SOILS AND HYDROLOGY OF SEABEE HOOK, CAPE HALLETT, ANTARCTICA.

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Abstract

The soils and hydrology of Seabee Hook, Cape Hallett, Antarctica were investigated during the 2003-04 and 2004-05 summer periods. Seabee Hook is a low lying spit that has been built up by the deposition of material, from nearby cliffs, by strong tidal currents. Seabee Hook is also the location of a large Adelie penguin (*Pygoscelis adeliae*) colony and was the location of a USA/NZ research base, occupied from 1957-73.

A soil map is presented of the Seabee Hook area. A soil association was identified between penguin mounds and intermound areas. Penguins build nests of stones on elevated sites, which at Cape Hallett are relict beach ridges. The penguins have exaggerated the topography of the beach ridges, primarily by adding 3–10 cm size stones ("penguin-stones") and guano, to form penguin mounds. Soils on penguin mounds contain guano in the upper 50 cm of the gravelly and sandy profile, and the guano layer overlies sub-rounded beach-deposited gravel and sand. Soils between beach ridges contain a thin veneer (<3 cm) of guano overlying the same basaltic gravelly sand found in the lower parts of the mound soils. The soils formed on the mounds have been classified using USDA Soil Taxonomy as Typic Haplorthels, and the soils formed between mounds have been classified as Typic Haplorthels/Typic Aquorthels depending on their soil moisture contents.

The soil of the penguin mounds was enriched in many elements including nitrogen, organic carbon, phosphorus, cadmium, zinc, copper and it had increased electrical conductivity in soil horizons influenced by penguin guano compared to guano free horizons, soils from intermound areas, and soils away from the penguin colony.

Radiocarbon dates from five penguin bones buried at the bottom of soil profiles indicate that Seabee Hook has been colonized by penguins for at least 1000 years. That the colonization of Seabee Hook may have been rapid is evidenced by the consistent thickness of "penguin stones" and guano on top of the beach ridges throughout the area.

Groundwater was situated perched above the ice cement as a shallow (<1–30 cm thickness of groundwater) unconfined aquifer. Groundwater within the penguin colony was sourced from melting snow drifts and ground ice. The occurrence of groundwater within the penguin colony at Seabee Hook showed considerable spatial and temporal variations over the 2003-04 and 2004-05 summers, with ice cement levels decreasing from November and groundwater beginning to accumulate in early-December. Groundwater velocity through the permeable gravel and sand (porosity 23–33%) was up to 7.8 m day^{-1}, with hydraulic conductivities of 5×10^{-4} m s^{-1} to 5×10^{-9} m s^{-1}. Groundwater abundance varied on an annual basis depending on the amount of snowmelt occurring during summer. The 2003-04 summer had a higher water table within the penguin colony than the 2004-05 summer. During 2003-04, surface water commonly occurred as ephemeral and intermittent streams and ponds. During 2004-05, water was mostly confined to groundwater within the penguin colony, where it occurred in topographic lows. Surface water was present in only a few ponds within the colony during 2004-05, and was more common in the high meltwater zones away from the penguin colony.

The penguins and close proximity to the ocean have affected the groundwater chemistry, with groundwater in the penguin colony elevated in salt (14 times more sodium, 41 times more potassium), nitrogen (7 times more nitrate, 416 times more ammonia), and phosphorus (33 time more total phosphorus) compared to groundwater sourced away from the penguin colony on Seabee Hook and also compared to other terrestrial waters in Antarctica.

Acknowledgments

Firstly I need to thank my academic supervisors Megan Balks and Dave Campbell for doing a fantastic job at covering my writing attempts in red pen, always being encouraging, and for giving me the opportunity to do research in the amazing Antarctic continent. The experiences I gained at Cape Hallett won't be easily forgotten.

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Chapter 1
Introduction

Antarctic soil

A lack of ice cover is a prerequisite for the development of soils in Antarctica, and occurs in coastal areas, mountaintops and cold desert regions (Beyer *et al.* 1999). Antarctic soils are usually characterised by a stony profile with poorly developed horizonation. The combination of a lack of significant biological activity, low average temperatures and low moisture content reduces the rate of weathering (Campbell & Claridge 1982).

Increases in water content, temperature and organic matter content within a soil lead to an increase in the rate of soil formation processes, leaving a more developed soil profile. Areas of lower latitude and close proximity to the coast generally have higher rates of soil formation, due to higher air and soil temperatures, and water contents (Beyer *et al.* 1999).

Although organic matter content is very low in many Antarctic soils, there are specific cases where organic matter content is high. Soils located on the coast where seabirds bring ashore organic matter in the form of guano, bird remains, feathers and egg shells have a higher organic matter content than other Antarctic soils (Orchard & Corderoy 1983). The organic matter brought ashore by penguins form the most significant additions of organic matter added to any Antarctic soil (Campbell & Claridge 1987).

Penguins on the Antarctic continent nest in colonies, at sites which are used year after year. Adelie penguin (*Pygoscelis adeliae*), colonies are located on ice free areas, with sufficient stones present to build nests, and within walking distance of the open ocean. Adelie penguins alter the topography of the landscape by moving stones to exaggerate higher elevated areas for nest building, and subsequently adding guano to the nesting areas.

Syroechkovsky (1959) was the first to suggest the name, ornithogenic soils, which is now commonly used to describe soils which are heavily influenced by ex-situ organic material, derived from birds in all climate regions.

Antarctic hydrology

The mean annual temperature throughout Antarctica is below 0°C, (Campbell & Claridge 1987) and therefore water in Antarctica is usually frozen. During a short period in the austral summer, 24 hour solar radiation allows temperatures to increase sufficiently for meltwater generation (Campbell & Claridge 1987).

In coastal environments meltwater is often sourced from snowdrifts and ground ice. If meltwater is in sufficient volumes it can percolate through the soil and accumulate above the ice cement to form a perched shallow, unconfined aquifer. Groundwater may flow above the ice cemented layers during the summer months until it refreezes with the onset of winter. While flowing, the groundwater potentially carries nutrients, or in some cases contaminants, to other areas of soil, the ocean, a lake or stream (Snape *et al.* 2001).

Cape Hallett

Cape Hallett (72°19'S 170°16'E) is located on the southern side of Moubray Bay, in northern Victoria Land, along the western Ross Sea coast (Figure 1). Seabee Hook is located near the end of Hallett Peninsula, and encloses Willett Cove (Figure 2).

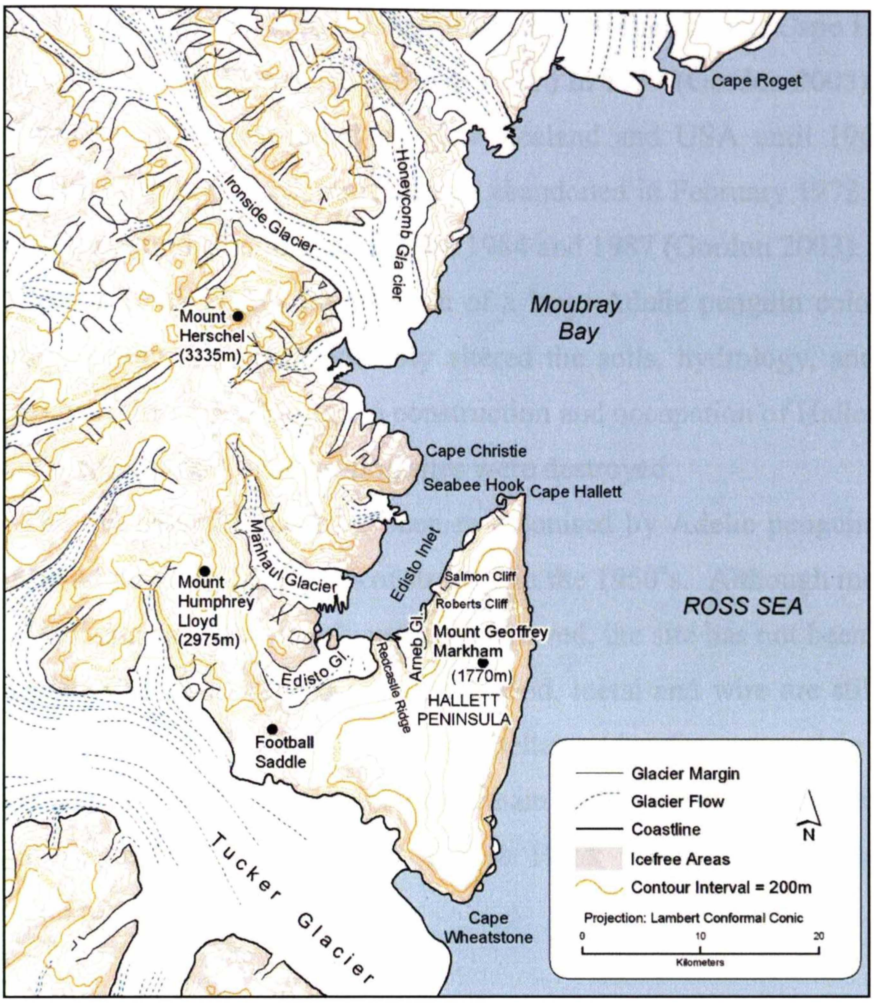

Figure 1: Seabee Hook and Cape Hallett in northern Victoria Land. (Source: www.lgp.aq)

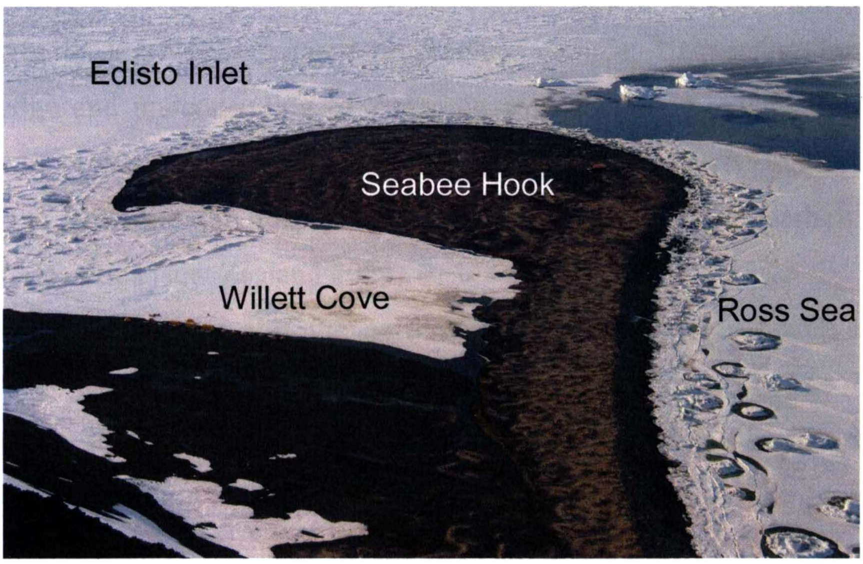

Figure 2: Seabee Hook as viewed from Cape Hallett Peninsula (Photo: D. Campbell)

A base (Hallett Station) was established on Seabee Hook, Cape Hallett, as part of the International Geophysical Year (IGY) in 1957 (Gordon 2003). Hallett Station was occupied year-round by New Zealand and USA until 1964, when summer only operations were run, and was abandoned in February 1973, with the removal of most of the buildings between 1984 and 1987 (Gordon 2003).

Seabee Hook is also the location of a large Adelie penguin colony. The presence of penguins has considerably altered the soils, hydrology, and general morphology of the area. During the construction and occupation of Hallett Station a large area (~2 ha) of Adelie nesting sites were destroyed.

The old base site has now been re-colonised by Adelie penguins, which were present before the base was constructed in the 1950's. Although most of the physical indications of the base have been removed, the site has not been returned to an undisturbed state. Debris including wood, metal and wire are still present around Seabee Hook, along with a large fueltank (due for removal in 2005-06 summer). Hydrocarbons from fuel spills remain within the soils near the old base site, and the meltwater present at Seabee Hook presents a mechanism for distribution of the contaminants.

Reasons for study

This study is part of a Landcare Research led Antarctic research programme investigating the environmental protection of Antarctic soils. The objectives of the K123 research programme include; "increasing fundamental knowledge and understanding of Antarctic soils including soil distribution and climate, microbial diversity, and vulnerability to human impacts" and "developing mitigation strategies for management and remediation of hydrocarbon spills on soils" (Antarctica New Zealand 2004).

Seabee Hook is also the northern-most location for research under the Latitudinal Gradient Project (LGP) (www.lgp.aq) (Figure 3). The LGP is a project run in conjunction with Antarctica New Zealand, the United States Antarctic programme, and the Italian Antarctic programme. The LGP aims to research changes that occur in the environment along a latitudinal gradient in the Ross Sea region by understanding the complex ecosystems that exist along the Victoria Land coast and determining the effects of latitudinal change on these ecosystems. The LGP provides a framework under which multidisciplinary and international projects can be carried out. The LGP has a number of key questions of which two are addressed in this thesis.

1. To what extent does soil development (e.g. degree of weathering, carbon content and nutrient accumulation) change with latitude and therefore influence terrestrial ecosystems?
2. How does climate affect the availability of free water and how does this change in space and time?

