

Soils of Seabee Hook, Cape Hallett, northern Victoria Land, Antarctica

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Abstract: The soils of the Seabee Hook area of Cape Hallett in northern Victoria Land, Antarctica, were mapped and characterized. Seabee Hook is a low-lying gravel spit of beach deposits built up by coastal currents carrying basalt material from nearby cliffs. Seabee Hook is the location of an Adélie penguin (*Pygoscelis adeliae*) colony which influences the soils with additions of guano, dead birds, eggshells and feathers. A soil-landscape model was developed and a soil association was identified between the soils formed on mounds (relict beach ridges) favoured by penguins for nests (Typic Haplorthel) and the soils in the areas between the mounds (Typic Haplorthel/Typic Aquorthel). Soils formed on the mounds inhabited by penguins contained guano in the upper 50 cm, overlying sub-rounded beach-deposited gravel and sand. Soils between mounds had a thin veneer (< 5 cm) of guano overlying basaltic gravelly sand similar to that in the lower parts of the mound soils. The soils had high concentrations of nitrogen, organic carbon, phosphorus, cadmium, zinc, copper, and increased electrical conductivity, within horizons influenced by penguin guano. Five buried penguin bones were collected from the base of soil profiles and radiocarbon dated. The dates indicate that Seabee Hook has been colonized by penguins for at least 1000 years.

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Key words: Antarctic soil, carbon dating, guano, Latitudinal Gradient Project, ornithogenic, XRF

Introduction

Cape Hallett is located in northern Victoria Land, Antarctica. It is a 36 km long peninsula formed from a basalt shield volcano with a summit of 1740 m (Harrington *et al.* 1967). There are a number of basalt volcanoes in the district, and some sedimentary rocks on the northern side of Edisto Inlet (Harrington *et al.* 1967). Near the end of the Cape Hallett peninsula is a spit named Seabee Hook, (Fig. 1) the location of an Adélie penguin (*Pygoscelis adeliae*) colony and the site of a USA/NZ base from 1957–73.

Antarctic soils form in ice-free areas, with the largest area in the McMurdo Dry Valleys. Soils within Antarctic penguin colonies are described as ornithogenic, due to the presence of organic materials including, guano, dead birds, feathers and eggshells (Syroechkovsky 1959). Ornithogenic soils have been especially closely studied near the Polish base on King George Island (Pietr *et al.* 1983, Tatur & Myrcha 1983, 1984, Myrcha *et al.* 1985, Tatur & Barczuk 1985, Tatur 1989, Myrcha & Tatur 1991, Tatur *et al.* 1997, Juchnowicz-Bierbasz & Rakusa-Suszczewski 2002, Tschërko *et al.* 2003, Zdanowski *et al.* 2005).

The ornithogenic soils on the Antarctic islands differ from continental ornithogenic soils due to increased liquid water present from rainfall and meltwater in the maritime Antarctic (Myrcha & Tatur 1991). Continental ornithogenic soils have been studied mostly on and around Ross Island

(Ugolini 1972, Orchard & Corderoy 1983, Ramsay 1983, Speir & Cowling 1984, Speir & Ross 1984, Ramsay & Stannard 1986, Heine & Speir 1989, Porazinska *et al.* 2002) with some research conducted along the northern Victoria Land coast, including Cape Hallett (Harrington & McKellar 1958, Benes 1960, Claridge 1965, Campbell & Claridge 1966, McCraw 1967) and also near Casey Station (Roser *et al.* 1993). Soils in all penguin colonies are generally high in total phosphorus (P), organic carbon (C), and total nitrogen (N) with high electrical conductivity (EC) values and large variations in pH (Ugolini 1972, Speir & Cowling 1984, Tatur & Myrcha 1984, Tatur 1989).

Phosphatised rock was found below the guano layer on King George Island (Tatur & Barczuk 1985, Tatur 1989, Myrcha & Tatur 1991), but there have been no reports of phosphatised rock within Antarctic continental ornithogenic soils.

Microbiological activity is higher in ornithogenic soils than in non-ornithogenic soils in Antarctica (Orchard & Corderoy 1983, Ramsay 1983, Roser *et al.* 1993, Tschërko *et al.* 2003, Zdanowski *et al.* 2005). Increased microbial activity may be expected to increase the numbers of invertebrates found in ornithogenic soils, however Porazinska *et al.* (2002) found this was not the case on Ross Island.

McCraw (1967) included soil descriptions of the top 10 cm from an ornithogenic soil, scree soil and beach gravel

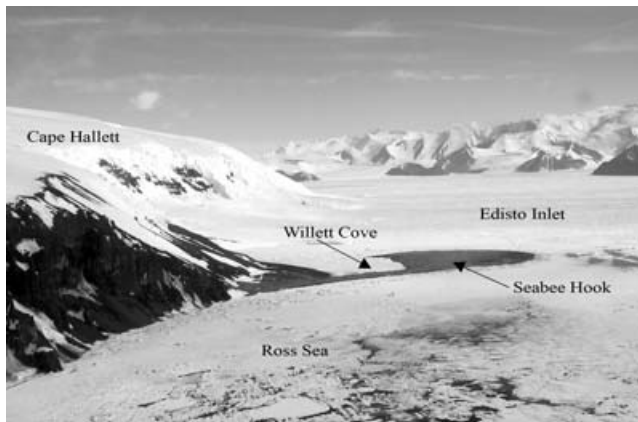


Fig. 1. Key features within the Cape Hallett area (photograph taken in December 2004 looking towards the south).

at Seabee Hook. Soils of the wider Cape Hallett region within Edisto Inlet were described, including scree soils similar to those found at Seabee Hook, by Campbell & Claridge (1968).

Dates for penguin habitation of 545–5840 ^{14}C years BP have been reported for abandoned penguin colonies on raised beach ridges from around the Ross Sea region (Hall *et al.* 2004) and increases in penguin population during times such as the Medieval Warm Period (Baroni & Orombelli 1994) have been noted. Previously reported dates for currently inhabited penguin colonies in the Ross Sea range from about 1200 to 8000 years (Harrington *et al.* 1967, Speir & Cowling 1984, Baroni & Orombelli 1994).

The Latitudinal Gradient Project (LGP) question to which we are contributing is: “to what extent does soil development (e.g. degree of weathering, carbon content and

nutrient accumulation) change with latitude and therefore influence terrestrial ecosystems?” (Howard-Williams *et al.* 2006). The objective of this paper is to map and characterize the soils at the northern end of the proposed LGP transect for later comparison with the soils in other locations.

The environment

Physiography

Seabee Hook is a low-lying area of gravel beach-deposited material, with a maximum elevation of *c.* 5 m a.s.l., formed from the gradual build-up of a series of beach ridges (Fig. 2). The current penguin nests are situated on hummocky topography. The mounds are beach ridges that have been accentuated by penguins bringing in stones for nests from nearby areas. Seabee Hook is adjacent to a steep ($\sim 30^\circ$) slope to the south-east. A moraine forms the lower part of the slope on the southern section of the map. The slope accumulates snowdrifts that provide meltwater to the flat land at the base of the slope during summer, contributing to a wetland area.

