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Metal contamination of soils at Scott Base, Antarctica

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Abstract

Soil samples taken from excavated pits on traverses across New Zealand's Scott Base, Antarctica, were leached with water and 0.01 M HNO_3 and the leachates analysed for Ag, Al, As, Cd, Cr, Cu, Fe, Mn, Ni, Pb and Zn. The soils had high conductivity and pH values generally increasing with depth and in the range 8.3–10.1. The water leachate generally contained most of the extractable metals except Mn and Cd, and As. Linear relationships were observed between some metals leached into alkaline solution and the Fe in those solutions. The ratios to Fe were comparable to those of the host basanite, and this observation is interpreted as showing that these metals are incorporated in fine mineral particulates derived directly from the rock mass. Outliers in leachable metal concentrations in the soils indicated appreciable contamination of the soil from anthropogenic sources with Ag, Cd, Cu, Pb and Zn as well as As. In some locations high concentrations of Ag and Cd correspond to specific sources and drainage channels. High concentrations of Pb were widely spread and in the top soil layers whereas the elevated concentrations of Zn were distributed throughout the soil profiles indicating atmospheric sources and different mobilities within the soils. Transport within the soils is evident for some metals, as is lateral movement over and through the soils. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Two permanent bases are located on the Hut Point Peninsula, Ross Island, Antarctica, within 2 km of each other with New Zealand's Scott Base accommodating between 10 and 100 people in winter and summer respectively, while the USAs McMurdo Station has up to 1200 people in residence. Both stations serve as research bases and staging posts for expeditions further afield. Activity is thus intense particularly in summer, with continuous construction, vehicular traffic and earth moving operations.

Construction at Scott Base commenced in 1957 and since then the local environment has been significantly altered by 40 a of human activity. This has resulted in considerable reduction of snow, moss and lichen cover, and moving of soils during construction activities, with resulting soil slumping and permafrost melting (Campbell and Claridge, 1987). The soils have been subjected to spillages and the dumping of wastes such as laboratory chemicals, oils and fuels, timber and other refuse.

For the purposes of this paper the terms "heavy metals" and "metals" will include As, as it is commonly treated in environmental contamination literature as one of the suite of elements referred to as the "heavy metals".

A study of the heavy metal contents of surface waters in the Ross Dependency of Antarctica showed elevated levels of most heavy metals in melt-waters

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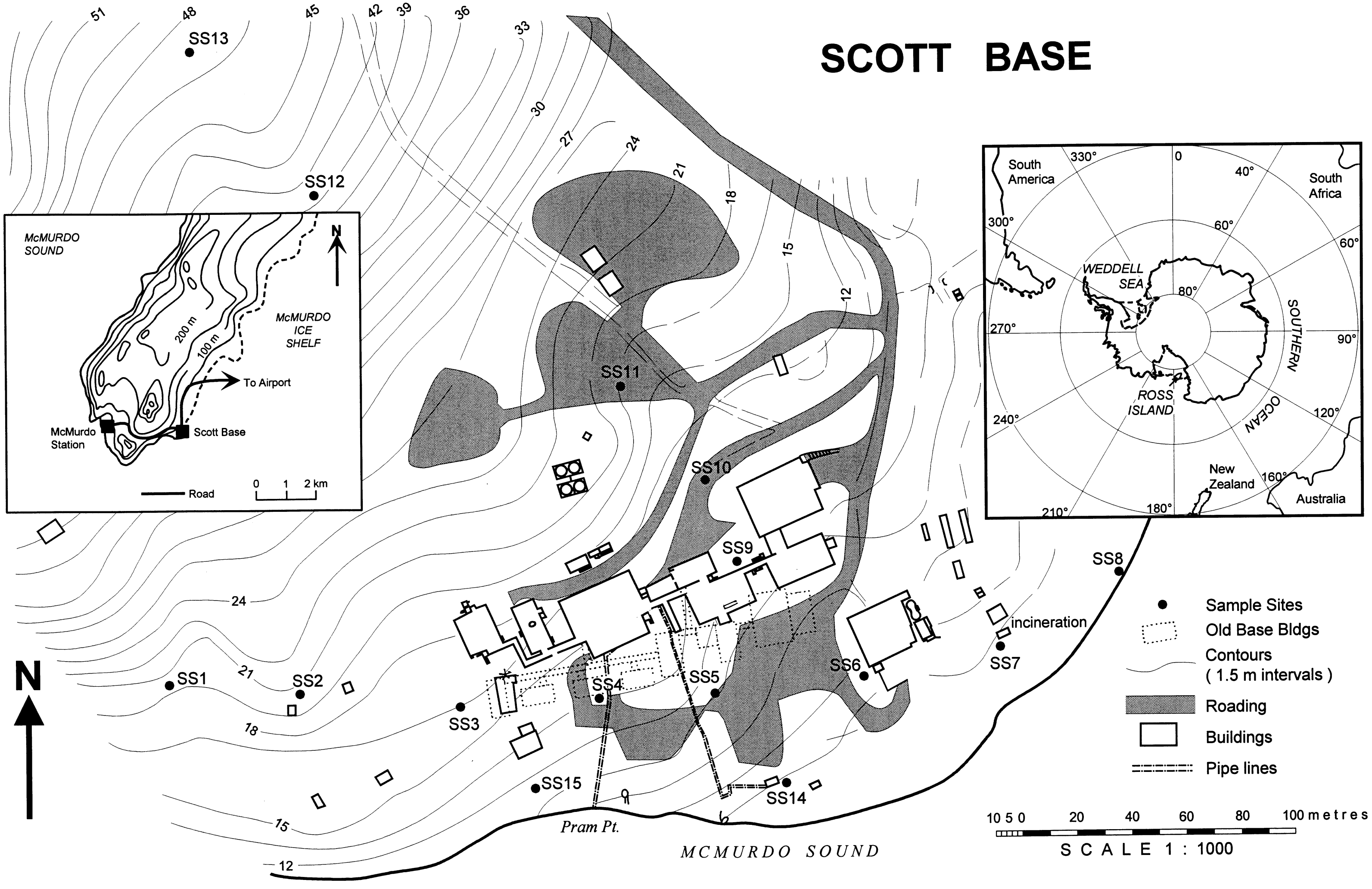

Fig. 1. Location of Scott Base in Antarctica and sampling sites (●) in relation to the base buildings.

from the Hut Point Peninsula (Sheppard et al., 1997). The presence of salt efflorescence on the soil surfaces (particularly recently disturbed soils) attests to the mobility of soluble components in and over the active layer of the soils. The location of the metal contaminants within the soils and the mobilities of these contaminants have been investigated in order to better understand the processes which control the mobility and location of heavy metals and As in the Antarctic environment. The study was restricted to the easily mobile fraction of the total metals.

1.1. Environmental setting

Pram Point, the site of Scott Base (Fig. 1), is formed from scoriaceous flows of basalts of the McMurdo Volcanics Formation (Kyle, 1990), which have been considerably fractured by freeze–thaw processes. The surface has been modified by ice which filled McMurdo Sound to 300 m or more during periods of low sea level, the last of these occurring during the late Pleistocene.

At Scott Base the dominant surface winds are from the north-east (Bromley, 1994), although at higher altitudes the wind flow is predominantly from the south as are the stronger surface winds. The anomalous direction of the Scott Base wind is caused by local topography that diverts air from the south (T. Clarkson, personal communication, 1995).

A small number of soil and marine sediment contamination studies have been carried out on the Hut Point Peninsula. Greenpeace (Inc.) sponsored a study in 1987 and 1988 which extracted 5 soil samples with strong acid and analysed the extracts for heavy metals (Johnston and Stringer, 1988). They found "extreme" contamination with Pb and Ag in single samples, as well as some evidence of elevated Cd, Cu and Zn. The sampling methods used in the study are not clear (whether, for instance, they were surface scrapings or deeper samples) and only the most obviously contaminated sites appear to have been selected for the study.

Soils from Marble Point (on the opposite side of McMurdo Sound from Ross Island, and the site of extensive earthworks and occupation in the late 1950s), and from a single core taken from Scott Base, were analysed for Cu, Pb and Zn using sequential extraction techniques (Amin, 1993; Claridge et al., 1995). Obviously contaminated soils and a remote control site were sampled and a drilled core was used. No control sampling was carried out for Scott Base, so contamination from the sampling procedure could not be assessed. The findings for the Scott Base sample were of higher levels of Cu, Pb and Zn in the top 8 cm, with an inference that fluctuations in the moisture levels of the subsurface soil above the permafrost causes retention of these metals in the top of the soil profile. The speciation of the metals inferred from the sequential extractions were concluded to be:

Zn:
Oxide > Carbonate > Organic matter > Exchangeable
Pb:
Organic matter > Oxide > Carbonate > Exchangeable
Cu:
Organic matter > Carbonate > Exchangeable ≈ Oxide

However, the limitations of the assignment of these associations on the basis of sequential extractions (Kheboian and Bauer, 1987; Nirel and Morel, 1990) require that considerable caution must be used in accepting the speciation patterns, especially in soils that have very different chemical properties (e.g., high pH and low organic content) and physical environments to the materials for which the extraction system was designed.

Lenihan et al. (1990) and Kennicutt et al. (1995) have shown enrichment of Ag, As, Cd, Cu, Hg, Pb, Sb, Sn and Zn in marine sediments in an area offshore from McMurdo Station that receives surface drainage, air-fall precipitation and sewerage from the station. Nickel and Cr concentrations in the sediments were not higher than is normal for basaltic debris. The techniques used involved either total digestion of samples, or very strong acid leaching in hot HNO_3 prior to analysis. With such aggressive techniques it is difficult to distinguish between mobile or easily leachable fractions and that bound in native mineral grains, to the extent that only gross contamination is likely to be detected and more subtle signals overlooked.

The presence of elevated concentrations of metals in surface meltwaters in the vicinity of Scott Base (Sheppard et al., 1997), together with the presence of salt efflorescence on the soil surfaces (particularly where the soil had been disturbed recently) attests to the mobility of soluble salts in and over the active layer of the soils. The location of the metal contaminants within the soils in the vicinity of Scott Base and the mobilities of these contaminants is the subject of this report so the easily mobilised fraction of the total metals was investigated.