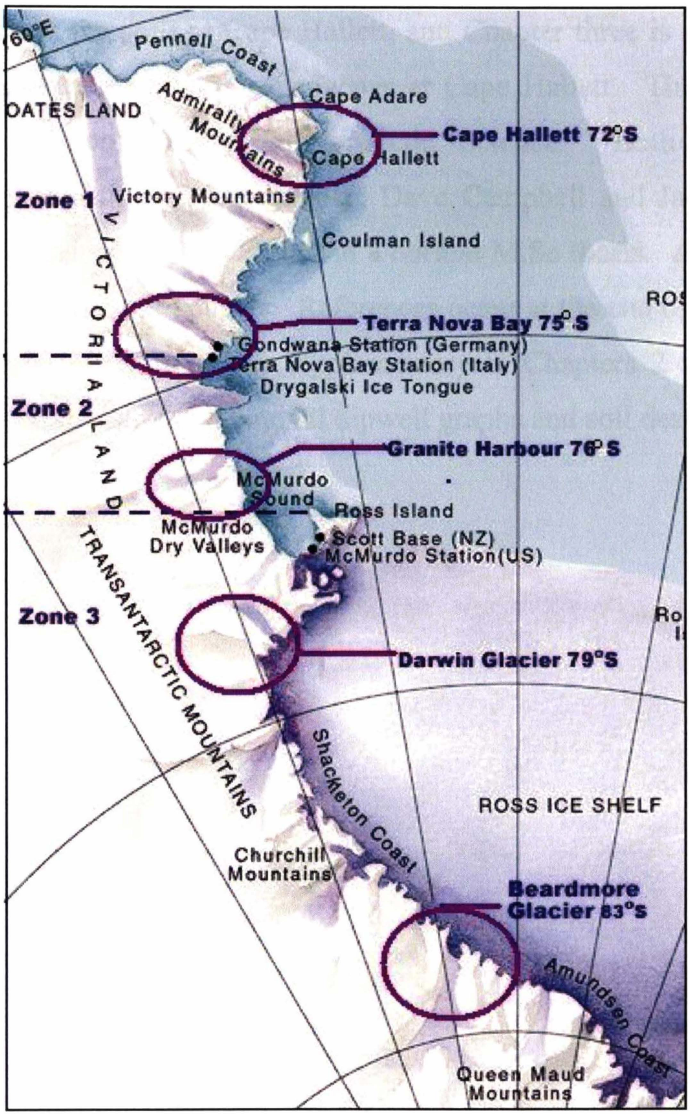

Figure 3: Proposed study locations for the Latitudinal Gradient Project. Cape Hallett is the northern most location (Source: www.lgp.aq).

Thesis objectives

The objectives of this thesis were to:

1. Complete a detailed soil map of the Seabee Hook area of Cape Hallett.

2. Characterise the soils from the Cape Hallett area.
3. Determine the spatial and temporal extent of meltwater at Seabee Hook, including meltwater sources, seasonal water table and ice-cemented permafrost variations, groundwater flow direction, flow speed variations and groundwater chemistry.

Organisation of Thesis

The core of this thesis is two papers. Chapter two is a paper which describes and maps the soils at Cape Hallett, and Chapter three is a paper which describes and characterizes the groundwater at Cape Hallett. The papers have been submitted for publication in Antarctic Science. Both papers have contributions of co-authors, Megan Balks, Dave Campbell and Jackie Aislabie, who acted as supervisors as they would in a normal M.Sc thesis. A final chapter draws conclusions from both papers. References occur at the end of each chapter. Five detailed appendices give data supplementary to Chapters 2 and 3 for soil chemistry, tracer tests, carbon dating, all dipwell graphs and soil descriptions.

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Chapter 2
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 tidal currents depositing basalt material from nearby cliffs. Seabee Hook is the location of an Adelie penguin (*Pygoscelis adeliae*) colony which influences the soils with additions of guano, dead birds, eggshells and feathers. A soil association was identified between the soils formed on relict beach ridges (Typic Haplorthels), favoured by penguin nests and the soils in the areas between the beach ridges (Typic Haplorthels/Typic Aquorthels). Soils formed on the relict beach ridges contain guano in the upper 50 cm, overlying sub-rounded beach-deposited gravel and sand. Soils between beach ridges contain a thin veneer (<3 cm) of guano overlying the same basaltic gravelly sand found in the lower parts of the mound soils.

Chemical analysis shows high concentrations of nitrogen, organic carbon, phosphorus, cadmium, zinc, copper and increased electrical conductivity within soil horizons influenced by penguin guano.

Five buried penguin bones were collected from the bottom of soil profiles and radiocarbon dated. The dates indicate that Seabee Hook has been colonized by the penguins for at least 1000 years.

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). At the end of the Cape Hallett peninsula a spit has formed from basalt debris derived from the nearby cliffs (Figure 1). Strong tidal currents deposit the basalt material to build the spit. Seabee Hook is the location of an Adelie penguin (*Pygoscelis adeliae)* colony and was the site of a USA/NZ base from 1957–73.

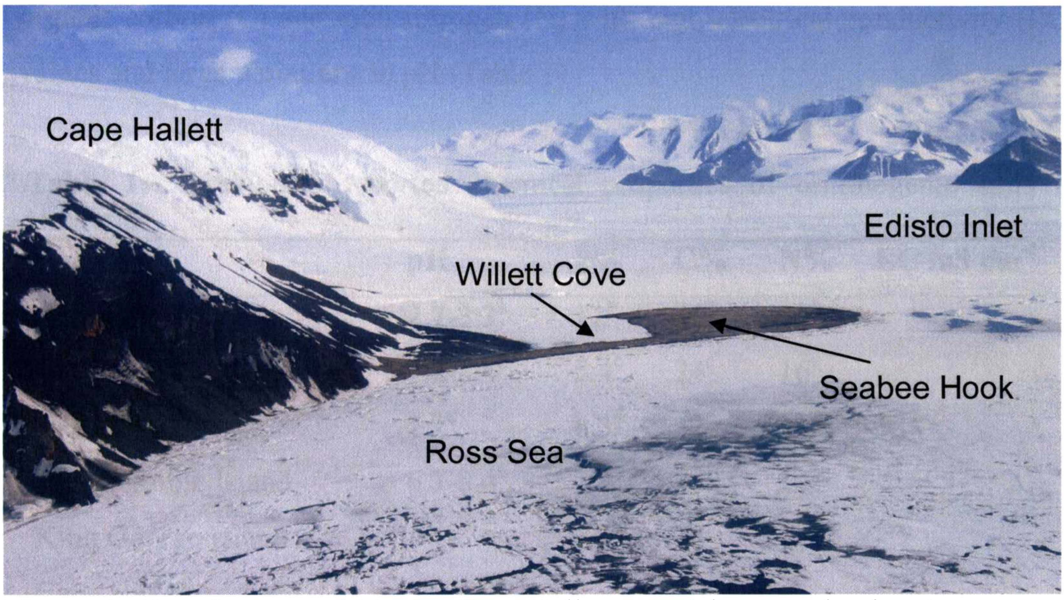


Figure 1: Key features within the Cape Hallett area (photograph taken in December 2004 looking towards the south).

Soils in Antarctica form in ice-free areas, the largest of these areas being the McMurdo Dry Valleys. The first Antarctic soils mapped were within the Taylor Valley (McCraw 1967). The soils within the Cape Hallett area were first described by Campbell & Claridge (1968).

Soils within Antarctic penguin colonies are described as ornithogenic, due to the presence of organic materials including, guano, dead birds, feathers and egg shells (Syroechkovsky 1959). Ornithogenic soils have been studied near the Polish base on King George Island (Pietr *et al.* 1983, Tatur & Myrcha 1983, Tatur & Myrcha 1984, Myrcha *et al.* 1985, Tatur & Barczuk 1985, Tatur 1989, Myrcha & Tatur 1991, Tatur *et al.* 1997, Juchnowicz-Bierbasz & Rakusa-Suszczewski 2002, Tscherko *et al.* 2003, Zdanowski *et al.* 2005). The ornithogenic soils on the sub-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 some work near Casey Station (Roser *et al.* 1993).

Soils in 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 (Table 1).

Table 1: Previously reported chemical properties of ornithogenic soils in Antarctica.

Location	pH	P%	C%	N%	EC mS cm^{-1}
Anvers Island	2.7-3.3[a]	12[b]	30[b]	30[b]	-
Cape Bird	7.2-8.4[c]	5.4[c]	24[c]	16[c]	-
Cape Royds	7.2[d]	6.3[d]	22[d]	11.6[d]	18[d]
Inexpressible Island	6.7-8.4[e]		17.5[e]	14[e]	-
King George Island	-	14[b/f]	18[f]	7[f]	-
Cape Hallett scree	5.3-6.9[g/h]	-	-	-	-
Cape Hallett ornithogenic	7.4[g/h]	-	-	-	-

a- Juchnowicz-Bierbasz & Rakusa-Suszczewski 2002. b- Tatur 1989. c- Speir & Cowling 1984. d- Ugolini 1972. e- Campbell & Claridge 1966. f- Tatur & Myrcha 1984. g- Claridge 1965. h- McCraw 1967.

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

Microbiological activity is higher in ornithogenic soils compared to non-ornithogenic soils in maritime Antarctica (Tscherko *et al.* 2003). The enzyme activity and biomass of ornithogenic soils was higher near penguin colonies in a transect which included both ornithogenic and non-ornithogenic soils at King George Island (Tscherko *et al.* 2003). At Admiralty Bay, total bacterial biomass ranged from 594 µg C g^{-1} dry weight in fresh guano to 9101 µg C g^{-1} dry weight after 42 days exposure in situ during January (Zdanowski *et al.* 2005). CO_2 evolution was higher in ornithogenic soils at Cape Bird (Orchard & Corderoy 1983) compared to non ornithogenic soils. Increased microbial biomass was found under ornithogenic soils at the Windmill Islands (Roser *et al.* 1993) and at Cape Bird (Ramsay 1983). 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 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).

Since McCraw's map of the Taylor Valley (1967), soil mapping has not continued in Antarctica until now. In this paper we characterize and map the soils in the Seabee Hook area of Cape Hallett. The Latitudinal Gradient Project (LGP) (Howard Willams *et al.* this edition [Antarctic Science LGP Special Edition]) questions to which we are contributing is: "to what extent soil development (e.g. degree of weathering, carbon content and nutrient accumulation) changes with latitude and how it therefore influences terrestrial ecosystems" (www.lgp.aq). 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.

Methods

Soils were examined by digging pits to the depth of ice cement (approximately 80 cm at maximum thaw in early January). Soil descriptions included here were all made in January 2005 and follow guidelines given by 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 predictions. Samples were air dried in Antarctica then sealed in plastic bags for transport to a New Zealand laboratory.

A small climate station was installed at Seabee Hook over the 2004-05 season. Data were collected from the climate station from December 8 2004 until February 24 2005. Data collected at the Seabee Hook climate station included air temperature and relative humidity (Humitter 50Y Vaisala, Finland), incoming solar radiation (LI200X, LI-COR, Lincoln, NE, USA) windspeed, wind direction (A101M, W200P, Vector Instruments, Clwyd, UK), soil temperature (107 probe, Campbell Scientific, Logan, Utah) and soil moisture (Hydra soil moisture probe, Stevens Vitel Inc, Chantilly, Virginia, USA). The data was collected using a datalogger (CR10X, Campbell Scientific).

Soil pH, electrical conductivity (EC), total organic carbon and total nitrogen were measured following methods described in Blakemore *et al.* (1987). Soil samples were sieved to <2 mm. For total organic carbon and total nitrogen soils were finely ground and sieved to <0.25 mm. All chemical analyses were carried out in duplicate with the mean results reported. Full datasets are included in Hofstee (in prep) [Appendix 1].

Soil pH was measured using distilled water as a suspending medium. A soil to water ratio of 1:2.5 was used for most soils, however soils with highly absorbent organic matter needed a soil:water ratio of 1.5 to create a useable slurry. Soil pH was measured using an Orion pH meter. EC was measured by weighing a 1:5 ratio of soil to water into a centrifuge tube and shaking on an end-over-end shaker for 30 minutes. Samples were then centrifuged for 10 minutes at 3000 r.p.m. and measured using an EDT conductivity probe (model GP383).

Total organic carbon (TOC) was measured using colorimetric determination of organic carbon (Blakemore *et al.* 1987). Wet oxidation of the carbon present using dichromate was undertaken. The amount of reduced chromium was then measured using a spectrophotometer. Total nitrogen (N) was measured using the Kjeldahl digestion of Blakemore *et al.* (1987).