Soils at Seabee Hook can be divided into those strongly influenced by penguins (ornithogenic) and those minimally impacted by penguin activity (non-ornithogenic). The ornithogenic soils are found within the penguin nesting area and in areas affected by water runoff from the penguin nesting area. Adélie penguins use stones with a diameter of 3–10 cm to build nests on already raised areas on Seabee Hook. The raised areas provide some protection from meltwater. It is on the mounds that the penguins deposit most of their guano, leading to development of raised areas with “penguin stones” and guano accumulations, and low-lying areas that comprise gravel and sand, and are depleted of 3–10 cm size stones as penguins remove them to the

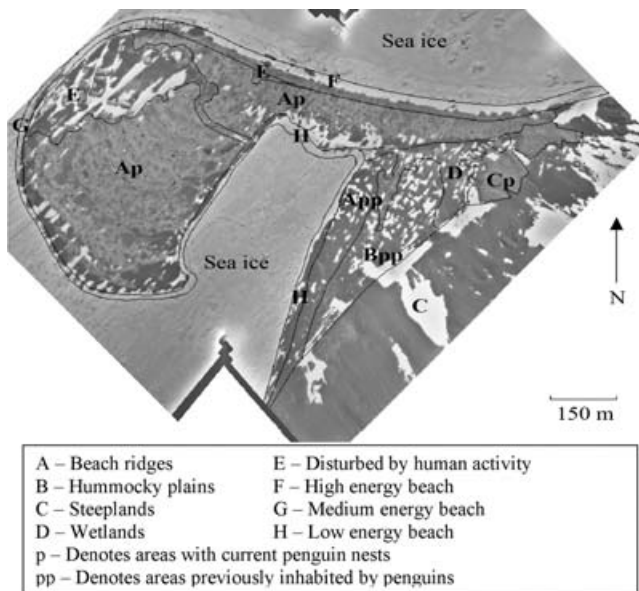


Fig. 2. Physiographic map of Seabee Hook.

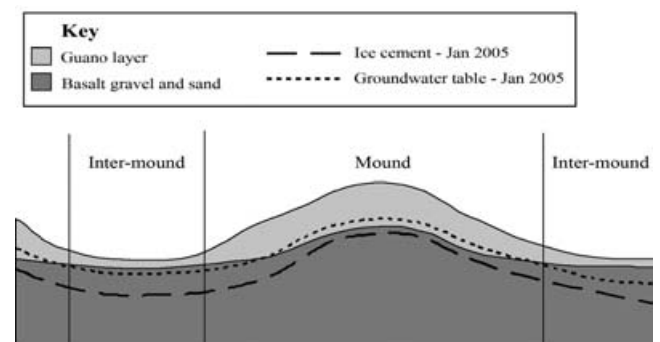
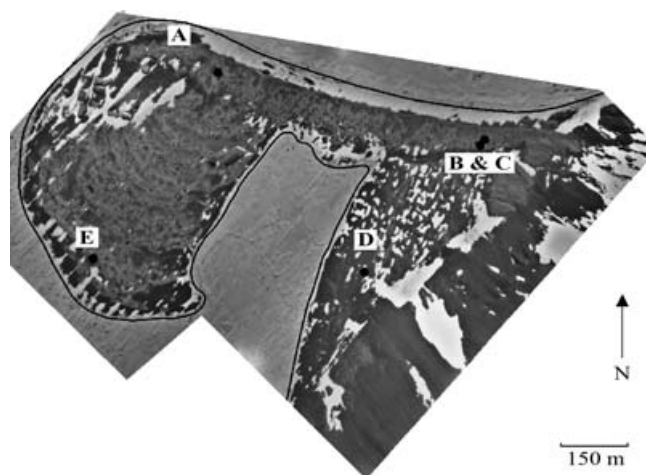


Fig. 3. Soil landscape model showing the soil association relationship between penguin mounds and inter-mounds at Seabee Hook. (Notes: Diagram is not to scale. The depth of guano accumulation on top of mounds was up to about 50 cm with 0–5 cm of guano material in inter-mound areas. Mounds varied from about 10 to 30 m across and the distance between mounds varied from about 10 to 100 m. The height of mounds ranged from about 1 to 3 m).



Sample	Lab. no.	Depth (cm)	$\delta^{13}\text{C}\%$	C.R.A. ¹ (yr BP)	Cal 68% ² (yr BP)	Cal 95% ³ (yr BP)
A	Wk16678	70–80	-19.3 ± 0.2	1113 ± 215	230–155	424–
B	Wk16679	70–80	-25.7 ± 0.2	1409 ± 52	360–80	428–
C	Wk16680	90	-26.5 ± 0.2	1723 ± 134	660–360	850–1000
D	Wk16684	35	-26.4 ± 0.2	1835 ± 159	790–450	1000–250
E	Wk16685	40	-22.9 ± 0.2	2325 ± 33	1180–940	1290–840

Fig. 4. Locations, depths and radiocarbon dates of *Pygoscelis adeliae* bones (Wk16679–85) and eggshell (Wk16678). Radiocarbon ages calibrated using a .R of 811 ± 102 years.

mound areas (Fig. 3). The low-lying “intermounds” may have guano within the upper part of the profile, primarily from guano rich water running off nearby mounds.

Mosses (predominantly *Bryum subrotundifolium*), lichens (11 species), and algae (two species) have been recorded at Seabee Hook (Rudolph 1963, Brabyn *et al.* 2005). Moss is most abundant in the wetland zone near the base of the cliff (Fig. 2) and contributes to the organic matter present in some soils. Most nests of south polar skua (*Catharacta skua maccormicki*) are on the scree slope and moraine, with some nests on the beaches near the penguin colony. The skuas add organic matter including guano, feathers, eggshells and penguin remains to the soil near their nest sites.

During the last ice advances, the Ross Sea, including the area currently occupied by Seabee Hook, was filled by ice (Harrington & McKellar 1958). The grounding line of the marine-based Antarctic ice sheet may have been further south than Cape Hallett, near the Mariner Glacier (Baroni & Orbelli 1994). In either case it is likely that the glaciers from the Edisto Inlet would have expanded to cover the present location of Seabee Hook. Seabee Hook has formed during the Holocene as a result of strong currents sweeping material along the coast from the cliff of Cape Hallett and re-depositing it as a series of beach ridges. It is likely that penguins did not occupy the Hook until after it had formed in its entirety. Evidence for this is the even thickness of the layer of “penguin stones” and guano on both current and previously inhabited penguin mounds. Five samples of

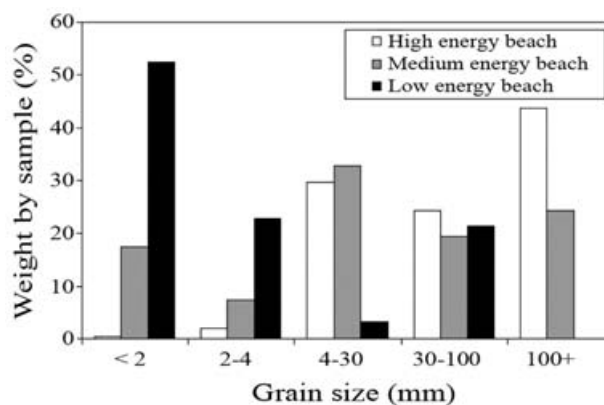


Fig. 5. Grain size of material found on high, medium, and low energy beaches at Seabee Hook.

penguin bone and eggshell were radiocarbon dated (Fig. 5).

Late colonization is supported by the presence of the oldest date, (E on Fig. 4), at a relatively shallow depth of 40 cm on the geologically youngest part of the spit. The radiocarbon dates indicate that Seabee Hook was colonized by penguins at least 1000 years BP (Fig. 4).

