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

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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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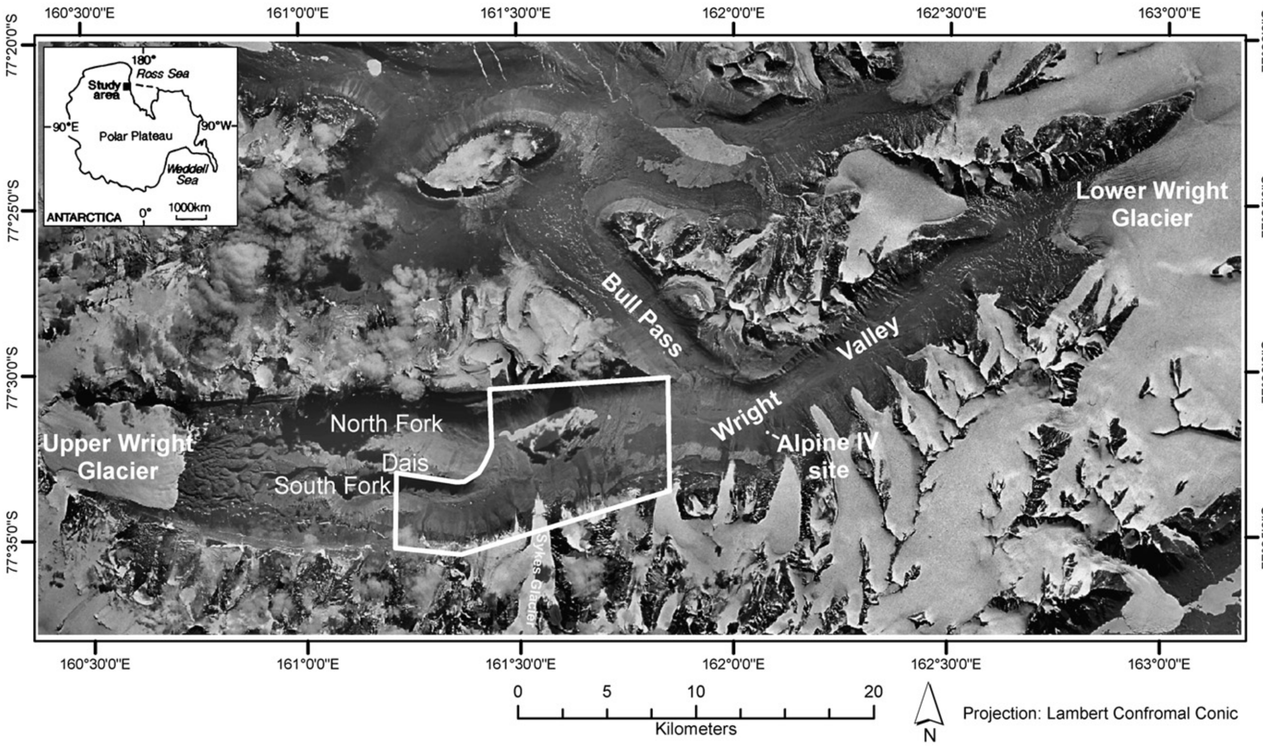

Fig. 1. Location diagram of study site and Alpine IV soil sample location to the east of the study site.