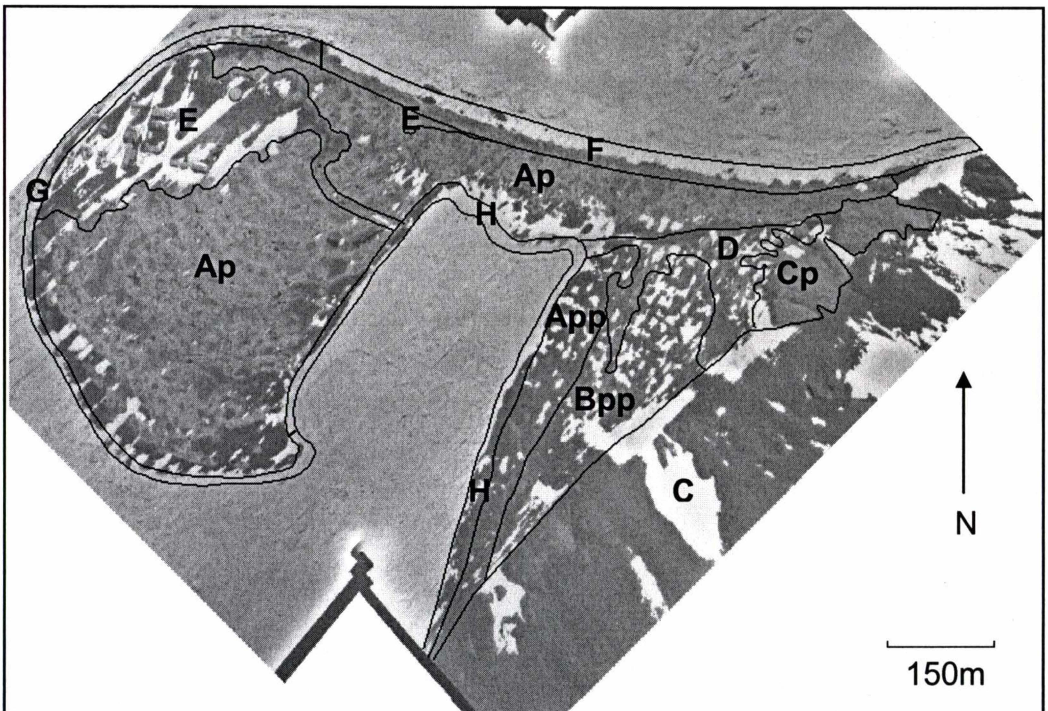
Total element analysis was carried using X-ray fluorescence (XRF). Samples were ground to very fine powder, and combined with 10–20 drops of PVA-ethanol glue to bind the sample and pressed into a disc at 620 kPa before being dried and analyzed.

Radiocarbon determinations 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 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 years (Reimer 2005).

The Environment

Physiography

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



A – Beach ridges
B – Hummocky plains
C – Steeplands
D – Wetlands
E – Disturbed by human activity
F – High energy beach
G – Medium energy beach
H – Low energy beach
p – Denotes areas with current penguin nests
pp – Denotes areas previously inhabited by penguins

Figure 2: Physiographic map of Seabee Hook.

Organisms

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. During nest building, Adelie penguins accumulate stones with a diameter of 3–10 cm, "penguin-stones", which they can carry in their beaks. The stones are used to build nests on already raised areas on Seabee Hook (Figure 3). The raised areas provide some protection from meltwater, being drier than the surrounding low-lying areas. 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 which comprise of beach gravels and sand which are depleted of 3–10 cm size stones as penguins remove them to the mound areas. The low-lying "intermounds" may have guano within the upper part of the profile, primarily from guano rich water running off nearby mounds.

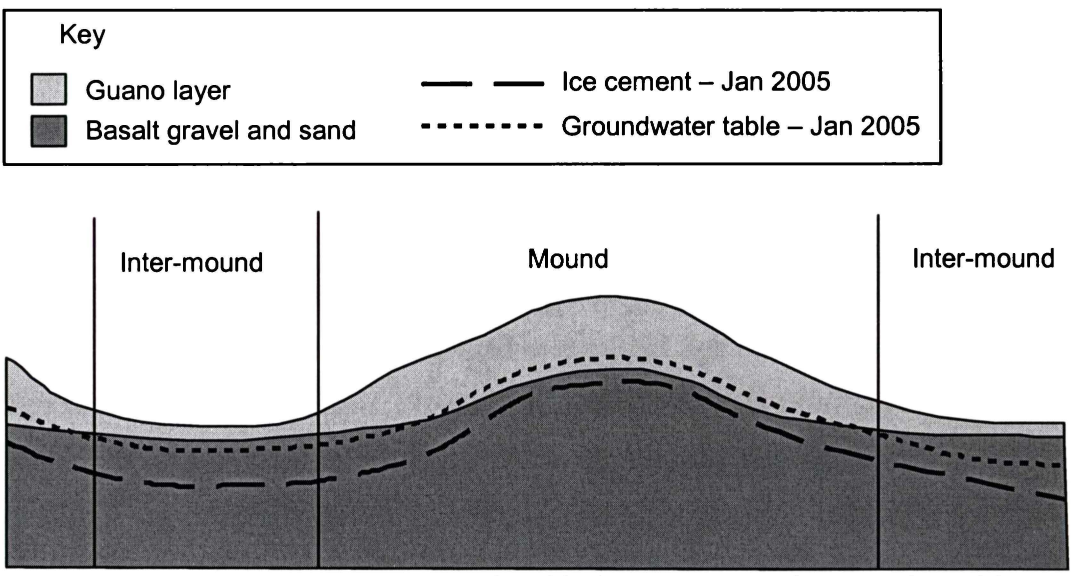


Figure 3: Schematic diagram of relationship between penguin mounds and inter-mounds at Seabee Hook.

Some non-ornithogenic areas are influenced by the mosses, lichens, and algae found in relative abundance at Seabee Hook (Rudolph 1963). Mosses are most abundant in the wetland zone near the base of the cliff (Figure 2) and contribute to the organic matter present in some soils. South Polar Skua (*Catharacta skua maccormicki*) nest at Seabee Hook, most of their nests are located 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 around their nest sites.

Parent Material

The soils mapped at Seabee Hook are 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 supplies the material of Seabee 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 originate 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 size of the gravel and sand on the beaches was influenced by the wave energy reaching each beach (Figure 4). Beaches along sheltered Willett Cove (Figure 1) have sea ice for the majority of the summer, with break out only occurring later in the summer, if at all. The Willett Cove beach is near penguin nests, allowing guano rich runoff to flow through the gravel and sand, increasing the organic content in the upper 2 cm. The lack of high energy waves mean the organic matter is not reworked and remains within the beach material. The low energy of the waves coming into the beach at Willett Cove results in a small average grain size of beach material (Figure 4). The highest energy beach was that exposed to the Ross Sea on the north east edge of Seabee Hook. The beach is exposed to high energy seas resulting from storms within the Ross Sea. During the 2004–05 season, one such storm created breaking waves approximately 8 m high. Waves of this size and larger lead to a steep beach with the occurrence of some large (>1 m diameter) boulders, and generally a large grain size (Figure 4). A medium energy beach occurs along the coast of Edisto Inlet (Figure 4).

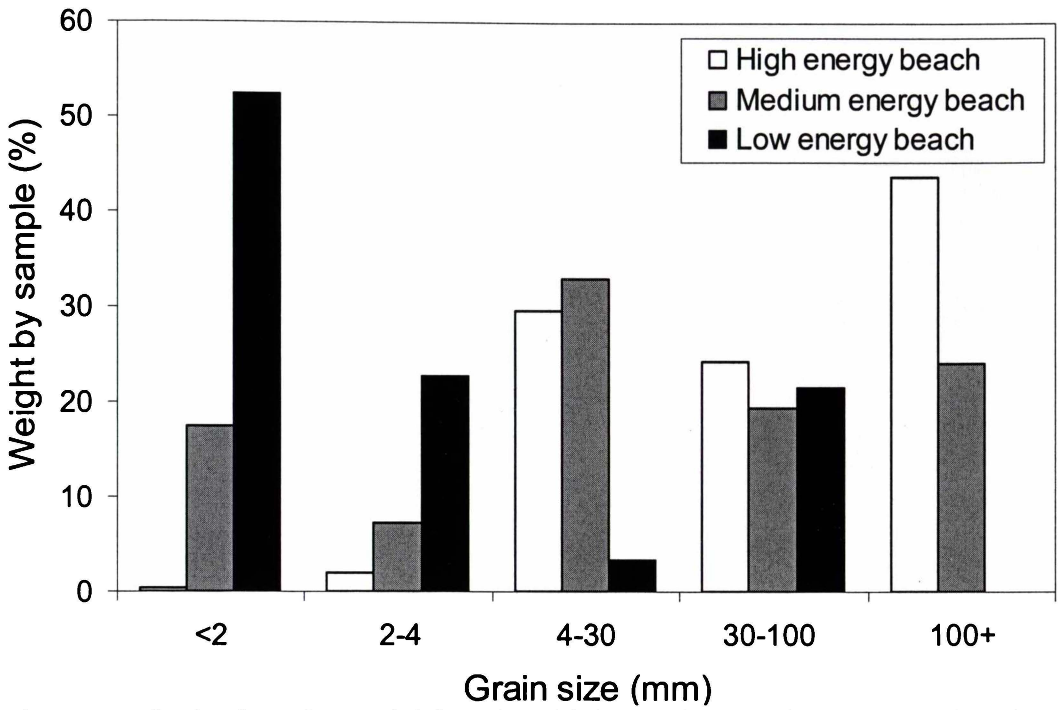
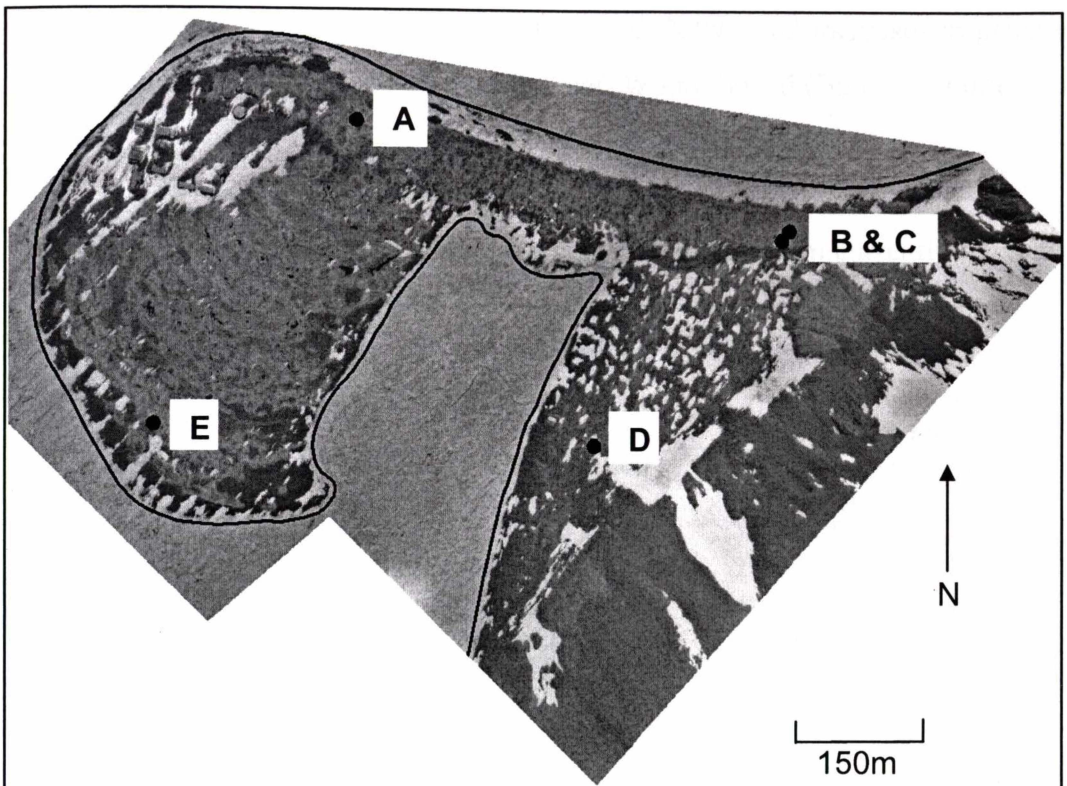


Figure 4: Grain size of material found on high, medium, and low energy beaches at Seabee Hook.

Time

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 & Orombelli 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 penguin bone and eggshell were radiocarbon dated (Figure 5).



Site	Lab. number	Depth (cm)	δ13C‰	C.R.A.[1] (yr B.P.)	Cal 68% [2] (yr B.P.)	Cal 95% [3] (yr B.P.)
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	850-100
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

Figure 5: Locations, depths and radiocarbon dates of *Pygoscelis adeliae* bones (Wk16679-85) and eggshell (Wk16678). ([1]Conventional radiocarbon age, [2]Calibrated age at 1σ, [3]Calibrated age at 2σ.)

Late colonization is supported by the presence of the oldest date, (E on Figure 5), at a relatively shallow depth of 40 cm on the geologically youngest part of the spit. The radiocarbon dates indicate that Seabee Hook was likely first colonized by penguins at least 1000 years BP (Figure 5).

Radiocarbon dates obtained for other inhabited colonies around the Ross Sea region give dates much older than the dates from Cape Hallett (Table 2). Seabee Hook may have been inhabited by penguins later than other areas of the Ross Sea due to the building of Seabee Hook occurring in the Holocene. Older dates (<24 000 years) (Hall *et al.* 2004) have been reported for abandoned penguin colonies from around the Ross Sea region, but relate to penguins leaving the Ross Sea region during the last glacial maximum and returning during the

Holocene (Baroni & Orombelli 1991, Hall *et al.* 2004), and increases in penguin population during times such as the Medieval Warm Period (Baroni & Orombelli 1994).

Table 2: Radiocarbon dates for penguin bone and guano from currently inhabited penguin colonies from Victoria Land.