Parent material

The soils mapped at Seabee Hook were all formed from a combination of basaltic sand, gravel and rock materials along with penguin guano and remains. Weathering from the nearby basaltic rock outcrops supplied the material of the Hook. The parent material varies in grain size and roundness. The soils formed near the beaches, and on the main part of Seabee Hook all originated from sub-rounded to rounded beach gravels and coarse sand. Soils formed on, and near, the steep scree slope comprise angular medium to very coarse gravel and boulders.

The materials on the beaches consisted of unconsolidated beach sand, gravel and boulders. The particle size of the gravel and sand on the beaches was influenced by the wave energy reaching each beach (Figs 2 & 5). Beaches along Willett Cove have sea ice for the majority of the summer, with ice breakout only occurring later in the summer, if at all. The Willett Cove beach is sheltered from waves and it receives considerable guano-rich runoff, which contributes organic material to the upper 2 cm. The lack of high energy waves means the organic matter is not reworked and remains within the beach material, which comprises predominantly sand and silt size particles (Fig. 5). The highest energy beach was that exposed to the Ross Sea on the north-east edge of Seabee Hook, which is subject to high-energy seas during late-summer storms. In the 2004–05 summer, one storm created breaking waves *c.* 8 m high. The vigorous wave action provides a steep beach with gravel and coarser materials predominating, including some large (> 1 m diameter) boulders. A medium energy beach

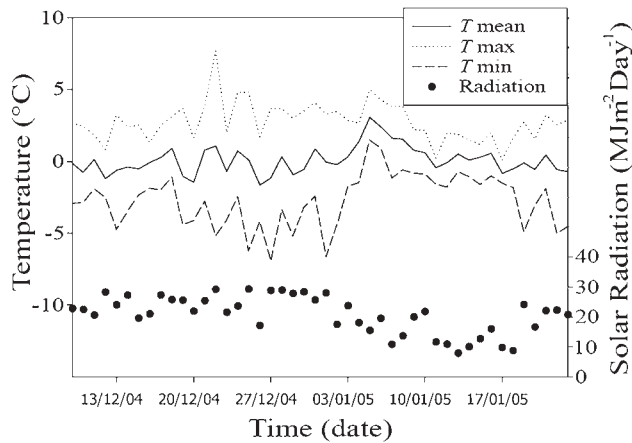


Fig. 6. Daily mean, minimum and maximum air temperature at Seabee Hook from mid December 2004 to late January 2005.

occurs along the coast of Edisto Inlet.

Climate

The climate at Cape Hallett is relatively mild compared to other regions of continental Antarctica. Data from the climate station located at Seabee Hook over the 2004–05 summer show that the mean air temperature was frequently above 0°C, and the maximum daily air temperature was above 0°C almost every day from mid December 2004 to late January 2005 (Fig. 6). Similar results have been reported from the climate station installed from 1957–64, with January air temperatures frequently above 0°C (US Weather Bureau 1963a, 1963b, 1964a, 1964b, 1965a, 1965b). Further climate data for Cape Hallett are available from the Latitudinal Gradient Programme website (www.lpg.aq).

Wind direction at Cape Hallett was predominantly from a SSE to WSW direction during the 2004–05 summer (Fig. 7)

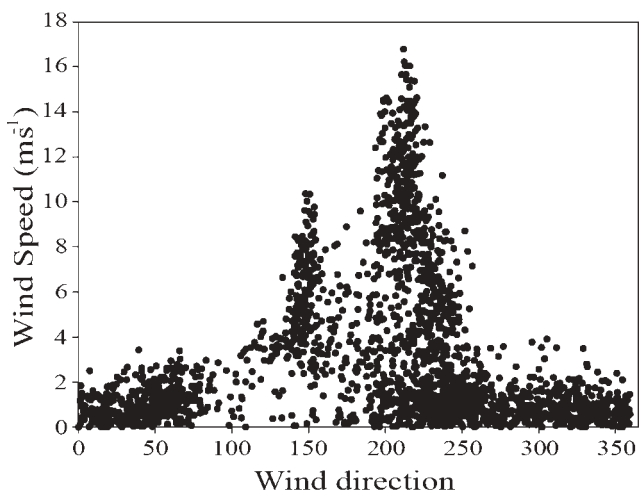


Fig. 7. Wind speed and wind direction at Seabee Hook from mid December 2004 to late January 2005.

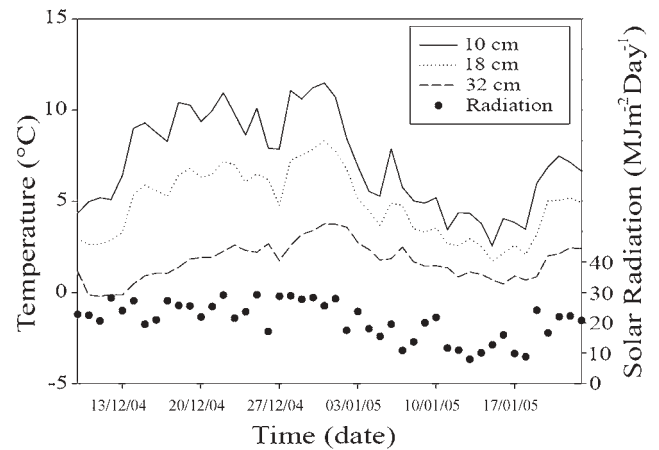


Fig. 8. Daily mean soil temperatures at 10, 18 and 32 cm depth in an intermound soil at Seabee Hook from mid December 2004 to late January 2005.

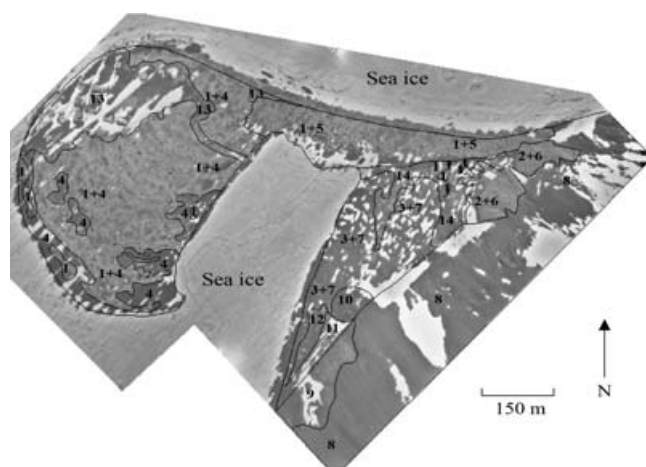
and also during the summers of 1957–64 (US Weather Bureau 1963a, 1963b, 1964a, 1964b, 1965a, 1965b).

Soil temperatures in January were constantly above 0°C at depth (Fig. 8), allowing melt to occur and groundwater to accumulate within a number of soil profiles. Meltwater within soil profiles originated from snow drifts, ice formed within the soil and water that moved down the cliffs and across the south-eastern part of the mapped area. The amount of liquid water at the soil surface was observed to vary from abundant surface water flow observed in January 2003–04 to water largely confined as groundwater in January 2005. January 2006 was observed to be dominated by cloudy conditions (in contrast to January 2005) so there was less diurnal temperature variability near the soil surface than might occur in some summer seasons. The depth to ice cement was greater at Cape Hallett (~80 cm) than at other locations reported in the McMurdo Sounds region, where permafrost is up to 60 cm deep (Campbell *et al.* 1997).