2. Methodology

2.1. Sampling

Seventy two soil samples were collected from the sides of 15 shallow pits excavated approximately 50 m apart along two traverses across the Scott Base site (Fig. 1). Sites were selected as near as possible to predetermined points (making allowance for buildings, cables, busy roads and the like) in order to minimise any bias. The pits were excavated with steel shovels

Table 1
Soil sample depths, descriptions, fine fraction, moisture and C content, pH and conductivity of water extracts of the soils

Sample pit	Layer	Depth (cm)	< 2 mm (%)	Excess moisture (%)	Moisture (%)	Carbon total (g/kg)	pH	Conductivity (μS/cm)	Comments
SS1	A	0–2	39.4		0.8	7.0	9.0	7360	
	B	2–5	33.4		1.4	3.7	9.1	4090	
	C	5–15	54.4		3.0	2.0	9.6	1320	
	D	15–25	80.4		3.4	1.0	9.8	780	
	E	25–40	70.5		5.0	< 0.1	10.1	570	
SS2	A	0–2	65.1		7.2	0.8	8.6	110	
	B	2–5	67.3		7.3	1.5	8.9	50	
	C	5–12	78.3		3.9	0.2	8.9	50	
SS3	A	0–2	84.9		7.5	0.8	9.5	220	Wood fragments
	B	2–5	75.8		8.9	1.8	9.4	100	
	C	5–10	65.1		9.4	1.2	9.4	90	
	D	10–20	76.7	7.1	3.4	2.7	9.2	140	
SS4	A	0–2	72.6		1.4	2.1	8.7	1840	Wood fragments
	B	2–5	51.5		2.8	0.9	9.2	510	Wood fragments
	C	5–15	48.0		4.8	2.1	9.4	290	Wood fragments
	D	15–25	65.6		6.3	1.7	9.6	260	Wood fragments
	E	25–40	76.0		8.4	2.1	9.4	230	
SS5	A	0–2	39.0		1.3	6.0	8.6	2440	Wood fragments
	B	2–5	43.6		2.6	7.2	8.8	1240	Wood fragments, Dieseil/oil smell
	C	5–15	59.3		4.5	4.3	9.2	500	Wood fragments, Slight Diesel smell
	D	15–25	49.2		6.1	1.0	9.7	480	Trace of diesel, plastic fragments
	E	25–35	50.3		4.3	0.4	9.6	490	Trace of diesel, plastic fragments
	F	35–47	60.5		4.7	0.1	9.6	680	Trace of diesel, plastic fragments
SS6	A	0–2	94.9		2.9	6.5	9.4	700	Steel nail, wood fragments, misc. debris
	B	2–5	49.3		7.8	4.3	9.6	480	Wood fragments, Slight Diesel smell
	C	5–15	56.4		8.8	3.7	9.3	680	Jute or hessian fabric
	D	15–30	74.4		4.5	1.5	9.2	950	
SS7	A	0–2	54.8		1.2	2.4	8.4	3140	Wood fragments
	B	2–5	43.6		3.7	2.9	8.7	720	
	C	5–15	53.1		4.5	3.5	9.2	350	
	D	15–30	77.3		4.2	2.4	8.9	220	
SS8	A	0–2	52.9		2.9	2.2	8.9	430	Steel nail
	B	2–5	53.8		4.8	1.8	9.4	170	
	C	5–15	64.7		6.0	1.8	9.5	130	
	D	15–30	74.8	0.1	6.4	1.5	9.5	110	
SS9	A	0–2	59.7		4.6	3.0	8.3	11900	Steel nail, Diesel odour
	B	2–5	59.8		5.6	3.9	9.1	1760	Strong fuel smell
	C	5–15	59.9		5.0	4.9	8.9	1250	Strong fuel smell
	D	15–25	70.9		6.4	3.3	8.9	1240	Strong fuel smell, rubber (?) strips
	E	25–35	61.9	6.0	1.4	1.8	8.8	1820	Strong fuel smell
	F	35–46	66.8	14.8	3.9	2.5	8.4	3550	Strong fuel smell
SS10	A	0–2	37.5		4.3	0.6	9.0	960	
	B	2–5	53.4		4.9	1.3	9.5	260	
	C	5–10	47.9		5.3	3.1	9.4	170	
	D	10–20	67.5		5.4	0.7	9.5	190	
	E	20–30	61.6		5.1	0.5	9.7	210	
	F	30–40	66.2		6.5	0.5	9.7	190	
SS11	A	0–2	66.4	3.2	8.3	1.6	8.8	1320	
	B	2–5	54.6	3.7	7.3	0.8	9.4	280	
	C	5–10	53.3	3.7	7.2	0.9	9.4	200	
	D	10–20	73.1		9.9	1.0	9.4	200	
	E	20–30	50.5	9.1	0.8	0.5	9.4	310	

Table 1 (*continued*)

Sample pit	Layer	Depth (cm)	< 2 mm (%)	Excess moisture (%)	Moisture (%)	Carbon total (g/kg)	pH	Conductivity (μS/cm)	Comments
SS12	A	0–2	46.6		1.1	3.2	9.7	870	
	B	2–5	39.4		2.2	3.1	9.2	1670	
	C	5–15	53.1		2.9	1.1	9.4	230	
	D	15–25	36.1		3.1	1.1	9.2	80	
	E	25–35	56.8		3.5	1.7	9.2	50	
	F	35–45	60.2		2.7	1.1	9.2	50	
SS13	A	0–2	40.8		1.6	4.2	8.7	1470	
	B	2–5	25.6		4.9	2.2	9.5	110	
	C	5–10	38.3		6.6	1.5	9.3	90	
	D	10–20	35.7		5.6	3.9	9.3	70	
	E	20–30	39.7		5.2	1.1	9.3	60	
SS14	A	0–2	52.7		3.6	6.1	9.1	6080	Wood fragments, diesel odour
	B	2–5	51.9		5.5	5.1	9.7	570	Strong diesel odour
	C	5–15	55.7		5.1	4.4	9.7	550	Strong diesel odour
	D	15–25	83.2		5.8	3.8	9.7	670	Strong diesel/petrol odour
SS15	A	0–2	57.4		6.0	1.7	8.8	1130	
	B	2–5	78.5		6.5	1.5	9.4	190	Wood fragments
	C	5–15	64.3	4.5	2.3	2.6	9.4	160	
	D	15–25	54.7	4.5	4.2	1.3	9.4	140	
	E	25–33	66.5	6.2	0.9	3.7	9.2	150	

and crowbars down to frozen ground, beyond which further excavation was extremely difficult. Detailed descriptions were made of the soils in the profiles in pits and these are available upon request from the authors. In the undisturbed sites no horizon development or other pedological differentiation was observed in these unweathered soils. Below the stony pavement the soil is loose and generally contains 20–50% of fine earth (<2 mm).

The samples from sites SS1 and SS13 were selected as baseline sites since they were located outside the area of obviously disturbed soils and outside the area of base buildings. A subsequent inspection indicated that the surface soil may have been partially removed from site SS1 soon after Scott Base was established in 1957.

The sampling of the soils was carried out with plastic tools only. Soil material was scraped from around larger stones directly into polythene pots using polystyrene or polythene scoops. This necessarily resulted in the erosion of these tools and entrainment of scraps of the plastic in the samples. Because of the extreme disturbances to most of the soil materials from cut and fill activities and the absence of identifiable pedologic horizons, the soils were sampled at constant depth intervals. These were generally 0–2 cm, 2–5 cm, 5–10 cm, and 10 cm intervals further down.

Once samples were collected, the pots were sealed with wadded plastic caps, labelled and stored for shipment back to New Zealand. In the laboratory, subsamples were sieved to less than 2 mm using plastic (PVC/nylon) sieves, then air dried. Some very wet samples were allowed to air dry so that the subsampling could proceed without loss of salts in a separate water phase. The weight loss over the period of air drying is used to calculate the excess moisture (Table 1). No metal implements were used in processing and precautions were taken to minimise contamination from airborne dust. All analytical results reported, except for size fraction and excess moisture content, apply to the air-dried <2 mm fraction and not the soil as a whole.

2.2. Analytical methods

Moisture contents were measured by drying a subsample at 130°C and determining the weight loss. The soil pH was measured using a glass electrode on a 1:5 mixture of soil to deionized water after shaking for 10 min (Blakemore et al., 1987). The solution conductivity was measured on the same supernatant solution. Carbon contents were measured by digestion of a finely ground portion of dry material with chromic acid ($Na_2Cr_2O_7$ in H_2SO_4) and measuring the reduction of Cr(VI) to Cr(III) colorimetrically, using sucrose as a standard (Metson, 1956). This method determines total reducible species, which are usually dominated by C in soils.