Lab number	^{14}C date (yr B.P)	Location	Source
NZ5990	8080 ±160	Cape Bird	Heine & Spier 1989
NZ R384	1210 ± 70	Cape Hallett	Harrington & McKellar 1958, revised to modern by Harrington *et al.* 1967
NZ5590	7070 ± 180	Cape Bird	Speir & Cowling 1984
GX 13615	6335 ± 110	Inexpressible Island	Baroni and Orombelli 1994
QL141	5340 ± 50	Franklin Island	Baroni and Orombelli 1994
NZ6906A	4490 ± 280	Franklin Island	Baroni and Orombelli 1994

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 daily 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 (Figure 6). Similar results have been reported from the climate station installed from 1957–64, with January air temperatures frequently above 0°C (U.S. Weather Bureau 1963a, 1963b, 1964a, 1964b, 1965a, 1965b).

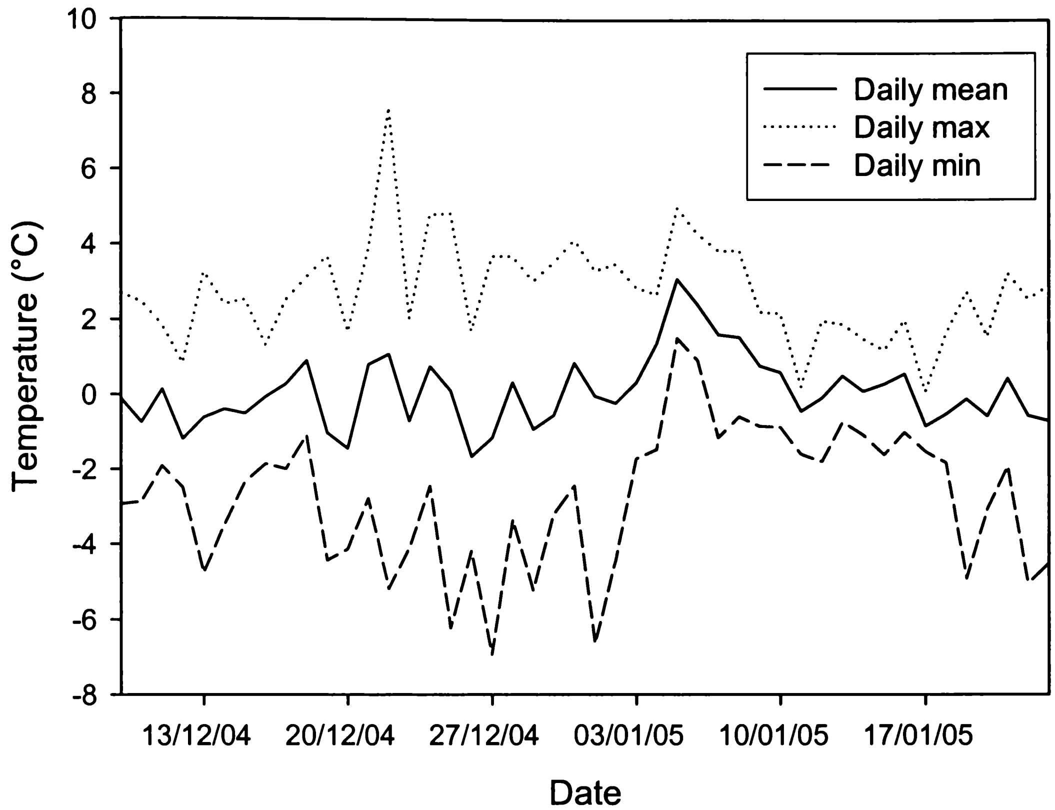


Figure 6: Daily mean, minimum and maximum air temperature at Seabee Hook from mid December 2004 to late January 2005.

Wind direction at Cape Hallett was predominantly from a SSE to WSW direction during the 2004–05 summer (Figure 7) and also during summers of 1957–64 (U.S. Weather Bureau 1963a, 1963b, 1964a, 1964b, 1965a, 1965b).

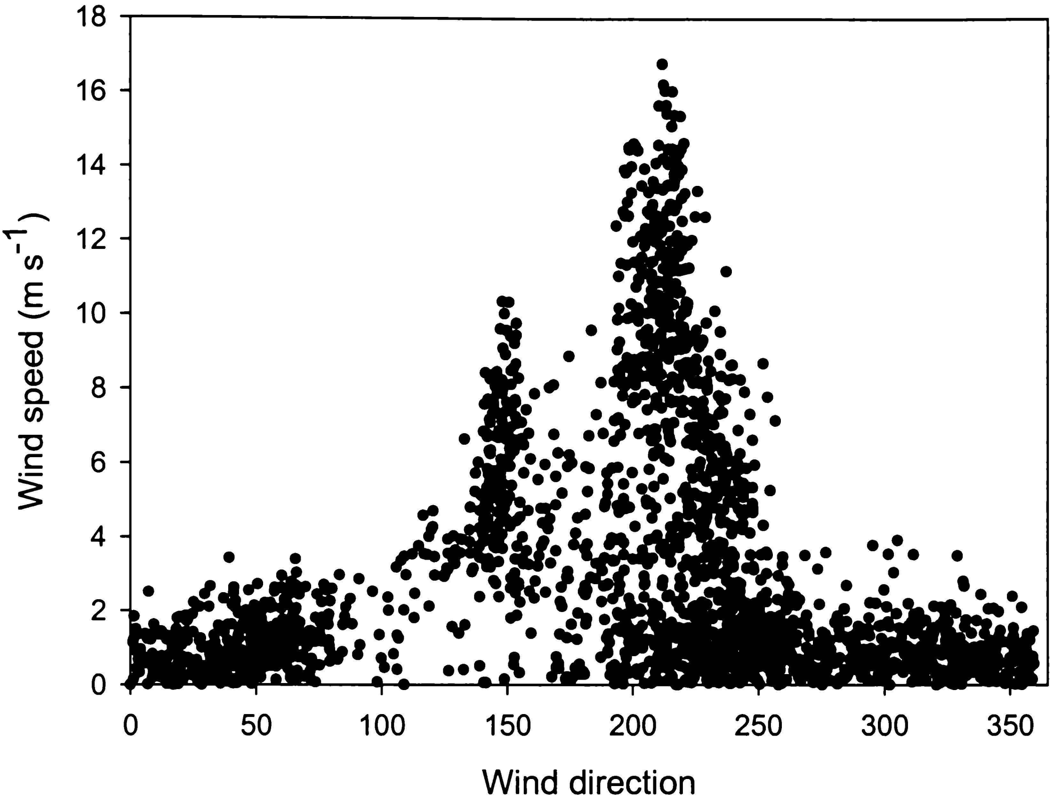


Figure 7: Wind speed and wind direction at Seabee Hook from mid December 2004 to late January 2005.

Soil temperatures from an intermound soil in January were constantly above 0°C at depth (Figure 8), allowing melt to occur and groundwater to accumulate within the soil. Meltwater within soil originates from snow drifts, ice formed within the soil and water that moves down the cliffs and across the southeastern 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 2004 and largely confined as groundwater in January 2005. The depth to ice cement was deeper at Cape Hallett (~80 cm) than locations reported in the McMurdo Sounds region, where permafrost is up to 60 cm deep (Campbell *et al.* 1997).

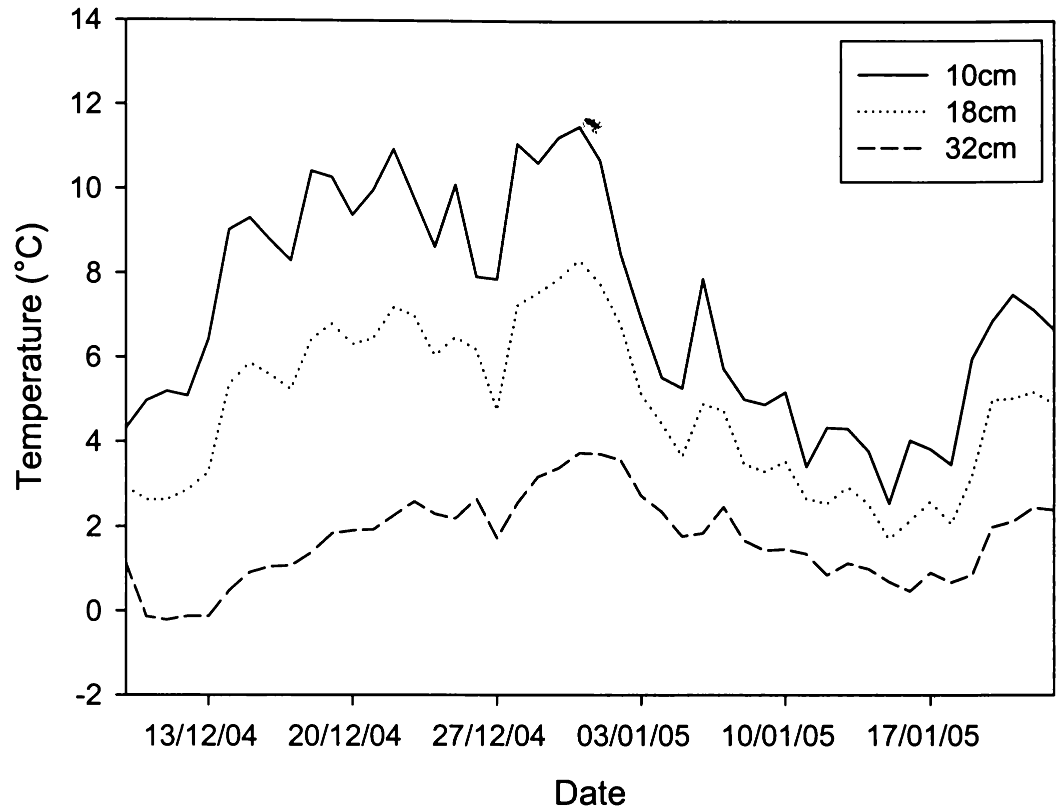
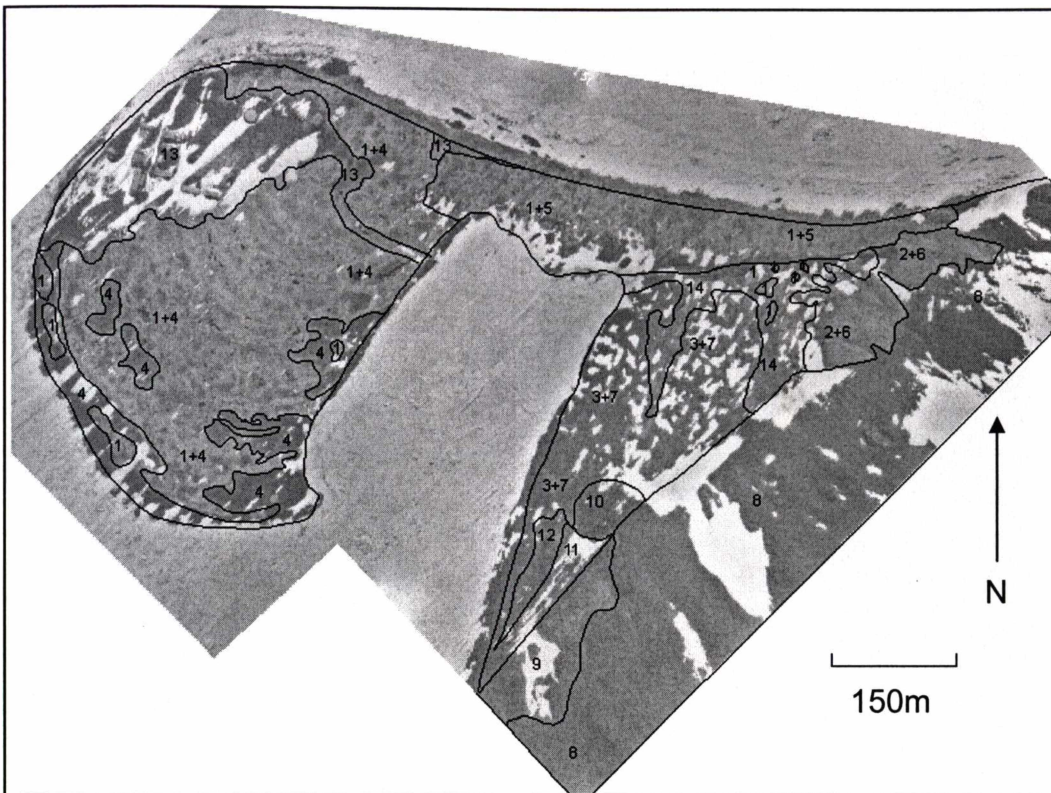


Figure 8: Daily mean soil temperatures at 10, 18 and 32 cm depth in an intermound soil at Seabee Hook from mid December 2004 to late January 2005.