Methods

Soils were examined by digging pits to the depth of ice cement (*c.* 80 cm at maximum thaw in early January). Soil descriptions included here were all made in January 2005 and follow Milne *et al.* (1995). Soil classification followed USDA soil taxonomy (Soil Survey Staff 2003). A soil map was constructed by landscape interpretation and excavation of soil pits to confirm or refine predictions. Samples were air dried in Antarctica then sealed in plastic bags for transport to a New Zealand laboratory.

Climate data were recorded on the Seabee Hook, from 8 December 2004–24 February 2005, including air temperature (Vaisala Humitter 50Y humidity and temperature sensor), incoming solar radiation (Licor LI200X pyranometer) windspeed (Vector pulse output anemometer A101M), wind direction (Vector potentiometer



Physiographic Legend		Pedologic Legend	
Physiographic position	Map Unit	Soil Order	Map Unit
<i>Soils of the penguin mound association</i>			
Formed on mounds currently colonized by penguins	1,2	Typic Haplothel	1,2,3,5,6,8,9,11,12,13
Formed on mounds previously colonized by penguins	3	Typic Aquorthel	4,7,14
Formed on intermound areas currently colonized penguin mounds	4,5,6	Typic Haploturbel	10
Formed on intermound areas previously colonized penguin mounds	7		
<i>Soils of the steeplands</i>			
Formed on scree slopes	8		
Formed on moraine surfaces	9		
<i>Soils of the plains</i>			
Formed on colluvial fan	10		
Formed on flat colluvial areas	11		
Formed on paleo-beach ridges	12		
Formed on disturbed areas	13		
Formed on wetlands	14		

Fig. 9. Soil map of the Seabee Hook area of Cape Hallett (areas with soil associations are marked as x + y on the map).

windvane W200P), and soil temperature (Campbell 107 temperature probes). The data were collected using a datalogger (CR10X, Campbell Scientific, Logan, Utah).

Soil pH, and electrical conductivity (EC) were measured following Blakemore *et al.* (1987) using distilled water as a suspending medium. Soil pH was measured using an Orion pH meter and EC was measured using an EDT conductivity probe (model GP383).

Total organic carbon (TOC) was measured using colorimetric determination of organic carbon (Blakemore *et al.* 1987). Total nitrogen (N) was measured using Kjeldahl digestion (Blakemore *et al.* 1987). Total element analysis was carried using X-ray fluorescence (XRF) on samples that were ground to a fine powder, and combined with 10–20 drops of PVA-ethanol glue to bind the sample and pressed into a disc at 620 kPa before being dried and analysed. All chemical analyses were carried out in duplicate with the mean results reported. Full datasets are included in Hofstee (2006). In the results and discussion ratings (such as “very low” or “high”) for chemical properties follow Blakemore *et al.* (1987).

Radiocarbon dates were measured at the University of Waikato Radiocarbon Dating Laboratory. Dates were determined using standard radiometric dating techniques and one sample (Wk16685) by Accelerator Mass Spectrometry (AMS). Radiocarbon dates were calibrated

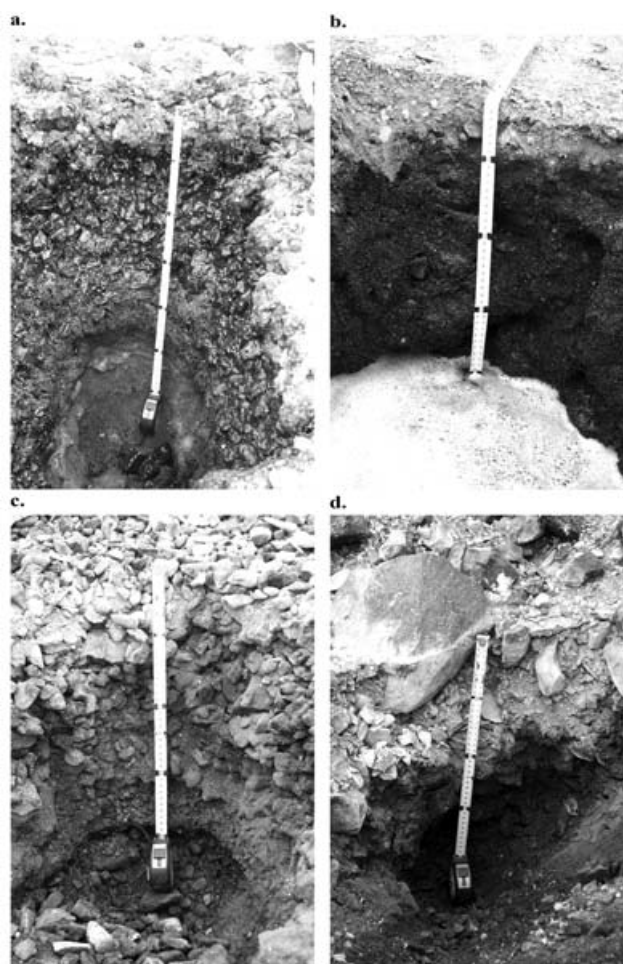


Fig. 10. Soils at Cape Hallett. **a.** mounds currently colonized by penguins (Unit 1), **b.** intermound areas of currently colonized penguin mounds (Unit 5), groundwater at 40cm, **c.** mounds previously colonized by penguins (Unit 3), **d.** moraine surfaces (Unit 9).

using the marine calibration curve of Hughen *et al.* (2004), and the program OxCal v3.10 (Bronk-Ramsey 2005), using a reservoir correction of 811 ± 102 yrs (Reimer 2005 see <http://calib.qub.ac.uk/marine>).

Results

The majority of the soils at Seabee Hook were mapped as soil associations of penguin mound and intermound areas (Figs 9 & 10) in accordance with the soil landscape model (Fig. 2). Soils not influenced by penguins (non-ornithogenic) make up the remainder of the study area and range from wetlands to steep scree slope soils. Soil map unit descriptions are included in Appendix A and further detailed information is included in Hofstee (2006).

Soils of the penguin mound associations

Ornithogenic soils at Cape Hallett were grouped into four

soil associations related to the mounds and intermounds, the angularity of gravel materials and the presence or absence of active penguin nests (Fig. 9). Mounds with currently active penguin nests (Soil Map Units 1 and 2, Fig. 10a) had a compacted layer of fresh guano in the upper 2–4 cm. From 4 cm to about 50 cm depth "penguin stones" were combined with guano, dead birds, feathers, and eggshells. Beneath the penguin influenced horizons was unweathered beach or fan-derived gravels and sands.

Not all penguin mounds at Seabee Hook were colonized every year by breeding penguins. Mounds beneath the steep scree slope (Soil Map Unit 3, Fig. 10c) were not inhabited in the 2003/04 or 2004/05 summers and aerial photos showed no penguin nests in Unit 3 since 1957. However the mounds had been colonized in the past as "penguin stones" and highly decomposed organic matter were present in the top part of the profile.

Within intermound areas (Soil Map Units 4, 5 and 6, Fig. 10b) penguins had removed "penguin stones" from the ground surface to adjacent mounds. Some guano was accumulated in intermound areas, predominantly from water runoff from the mounds and also from direct penguin introduction of guano, dead birds, feathers and eggshells. The amount of runoff and guano in the intermound areas varied in depth from minimal up to a maximum of about 5 cm. Intermound areas in the zone previously inhabited by penguins (Soil Map Unit 7) comprised basalt gravel and sand, and lacked the guano layer found in the intermound areas near active penguin nests.