The planned sequence for the extraction of the "soluble" or mobile metals was to extract sieved samples

Table 2

Water and acid leachable metal contents of soils. The acid leachate was cold 0.01 M HNO_3. Al, Cr, Fe and Mn were extracted sequentially (i.e., the same soil sample was used for both extracts); the remainder were extracted separately

Sample	Layer	Ag µg/kg water	Ag µg/kg acid	Al mg/kg water	Al mg/kg acid	As µg/kg water	As µg/kg acid	Cd µg/kg water	Cd µg/kg acid	Cr µg/kg water	Cr µg/kg acid	Cu µg/kg water	Cu µg/kg acid	Fe mg/kg water	Fe mg/kg acid	Mn mg/kg water	Mn mg/kg acid	Ni µg/kg water	Ni µg/kg acid	Pb µg/kg water	Pb µg/kg acid	Zn µg/kg water	Zn µg/kg acid
SS1	A	0.25	0.50	0.15	1.3	50	68	1.1	23	3.9	0.0073	64	17.5	< 0.025	1.35	< 0.01	0.18	25	98	7.5	0.5	313	20
	B	0.13	< 0.25	3.3	2.5	38	60	1.1	0.50	8.0	0.0073	28	15.0	3.8	3.0	0.063	0.45	16	47.5	14	< 0.3	438	7.5
	C	3.0	< 0.25	125	65	24	33	2.8	0.25	94	0.060	300	12.5	150	70	2.4	1.8	123	37.5	41	1.0	1038	20
	D	4.8	< 0.25	188	20	21	22	3.4	0.25	150	0.016	338	10.0	213	17	3.4	1.1	188	37.5	73	0.5	1250	15
	E	2.8	< 0.25	138	6.5	14	20	2.2	0.50	103	0.0058	288	12.5	163	1.1	2.5	1.5	150	42.5	39	0.3	1075	13
SS2	A	1.5	< 0.25	48	48	11	28	1.6	1.8	34	0.0030	213	70	57	0.275	1.2	10.0	50	120	55	1.0	638	138
	B	1.5	< 0.25	43	63	7.9	23	2.3	1.8	33	0.0040	150	30	52	0.48	1.3	10.3	54	143	31	0.5	575	123
	C	1.0	< 0.25	31	150	5.6	12	1.6	3.0	23	0.0053	138	38	38	0.73	0.93	13.5	45	133	24	3.5	513	163
SS3	A	34	0.75	49	21	15	35	3.4	4.3	41	0.012	275	275	57	0.65	1.0	9.5	56	120	98	9.8	888	1050
	B	23	< 0.25	85	25	15	18	2.2	3.5	65	0.0088	263	53	100	1.48	1.7	7.5	104	150	79	3.5	1038	500
	C	16	< 0.25	238	21	24	40	4.7	1.0	175	0.017	338	28	288	20	4.4	3.3	288	118	63	< 0.3	1375	25
	D	60	< 0.25	275	30	39	30	5.9	1.3	213	0.018	450	35	325	30	4.6	2.8	288	90	105	< 0.3	1625	28
SS4	A	3.9	0.50	2.6	13	29	40	2.3	6.0	6.5	0.019	104	60	2.8	12	0.29	7.0	20	120	60	1.8	388	228
	B	150	0.50	73	12	26	33	2.4	3.8	61	0.011	200	43	88	12	1.6	8.0	104	95	91	1.8	850	135
	C	388	1.00	109	7.5	34	58	14.5	4.0	105	0.023	263	83	125	7.5	2.6	9.8	150	63	175	8.0	1375	138
	D	69	< 0.25	363	38	55	65	7.3	2.3	300	0.055	525	45	463	48	8.7	1.5	438	25	150	1.8	2250	5.0
	E	388	0.75	213	7.3	31	58	6.7	0.20	213	0.043	350	65	263	5.3	5.3	12.8	263	53	138	1.8	1375	30
SS5	A	1.3	0.50	4.6	10	36	68	1.1	4.0	6.4	0.028	99	83	5.5	12	0.088	5.5	44	88	10	7.8	400	65
	B	8.3	0.25	37	3.5	38	63	2.0	2.0	34	0.013	138	73	47	3.8	0.69	0.55	59	45	51	6.3	738	33
	C	5.8	0.50	175	6.3	36	45	3.4	1.0	119	0.022	275	70	213	6.8	4.0	7.3	188	43	200	6.0	1163	25
	D	1.8	< 0.25	57	1.8	18	33	3.0	< 0.25	38	0.0085	175	18	70	1.9	1.2	1.0	58	2.5	34	< 0.3	675	5.0
	E	0.5	< 0.25	10	1.3	10	23	1.1	0.50	8.5	0.010	53	18	12	1.2	0.19	0.50	16	7.5	15	0.5	450	7.5
	F	0.4	0.25	13	11	10	25	1.8	0.25	11	0.0093	73	23	15	11	0.25	1.0	20	< 0.25	38	1.8	538	13
SS6	A	11	< 0.25	250	15	375	675	17	3.5	263	0.053	700	325	313	17	4.5	1.3	288	38	1163	45.0	3750	133
	B	11	< 0.25	125	12	213	450	10	7.0	150	0.15	325	170	163	13	2.2	1.9	150	48	638	148	4750	300
	C	8.6	< 0.25	238	30	78	78	9.3	7.5	200	0.043	375	53	300	35	4.6	5.3	288	63	488	8.3	2125	110
	D	5.0	< 0.25	188	16	43	55	5.8	0.75	150	0.030	250	18	238	19	3.8	1.5	225	10	79	1.0	1375	7.5
SS7	A	0.38	0.50	0.26	3.3	68	60	3.3	45	4.8	0.0045	213	220	< 0.025	2.5	0.18	7.8	75	275	24	12.3	975	3050
	B	3.3	< 0.25	61	2.8	74	173	6.0	13	55	0.0040	425	300	76	0.40	1.0	7.5	95	153	175	8.8	1125	2000
	C	1.5	< 0.25	21	12	50	50	3.0	15	19	0.0005	150	160	26	1.3	0.33	8.3	35	108	94	7.0	575	2000
	D	2.3	0.25	89	233	30	40	2.8	19	65	0.0068	163	650	109	13	1.6	5.3	103	105	56	11.8	800	2675
SS8	A	1.3	< 0.25	11	7.8	25	40	1.8	0.50	8.6	0.022	188	18	12	8.0	0.14	0.50	30	23	64	1.5	600	18
	B	1.8	< 0.25	84	0.5	26	45	2.7	0.25	56	0.0040	119	15	100	< 0.05	1.6	1.1	79	15	73	0.8	700	20
	C	3.0	< 0.25	150	0.3	30	45	3.2	0.50	103	< 0.00025	213	15	175	< 0.05	2.8	1.5	138	20	80	0.3	975	13
	D	1.6	< 0.25	82	3.3	21	25	4.2	1.3	60	0.0048	150	15	94	0.3	1.5	5.8	89	45	68	2.3	775	48
SS9	A	0.38	0.25	0.18	1.5	150	188	4.4	12	15	0.0025	84	88	< 0.025	1.2	1.0	5.0	101	155	13	0.8	425	143
	B	2.3	< 0.25	117	1.0	73	98	2.6	1.5	79	0.015	200	33	138	0.8	2.3	5.5	119	38	59	0.8	913	35
	C	2.4	< 0.25	138	2.0	53	70	8.0	1.0	78	0.0065	200	38	150	1.6	2.1	6.8	138	38	54	1.5	925	105
	D	1.9	< 0.25	104	0.8	50	80	3.3	1.5	70	< 0.00025	188	40	117	0.5	1.8	8.3	96	48	56	1.8	850	55
	E	0.75	< 0.25	19	1.5	41	60	0.51	2.5	16	0.0005	80	60	22	1.2	0.64	7.8	33	75	16	< 0.3	375	143
	F	0.38	< 0.25	1.0	1.3	45	108	0.73	6.3	6.3	0.0018	54	75	1.0	0.8	1.0	10.5	40	95	15	0.3	300	90
SS10	A	0.88	< 0.25	37	0.5	15	35	2.1	< 0.25	29	< 0.00025	64	20	41	0.2	0.65	1.1	44	20	23	< 0.3	513	18
	B	1.5	< 0.25	76	3.0	15	33	2.0	< 0.25	51	< 0.00025	138	15	86	1.2	1.4	1.6	68	20	31	0.8	613	2.5
	C	0.50	< 0.25	19	7.5	31	45	1.0	< 0.25	14	< 0.0083	43	13	21	2.5	0.35	1.9	19	33	21	0.3	350	10
	D	0.50	< 0.25	27	11	76	153	2.3	< 0.25	19	0.0018	61	15	28	7.0	0.49	1.7	21	25	35	1.5	2375	0.5
	E	0.38	< 0.25	20	8.8	33	38	0.29	< 0.25	15	0.016	53	15	21	7.3	0.35	1.7	16	20	13	< 0.3	325	7.5
	F	0.88	< 0.25	41	8.3	11	22	0.94	< 0.25	33	0.012	68	15	47	7.3	0.70	2.3	45	5.0	19	< 0.3	400	5.0
SS11	A	1.8	< 0.25	79	1.3	26	58	3.4	< 0.25	64	0.012	99	23	96	1.2	1.4	0.70	95	3	31	< 0.3	700	< 2.5
	B	7.1	< 0.25	338	0.8	45	48	4.9	< 0.25	275	0.012	388	15	425	0.5	6.5	1.0	375	< 0.25	86	< 0.3	1625	2.5
	C	4.5	< 0.25	163	0.3	31	45	62	< 0.25	150	0.0073	213	13	200	< 0.05	3.1	0.93	188	< 0.25	53	< 0.3	1025	< 2.5
	D	1.1	< 0.25	48	0.5	15	45	1.4	< 0.25	44	0.0050	73	18	57	0.2	0.93	0.80	55	< 0.25	16	< 0.3	463	7.5
	E	1.5	< 0.25	66	0.3	20	33	1.9	< 0.25	59	0.012	100	15	82	0.1	1.3	0.38	76	< 0.25	23	< 0.3	513	< 2.5
SS12	A	1.8	< 0.25	70	3.0	33	45	2.9	< 0.25	59	0.012	188	30	76	2.8	1.2	0.08	68	5.0	40	1.3	600	7.5

Table 2 (*continued*)