Soil distribution and characterization

The majority of the soils at Seabee Hook were mapped as soil associations of penguin mound and intermound areas (Figures 9 and 10). Soils not influenced by penguins (non-ornithogenic) make up the remainder of the study area and range from wetlands to steep scree slope soils. The soil structures for all the soils described at Seabee Hook were apedal. The soils on currently inhabited penguin mounds had a massive structure in the guano-rich horizons and the remaining soil materials all had single grained soil materials. All soils at Seabee Hook are Gelisols due to the occurrence of permafrost within the first metre below the surface (Soil Survey Staff 2003). Soils with organic matter introduced by penguins have been classified following USDA soil taxonomy (Soil Survey Staff 2003) as Typic Haplorthels. 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 intermounds (Typic Aquorthels). Soils occurring between the mounds and intermounds can be classified as Aquic Haplorthels because of their high water table. Soils formed away from penguin mound associations at Seabee Hook were classified as Typic Haplothels, with one soil classified as a Typic Haploturbel. All soils at Cape Hallett have been classified to the family level as fragmental, mixed, hypergelic. More detailed descriptions of soil map units can be found in Hofstee (in prep) [Appendix 5].



Physiographic Legend		Pedalogical Legend	
Physiographic position	**Map Unit**	**Soil Order**	**Map Unit**
Soils of the penguin mound association		*Typic Haplorthels*	1,2,3,5,6 8,9,11,13
Formed on mounds currently colonized by penguins	1,2	*Typic Aquorthel*	4,7,14
Formed on mounds previously colonized by penguins	3	*Typic Haploturbel*	10
Formed on intermound areas of currently colonized penguin mounds	4,5,6		
Formed on intermound areas of previously colonized penguin mounds	7		
Soils of the steeplands			
Formed on scree slopes	8		
Formed on moraine surfaces	9		
Soils of the plains			
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		

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

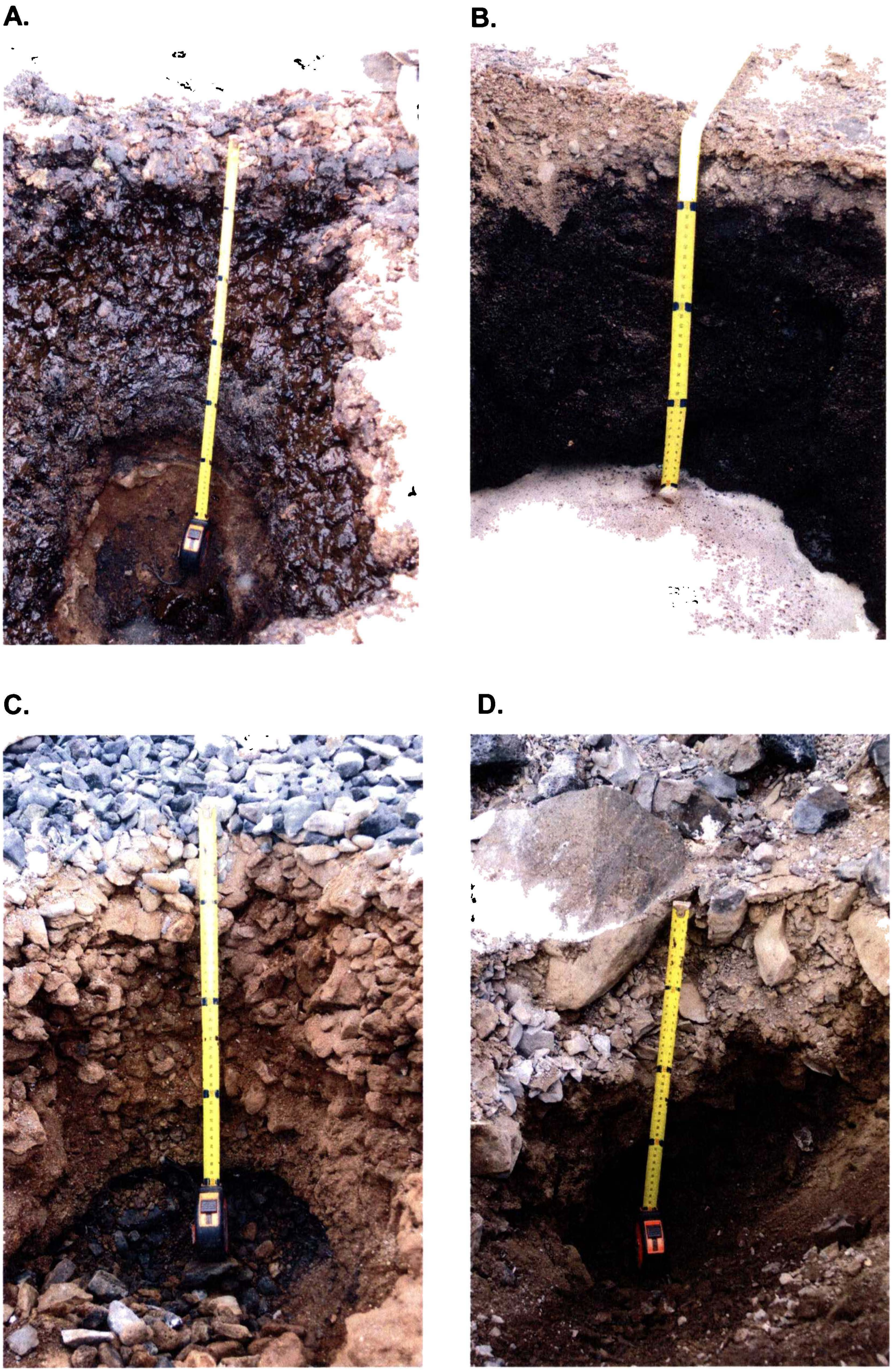


Figure 10: Soils at Cape Hallett. A–mounds currently colonized by penguins (Unit 1), B–intermound areas of currently colonized penguin mounds (Unit 5), groundwater at 40cm, C–mounds previously colonized by penguins (Unit 3), D–moraine surfaces (Unit 9).

Soils of the penguin mound association

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 (Figure 9).

Soils formed on mounds currently inhabited by penguins

Mounds with currently active penguin nests over summer 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 un-weathered beach or fan-derived gravels and sands.

Unit 1

The mounds within Unit 1 were on beach ridges (Figure 9, 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.

Unit 2

The mounds on the fan (Figure 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.

Soils formed on mounds previously inhabited by penguins

Not all penguin mounds at Seabee Hook were colonized every year by breeding penguins. Mounds beneath the steep scree slope were uninhabited in the 2004–05 summer and have been since at least 1957 as evident from aerial photos. It was evident that 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.

Unit 3

The 0–5 cm depth comprised clean "penguin-stones" overlying guano with "penguin-stones" to a depth of 50 cm (Figure 9, Figure 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 34) 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.

Soils formed on intermound areas of currently inhabited penguin mounds

Intermound areas are influenced by penguins, with "penguin-stones" exposed at the surface removed to the adjacent mounds, and some guano received mainly from water runoff from the mounds. Penguin traffic also produces some guano, and the general presence of penguins in the area provides dead birds, feathers and eggshells. The amount of runoff and guano in the intermound areas varies in depth ranging from minimal up to a maximum depth of about 3 cm.

Unit 4

The soils of unit 4 occur in the intermound areas on the main section of Seabee Hook (Figure 9, 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.

Unit 5

Unit 5 (Figure 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.

Unit 6

The intermound areas on the fan (Figure 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.

Soils formed on intermound areas of previously inhabited penguin mounds

Intermound areas in the zone previously inhabited by penguins comprised basalt gravel and sand, lacking the guano layer found in the intermound areas near active penguin nests.

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 (Figure 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.

Soils of the steeplands

The steepland area comprises the cliffs and slopes of Cape Hallett Peninsula to the east of Seabee Hook (Figure 2). Basalt covers the entire slope (~30°), with a number of large permanent snow drifts and a small glacier. Many skuas nest on the steeplands during the summer. Ice cement was at a shallower (30-45 cm in mid January 2005) depth than areas on Seabee Hook (~80 cm in mid Janurary 2005) probably due to greater shading received on the slope during the night.

Soils formed on scree slopes

The majority of the scree slope 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.

Unit 8

The angular basalt on the scree slope (Figure 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.

<u>*Soils formed on moraine surfaces*</u>

A moraine was situated on the south end of the steeplands. The moraine was likely to be a lateral moraine from glaciers progressing down Edisto Inlet during the last glaciation. The dominance of basalt in the surrounding geology created a moraine composed entirely of moderately weathered angular basalt.

Unit 9

Silt sized material comprised up to 10% of the <2 mm fraction within the moraine profile (Figure 9, 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.

Soils of the plains

<u>*Soils formed on colluvial fan*</u>

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

Unit 10

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

Soils formed on flat colluvial surfaces

The dominant material was rounded basalt boulders however angular boulders were present on the surface, having fallen from the slope above.

Unit 11

The large angular boulders on the surface and the lack of relief distinguish Unit 11 from surrounding areas (Figure 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.

Soils formed on paleo beach ridges

Paleo-beach ridge soils had a similar geomorphology to the penguin mound and intermound association occurring on Seabee Hook, but were not composed of the same sized "penguin-stones", rather, the gravel and boulders were considerably coarser grained.

The stones that make up the hummocky topography are all subrounded, indicating that they had received wave action, and therefore had not fallen directly from the scree slope.

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 (Figure 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 descriptions

Depth (cm)	Description
Mounds:	
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.

Soils formed on disturbed areas

Unit 13

Activities associated with Hallett Station led to extensive areas of disturbed soil at Seabee Hook (Figure 9). 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.

Soils formed on wetlands

During much of the summer period the wetland area was saturated with meltwater, either in pools or in ephemeral streams. In areas which had no surface water, groundwater was often present within 10 cm of the soil surface.

Unit 14

The wetland area had an abundance of mosses, lichen and algae. In order to prevent damage to the plants in such an environmentally sensitive area soil excavation and descriptions were not undertaken.

Soil chemical properties

There were distinct differences in soil pH, EC and TOC and N contents between soils formed on mounds compared to soils formed without guano influence (Table 3). Ratings for chemical properties follow Blakemore *et al.* (1987). Soils formed on penguin inhabited mounds had a very high EC, very high total nitrogen and medium to high total organic carbon content.

EC was higher in soils formed from guano than in mineral soils. EC was as high as 43 mS cm^{-1} in mound soils, however generally most mound soils had a maximum EC of around 15 mS cm^{-1} (Table 3) in the upper horizon, which is similar to EC of 18 mS cm^{-1} reported at Cape Royds (Table 1). 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 (2-<1 mS cm^{-1}) in the lower horizons (Table 3).

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 3). Other locations around the Ross Sea region have higher (>30%) organic carbon contents, and maritime soils have similar (about 18%) organic carbon contents (Table 1). The organic carbon in the intermound soil varied considerably, but was higher near the surface than at the base of the profile (Table 3). Soils on mounds have a high organic matter content, however at Cape Hallett 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.

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 3) which 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%) (Table 1). 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 3).

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.

Table 3: Soil chemical data for Cape Hallett soil map units.

	Depth (cm)	pH	EC (mS cm^{-1})	Total OC (%)	Total N (%)
Soils of the penguin mounds					
Formed on mounds currently colonized by penguins					
Unit 1	0-4	-	-	17.6	8.88
	4-15	7.5	27.40	16.8	1.90
	15-25	7.0	13.36	11.0	1.81
	25-55	7.3	5.21	3.2	1.59
	55-70+	7.8	0.97	3.0	0.66
Unit 1	0-4	5.8	23.5	9.9	12.07
	4-20	6.6	43.00	10.0	4.09
	20-60	6.2	32.6	11.4	3.76
	60-70	7.6	2.72	5.5	2.40
	70-80	8.1	1.41	7.2	2.69
	80-90	8.3	0.56	0.17	0.60
	90-95+	7.4	2.26	5.9	2.99
Unit 2	0-2	-	22.80	11.2	14.53
	2-10	-	-	9.2	4.65
	10-20	-	-	11.5	4.17
	20-40	6.3	25.10	6.4	4.02
	40-50+	-	-	7.9	2.78
Formed on mounds previously colonized by penguins					
Unit 3	0-2	-	-	8.4	2.31
	2-25	6.7	18.20	6.6	4.04
	25-35	6.9	11.31	3.6	2.62
	35-55	7.1	-	4.1	2.09
	55-80	-	-	2.6	0.92
	80-100+	7.5	1.24	1.1	0.66
Formed on intermound areas of currently colonized penguin mounds					
Unit 4	0-2	7.9	2.01	13.0	2.45
	2-4	6.7	0.41	6.4	0.65
	4-63+	6.9	0.67	3.8	0.53
Unit 5	0-4	7.2	2.87	6.8	2.86
	4-10	6.4	0.56	1.6	0.43
	10-30	6.4	1.04	5.1	1.38
	30-50	7.2	1.20	1.9	3.01
	50-60+	7.0	1.83	0.94	3.05
Unit 6	0-5	6.4	0.97	2.2	0.44
	5-30	4.4	1.23	6.9	0.79
	30-60+	5.8	0.59	7.0	1.01
Formed on intermound areas of previously colonized penguin mounds					
Unit 7	0-2	5.1	0.45	5.0	0.87
	2-5	4.9	0.25	4.9	0.94
	5-40+	4.4	0.08	0.39	0.16

	Depth (cm)	pH	EC (mS cm^{-1})	Total OC (%)	Total N (%)
Soils of the steeplands					
Formed on scree slopes					
Unit 11	0-10+	-	-	5.3	1.21
Formed on moraine surfaces					
Unit 12	0-2	6.9	1.75	1.7	0.97
	2-20	4.7	0.55	1.0	0.55
	20-45+	3.8	0.22	0.53	0.17
Soils of the plains					
Formed on colluvial fan					
Unit 13	0-2	6.1	0.34	0.89	0.23
	2-35	6.1	0.13	1.5	0.25
	35-40+	6.4	0.04	0.00	0.10
Formed on flat colluvial areas					
Unit 14	0-2	6.3	0.04	0.75	0.07
	2-10	6.8	0.02	1.0	0.05
	10-50+	7.2	0.01	0.68	0.05
Formed on paleo beach ridges					
Unit 15	0-2	6.0	0.39	0.62	0.14
	2-25+	5.3	0.12	0.21	0.00
Unit 15	0-2	6.7	0.47	3.2	0.28
	2-10	5.3	0.28	0.89	0.18
	10-25	4.0	0.17	0.60	0.08
	25-65+	5.5	0.08	0.11	0.03
Formed on disturbed areas					
Unit 16	0-4	6.9	32.80	8.7	10.14
	4-10	6.8	8.52	6.0	3.54
	10-30+	7.1	1.97	3.0	1.85
Formed on wetlands					
Unit 17	0-2	4.7	0.29	2.4	0.36
	0-2	5.4	0.09	7.0	0.80
	0-2	6.4	0.10	11.2	0.95
	0-2	6.3	0.03	2.7	0.31
	0-2	6.9	0.17	1.3	0.38
	0-2	6.8	0.29	2.9	0.46
	0-2	-	-	10.4	1.81
	0-2	-	-	5.6	0.71
Materials of the beaches					
Materials of high energy beaches					
	0-10+	6.4	0.35	0.00	0.03
Materials of low energy beaches					
	0-2	7.2	2.06	42.4	0.66
	2-20+	7.2	0.96	2.7	0.29

XRF - Total Element Analysis

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

Table 4: Results from XRF analysis (A dash indicates composition less than detection limit).