Soils of the steep lands

The steep land area comprised the basalt cliffs and slopes of Cape Hallett Peninsula to the east of Seabee Hook (Fig. 2). The slope (~30°), had a number of permanent snow drifts and a small glacier. Skuas nested there during the summer. Ice cement was at a shallower depth (30–45 cm in mid January 2005) than on Seabee Hook (~80 cm in mid January 2005) probably due to greater shading received on the slope during the night.

The majority of the scree slope (Soil Map Unit 8) consisted of angular basaltic lava and scoria gravels and boulders. The slope stability varied from active fans to slightly more stable slopes, with lichen present on some more stable areas. A moraine (Soil Map Unit 9, Fig. 10d) was situated at the southern end. The moraine was likely to be a lateral moraine from glaciers progressing down Edisto Inlet during the last glaciation. The moraine was composed of locally derived, moderately weathered, angular basalt.

Soils of the plains

A low angle colluvial fan comprised the lower extension of a large fan situated on the scree slope. The lower section had very little slope (< 3°) and was therefore included with the

soils of the plain (Soil Map Unit 10). Patterned ground has formed on the surface with some patterns 1 m in diameter. Other areas of the plain had patterned ground features of around 10 m diameter.

Within the flat colluvial surface (Soil Map Unit 11) rounded basalt boulders predominated with angular boulders present on the surface, having fallen from the slope above. The series of palaeo-beach ridges at the south-eastern edge of Edisto Inlet (Soil Map Unit 12) had a similar geomorphology to the penguin mound and intermound association on Seabee Hook, but were composed of coarser gravels and boulders than those on Seabee Hook. The stones were all subrounded, indicating that they had received wave action, and therefore had not fallen directly from the scree slope.

Activities associated with Hallett Station led to extensive areas of disturbed soil at Seabee Hook (Fig. 9, Soil Map Unit 13). In some areas soil had been disturbed by bulldozing for construction of buildings and roads. Some areas, away from buildings, had been used as rubbish dumps, with soil bulldozed over garbage. Hydrocarbon spills had contaminated soil in some areas, particularly near former fuel tank and drum storage sites. During partial remediation of the site in 1987 a number of artificial penguin mounds were created with a bulldozer to encourage penguin nesting. Penguins had accepted these mounds and had re-created a new layer of "penguin stones" and guano, to a depth of 10 cm since the construction of the mounds. Beneath the "penguin stones", the bulldozed mounds comprised a mixture of aged guano, beach gravel and sand.

During much of the summer period the wetland area (Soil Map Unit 14) was saturated with meltwater, either in pools or in ephemeral streams. In areas that had no surface water, groundwater was often present within 10 cm of the soil surface. The wetland area had an abundance of mosses, lichen and algae.

Soil chemical properties

There were distinct differences in soil pH, EC and TOC and N contents between soils formed on mounds and soils formed without guano influence (Table I). Soils formed on penguin-inhabited mounds had a very high EC, very high total nitrogen and medium to high total organic carbon content. In mound soils, EC decreased to very low values of around 1–2 mS cm⁻¹ at the base of the mounds. The intermound soils had some higher EC values in the upper horizon (up to 3 mS cm⁻¹), however the EC values at the base of intermound soils were similar to EC values at the base of mound soils. In non-ornithogenic soils EC values were medium to very low (< 1 mS cm⁻¹) in the lower horizons (Table I).

Nine samples were analysed using X-Ray Fluorescence (XRF) (Table II). The two upper samples from Unit 1 (4–15 cm and 15–25 cm) were from heavily guano

Table I. Soil chemical data for Cape Hallett soil map units.

	Depth cm	pH	EC mS cm ⁻¹	Total OC %	Total N %		Depth cm	pH	EC mS cm ⁻¹	Total OC %	Total N %
Soils of the penguin mounds						Soils of the steep lands					
Formed on mounds currently colonized by penguins						Formed on scree slopes					
Unit 1	0-4	-	-	17.6	8.88	Unit 8	0-10+	-	-	5.3	1.21
	4-15	7.5	27.40	16.8	1.90	Formed on moraine surfaces					
	15-25	7.0	13.36	11.0	1.81	Unit 9	0-2	6.9	1.75	1.7	0.97
	25-55	7.3	5.21	3.2	1.59		2-20	4.7	0.55	1.0	0.55
	55-70+	7.8	0.97	3.0	0.66		20-45+	3.8	0.22	0.53	0.17
Soils of the plains						Soils of the steep lands					
Formed on colluvial fan						Formed on scree slopes					
Unit 1	0-4	5.8	23.5	9.9	12.07	Unit 10	0-2	6.1	0.34	0.89	0.23
	4-20	6.6	43.00	10.0	4.09		2-35	6.1	0.13	1.5	0.25
	20-60	6.2	32.6	11.4	3.76		35-40+	6.4	0.04	0.00	0.10
	60-70	7.6	2.72	5.5	2.40	Formed on flat colluvial areas					
	70-80	8.1	1.41	7.2	2.69	Unit 11	0-2	6.3	0.04	0.75	0.07
	80-90	8.3	0.56	0.17	0.60		2-10	6.8	0.02	1.0	0.05
	90-95+	7.4	2.26	5.9	2.99		10-50+	7.2	0.01	0.68	0.05
Formed on paleo beach ridges						Formed on paleo beach ridges					
Unit 2	0-2	-	22.80	11.2	14.53	Unit 12	0-2	6.0	0.39	0.62	0.14
	2-10	-	-	9.2	4.65		2-25+	5.3	0.12	0.21	0.00
	10-20	-	-	11.5	4.17	Soils of the plains					
	20-40	6.3	25.10	6.4	4.02	Formed on colluvial fan					
	40-50+	-	-	7.9	2.78	Unit 12	0-2	6.7	0.47	3.2	0.28
Formed on mounds previously colonized by penguins						Formed on colluvial fan					
Unit 3	0-2	-	-	8.4	2.31		2-10	5.3	0.28	0.89	0.18
	2-25	6.7	18.20	6.6	4.04		10-25	4.0	0.17	0.60	0.08
	25-35	6.9	11.31	3.6	2.62		25-65+	5.5	0.08	0.11	0.03
	35-55	7.1	-	4.1	2.09	Formed on disturbed areas					
	55-80	-	-	2.6	0.92	Unit 13	0-4	6.9	32.80	8.7	10.14
	80-100+	7.5	1.24	1.1	0.66		4-10	6.8	8.52	6.0	3.54
Formed on intermountain areas of currently colonized penguin mounds						Formed on disturbed areas					
Unit 4	0-2	7.9	2.01	13.0	2.45		10-30+	7.1	1.97	3.0	1.85
	2-4	6.7	0.41	6.4	0.65	Formed on wetlands					
	4-63+	6.9	0.67	3.8	0.53	Unit 14	0-2	4.7	0.29	2.4	0.36
Soils of the plains						Formed on wetlands					
Formed on colluvial fan						Formed on wetlands					
Unit 5	0-4	7.2	2.87	6.8	2.86		0-2	5.4	0.09	7.0	0.80
	4-10	6.4	0.56	1.6	0.43		0-2	6.4	0.10	11.2	0.95
	10-30	6.4	1.04	5.1	1.38		0-2	6.3	0.03	2.7	0.31
	30-50	7.2	1.20	1.9	3.01		0-2	6.9	0.17	1.3	0.38
	50-60+	7.0	1.83	0.94	3.05		0-2	6.8	0.29	2.9	0.46
Formed on intermountain areas of previously colonized penguin mounds						Materials of the beaches:					
Unit 6	0-5	6.4	0.97	2.2	0.44	Materials of high energy beaches					
	5-30	4.4	1.23	6.9	0.79		0-10+	6.4	0.35	0.00	0.03
	30-60+	5.8	0.59	7.0	1.01	Materials of low energy beaches					
Formed on intermountain areas of currently colonized penguin mounds						Formed on wetlands					
Unit 7	0-2	5.1	0.45	5.0	0.87		0-2	7.2	2.06	42.4	0.66
	2-5	4.9	0.25	4.9	0.94		2-20+	7.2	0.96	2.7	0.29
	5-40+	4.4	0.08	0.39	0.16	Materials of the beaches:					

impacted soil, and are effectively an analysis of the guano. The sample from the base of a Unit 1 soil profile was taken from within the subrounded basalt gravel and sand, common to all profiles on the hook.