Sample	Layer	Ag µg/kg water	Ag µg/kg acid	Al mg/kg water	Al mg/kg acid	As µg/kg water	As µg/kg acid	Cd µg/kg water	Cd µg/kg acid	Cr µg/kg water	Cr µg/kg acid	Cu µg/kg water	Cu µg/kg acid	Fe mg/kg water	Fe mg/kg acid	Mn mg/kg water	Mn mg/kg acid	Ni µg/kg water	Ni µg/kg acid	Pb µg/kg water	Pb µg/kg acid	Zn µg/kg water	Zn µg/kg acid
	B	3.5	< 0.25	138	85	30	68	3.4	< 0.25	113	0.088	225	23	150	95	2.1	1.3	123	7.5	39	1.5	838	10
	C	4.3	< 0.25	225	8.5	23	22	3.9	< 0.25	175	0.014	250	7.5	238	7.5	3.4	0.50	188	13	49	< 0.3	1188	2.5
	D	3.4	< 0.25	163	3.5	15	13	2.1	0.50	118	0.0070	188	15	163	0.4	2.5	1.1	150	48	40	< 0.3	863	5.0
	E	2.6	< 0.25	109	11	11	12	3.1	0.50	76	0.0013	138	5.0	120	0.5	1.8	2.3	101	48	33	< 0.3	713	7.5
	F	1.9	< 0.25	80	13	10	7	1.8	1.3	55	0.0080	110	13	86	3.5	1.3	3.3	75	83	33	2.0	563	40
SS13	A	0.75	< 0.25	31	0.3	19	20	1.7	0.75	26	0.0015	96	23	32	0.2	0.46	1.2	36	43	30	2.5	425	15
	B	2.6	< 0.25	138	14	13	8	4.3	0.50	90	0.0008	150	7.5	138	0.1	2.1	3.5	125	48	375	< 0.3	1088	10
	C	3.5	< 0.25	175	5.8	18	10	3.2	0.25	110	< 0.00025	188	5.0	175	< 0.05	2.7	1.7	163	48	73	< 0.3	1100	7.5
	D	3.8	< 0.25	163	7.8	18	9	3.8	0.75	109	0.0015	175	5.0	175	0.3	2.6	2.1	163	60	54	1.3	988	15
	E	9.4	< 0.25	150	5.0	19	11	2.2	0.50	94	0.0018	188	7.5	163	< 0.05	2.5	2.0	138	48	41	0.5	925	15
SS14	A	0.50	5.5	1.3	8.0	213	950	2.3	2.8	15	0.012	325	1275	0.93	5.3	0.11	5.5	48	300	43	1400.0	475	8875
	B	0.63	< 0.25	32	2.8	60	68	4.1	0.38	30	0.0030	175	128	23	1.3	0.44	6.5	40	85	313	108	788	1725
	C	4.9	0.25	11	1.8	45	88	3.0	0.53	15	0.0053	101	168	8.2	0.3	0.15	0.55	20	98	138	163	488	2350
	D	12	0.75	9.0	5.8	41	95	1.0	1.0	12	0.0025	71	138	7.7	2.5	0.16	4.5	3875	30	51	108	525	120
SS15	A	300	47.5	86	0.5	28	43	3.7	3.5	70	0.0045	225	95	95	0.2	1.8	4.5	115	75	80	3.0	950	98
	B	488	0.75	175	1.3	29	28	6.3	2.0	125	< 0.00025	325	30	188	0.1	3.3	5.8	188	63	108	0.5	1375	43
	C	213	1.75	76	0.5	19	30	80	1.0	55	0.0010	150	35	88	0.3	1.5	3.3	85	55	90	2.3	700	23
	D	613	1.50	200	0.8	29	28	5.0	1.0	150	0.0008	350	25	238	0.4	4.1	3.3	213	50	80	0.3	1250	18
	E	313	2.50	138	0.3	28	21	2.9	1.0	93	0.0010	225	18	150	0.2	2.5	2.0	150	63	51	0.8	1063	28
Blanks		0.25	0.50	0.03	0.1	0.4	< 1.0	1.8	< 0.25	1.0	0.0025	103	< 2.5	< 0.025	0.1	< 0.01	< 0.025	9	< 0.25	19	< 0.3	350	< 2.5
		< 0.1	0.50	< 0.01	0.1	2.0	< 1.0	1.0	< 0.25	1.6	0.0018	263	< 2.5	< 0.025	0.2	< 0.01	< 0.025	16	< 0.25	23	2.3	450	< 2.5
		< 0.1	0.25	0.01	0.1	< 0.13	< 1.0	1.6	< 0.25	1.1	0.0018	71	4.8	< 0.025	0.1	< 0.01	< 0.025	8	0.50	14	18.5	288	5.75
		< 0.1	0.50	0.01	0.1	0.8	< 1.0	4.9	< 0.25	2.5	0.048	74	< 2.5	< 0.025	0.1	0.01	< 0.025	58	< 0.25	34	< 0.3	463	< 2.5
		< 0.1	< 0.25	0.01	0.5	0.9	< 1.0	1.2	< 0.25	1.0	0.0055	34	< 2.5	< 0.025	0.2	< 0.01	< 0.025	3	< 0.25	15	< 0.3	350	< 2.5
		< 0.1	0.25	< 0.01	< 0.1	0.3	< 1.0	1.0	< 0.25	1.0	0.0040	213	< 2.5	< 0.025	< 0.05	< 0.01	< 0.025	13	< 0.25	13	< 0.3	260	< 2.5
		< 0.1		0.01	0.4	0.4		1.9		1.0	0.0023	250		< 0.025	0.1	< 0.01	< 0.025	16		14		400	
		< 0.1		< 0.01	0.1	< 0.13		1.1		1.0	0.0043	53		< 0.025	0.1	< 0.01	< 0.025	5		13		280	
		< 0.1		0.01	0.3	0.8		0.9		1.0	0.0030	138		0.025	0.1	0.01	< 0.025	19		11		340	
		< 0.1		0.03	4.3	1.8		1.3		1.0	0.0023	200		< 0.025	0.9	< 0.01	0.08	11		13		330	
		< 0.1			1.3						0.0030				0.4		0.03						

first with deionized water (water extract) followed by 0.01 M HNO_3 (acid extract). The leaching was carried out by vigorously shaking 2 g dry soil with 25 ml of the deionized water for 1 h, centrifuging and decanting, then adding 25 ml of the acid and repeating the extraction procedure. The resulting pHs of the solutions was measured and ranged from 7.2 to 9.9 with a median value of 9.2 for the water extract; 2.2–5.2 (3.5 median value) for sequential acid; and 2.9–5.3 (3.7 median value) for the acid extract alone.

The supernatants were sealed in plastic containers and shipped for analysis of Ag, Al, As, Cd, Cr, Cu, Fe, Mn, Ni, Pb and Zn to the CSIRO Division of Energy Technologies, NSW, Australia. The analytical methods used were ICP-MS and ICP-OES as appropriate. Analytical quality was monitored in each batch of samples by repeat analyses, recoveries of spiked samples, and analysis of a certified reference material (Merck ICP4 100 ppb for Ni, Cu, Zn, Cd and Pb). Duplicates were generally within 10% or one last significant figure of each other except for Zn for which repeat analyses were generally within 20%. Recoveries were almost always between 90 and 110%. The determined concentrations of the metals in the reference material were within 5% of the certified values.

Some analytical results gave unacceptably high blanks, especially in the acid extracts, and this was eventually shown to be due to cross contamination through the use of inadequately cleaned centrifuge tubes. The extractions were repeated in the acid solution only and reanalysed, for Ag, As, Cd, Cu, Ni, Pb and Zn. These were not extracted with water first and the results should not be regarded as being equivalent to those that were i.e., Al, Cr, Fe and Mn. Some sets of analyses in the water extracts still had high concentrations of metals in the blanks, particularly for Cu, but the authors were not able to repeat these extractions and analyses.

3. Results

Table 1 lists the sample depths, moisture contents, excess moisture, total C, pH and conductivity while Table 2 lists the Al, Fe, Mn, As and heavy metal contents of the water and acid extracts of the soils.

3.1. Moisture contents

The moisture contents of the soils differ between the undisturbed and the disturbed sites. At the undisturbed or only slightly modified sites (SS1, SS12, SS13) the moisture content is lowest at the surface (0–2 cm) and increases with depth. The disturbed soils in most cases exhibit a moisture profile that is characteristic of undisturbed "wet" sites (Campbell et al., 1997) with an average moisture content per horizon of about twice that for the undisturbed soils. These significant differences in moisture characteristics of the disturbed soils may be due to soil compaction and/or a changed soil thermal regime. The lighter colour and smoother surface of the disturbed soils is likely to result in higher albedo for these surfaces with less energy available for soil thawing, with a resulting rise in the permafrost table and accumulation of water in the intermediate horizons. It is considered likely, based on the observations of soil moisture contents at undisturbed wet sites over several years, that there is a loss of subsurface moisture at the disturbed sites over winter months with a subsequent recharge following the initial summer thaw.

3.2. Soil pH

The leachates were all alkaline in reaction, with a median pH value of 9.3 and a range of 8.3–10.1. The pH was often higher at the base of a profile than at the surface. The high pH values are typical of soils in coastal regions subject to the influence of sea-spray (Campbell and Claridge, 1987). In these situations NaCl and Na_2SO_4 dominate the water-soluble salts in the soils. Because of the very low content of clay-size material and negligible organic matter content, these soils are very poorly buffered and very small amounts of CO_3^{2-} and HCO_3^- ions may result in the high pH values. Calcite coatings are present on the underside of surface stones. Higher pH values at the base of profiles may indicate higher CO_3^{2-}:HCO_3^- as a consequence of lesser atmospheric influence.

3.3. Conductivity

The measured conductivity of the water extract indicates the relative water-soluble salt content of the soil. The conductivities of the water extracts were generally less than 1000 μS/cm but in one case was as high as 12,000 μS/cm. In most soil profiles, including in the relatively undisturbed soils in SS1 and SS13, the highest conductivities were found in the surface layer samples, reinforcing the common observation of the movement of salts to the surface in response to loss of moisture by evaporation in the summer. A conductivity of 1000 μS/cm of the 1:5 soil extract equates approximately to a soluble salt content of 0.35% (Blakemore et al., 1987).

3.4. Carbon content

The organic C content of the samples varied from <100 to 7000 mg/kg. Published measurements of organic C in Antarctic soils are rare but Cameron (1974) quotes values ranging from 200 to 3500 mg/kg for some Antarctic soils with the highest value being in a soil from Mt Howe, the southernmost known soil outcrop on Earth, and, on the basis of the high C:N it was deduced that the C was probably derived from the coal measures in the parent material. The other soils measured had C contents ranging from 200 to 900 mg/kg. The soils from Scott Base have somewhat higher C contents than those described by Cameron, and lower than soils of the Arctic regions or from hot deserts (Cameron, 1974). Semi-arid soils of New Zealand have organic C contents ranging from 20,000 mg/kg in the surface horizon to less than 1000 mg/kg at 1 m depth (Blakemore and Miller, 1968).