Element and Dimension	*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 ppm	12150	11570	590	570	590	290	760	670	690
Cl ppm	10500	17300	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 ppm	4	11	180	180	170	160	150	150	160
Cr ppm	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 ppm	-	7	17	24	33	40	21	12	21
Ni ppm	9	14	72	38	37	130	15	15	13
Cu ppm	377	381	32	31	29	30	28	26	29
Zn ppm	520	580	130	130	120	120	140	130	130
Ga ppm	1	2	22	23	22	22	23	23	25
As ppm	13	10	-	1	2	0	4	5	6
Se ppm	43	41	1	1	1	-	1	1	1
Br ppm	431	433	9	5	5	5	8	6	6
Rb ppm	8	12	56	57	57	54	52	55	54
Sr ppm	1440	1600	970	970	960	890	1050	1040	1090
Y ppm	2	5	34	35	35	33	34	34	35
Zr ppm	18	48	390	400	404	378	401	410	433
Nb ppm	7	16	122	126	126	124	132	134	143
Mo ppm	1	2	5	6	6	5	5	5	6
Ag ppm	13	13	-	-	-	-	-	-	-
Cd ppm	16	14	-	-	-	-	-	-	-
Sn ppm	-	-	2	2	2	1	2	2	2
I ppm	23	16	-	-	-	-	-	-	-
Ba ppm	122	149	645	670	660	610	670	680	715
La ppm	12	8	76	79	75	74	77	78	81
Ce ppm	7	17	144	149	144	134	150	151	156
Nd ppm	-	9	59	60	54	47	57	61	61
Ta ppm	-	-	8	9	11	9	7	8	8
W ppm	-	-	132	146	168	215	79	94	92
Tl ppm	3	2	1	1	1	1	-	0	-
Pb ppm	4	6	6	6	5	6	6	5	6
Th ppm	4	6	13	13	12	11	12	13	13
U ppm	-	1	3	2	4	3	2	2	2

The samples from Units 4, 9 and 12 and the 55–70 cm sample from Unit 1 have signatures common to alkali basalts (R. Briggs, pers. comm, 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, sulfur, 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 3). 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) (Table 1). Lower phosphorus concentrations (5–6%) have been reported for other areas of the Ross Sea Region (Table 1).

Cadmium levels were high in guano derived material (14–16 ppm) and below the detectable limit in non-guano soils. Cadmium within guano originates from high cadmium levels in upwelling Antarctic water which is ingested through the food chain by Adelie penguins (Ancora *et al.* 2002). Cadmium in fresh penguin guano was reported to be around 5.5 ppm 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 ppm. The zinc concentrations in guano at Cape Hallett were comparable to zinc concentrations in decomposed guano at King George Island (646 ppm) in the maritime Antarctic (Zdanowski *et al.* 2005).

Copper content of around 400 ppm 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.

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 is likely to be applicable to other Adelie 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 programme region, allowing an extensive, thin, unconfined aquifer to develop above the ice cement during the summer. 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 to the last glaciation and possibly to earlier glacial events.

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Chapter 3 Hydrological characteristics of Seabee Hook, Cape Hallett, Antarctica

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Abstract

Seabee Hook is a low lying gravel spit adjacent to Cape Hallett, in the Ross Sea Region of Antarctica and hosts an Adelie penguin (*Pygoscelis adeliae)* colony. Dipwells were inserted to monitor changes in depth to, and volume of, groundwater and tracer tests were conducted to estimate aquifer hydraulic conductivity and groundwater velocity.

During summer (November-February), meltwater forms a shallow, unconfined, aquifer perched on ice cement. Groundwater volume on Seabee Hook, away from the neighbouring cliffs, depends on the amount of snowfall as meltwater was sourced from melting snow drifts and ground ice. Groundwater velocity through the permeable gravel and sand was up to 7.8 m day^{-1}, and hydraulic conductivities of 4.7×10^{-4} m s^{-1} to 3.7×10^{-5} m s^{-1} were measured.

The Adelie penguin colony on Seabee Hook, and the close proximity of the sea, affects groundwater chemistry, with elevated concentrations of salt (1205 mg L^{-1} sodium, 332 mg L^{-1} potassium), and nutrients (193 mg L^{-1} nitrate, 833 mg L^{-1} ammonia, 10 mg L^{-1} total phosphorus) compared to groundwater sourced away from the penguin colony on Seabee Hook, and other terrestrial waters in Antarctica.

Introduction

Liquid water in terrestrial Antarctica generally occurs as a result of melting from a previously frozen water source. Coastal regions are warmer and have higher precipitation than inland areas, resulting in greater meltwater generation near the coast. Meltwater sources on land in coastal areas include glaciers, snow drifts, and ground ice. Liquid water is critical for biological life and many soil forming processes, therefore warmer and wetter coastal regions of Antarctica have the potential for more abundant and diverse flora and fauna, and relatively well developed soils.

Cape Hallett (Northern Victoria Land, Antarctica, Figure 1) is a 36 km long peninsula formed from a basalt shield volcano (Mt Geoffrey Markham) with a summit altitude of 1740 m (Harrington *et al.* 1967). Seabee Hook is a spit of land formed near the end of the Cape Hallett peninsula from basalt debris derived from the nearby cliffs and deposited by strong tidal currents. Seabee Hook is the location of an Adelie penguin (*Pygoscelis adeliae*) colony and was the site of a USA/NZ base from 1957 to 1973.

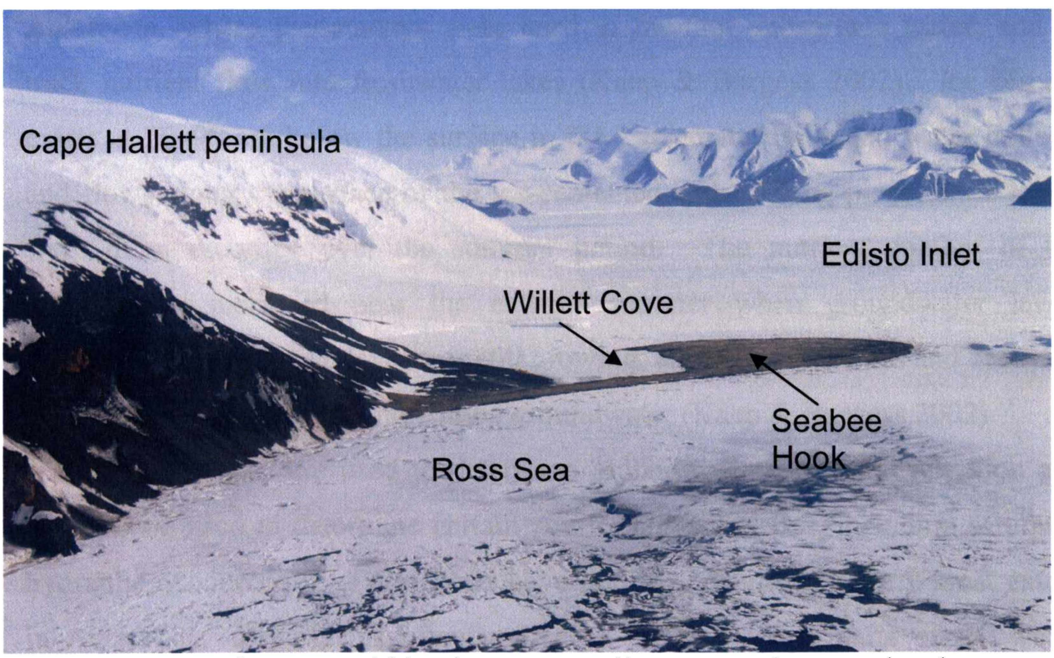

Figure 1: Key features within the Cape Hallett area (photograph taken on 6 December 2004 looking towards the south west).

Groundwater was present during the warmer summer months (December/January) at Seabee Hook. Meltwater from ground ice and snow drifts percolates through the permeable soil to form a thin, unconfined, aquifer perched above the ice cement. Groundwater in this form could be expected to occur in a number of coastal areas of Antarctica, but minimal documentation exists.

A similar groundwater system was described at Casey Station in the Windmill Islands, East Antarctica, where groundwater has been identified as a major pathway for contaminant transport (Snape *et al.* 2001a, Snape *et al.* 2001b, Snape *et al.* 2005). At the Old Casey site, groundwater was present for 2-3 months over the summer period with little or no surface runoff, but some surface runoff as ephemeral streams occurs at the Thala Valley and Wilkes Station (Snape *et al.* 2001a). The subsurface water was thought to move by "widespread dispersal" and also through "small channels" at the base of the active layer (Snape *et al.* 2001a). Trials were conducted on the use of permeable reactive barriers to remove contaminants from the groundwater at Casey Station, as subsurface flow is the main contaminant dispersal mechanism (Snape *et al.* 2001a). Hydrocarbons could potentially be mobilized by groundwater at Cape Hallett since spilled hydrocarbons from activities associated with Hallett Station are present in the soil and groundwater (Raytheon Polar Services Company 2001, 2003).

Shallow groundwater has also been reported at the Larsemann Hills, East Antarctica, where piezometers were used to monitor subsurface water, and to track nutrient flow into freshwater lakes (Kaup & Burgess 2002). Ice cement exists at 20–90 cm below the surface in the Larsemann Hills and water collects and flows along the surface of the ice-cemented soil. Rising piezometric levels were often recorded over the summer period. The nutrient content of the groundwater increased near the end of summer when groundwater levels decreased and the active layer was still growing, allowing salt brines and decaying organic matter to mix with remaining groundwater (Kaup & Burgess 2002).

Tracer tests are used to determine groundwater speed and direction and can also be used to determine certain aquifer characteristics, including saturated hydraulic conductivity. Tracer tests have not been employed to any great extent in Antarctica. Bromide is often used as a tracer in other parts of the world because it is relatively non-reactive with other ions and the porous medium (e.g. Forster *et al.* 1999, Vanderborght & Vereecken 2001, Lin *et al.* 2003). In the environmentally sensitive coastal Antarctic zone, bromide is a viable option as a tracer, as it occurs naturally within the groundwater at low concentrations and has minimal effect on the environment.

During environmental assessments of the Seabee Hook area in early 2003, a number of soil pits were excavated and groundwater levels were mapped (Raytheon Polar Services Company 2003). During late January and early February 2003 groundwater was encountered in 15 of 19 soil pits and the thickness of the water layer over the ice cement varied from <1 cm to more than 15 cm (Raytheon Polar Services Company 2003). A groundwater contour map was constructed of the area, which showed the highest hydraulic heads occurring at the highest elevation, near the old base, and piezometric surfaces sloping away towards the coast. Any pools of surface water were interpreted as surface expressions of the groundwater, rather than being perched above the groundwater. Groundwater was identified as a probable transport mechanism for hydrocarbons. Hydraulic gradients over the majority of Seabee Hook were calculated to be between 0.0010 and 0.0027 and groundwater velocities to be between 1 and 100 m day^{-1} (Raytheon Polar Services Company 2003). The soils of the Seabee Hook region have been characterized and mapped (Hofstee *et al.* submitted) [Chapter 2]. Soils of currently inhabited penguin mounds have a high nutrient status due to guano additions by penguins, while soils away from penguin influences are largely unweathered mineral soils (Hofstee *et al.* submitted) [Chapter 2].