Discussion

As all the soils at Seabee Hook have permafrost within one metre of the soil surface they are classified as Gelisols as defined by Soil Survey Staff (2003). Soils with organic matter introduced by penguins were classified as Typic

Haplorthels. At Cape Hallett the soil organic carbon content was below the 20% threshold required to classify soils as Histels, with much of the guano material present as phosphorus (12%), rather than organic carbon. Soils on abandoned penguin colonies have previously been classified as Lithic Haplorthels (Beyer *et al.* 1999). However, at Seabee Hook the abandoned colonies have been classified separately as mounds (Typic Haplorthels) and intermountains (Typic Aquorthels). Soils in the intergrade area between the mounds and intermountains, though not described in detail here, would be classified as Aquic

Table II. Results from XRF analysis (a dash indicates composition less than detection limit).

Element and dimension ppm	Unit 1 4–15 cm	Unit 1 15–25 cm	Unit 1 55–70 cm	Unit 4 2–4 cm	Unit 4 4–63 cm	Beach 0–20 cm	Unit 9 0–2 cm	Unit 9 2–20 cm	Unit 9 20–45 cm
Na%	3	2	4	4	5	5	4	4	4
Mg%	4	6	3	2	2	3	2	1	2
Al%	0	1	9	9	9	9	9	10	9
Si%	2	3	23	23	24	24	24	24	25
P%	9.8	12.3	1.1	0.8	0.7	0.4	1.4	1.4	1.2
S $\mu\text{g g}^{-1}$	12 150	11 570	590	570	590	290	760	670	690
Cl $\mu\text{g g}^{-1}$	10 500	17 300	1360	880	1030	1300	1310	900	750
K%	0.7	0.8	1.9	1.9	2.0	1.9	1.8	1.8	1.8
Ca%	9	12	6	6	6	6	6	5	5
Ti%	0.0	0.1	1.4	1.4	1.4	1.4	1.4	1.4	1.4
V $\mu\text{g g}^{-1}$	4	11	180	180	170	160	150	150	160
Cr $\mu\text{g g}^{-1}$	4	11	140	110	95	210	36	27	35
Mn%	0.0	0.0	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Fe%	1	1	8	8	8	8	8	8	9
Co $\mu\text{g g}^{-1}$	-	7	17	24	33	40	21	12	21
Ni $\mu\text{g g}^{-1}$	9	14	72	38	37	130	15	15	13
Cu $\mu\text{g g}^{-1}$	377	381	32	31	29	30	28	26	29
Zn $\mu\text{g g}^{-1}$	520	580	130	130	120	120	140	130	130
Ga $\mu\text{g g}^{-1}$	1	2	22	23	22	22	23	23	25
As $\mu\text{g g}^{-1}$	13	10	-	1	2	0	4	5	6
Se $\mu\text{g g}^{-1}$	43	41	1	1	1	-	1	1	1
Br $\mu\text{g g}^{-1}$	431	433	9	5	5	5	8	6	6
Rb $\mu\text{g g}^{-1}$	8	12	56	57	57	54	52	55	54
Sr $\mu\text{g g}^{-1}$	1440	1600	970	970	960	890	1050	1040	1090
Y $\mu\text{g g}^{-1}$	2	5	34	35	35	33	34	34	35
Zr $\mu\text{g g}^{-1}$	18	48	390	400	404	378	401	410	433
Nb $\mu\text{g g}^{-1}$	7	16	122	126	126	124	132	134	143
Mo $\mu\text{g g}^{-1}$	1	2	5	6	6	5	5	5	6
Ag $\mu\text{g g}^{-1}$	13	13	-	-	-	-	-	-	-
Cd $\mu\text{g g}^{-1}$	16	14	-	-	-	-	-	-	-
Sn $\mu\text{g g}^{-1}$	23	16	-	-	-	-	-	-	-

Haplorthels because of their high water table. Soils formed away from penguin mound associations at Seabee Hook were classified as Typic Haplorthels, and one soil (Unit 10) that was formed on patterned ground was classified as a Typic Haploturbel. All the soils at Cape Hallett were classified at the family level as fragmental, mixed, hypergelic.

The soil EC was higher in soils formed from guano (generally about 15 mS cm⁻¹) than in mineral soils (< 1 mS cm⁻¹, Table I). Mound soil ECs were similar to those reported at Cape Royds (18 mS cm⁻¹, Ugolini 1972). The organic carbon values were high (up to 18%) in the upper horizon of mound soils, and decreased in the lower horizons (to 1%) (Table I). Higher organic carbon contents (up to 30%) have been reported for other Antarctic ornithogenic soils (e.g. Tatur 1989) with levels of 22% reported at Cape Royds (Ugolini 1972) and 24% at Cape Bird (Speir & Cowling 1984). The organic carbon in the intermound soil varied considerably, but was higher near the surface than at the base of the profile (Table I).

Nitrogen originates from the high protein diet of the penguins (Ugolini 1972). Total nitrogen contents of up to 17% were recorded in the upper horizons of the mound soil

(Table I) that was similar to other locations around the Ross Sea region (14–16%), but considerably higher than total nitrogen reported in ornithogenic soils at King George Island (4%) (Tatur & Myrcha 1984). Nitrogen levels decreased through the soil profile to around 1% at the base. Soil profiles away from penguin influence had low nitrogen values, usually below 1% (Table I). The very low carbon:nitrogen ratio, (approximately 2), was similar to that reported in fresh guano deposits (Zdanowski *et al.* 2005). The majority of the total nitrogen is likely to be primarily in the form of ammonia (Ugolini 1972, Speir & Cowling 1984). Some loss of ammonia may have occurred during transport of samples to New Zealand, so the values reported here could be regarded as minimum values. Speir & Cowling (1984) reported that the uric acid content of ornithogenic soils was high (< 9%) at Cape Bird.

The samples from Units 4, 9 and 12 and the 55–70 cm sample from Unit 1 have signatures common to alkali basalts (R.M. Briggs, personal communication 2005) as would be expected as the samples originate either from the basaltic beach or scree materials. The abundance of sodium and chlorine in all samples was likely to have been the result of proximity to the ocean.

Phosphorus, sulphur, magnesium, calcium, arsenic, copper, zinc and cadmium were all concentrated within the guano rich Unit 1 samples compared to the basalt rich samples. Similarly high concentrations in fresh penguin guano have been previously reported (Ancora *et al.* 2002, Zdanowski *et al.* 2005).