There were no obvious traces of any plant life in the soils in the immediate vicinity of the base, although mosses, lichens and algae are found at sites further from the base. Undisturbed or relatively undisturbed soils were those with no obvious tracking and which had a smooth appearance and with little sign of overturned stones, which are recognised by the white coat-

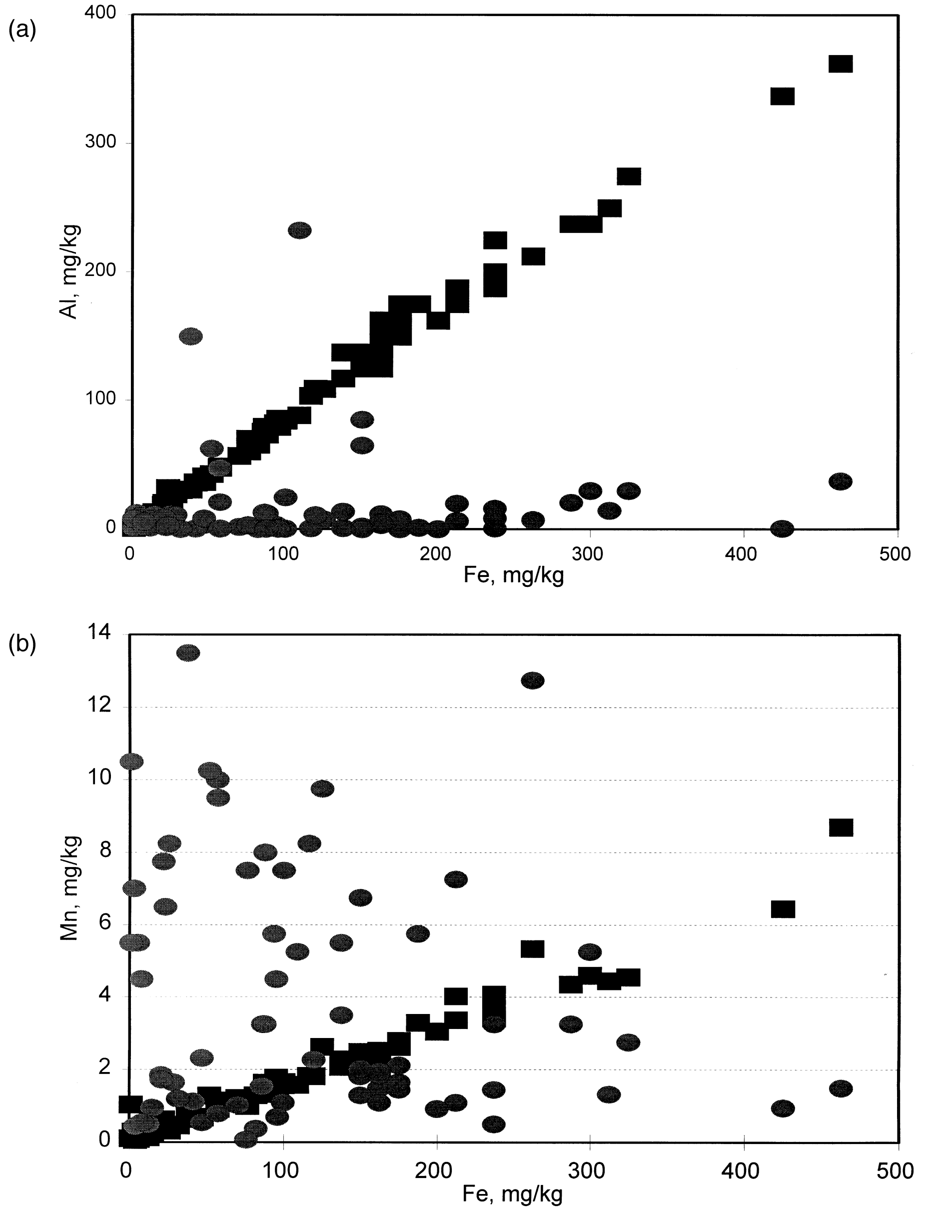

Fig. 2. Relationship between water extracted major metals and water extractable Fe from Scott Base soils. ● — acid extracts; ■ — water extracts; a — Aluminium; b — Manganese; c — Chromium; d — Nickel.

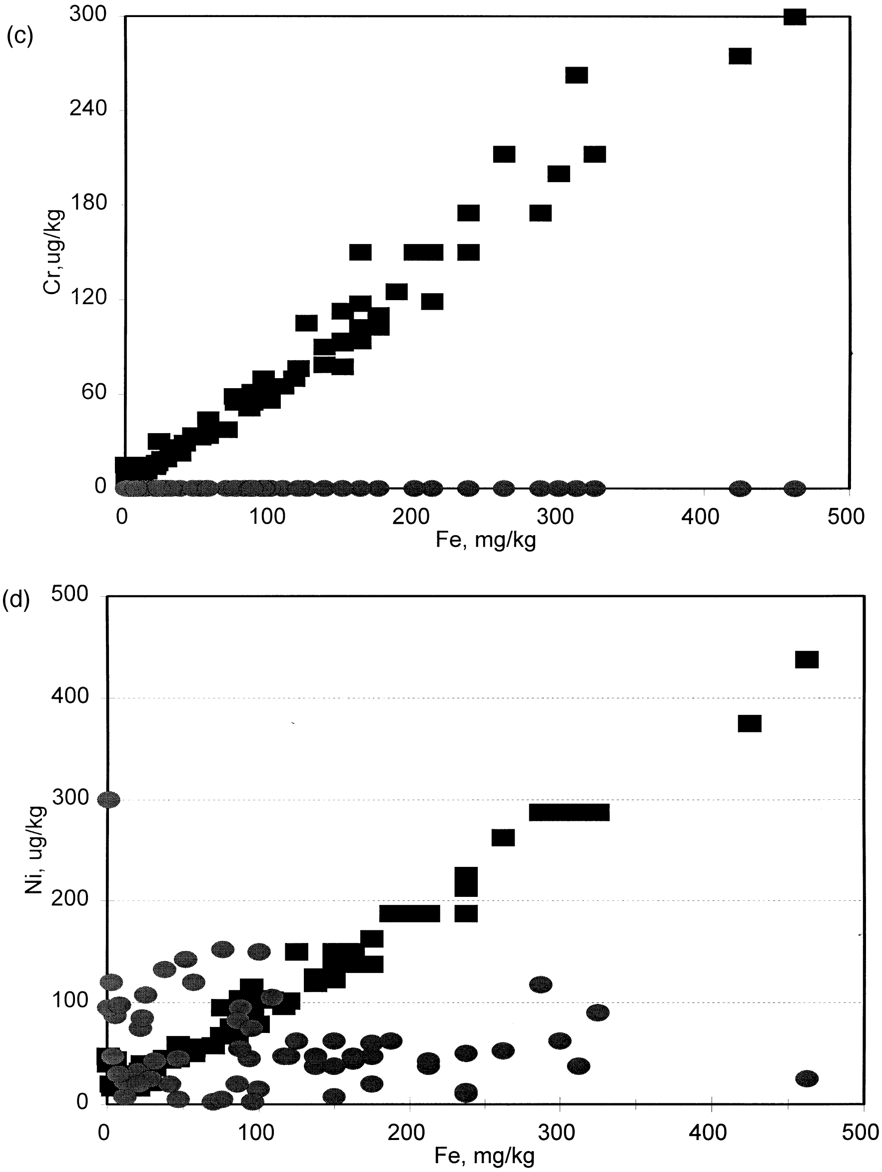

Fig. 2 (*continued*)

ing of calcite which forms on the undersides of surface stones in this area (Campbell and Claridge, 1987). Disturbed soils were those where there was evident surface disturbance by earthmoving or tracking, with many overturned stones and which were lighter in colour and rougher than the undisturbed soils. The undisturbed soils tended to have most of the C in the top 10 cm, but while some disturbed soils seem thoroughly mixed with regard to C, for instance SS4, SS9, SS15, some disturbed soils (SS5, SS6, SS14) show the surface enrichment in C. Locations from which samples smelling of fuel oils were obtained tended to have high C contents (SS5, SS9, SS14) in the top 15 cm of the soils. A common source of C is wood fragments found at depths to 25 cm in samples SS4, SS5, SS6, SS14. White plastic fragments were noted in some samples and are ascribed to erosion from the sampling tools themselves. These particles are considered to be unlikely to have contributed to the analysed C content, as they were resistant to the oxidation used in the analysis.

The reference site SS1, which seems to have had soils scraped from the surface, has 7000 mg/kg C in the surface. Other sites show high C contents at depth

(SS2, SS12, SS13) which may indicate some movement of organic C downwards in the soil profiles. Recent deposition of C may be indicated by the SS1 result. There may be an overall contamination of the site with "black carbon" (soot) from engine and heater exhausts from the base. Black carbon fallout can be detected at the South Pole, both from the station exhausts and from global fallout (Hansen et al., 1988).

Organic materials, such as humic acids, play an important role in the complexing and adsorption of heavy metal species in soil and sedimentary matrices. Because of the very low intensity of biological activity in Antarctic soils it must be expected that as the rate of decay of organic matter will be low and although the nature of the organic C in the Scott Base soils is unknown, the availability of suitable complexing organic compounds and substrates must be expected to be much less than in temperate soils.

3.5. *Aluminium, iron and manganese*

Aluminium, Fe and Mn are present in the water and acid extracts at levels 3 orders of magnitude greater than the trace elements. However concentrations of Al and Fe are mostly markedly higher in the water extracts than in the acid extracts, which, in contrast to the trace elements discussed later, were not sequential extracts, but carried out on separate samples.

A linear relationship exists between Al and Fe in the water extracts (Fig. 2a), but not in the acid extracts, implying that both metals occur in the same water extractable material. The Al/Fe ratio is about 0.85:1. Manganese in the water extracts also follows Fe but not as linearly as for Al.