Adelie penguins build nests of stones on elevated sites in order to elevate their eggs and chicks from the flood prone lower lying areas. If meltwater inundates the nests, flooding can lead to nest desertion, egg loss, and subsequent breeding failure (Taylor 1962). Smaller nest sizes are more likely to fail than large nests because of less protection against meltwater (Moreno *et al.* 1995). Storm waves can also result in nest flooding and reduced breeding success in Humbolt penguins (*Sphensicus humboldti*) (Paredes & Zavalaga 2001). Therefore the more meltwater that is present, the more likely it is that nest flooding will occur with consequent reduced breeding success of Adelie penguins.

This paper aims to characterize the extent, duration, and chemical properties of groundwater at Seabee Hook over the 2004-05 austral summer months, and consider the factors that affect the interannual variability of groundwater occurrence.

Methods

A small climate station was installed at Seabee Hook over the 2004-05 season (Figure 2). Measurements included air temperature and relative humidity at 1.85 m height (Humitter 50Y, Vaisala, Finland), incoming solar radiation (LI200X, LI-COR, Lincoln, NE, USA), windspeed and wind direction at 2.35 m, (A101M, W200P, Vector Instruments, Clwyd, UK), and soil temperature and moisture at 10, 18 and 32 cm (Hydra soil moisture probe, Stevens Vitel Inc, Chantilly, Virginia, USA). Data were collected from the climate station from 8 December 2004 until 24 February 2005 using a datalogger (CR10X, Campbell Scientific), sampling at 10 second intervals and averaged for 30 minute periods. Additional climate data were available from a US Antarctic Programme LTER (Long Term Ecological Research) climate station and a New Zealand NIWA (National Institute of Water and Atmospheric Research) soil temperature monitoring station (Figure 2). The NIWA station collected soil temperature data using a MRC probe (Measurement Research Corporation, Gig Harbor, WA, USA) and recorded temperature at 10 depths (5, 13, 20, 28, 36, 51, 66, 81, 97, and 112 cm), averaged for 2 hour periods.

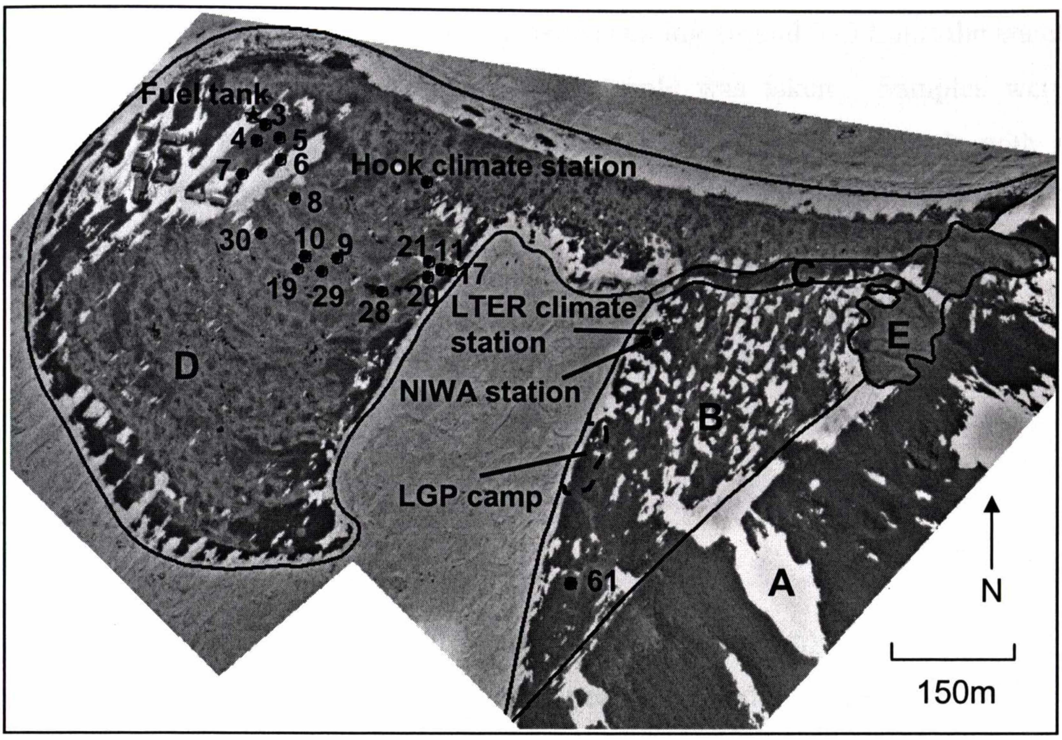

Figure 2: Seabee Hook, showing locations of groundwater monitoring sites, climate stations and hydrologically distinct areas. A – steep slope, B – wetland area, C – Intermittent stream, D – penguin nesting area on beach ridges, E – penguin nesting area on scree slope. Buildings near the fuel tank have since been removed and indicate the location of the old Hallett Station (Photo: Summer 1983).

Polyethylene dipwells were slotted through their entire length and installed to the depth of ice cement (approximately 80 cm). Soil pits were excavated to the depth of ice cement and dipwells inserted, with the excavations re-filled using the original material, repacked at the depth from which it had been excavated. Nine dipwells were installed during the 2003-04 summer with a further seven installed during the 2004-05 summer (Figure 2). Dipwells were monitored for changes in ice cement and groundwater levels once every two to seven days during the latter part of the 2003-04 summer season and every two days during the 2004-05 summer. Dipwells were capped when not in use and during winter.

Tracer tests were conducted at Seabee Hook using a pulse injection of 15 g L^{-1} Potassium Bromide into a dipwell. A network of sampling wells, slotted through their entire length, were located 1-2 m away, downstream from an injection dipwell. Injection of the tracer involved evacuating all of the water in the dipwell using a hand-pump and immediately pouring the tracer solution into the dipwell, thus minimizing the possibility of a locally high head at the injection point. Sampling was conducted hourly by evacuating around 3–5 times the water volume of the sampling well before the sample was taken. Samples were analysed using a bromide specific electrode (Br^- ion specific electrode with a Ag.AgCl reference electrode) and a pH/ion meter (692, Metrohm, Herisau, Switzerland).

Groundwater velocity was calculated from the time delay until the peak bromide concentration was detected in sampling wells during the tracer test,

$$v = \frac{d}{t} \tag{1}$$

where,

v = groundwater flow velocity (m s^{-1})

d = distance from injection dipwell to sampling piezometer (m)

t = time taken for bromide concentration to peak in a sampling piezometer (s)

Hydraulic conductivity was calculated using the results gained from tracer tests,

$$K = v\frac{L}{\Delta h} \tag{2}$$

where,

v = velocity from Equation 1 (m s^{-1})

L = horizontal distance between injection dipwell and sampling piezometer (m)

Δh = change in head between injection dipwell and sampling piezometer (m)

Total porosity was estimated by measuring the volume of a sample of soil solids by displacement in water. Porosity was then calculated as the difference between undisturbed soil volume and the volume of solids, expressed as a percentage. The undisturbed sample soil volume was measured by sand replacement (Burke *et al.* 1986), by refilling the excavated area with a known volume of <2 mm sand.

For groundwater chemistry, water samples were taken from groundwater monitoring sites 6, 8, 10, 19, 28, 29, 30, and 61 (Figure 2) using a hand pump, evacuating 3–5 times the water volume of each dipwell before sampling. Water chemistry data analyses were undertaken by Environmental Chemistry Laboratory (EClab), Landcare Research, Palmerston North, New Zealand. Soil pH, electrical conductivity, total dissolved solids, total organic carbon, calcium, magnesium, potassium, sodium, inorganic carbon, ammonia, nitrate, and phosphate were measured using the methods of the American Public Health Association (1998). Chloride was measured using the method of Skougstad *et al.* (1979). Total phosphorus was measured following the method of Hosomi & Sudo (1986).

Results and discussion

Overview of hydrological characteristics of Seabee Hook

Four spatial zones of distinct hydrology were identified at Seabee Hook during the summer months, due to differences in topography and uneven distribution of meltwater sources (Figure 2).

Area A was a steep slope (~30°) which, in the summer of 2004-05, had a number of semi-permanent snow drifts and a small glacier (not shown). The snow drifts and glacier were in direct sunshine for up to 16 hours per day, leading to meltwater generation throughout the summer months. The material on the slope was highly permeable course gravel and boulders which allowed rapid subsurface flow of meltwater.

Area B was defined as the area below the steep slope (area A), which received subsurface flow from the slope, and drained into Willett Cove. The topography of area B was hummocky with some evidence of previous use as a penguin nesting area. However there are no active nesting sites, aside from widely scattered South Polar Skua (*Catharacta skua maccormicki*) nests on elevated sites. Area B quickly became saturated during times of high meltwater production, with groundwater rising to form surface ponds and ephemeral streams. The reliable water supply has led to the growth of relatively abundant vegetation consisting of algae, mosses and lichens (Rudolph 1963). Area B comprised relict beach gravel and sand deposits.

Area C was a relatively large intermittent stream which was observed to flow into Willett Cove from early December 2004 to early February 2005. The source of water for the stream originated from area A, mostly via ephemeral streams and subsurface flow through area B. Some meltwater flowed directly from area A to the upper reaches of the stream. The stream was often frozen at night when the stream and the steep slope became shaded. The stream was also frozen during the day at times of low solar radiation and low air temperature.

Area D comprised the area currently inhabited by nesting penguins on Seabee Hook. The topography was hummocky, similar to that in area B. The highest elevation of area D was near the old fuel tank, on the north-west side of area D (Figure 2) and approximately 5 m above sea level. Area D had lower volumes of groundwater compared to areas A, B, and C since melting snow and ground ice were the only moisture sources. Presuming similar interannual meltwater production from ground ice, the depth of groundwater in area D was probably dependent on the amount of snow fall providing an additional meltwater source.

Area E comprised penguin mounds on the steep scree slope. Some meltwater from area A flowed through area E.

The rest of this paper will focus on the hydrological characteristics of area D, since this encompasses the majority of the penguin colony and is the area most strongly affected by past human activities.

Hydrological characteristics of area D

Groundwater within area D of Seabee Hook varied spatially and temporally. During the 2003-04 summer, surface water was frequently observed in low-lying areas. Surface water was only present in a small number of ponds during the 2004-05 summer, presumably as surface expressions of the water table, and the majority of the meltwater was confined to groundwater within the permeable gravel and sand of the low-lying areas (porosity 23-33%).

Early in the 2004-05 summer all dipwells were devoid of water, with no groundwater occurring at Seabee Hook. Soil temperatures started to rise above 0°C just below the soil surface in late November (Figure 3a) at the NIWA station, but groundwater did not start to accumulate until mid-December. During times when soil temperatures were above 0°C, any melt would have evaporated or refrozen when it percolated into the soil. Soil temperatures rose above 0°C to a depth of at least 28 cm, at the NIWA site within area B (Figure 3a) at the end of December 2004. The warmest temperatures occurred in late December coinciding with the summer solstice. At the Seabee Hook climate station soil temperatures were warmer than at the NIWA site. Soil at a depth of 32 cm reached up to 3.7°C in late December and early January (Figure 3b). The differences in temperature at these two sites, which are in reasonably close proximity to one another (~300 m), may be attributed primarily to topographic shading. The soil near the NIWA station was in an area shaded for a longer period each night by the Cape Hallett Peninsula. The depth to ice cement in January 2005 was deeper in area D (~80 cm) than it was in area B (~50 cm).

From early January 2005 soil temperatures began to decrease at both sites (Figure 3), coinciding with reduced incoming solar radiation as a result of a storm and a prolonged period of cloudy days from 2–18 January 2005. When sunny weather returned, soil temperatures increased briefly before declining towards the end of January.