The concentration of phosphorus within the basalt was about 1%, whereas phosphorus content of up to 12% occurred within the guano rich samples (Table I). The surface phosphorus concentrations compare to some maritime Antarctic soils where surface phosphorus concentrations of about 12% were reported at Anvers Island, Cormorant Island, and Seymour Island, all near the Antarctic Peninsula (Tatur 1989), while total P concentrations of (14%) were reported for soil materials from King George Island (Tatur & Myrcha 1984, Tatur 1989). Lower phosphorus concentrations (5–6%) have been reported for other areas of the Ross Sea (Ugolini 1972, Speir & Cowling 1984).

Cadmium levels were high in guano-derived material (14–16 $\mu\text{g g}^{-1}$) and below the detectable limit in non-guano soils. Cadmium within guano originates from high cadmium levels in upwelling Antarctic water that is ingested through the food chain by Adélie penguins (Ancora *et al.* 2002). Cadmium in fresh penguin guano was reported to be around 5.5 $\mu\text{g g}^{-1}$ by Ancora *et al.* (2002), which was lower than the cadmium found in the ornithogenic soil at Cape Hallett.

The zinc content was higher in guano rich soils than the basalt derived soil materials, with concentrations of around 500 $\mu\text{g g}^{-1}$. The zinc concentrations in guano at Cape Hallett were comparable to zinc concentrations in decomposed guano at King George Island (646 $\mu\text{g g}^{-1}$) in the maritime Antarctic (Zdanowski *et al.* 2005).

Copper content of around 400 $\mu\text{g g}^{-1}$ was reported in surface soils of King George Island, Anvers Island, Cormorant Island, and Seymour Island (Tatur 1989) and are comparable to the elevated copper found in surface soils of Cape Hallett.

Radiocarbon dates obtained for inhabited colonies around the Ross Sea region give dates much older than the dates from Cape Hallett (Speir & Cowling 1984, Heine & Spier 1989, Baroni & Orombelli 1991, 1994). Seabee Hook may have been inhabited by penguins later than other areas of the Ross Sea due to the building of Seabee Hook occurring only in the Holocene.

Conclusions

This paper reports on, and maps, the soil-landscape relationship for soils in the Seabee Hook area of Cape Hallett, Antarctica. The ornithogenic soils at Seabee Hook had high organic matter content, high electrical conductivity, and high concentrations of nitrogen, phosphorus, cadmium, zinc and copper, all due to additions

of penguin guano, dead birds, feathers and eggshells. The mineral soils comprised gravel and sand, dominated by weakly weathered basalts. The soil-landscape model (Fig. 3) is likely to be applicable to other Adélie penguin colonies on the Antarctic coast and could be tested at other sites of penguin habitation.

Seabee Hook has warmer summer temperatures and higher precipitation than many areas further south within the LGP region, allowing an extensive, thin, unconfined aquifer to develop above the ice cement during the summer (Hofstee *et al.* 2006). Compared to other locations in the Ross Sea Region, relatively active soil development occurs as a result of higher temperature and moisture as well as ornithogenic inputs. However, a relatively short time for soil formation limits the extent and development of weathering processes. The Seabee Hook spit comprises a series of beach ridges formed during the Holocene which thus constrains the maximum age of soils on the spit to less than 10 000 years. Radiocarbon dating indicates that penguins have been present on the entire spit area for at least 1000 years. Current penguin activity means that the ornithogenic soils are still actively up-building and developing. The soils on the lateral moraine at the foot of the steep slopes of the Cape Hallett Peninsula are older than 10 000 years, dating to at least the last glaciation and possibly to earlier glacial events.

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Appendix A. Soil map unit descriptions

Soil Map Unit 1

The mounds within Unit 1 were on beach ridges (Fig. 9 & Fig. 10a) and were characterized by "penguin stones" of rounded basalt gravel to a depth of about 50 cm. The surface of the mounds varied in colour during the summer as the penguin's diet changed and therefore so did the colour of the guano deposited on the soil surface. In January 2005 the ice cement was at 80 cm depth.

Typical profile description

Depth (cm)	Description
0–4	Dull orange (7.5YR 7/3) to light grey (7.5YR 8/2) dense guano, smooth distinct boundary,
4–20	Brownish black (7.5YR 2/2) to very dark reddish brown (5YR 2/4) extremely gravelly guano, sub-rounded coarse to very coarse basalt gravel "penguin stones", very sticky, wavy indistinct boundary,
20–30	Dark reddish brown (5YR 3/2), extremely gravelly guano, sub-rounded coarse to very coarse basalt gravel "penguin stones", very sticky, wavy indistinct boundary,
30–50	Brown (10YR 4/6) extremely gravelly guano, sub-rounded coarse to very coarse basalt "penguin stones", rounded basalt boulders, moderately sticky, wavy abrupt boundary,
50–80+	Reddish black (10R 1.7/1) to black (5YR 1.7/1) moderately gravelly coarse sand, sub-rounded coarse basalt gravel, rounded basalt boulders.

Soil Map Unit 2

The mounds on the fan (Fig. 9) were of "penguin stones" of locally derived angular scree. The penguin mound soils in the upper sections of the fan had a shallower penguin stone layer presumably because the higher areas are not colonized every year, or have only recently started being colonized. In January 2005 ice cement was at 50 cm.

Typical profile description

Depth (cm)	Description
0–2	Reddish brown (10R 5/4) to pale reddish brown (2.5YR 7/3) dense guano, wavy distinct boundary,
2–10	Dark reddish brown (5YR 3/2) extremely gravelly guano, angular, coarse to very coarse, basalt gravel "penguin stones", very sticky, wavy indistinct boundary,
10–20	Brown (7.5YR 3/2) extremely gravelly guano, angular coarse to very coarse basalt gravel

"penguin stones", very sticky, wavy indistinct boundary,

20–40	Dark brown (10YR 3/4) extremely gravelly guano, angular coarse to very coarse basalt gravel "penguin stones", very sticky, smooth abrupt boundary,
40–50+	Dull yellowish brown (10YR 5/4) very gravelly silt, angular very coarse basalt gravel.

Soil Map Unit 3

The 0–5 cm depth comprised clean "penguin stones" overlying guano with "penguin stones" to a depth of 50 cm (Fig. 9 & Fig. 10c). The guano was dry and decomposed with bird remains limited to feathers and bone material. Some relict mounds close to currently habited mounds did have some darker sticky guano material present, they lacked the compacted guano present on the surface at the inhabited sites. The clean gravels on the surface of formerly inhabited mounds indicate that compacted guano on the surface was washed off the surface stones by meltwater. The guano within the abandoned mounds had decomposed to a uniform colour and consistency. In January 2005 ice cement was at 80 cm.

Typical profile description

Depth (cm)	Description
0–2	Reddish black (2.5YR 2/1) sub-rounded basalt gravel "penguin stones" pavement, irregular indistinct boundary,
2–12	Dark reddish brown (5YR 3/4) extremely gravelly guano, sub-rounded coarse to very coarse gravel "penguin stones", wavy indistinct boundary,
12–55	Very dark reddish brown (5YR 2/4) extremely gravelly guano, sub-rounded coarse to very coarse gravel "penguin stones", smooth sharp boundary,
55–80+	Reddish black (2.5YR 2/1) slightly gravelly coarse sand, sub-rounded coarse gravel, sub-rounded boulders.