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

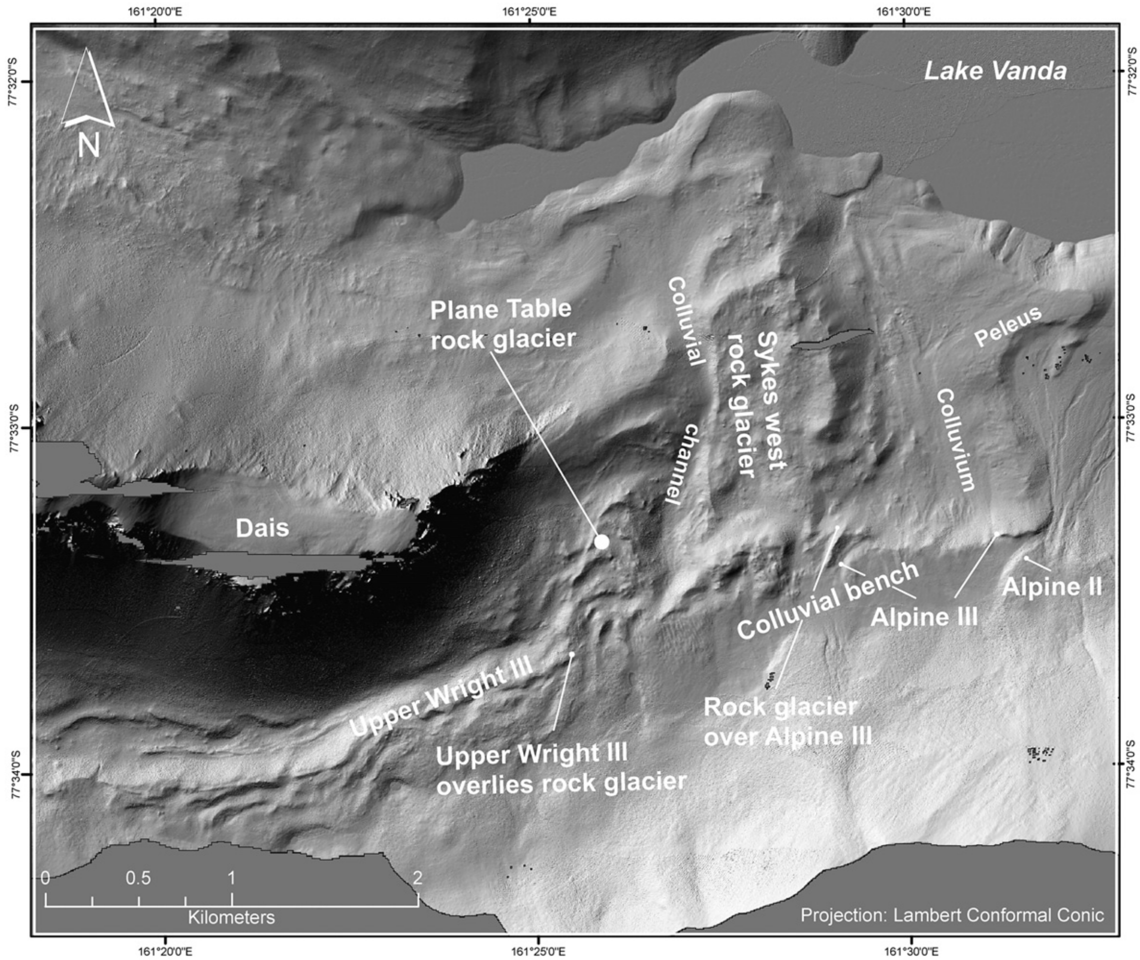

Fig. 2. LIDAR hillshade showing salient geomorphic features within the study site.

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.

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.

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.