Water extracted solutions were alkaline with a pH around 9 due to of the presence of traces of HCO_3^-, and were dominated by Na^+ ions. These conditions would disperse fine colloidal material, especially clay minerals. The finest of these ($<$ approx. 0.5 μm) would remain in suspension even after centrifugation at the speeds used in this study, and, at low concentration, would not be visible in suspension.

Although most of the clay-sized fractions of Antarctic soils are generally relatively coarse mica fragments (Campbell and Claridge, 1987), the weathering of dolerite produces fine-grained, Fe-rich smectites (Claridge and Campbell, 1984) with an Al/Fe ratio of 0.6:1, but containing only traces of Mn. Trace amounts of such smectite material are also present in soils of the Hut Point Peninsula area. These smectites would be easily dispersed in alkaline solution, but would be flocculated if the salt content of the water extract was too high or by acids of the strengths used for the acid extractions in this study. It was observed that the amounts of Al and Fe extracted were low when the conductivity, and hence salt concentration of the water extract, was high. Because of their large surface area and negative surface charge, these clay particles present sites for the adsorption of heavy metals, which provides an explanation for the observed linear relationship between the concentrations of Mn, Cr and Ni and that of Fe (Figs. 2b–d). The similarity of the ratios of Al, Fe and Mn in the extracts to those of basanite, which is the dominant rock of the Scott Base area (Kyle, 1990; Table 3) suggests that this may be the source of the colloidal material.

Table 3
Elemental ratios in whole rocks and water extracts. Water extract data are the slopes of clear linear relationships (for Al, Mn, Cr, Ni) or possible (minimum) linear relationships on plots against Fe contents. Rock data for basanites from Hutt Point Peninsula are from Kyle (1990)

Element ratio	Basanite	Water extracts
Al/Fe	0.78–0.86	0.86
Mn/Fe	0.016–0.018	0.016
Cr/Fe[a]	0.54–0.032	0.64
Cu/Fe[a]	0.060–0.043	0.10[b]
Ni/Fe[a]	0.32–0.026	0.94
Pb/Fe[a]	0.0092–0.019	> 0.36
Zn/Fe[a]	0.094–0.112	50

[a] Ratios have been multiplied by 1000.
[b] Acid extract.

In almost every case the amounts of metal extracted into the acid solutions were very much less than in the water extract. Since any clay particles would be flocculated by the acid extractants, the Al and Fe which was extracted is likely to be present as oxide coatings on soil particles. Fe, Al and Mn are released by weathering of rock particles and form coatings on soil particles, giving rise to the yellowish and reddish colour of soils and the reddish coatings on some surface stones sometimes referred to as desert varnish (Campbell and Claridge, 1987). This may be one of the sources of Al, Fe and Mn in the acid extracts of Scott Base soils.

Although the water extracts contain very much less Mn than Fe or Al, which would be a consequence of the low Mn content of the Fe-rich smectites that are considered to be the source of the Al and Fe, the proportion of Mn in the acid extracts is much higher. Unpublished analyses by one of us (GGC) of the oxide coatings on Antarctic soils show that they are largely Fe oxides (or oxy-hydroxides), but with measurable contents of Al and Mn, as appears in the acid extracts analysed here.

Sheppard et al. (1997) have suggested that physical disturbance of soils releases particles of Fe and Mn oxyhydroxides from coatings on soil particles which are then mobilised by water flowing over and in the soils and to which other heavy metals are adsorbed.

Very fine clays, rock particles and abraded surface coatings may also be significant in the transport of heavy metals in and over the soils in these environments, especially in the alkaline environments.

3.6. Heavy metals

A number of observations can be made about the distributions of the extractable heavy metals in the soils about Scott Base. In general, the metals are preferentially extracted into the water extract (i.e., into alkaline solution) rather than the acid extract. The exceptions are As, and Cd, Cu, Pb and Zn when these are present in particularly high concentrations, which indicates that the chemical form of the metal is important. If As was present as the arsenate anion, it would be expected to be more mobile in acidic solutions.

3.7. Silver

For most of the samples the Ag levels in the extracts were slightly higher than in the blanks. Silver concentrations were higher in the water extracts than in the acid extracts, in some cases by a factor of 400, indicating that Ag is more soluble in alkaline solution in the presence of SO_4 and Cl than in acid. Very high concentrations of Ag were found in the water extracts from sites SS3, SS4 and SS15, which are likely to have been contaminated by laboratory chemicals. Site SS3 is close to a storage site for equipment at the rear of the former science laboratory, site SS15 is directly downslope from the laboratory site, while SS4 was outside the building which contained a darkroom. Photographic chemicals may well have been disposed of at these sites, especially in the early years of Scott Base, and traces have remained even though the sites have been cleared and scraped subsequent to the removal of the old buildings.

Lower, but still significant amounts of Ag were found in extracts from sites SS5 and SS6, also downslope from the old base site. Because the bulk of the Ag is easily extracted by alkaline solution, Ag will be quite mobile in the soils. The observation of elevated levels of Ag in marine sediments immediately offshore from Scott Base (Anderson and Chagué-Goff, 1996) suggests that the Ag has moved to the shoreline and into the marine environment.

The lowest Ag concentrations were found in sites SS9 and SS10, while significantly higher amounts were found in the "reference" sites SS1 and SS13, and the sites uphill from Scott Base, SS11 and SS12. Site SS9 is very wet because the topography concentrates drainage, and may have been leached of all soluble Ag. The levels of Ag in the other sites may represent contamination by wind from the sites of high contamination or may represent the natural level of Ag in the soils. Elevated levels of Ag have been found in locations from Ross Island and the Antarctic mainland where human influences were expected to have been minimal (Sheppard et al., 1994, 1997).

3.8. Arsenic

Arsenic concentrations in the acid extracts were about twice those in the water extracts, indicating that As could be present in soils both as arsenate ions and as oxides. The highest concentrations were found in the surface layers but they did not decline markedly with depth. The lowest concentrations were found at site SS13, the "undisturbed" site well uphill from the base buildings, but the other baseline site, SS1, contained amounts comparable with many of the other sites around the base. The highest As concentrations were found in surface samples from sites SS6 (675 μg/kg) and SS14 (950 μg/kg), with lower values at site SS7 (70 μg/kg) and SS9 (190 μg/kg). Most of the other sites had concentrations <60 μg/kg in the surface layer. The two sites with very high As concentrations were disposal areas where timber (some of which would have been Cu–Cr–As treated) and other materials had been stored prior to disposal, while the other sites with moderately high As concentrations were also near and downstream from storage areas.

As well as these highly contaminated sites there appears to be a general contamination of the whole area with As, particularly at the surface, suggesting airborne contamination from the incinerator flue or from the oil-burning generators. Another potential source of As is erosion of the surface of Cu–Cr–As treated timbers used in the foundations of the new buildings of the base. Some treated timber scraps may have been disposed of in the incinerator. This could explain the increased concentrations of As in the SS1 site, downwind of the base and of the incinerator.

At site SS10, a site on the inner edge of a recently excavated road bench where overlying soil had been removed a few years previously, the highest As concentrations were found between 10 and 20 cm, indicating that As may be mobile in soils and be leached down and out of the system. The very wet site SS9 also had relatively high As concentrations at depth.

3.9. Cadmium

In some samples, including the "baseline" sites SS1 and SS13, concentrations of approximately 2 μg/kg Cd were found and this may represent the level in natural or undisturbed sites. As blanks for the water extracts were significantly high, the low values found should be treated with caution. At some sites, high concentrations were found in the acid extract (sites SS7, SS9 and SS14) while at others, (SS4, SS6, SS8, SS10-12 and SS15) highest values were found in the water extract. The high Cd concentrations were found in extracts from sites SS6, SS7, SS9 SS10 and SS14, all sites close to the base or down-slope, where material had been dumped or stored.

Cadmium is usually associated with Zn, and corrosion products of Zn-coated steel used in the construction of the older buildings may be the source of some of the Cd found in the soils. There is a good linear relationship between Cd and Zn in the water extracts, except for two high levels in two samples, SS15c and SS11c.

A weak linear relationship exists between Cd and Fe (Fig. 3a) if outliers from contaminated sites are