Soil Map Unit 4

The soils of Unit 4 occur in the intermound areas on the main section of Seabee Hook (Fig. 9 & Fig. 10b). The majority of the soil is the unweathered beach gravel and sand. The upper part comprised of a thin (< 2 cm) layer of guano. In January 2005 ice cement was at 63 cm and the water table was at 45 cm.

Typical profile description

Depth (cm)	Description
0–2	Dull yellowish orange (10YR 6/3) slightly gravelly dense guano, reddish black (10R 1.7/1) coarse sand, sub-rounded medium basalt gravel, wavy abrupt boundary,
2–4	Yellowish grey (2.5Y 5/1) very gravelly guano, reddish black (10R 1.7/1) sub-rounded medium to coarse basalt gravel, irregular diffuse boundary,
4–63+	Reddish black (10R 1.7/1) to black (5YR 1.7/1) very gravelly coarse sand, sub-rounded medium to coarse basalt gravel, sub-rounded basalt boulders.

Soil Map Unit 5

Unit 5 (Fig. 9) comprised layers of guano-dominant and gravel-dominant material to a depth of 60 cm (ice cement in January 2005). Gravel dominated layers appeared to be a result of storms where wave action deposited gravelly sand over guano runoff. Between storm events, runoff from mounds builds up a guano rich horizon. In January 2005 ice cement was at 60 cm.

Typical profile description

Depth (cm)	Description
0–4	Light grey (2.5Y 8/2) to brownish black (5YR 2/1) to dull yellowish brown (10YR 5/3) very slightly gravelly dense guano, coarse sand, sub-rounded very coarse basalt gravel, smooth abrupt boundary,
4–10	Brownish black (5YR 2/1) coarse sand, 5% guano, wavy abrupt boundary,
10–30	Dull yellow (2.5Y 6/4) slightly gravelly guano, 50% coarse black (7.5YR 2/1) sand, sub-rounded basalt boulders, wavy abrupt boundary,
30–50	Black (7.5YR 2/1) slightly gravelly coarse sand, 20% dull yellow (2.5Y 6/4) guano, sub-rounded basalt boulders, smooth abrupt boundary,
50–60+	Dull yellowish brown (10YR 5/4) guano, 30% coarse black (7.5YR 2/1) sand.

Soil Map Unit 6

The intermound areas on the fan (Fig. 9) contained angular gravel and cobble material. In January 2005 ice cement was at 60 cm.

Typical profile description

Depth (cm)	Description
0–5	Light grey (2.5Y 7/1) extremely gravelly dense guano, black (7.5YR 2/1) angular medium to very coarse basalt gravel, wavy indistinct boundary,
5–30	Dull yellowish orange (10YR 6/3) extremely gravelly silt, angular medium to very coarse basalt gravel, angular basalt boulders, wavy indistinct boundary,
30–60+	Dull yellowish orange (10YR 6/4) extremely gravelly silt, angular medium to very coarse basalt gravel, angular basalt boulders.

Soil Map Unit 7

The intermounds of Unit 7 occur below the steep scree slope in an area which receives meltwater runoff from the scree slope during the summer (Fig. 9). In January 2005 ice cement was at 60 cm and water table was at 45 cm.

Typical profile description

Depth (cm)	Description
0–3	Brownish grey (10YR 5/1) sub-rounded very coarse basalt gravel pavement, sub-rounded basalt boulders, moss, algae and penguin eggshell, wavy indistinct boundary,
3–60+	Black (5YR 1.7/1) extremely gravelly coarse sand, sub-rounded coarse to very coarse basalt gravel.

Soil Map Unit 8

The angular basalt on the scree slope (Fig. 9) had minimal weathering, with some sandy material present below 5 cm. In January 2005 ice cement was at 30 cm.

Typical profile description

Depth (cm)	Description
0–5	Brownish grey (7.5YR 4/1) moderately gravelly medium to coarse sand, medium to very coarse angular basalt gravel, wavy diffuse boundary,
5–30+	Brownish grey (7.5YR 4/1) very gravelly medium to coarse slightly sandy loam, very coarse angular basalt gravel.

Soil Map Unit 9

Silt sized material comprised up to 10% of the < 2 mm fraction within the moraine profile (Fig. 9 & Fig. 10d). The

silt material was lighter in colour, distinguishing the moraine from the surrounding scree slope. In January 2005 ice cement was at 45 cm.

Typical profile description

Depth (cm)	Description
0–2	Light grey (7.5YR 8/1) extremely gravelly sand, skua guano, brownish black (10YR 3/2) angular basalt boulders, wavy diffuse boundary,
2–45+	Dull yellowish brown (10YR 4/3) extremely gravelly sandy loam, coarse to very coarse brownish black (10YR 3/2) angular basalt gravel.

Soil Map Unit 10

In January 2005 an ice layer (possibly a glacial layer) was present at a depth of 40 cm, with fine material accumulated above the ice (Fig. 9).

Typical profile description

Depth (cm)	Description
0–2	Dark brown (7.5YR 3/3) very coarse angular basalt gravel, indistinct smooth boundary,
2–35	Brownish black (7.5YR 2/2) extremely gravelly fine sandy loam, medium to very coarse angular basalt gravel, smooth indistinct boundary,
35–40+	Brown (7.5YR 4/3) slightly gravelly fine sandy loam, medium angular basalt gravel.

Soil Map Unit 11

The large angular boulders on the surface and the lack of relief distinguishes Unit 11 from surrounding areas (Fig. 9). In January 2005 ice cement was at 60 cm.

Typical profile description

Depth (cm)	Description
0–2	Black (10YR 1.7/1) very coarse sub-rounded basalt gravel, very coarse angular basalt gravel, angular basalt boulders, wavy indistinct boundary,

2–60+	Black (10YR 2/1) moderately gravelly coarse sand, very coarse sub-rounded basalt gravel, sub-rounded basalt boulders.
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Soil Map Unit 12

The areas of higher relief of the hummocky topography had considerable amounts of fine material (up to 30% silt) to a depth of 10 cm (Fig. 9). The fine material was possibly organic matter added from the numerous skua nests in the area. Skua guano was re-precipitated on the underside of some boulders. In January 2005 ice cement was at 70 cm and the water table was at 65 cm.

Typical profile description

Depth (cm)	Description
0–2	Reddish black (10R 1.7/1) sub-rounded basalt boulder pavement, medium to very coarse sub-rounded basalt gravel, wavy distinct boundary,
2–10	Brownish black (5YR 2/2) very gravelly loamy sand, very coarse sub-rounded basalt gravel, sub-rounded basalt boulders, wavy distinct boundary,
10–65+	Reddish black (10R 1.7/1) medium to very coarse sub-rounded basalt gravel, sub-rounded basalt boulders.

Soil Map Unit 13

Disturbed areas comprised a range of soils modified by human activities. The soil properties varied depending on the nature of the disturbances which included bulldozing for construction of buildings and roads, rubbish dumps with soil bulldozed over garbage, hydrocarbon contaminated soil and artificial penguin mounds created with a bulldozer to encourage penguin nesting. Penguins had accepted these mounds and had re-created a new layer of "penguin stones" and guano, to a depth of 10 cm between the 1987 construction of the mounds and soil sampling in 2005. Beneath the "penguin stones", the bulldozed mounds comprised a mixture of aged guano, beach gravel and sand.

Soil Map Unit 14

In order to prevent damage to the plants in such an environmentally sensitive wetland area soil excavation and descriptions were not undertaken.