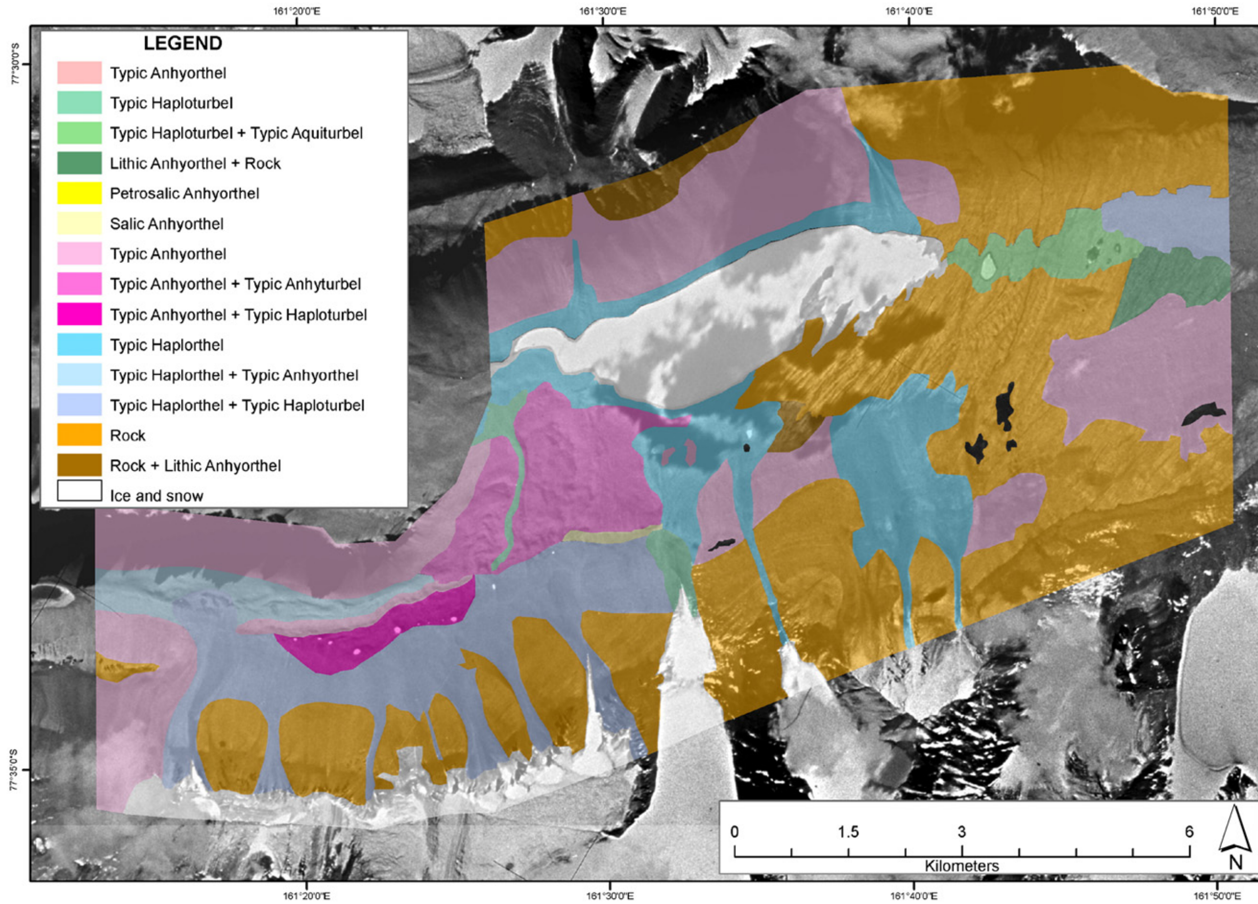

Fig. 3. Spatial distribution of USDA Soil Taxonomy Subgroups within the study site.

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

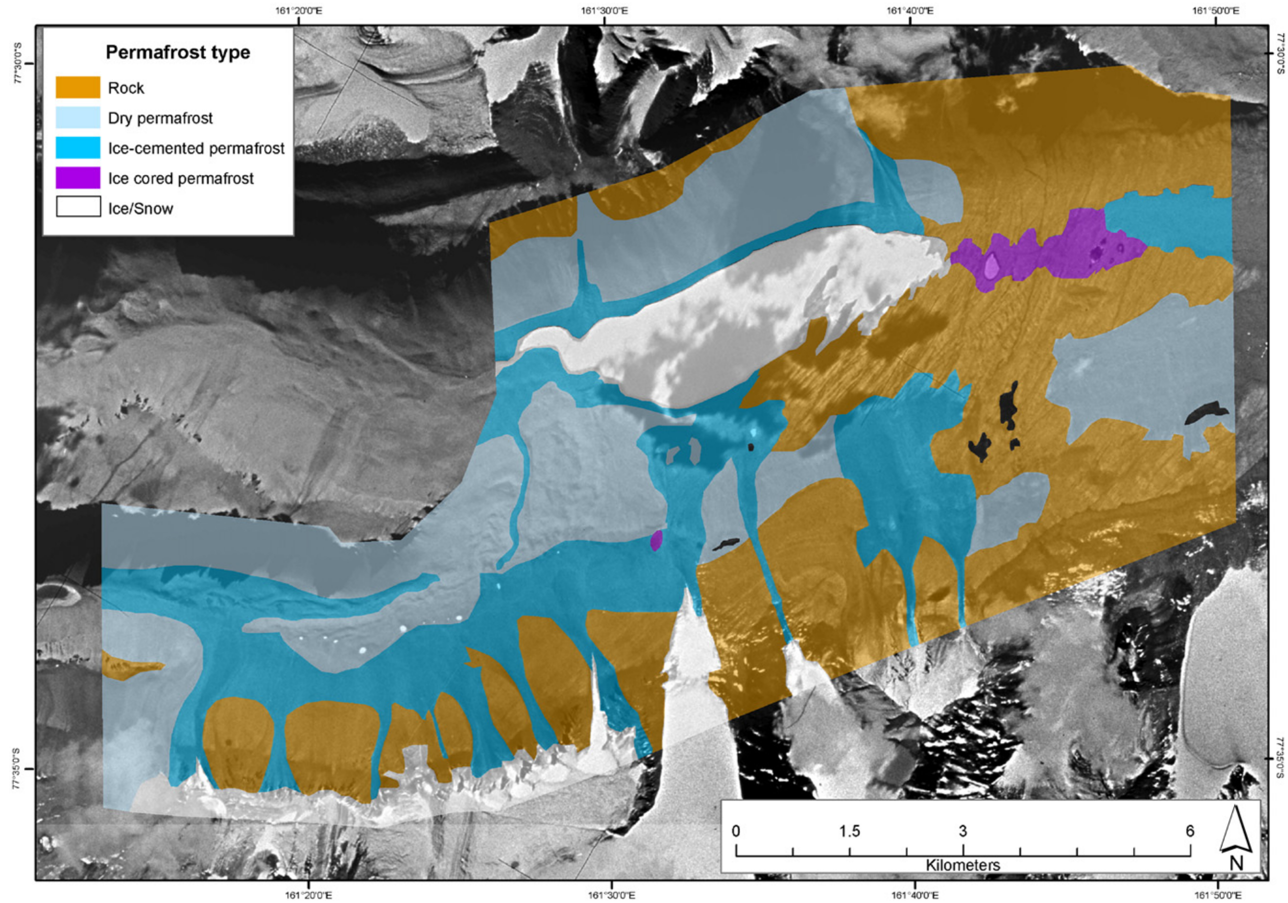

Fig. 4. Spatial distribution of permafrost types within the study site.

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.

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