI

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Geoderma 144 (2008) 43 – 49

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Soil distribution in the McMurdo Dry Valleys, Antarctica

J.G. Bockheim [a,*], M. McLeod [b]

[a] *Department of Soil Science, 1525 Observatory Drive, University of Wisconsin, Madison, Wisconsin 53706-1299, USA*
[b] *Landcare Research, Private Bag 3127, Hamilton, New Zealand*

Abstract

The McMurdo Dry Valleys (MDVs) are the largest ice-free area (ca. 6692 km^2) 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.

Keywords: Gelisols; Polar soils; Soil maps; Soil classification; Soil development

1. Introduction

At 6692 km^2 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, 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^2), which includes Minna Bluff and the Brown Peninsula; the Denton Hills (753 km^2), which comprise the eastern foothills of the Royal Society Range; and the Convoy Range (661 km^2), which includes the Convoy Range, the Coombs Hills, 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^2), which includes Barwick,

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* Corresponding author.
E-mail address: bockheim@facstaff.wisc.edu (J.G. Bockheim).

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doi:10.1016/j.geoderma.2007.10.015

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

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^{-1} (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 soil-moisture 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 (~ 11 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

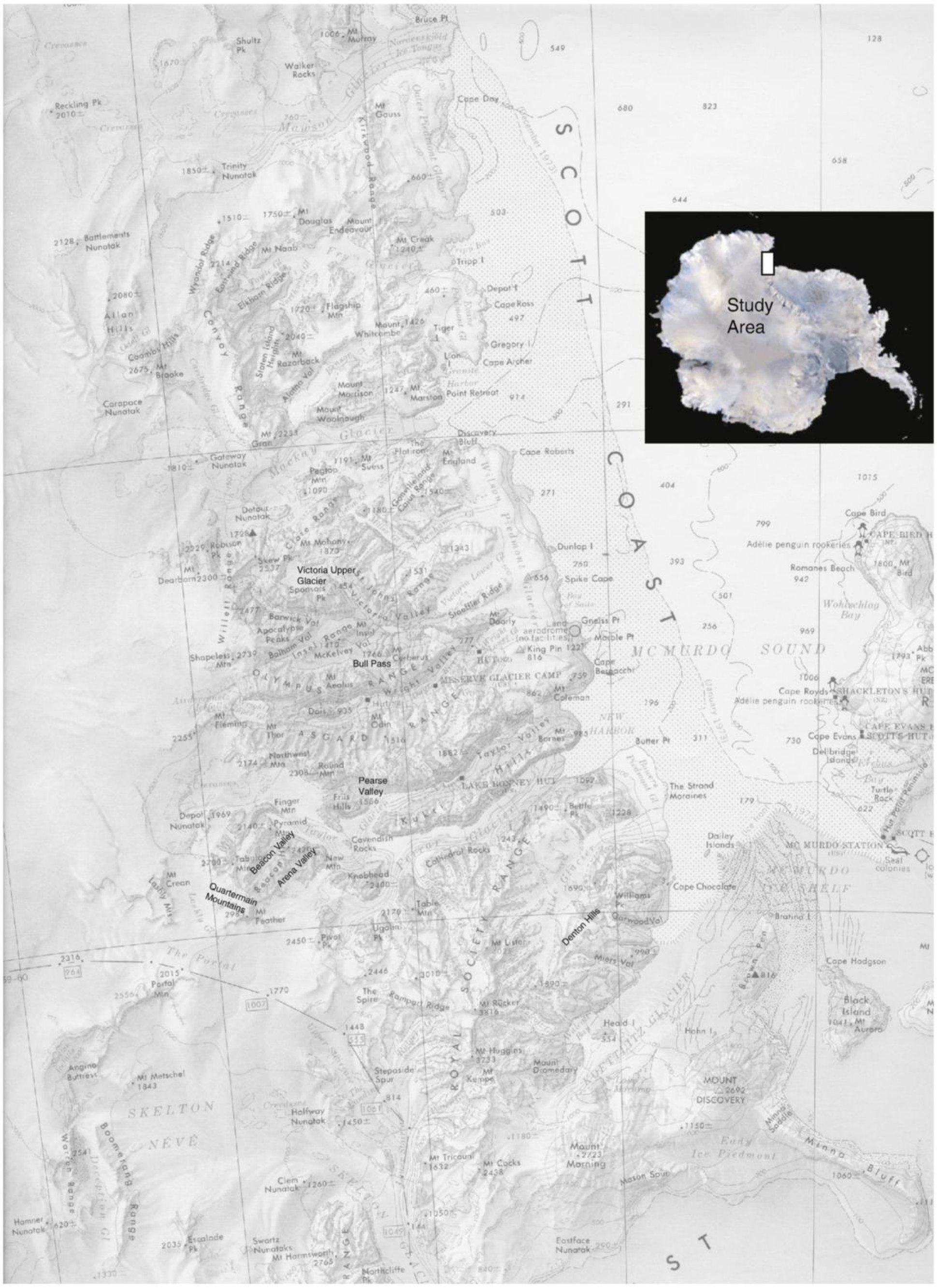

Fig. 1. The McMurdo Dry Valley region with place names (base map United States Geological Survey, 1:1 million topographic map of McMurdo Sound area).