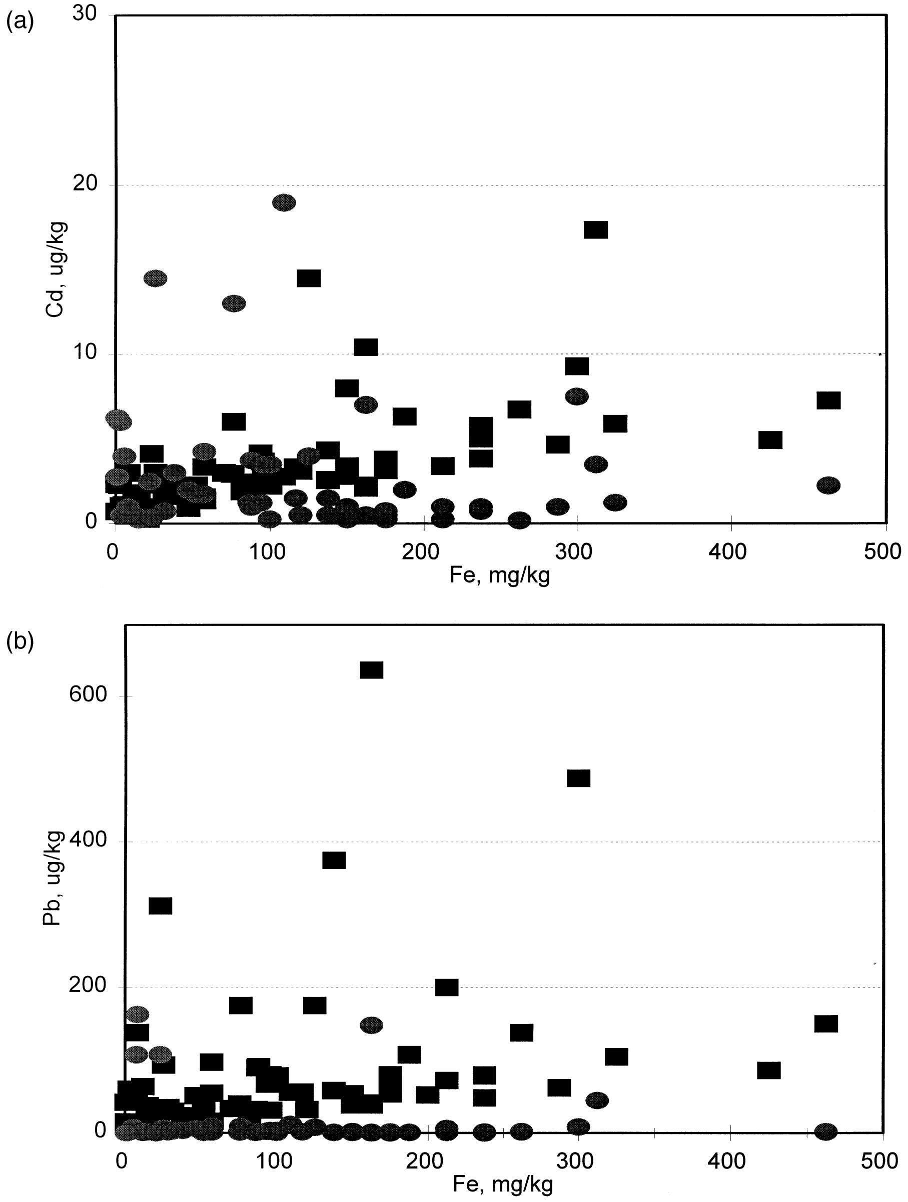

Fig. 3. Relationship between water and acid extracted trace metals and water extractable Fe from Scott Base soils. Some extreme values of the trace metals are not included for illustrative clarity. The approximately linear lower limit for the water extracts is considered to be due to the dominance of fine clay particles in the samples and the ratio is interpreted to be the baseline composition. Contamination from external sources is therefore implied by the sample points above this line. ● — acid extracts; ■ — water extracts; a — Cadmium; b — Lead; c — Zinc.

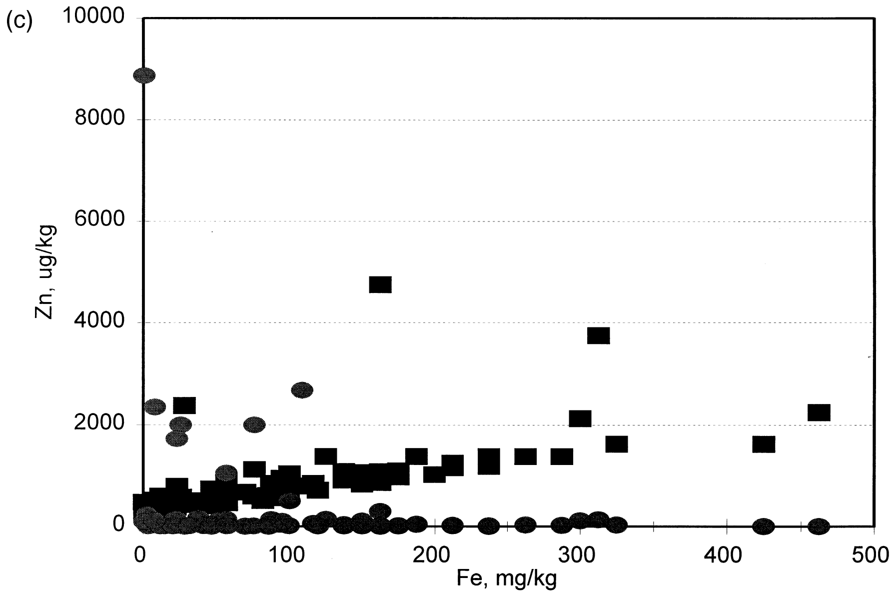

Fig. 3 (*continued*)

excluded, indicating that Cd is part of the clay or rock comprising the particulates in solution. The outliers are thus likely to result from contamination.

3.10. Chromium

The alkaline extract removed much more Cr from the soils compared to the sequential acid extract that had extremely low Cr concentrations <0.02 μg/kg. The amounts of Cr extracted from the baseline samples (SS1 and SS13) were within the range of the other sites so that contamination by Cr cannot be discerned clearly from the concentrations. The very clear linear relationship between Cr and Fe (Fig. 2c) and the similar ratio to that of the parent rock (Table 3) is interpreted as indicating that the Cr in the extracts is associated with readily dispersible clay or rock particles. Only at site SS6, where the soil has been moved to form a pad, and which was found to contain much debris, such as wood and steel nails, do the analytical results show reasonably confidently that contaminant Cr was present.

3.11. Copper

The analytical blanks for Cu in the water extracts are very high relative to the samples. The levels determined in the "baseline" samples (SS1 and SS13) are similar to or lower than the blank levels so this data must be treated with extreme caution and is not discussed further here. The samples extracted with acid had much lower blanks and are considered more reliable.

The concentrations of Cu in the acid extracts of samples from most of the sites were higher than those from the "baseline" sites SS1 and SS13. The highest concentrations were found at sites SS6 and SS14, both sites where materials had been disposed of or stored and which could have accumulated corrosion products of Cu from electrical wire or Cu tubing scraps. Lower but still significant concentrations of Cu were found at sites SS3, SS4, SS5, SS9 and SS15, all down-slope of the base site. At the very highly contaminated site the Cu is concentrated at the surface, but at other sites, notably SS7, Cu contamination is high throughout the soil profile, indicating that either there has been mechanical mixing of the soil, or that particulate Cu is able to move into the coarse soils.

There is little or no relationship between Cu and Fe, indicating that acid-extractable Cu is not attached to mineral particles.

3.12. Nickel

Water extracted Ni is similar to Cr in having a clear linear relationship with Fe, indicating that some of the Ni in the samples is associated with fine particulate matter, either as part of the structure or on exchange sites. Nickel concentrations tend to be higher at depth, even at the "baseline" sites. The Ni/Fe ratio in the extracts is somewhat higher than in the local rock, reinforcing the interpretation that Ni is associated with mineral matter. The anomalous value of 3875 μg/kg found for sample SS14 d is unexplained and contamination or analytical error cannot be dismissed as the cause.

The Ni concentration in the acid extracts shows no clear pattern, either in relation to any other variable or to depth. Most are comparable to the "baseline" sites, although generally higher and may represent an overall contamination of the site by dust or fallout from diesel exhaust or other sources. The highest values are found at sites SS7 and SS14, down-slope of the base, which also have high levels of other contaminants. In contrast to the water extracts, acid-extractable Ni is highest near the surface, which would be expected from air-borne contamination.

3.13. Lead

The Pb levels in the water extracts are all significantly higher than the blanks, despite these being relatively high. Because of the linear relationship between Pb and Fe below 100 μg/kg (Fig. 3b), these are considered as "natural" compositions; higher levels are then interpreted as the result of contamination. At least one sample from each site over the entire lower base area is above this line. Significantly higher levels, such as at sites SS6, SS13 and SS14, may represent sites of battery acid spills, where the Pb would be in an ionic form.

All the acid extracts have low Pb concentrations, except at sites SS6 and SS14. These two sites are adjacent to and down-slope of the base waste packaging area. The acid-soluble Pb contamination may indicate Pb oxide contamination, suggested sources being from crushed Pb-acid batteries and paint residues.

High levels of Pb were extracted from samples from the uphill "baseline" site SS13, where the 2–5 cm layer has relatively high Pb concentrations in the water extracts (37.5 μg/kg). The supposition is that this Pb is derived from airborne particulates from vehicles — the major road between the US McMurdo Station and the snow runway runs above this site. In a situation such as Scott Base, Pb contamination from particulate fallout derived from the use of leaded fuel in motor vehicles must be suspected as such fuels have been in common usage about Scott Base. SS6 is also immediately adjacent to a busy road at Scott Base, so the Pb may also originate from burned fuel, but, since the soils from this site contain high levels of other heavy metal residues it may represent general contamination, or contamination from spilled leaded fuel. Some of the paints used on the base may have contained Pb: early photographs show that parts of the original base were originally painted with what seems to be a red lead primer.

It is worth noting that the high Pb levels occur where soil has a low conductivity, and except for one sample (the top layer of SS6) there seems to be a tendency for higher concentrations to be associated with higher moisture contents (although the converse does not necessarily apply). This behaviour suggests that Pb is not particularly mobile in these soils, vertically or laterally.

3.14. Zinc

The blank Zn levels in the water extracts are relatively high and consistent at about 350 μg/kg, but very low for the acid extracts. However, even if results below 500 μg/kg for the water extracts are ignored, a linear relationship with Fe concentration (with a positive intercept on the Zn axis) is apparent (Fig. 3c), with clear higher levels at some sites. The "baseline" sites have extractable levels above 1000 μg/kg. Anomalous high levels of Zn (i.e., above the Fe–Zn line, for both of the extracts) were found at sites SS6, SS7, SS10 and SS14 and in most of these the Zn is well distributed through the soil profile. All of these are in the more actively used parts of the base, from the point of view of materials storage, processing, disposal and handling. The common use of galvanised materials, and their potential incineration, are the most likely source, and the Zn seems to be quite mobile, as it is found in drainage areas (SS14, SS7) and throughout the soil profiles.

4. Discussion

Soils of the Scott Base area are similar to other soils of the Antarctic coastal regions (Campbell and Claridge, 1987) in being alkaline and containing small amounts of soluble salts. The salts are expected to be largely NaCl and $NaSO_4$, by analogy with other soils of the Hut Point Peninsula. During the summer period, the upper part of the soil profile is usually dry, with moisture contents between 2 and 5%, while the ice-cemented permafrost beneath may contain between 10 and 60% of moisture as ice (Campbell et al., 1994). The soils are below freezing point for most of the year and any water is present as ice or, during freezing, salts may be concentrated into brine, which can remain unfrozen at low temperatures and be present in the soil as thin films on mineral grains or in cracks. Depending on topography and prevailing temperature, some soils may receive excess moisture from melting snow or down-slope flow and become saturated to the surface.