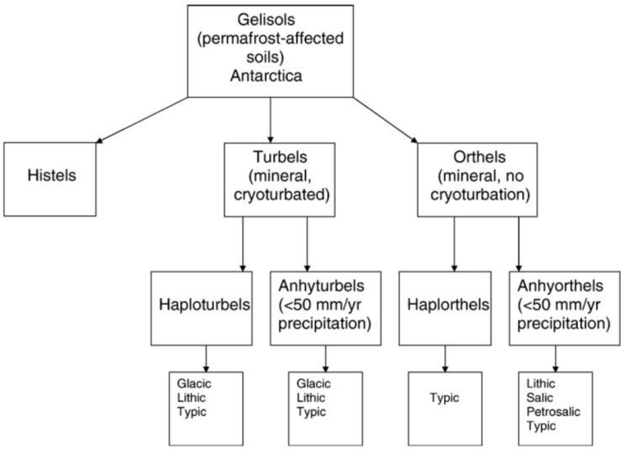

Fig. 2. Key for classifying Gelisols in the McMurdo Dry Valleys.

ice-free areas on nunataks in the region. To our knowledge, salt-enriched 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 million-scale soil map of the MDVs.

4.6. Wright Valley

In Wright Valley Glacic Haploturbels (~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 (~3%) occur on Onyx and Wright drifts of likely early Quaternary age; and Petrosalic Anhyorthels (~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

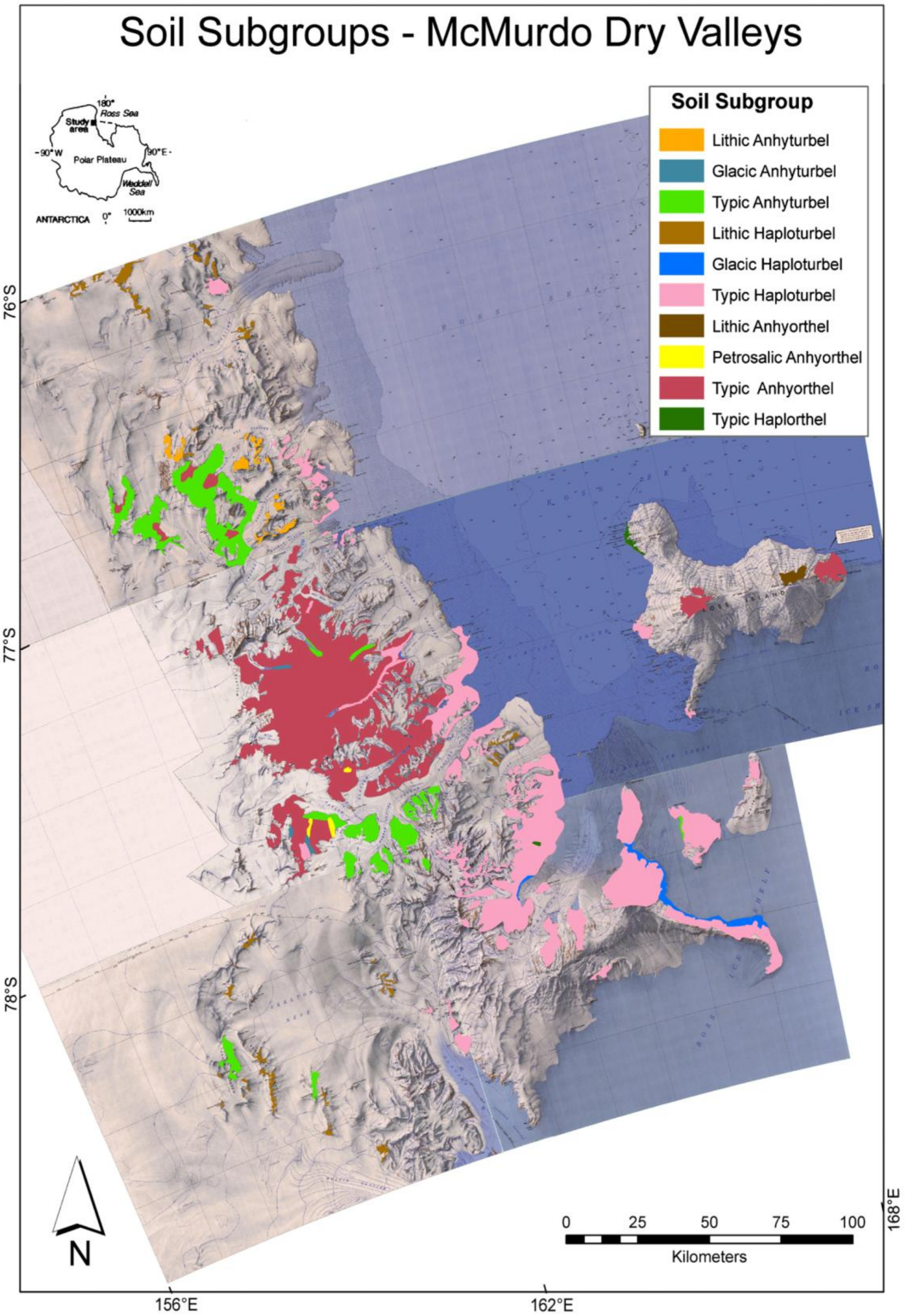

Fig. 3. Reconnaissance soil map (1:2 million scale) of the McMurdo Dry Valleys (base maps 1:250,000 topographic maps from U.S. Geological Survey).

Table 1
Distribution of soil subgroups in the McMurdo Dry Valleys

Location	Total	No. of soil pits	GAt	GHt	LAo	Lat	Area (km^2) LHt	Ps/PnAo	TAt	TAo	THo	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 (~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 Quaternary 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.

Acknowledgments

This research was partially supported by a grant from the National Science Foundation, OPP-0425692 (JGB) and the New Zealand Ministry of Research, Science and Technology capability fund (MM).

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