This investigation has shown that the soils of the Scott Base area are measurably contaminated with Ag, As, Cd, Cu, Pb and Zn. The contamination is concentrated at sites where materials have been dumped or stored, but is detectable over most of the site. The levels of metals found in the surface waters in Scott Base (Sheppard et al., 1997) correlate well with the composition and location of the contamination within the soils.

Three major processes can be invoked that may have caused major redistribution of contaminants from possible sources. These processes are: surface water flow, water percolation through the soils, and distribution by wind. Lateral and uphill transport from the incinerator and generator flues across the face of the base is strongly indicated by the distribution of some metals. The efficiency of the distributive processes in and within the soils is dependent on the chemical environment and the chemical and physical form by which the species is introduced.

A cartoon of the sequence of processes in the active layer over the climatic seasons is shown in Fig. 4 to illustrate the redistribution processes for metals deposited on soil surfaces, and located within soils, and how these vary over a year. Movement of water within soils has been well described, as have long term temperature and relative moisture profiles in Antarctic soils (Campbell et al., 1994; Balks et al., 1995). The processes involve dissolution and transport of contaminants into soils from the surface with the onset of thaw, and the lateral movement of soluble or fine particulate contaminants down-slope, within the soils and to the surface as slope and soil structures dictate flowpaths. This will continue until the soil refreezes, and even then there may be some movement of brines. Redistribution of contaminants as dust particles by wind, especially where soils are disturbed, will be a continuous process when soils are thawed and dry. Quantification of the rates of movement and details of the processes that apply for each specific contaminant requires more detailed study.

The results of this study suggest that the bulk of metals such as Fe, Al, Ni, Cr and Mn are associated with very fine particle size smectite clays formed by weathering within the soil and that all or most of these metals are derived from the native rock, rather than being added contaminants. The smectites are readily dispersed by alkaline soil solutions and provide a major medium for the transport of heavy metals within the soils. The heavy metals in the soils may be mobilised as a result of activities at the base, especially earthmoving operations. The mechanisms for this are entirely mechanical — the dispersion and release of the particulates by rubbing and grinding of the soil particles, the creation of enhanced porosity in the soils, the melting out of permafrost water and mobilisation of alkaline solutions carrying the particles, and the creation of open surface drainage channels to enhance the movement of water from the site. Indeed, the progressive loss of snow cover at the site has been ascribed to dusts from base activities (Campbell and Claridge, 1987) coating snow-banks, which has enhanced the need for drainage over the site.

The chemical environment within the soils varies with regard to salinity and pH. Waters carrying metals at lower pH and higher salinity (dominantly Cl and SO_4 salts, with significant HCO_3, and with pH between 8 and 9 — Sheppard et al., 1997) percolate into deeper soils where the pH is higher and the mobility of the particulates is thus higher. This process is episodic, because for most of the year there is little liquid water available, and temperatures within the soils are very low, falling as low as −30°C during August or September. The salinity is highest at the surface because of the evaporation of saline waters at the surface, indicating that water movement is dominantly towards the surface. Only at times of high water flow, such as during snow melt in early summer (December) will the soils approach saturation and flow directions be downward and lateral within the soils. Surface transport via flowing water has already been demonstrated (Sheppard et al., 1997). Melting permafrost and ice in disturbed soils (Campbell et al., 1994) in the active zone will also mobilize contaminants.

Air movement will transport particulates from initial sources, particularly during light winds when deposition is more likely. Additionally, during high winds, and particularly during summer when soils are dry and unfrozen, remobilization of surface dusts and fine-grained material will spread introduced material as well as erode exposed surfaces. These surfaces themselves then provide additional sources of contaminants. Diesel-fuelled generators and heaters are sources of C (in the form of soot) which will incorporate As, and possibly heavy metals, while Pb derives largely from vehicle exhausts. These give rise to low level but widespread contamination of soils with heavy metals.

5. Conclusions

The operation of any facility on bare ground in Antarctica must be expected to leave an imprint of a variety of materials and disturbances in the soils. This study focused on metals and has shown that nearly 40 a of human activity at Scott Base has resulted in the accumulation of Ag, As, Cd, Cu, Pb and Zn. The method of introduction onto and into the soils and the chemical and physical environment within the soils have resulted in differential movement of the metals, with the agents of mobilisation being surface and subsurface water flow, redistribution of surface material by wind, and the movement of particulates carrying heavy metals.

The saline, oxidising and alkaline environment of the soils and the variations of these within the soil profiles cause the episodic mobilisation and retention of

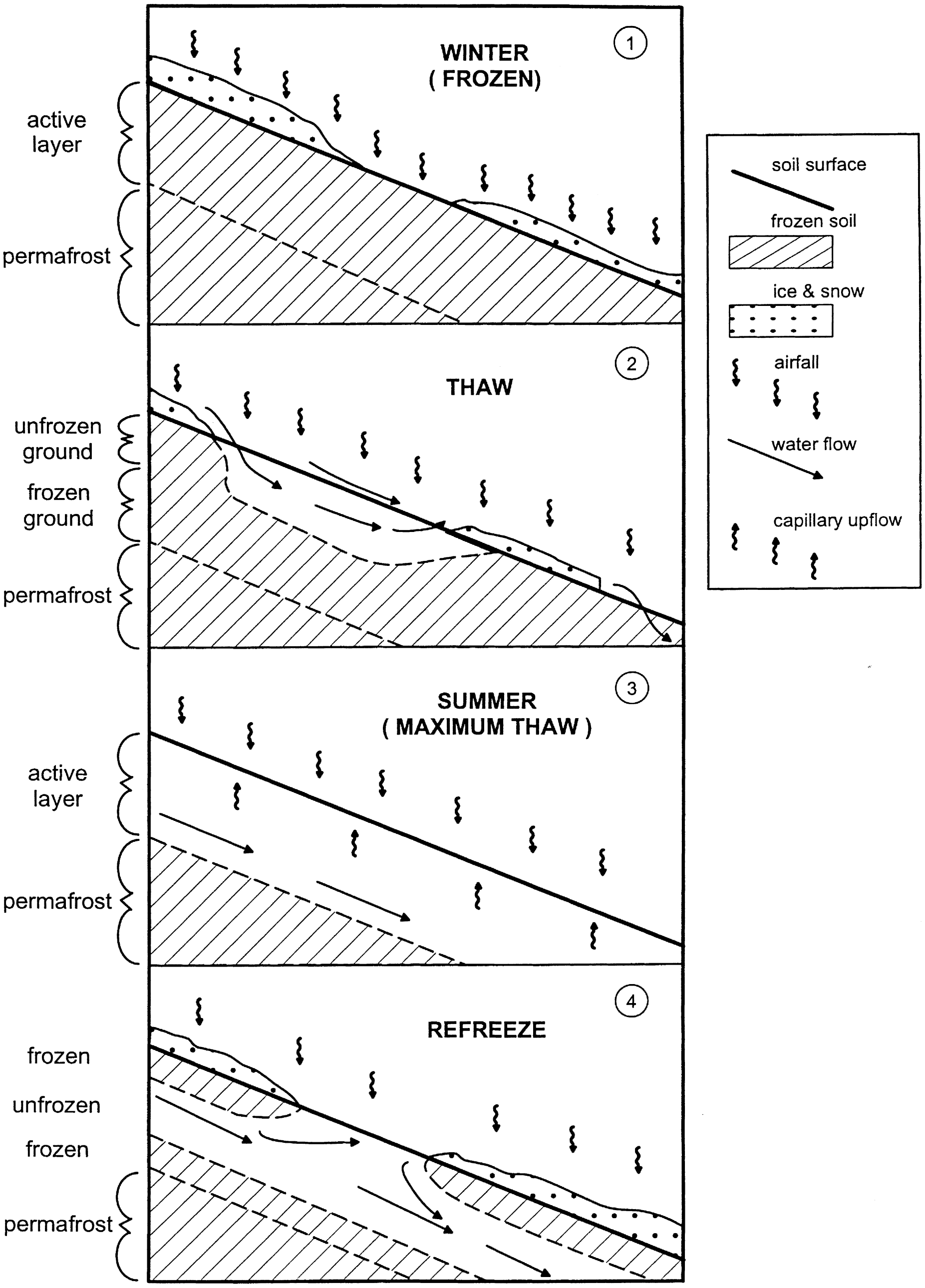

Fig. 4. Cartoon illustrating the physical and hydrological processes operating in soils to control the redistribution of soluble material in Scott Base soils. (A) Frozen. All soil is frozen, with intermittent snow cover. Interstitial brines are the only liquid phase, and liquid water movement is restricted. Contaminants may enter the system by atmospheric fallout of particulate, blown and eroded material, and from snow. (B) Thaw. Progressive melting of snow and the active layer in the soil from above. Human activity at the base increases, resulting in more contaminant addition to surface of the soil and snow. Water flows into the soils and downslope, moving contaminants. Dissolution of salts on soil surface and transport down into the soil profile. pH increase with movement into the soil causes precipitation of metals as hydroxides and carbonates. (C) Maximum thaw. Activity about the base is at a maximum, with maximum soil disturbance and dust creation, resulting in the deposition of particulates onto soil surfaces. The melting of disturbed permafrost results, with evaporation of moisture from the soil surface and the transport of salts back to the surface. Metals are left behind in the soil, at depth or at the surface, depending on their mobility. (D) Refreezing. Particulate deposition diminishes with decline in activity. Snow begins to accumulate and the soil active layer refreezes from the bottom up and the top down. Increasing salinity of soil solution mobilizes some metals and particulates and promote their redistribution. Temperature cycling (during weather cycles) will be important in accelerating this process.

the metals, in response to melt/thaw cycles and the movement of water over and through the soils. Penetration of the soils by the metals originally deposited on the surfaces is apparent as is the down-slope movement. Different metals progress at different rates, but the elucidation of the details of this and the detailed chemical processes require further work.

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