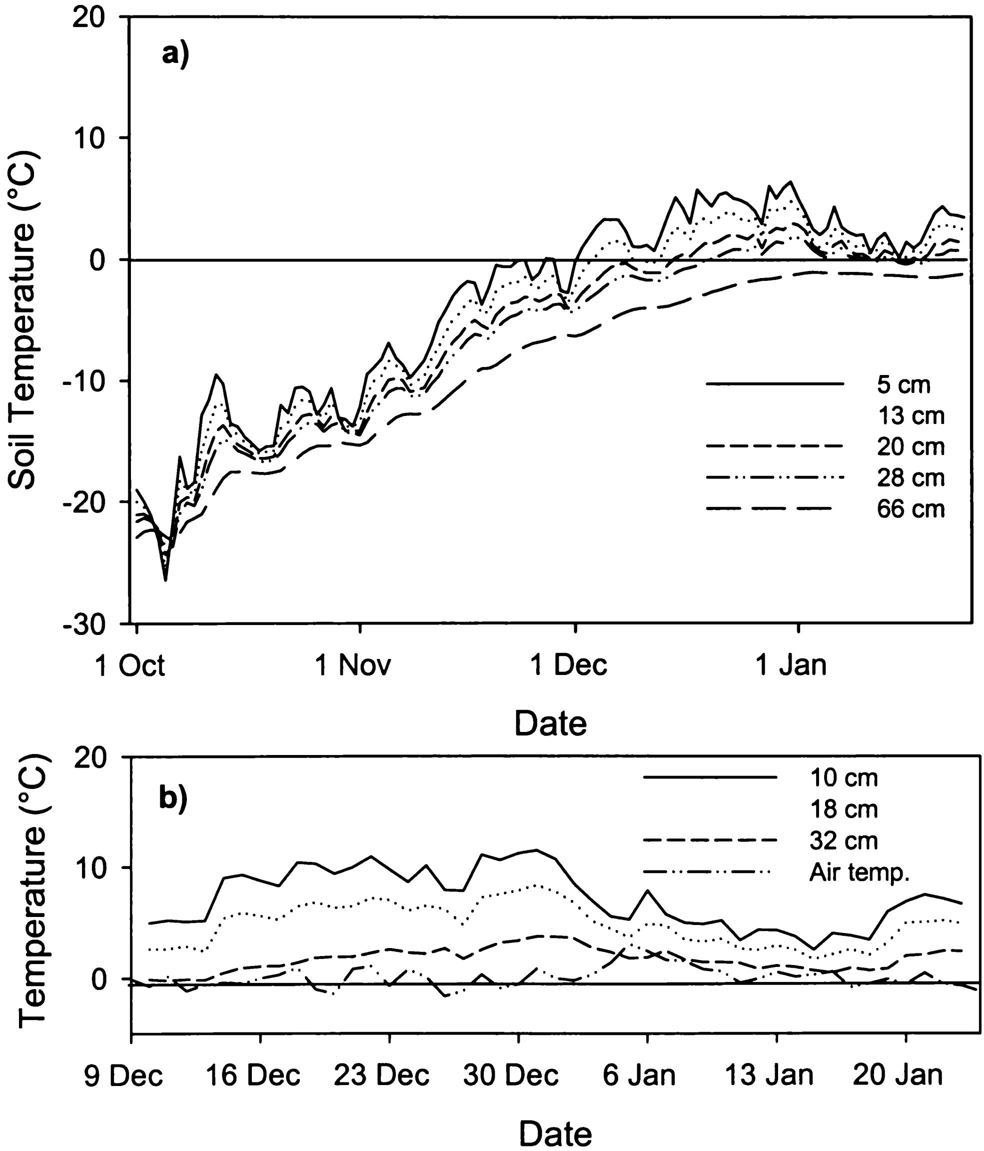

Figure 3: Average daily soil temperature at Seabee Hook (horizontal lines indicate 0°C). **a)** At the NIWA climate station, from October 2004 to the end of January 2005. **b)** At the Seabee Hook climate station from 10 December 2004 to 25 January 2005 (includes daily mean air temperature).

Soil liquid moisture contents measured at the Seabee Hook climate station were higher than recorded for most other soils in the Ross Sea region of Antarctica (e.g. data from Campbell *et al.* 1997, Wall *et al.* 2004), reflecting the more northerly coastal setting, warmer temperatures and higher precipitation. Volumetric soil liquid moisture contents were similar throughout all depths of the soil profile and remained relatively constant through the summer, although a slight decrease in soil liquid moisture content occurred between mid December 2004 and the end of January 2005 (Figure 4). The accuracy of the probes is thought to be ±3% (Wall *et al.* 2004), while resolution is approximately ±1%. Given that the probes remained undisturbed it is likely that the reduction in liquid soil moisture content by 1 – 2% from mid December 2004 to end January 2005 occurred. Soil drying at 10 cm depth is probably driven by evaporation, while the relatively larger amount of drying at 32 cm is likely caused by melting and retreat of ice cement.

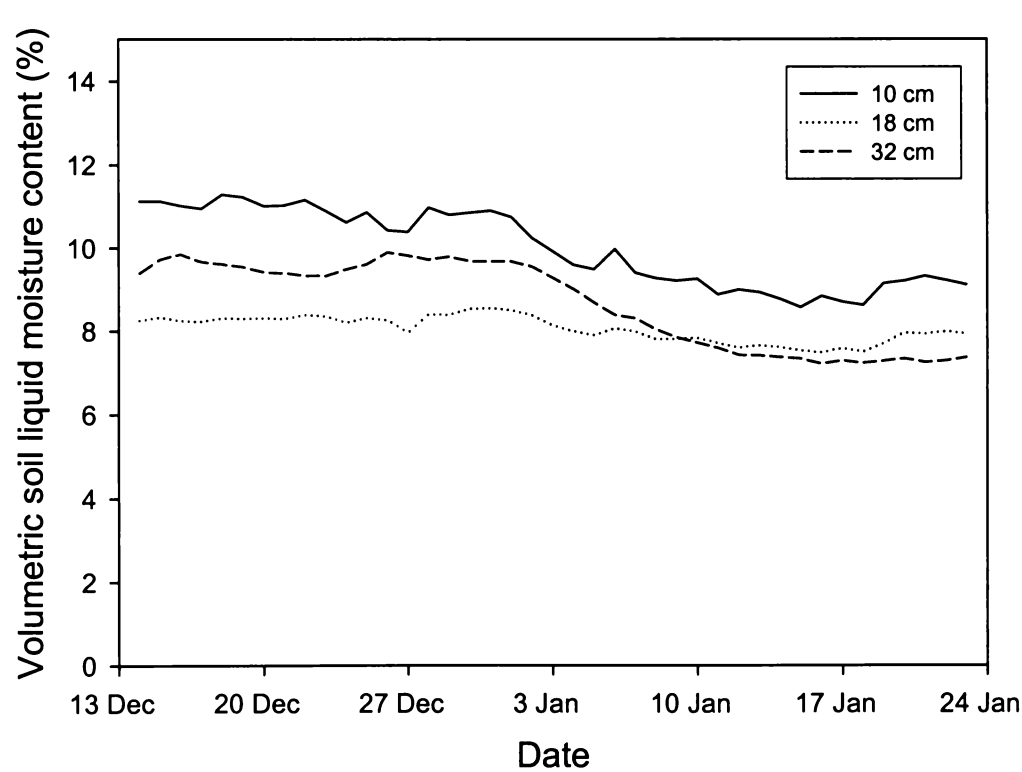

Figure 4: Volumetric soil liquid moisture content at Seabee Hook climate station from mid December 2004 to the end of January 2005.

Where soil temperatures were greater than 0°C, meltwater accumulated to form a perched, shallow unconfined groundwater at Seabee Hook. Depth to ice cement increased over the 2004-05 summer from a minimum of approximately 5 cm below the soil surface in early December 2004 (Figure 5a), to approximately 80 cm below the soil surface in late-December 2004 to early January 2005. The depth to groundwater also increased between early December 2004 and the end of January 2005. The thickness of the saturated zone varied from <1 cm to 30 cm during the 2004-05 summer. In all dipwells the ice cement level dropped below the bottom, or apparent bottom, of the dipwell (Figure 5). Many of the dipwells accumulated up to 5 cm of fine material in the bottom between January 2004 and January 2005. The dipwells were installed at approximately the maximum thaw depth during January 2004, and during the 2004-05 season soils thawed to depths greater than or equal to the base of the dipwells.

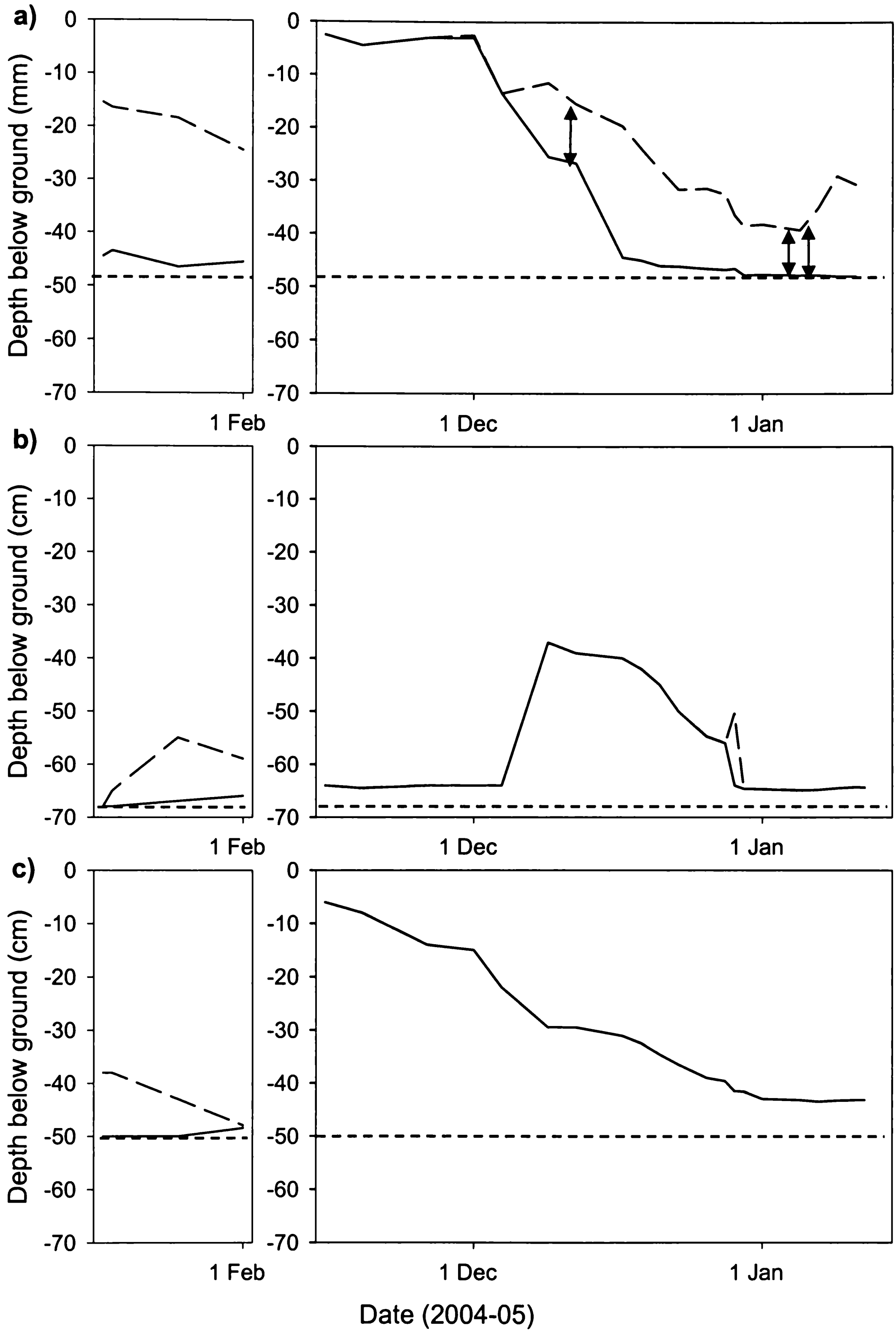

Figure 5: Depth to water table (long dash) and ice cement (solid), during 2003-04 summer (left) and 2004-05 summer (right). Short dashed horizontal lines indicate depth of dipwells **a)** Site 11 (arrows indicate times and depths of tracer tests) **b)** Site 3 **c)** Site 7.

Areas of Seabee Hook with a higher elevation, including penguin mounds and the area near the old base site and fuel tank (Figure 2), had different patterns of depths to ice cement and groundwater compared to intermound areas. No, or very little, groundwater was observed in topographic highs (sites 3, 4, 7, and 9) throughout the 2004-05 summer. Any meltwater generated within the higher areas may have migrated downslope, or the ice cement present may not have had enough water content to cause saturation of the soil once it melted. In early December when groundwater was accumulating in the low-lying areas of Seabee Hook, a shallowing of ice cement (total shallowing of up to 30 cm within one week) occurred in most areas of higher elevation (sites 3, 4, and 9) (Figure 5b), including penguin mounds and the area near the old fuel tank. The shallowing of ice cement was possibly due to groundwater flowing into an area of frozen but unsaturated soil. Continued increase in soil temperatures led to a subsequent increase in depth to ice cement, sometimes with the accumulation of a small amount of groundwater. Dipwell 7 had no groundwater recorded during the 2004-05 summer, and the depth to ice cement increased between early December 2004 and late January 2005 (Figure 5c).

In the 2003-04 summer groundwater was more extensive than during the 2004-05 summer, reflecting the temporal variability of the groundwater system. Groundwater was present in all groundwater monitoring dipwells during the 2003-04 summer, but only at sites 5, 6 8, 10, and 11 during the 2004-05 summer. During the 2003-04 summer a number of storms produced snowdrifts which were probably the main source of meltwater. There were no major snowstorm events in the 2004-05 summer, leading to less meltwater availability and deeper water table depths.

The depth to groundwater in early February 2004 was often the same as the depth to the ice cement recorded in mid November 2004 (Figure 5b). However, in some cases the depth to ice cement was shallower in mid-November 2004 than in early February 2004 (Figure 5a, c). The difference was possibly due to the occurrence of a melt event leading to water flowing into frozen but unsaturated soil, suggesting that some melting must have occurred in some areas of Seabee Hook between early February and mid November 2004.

Groundwater at Cape Hallett flowed mostly through the low-lying areas between penguin mounds during the 2004-05 summer, since penguin mounds and higher elevated areas did not accumulate any groundwater.

Groundwater velocity was estimated using bromine tracer tests near groundwater monitoring site 11 (Figure 2), at the convergence of two shallow valleys (Figure 6). Three separate tracer tests (11 December 2004, 3 and 6 January 2005) were conducted during the 2004-05 summer to encompass varying ice cement and groundwater depths.

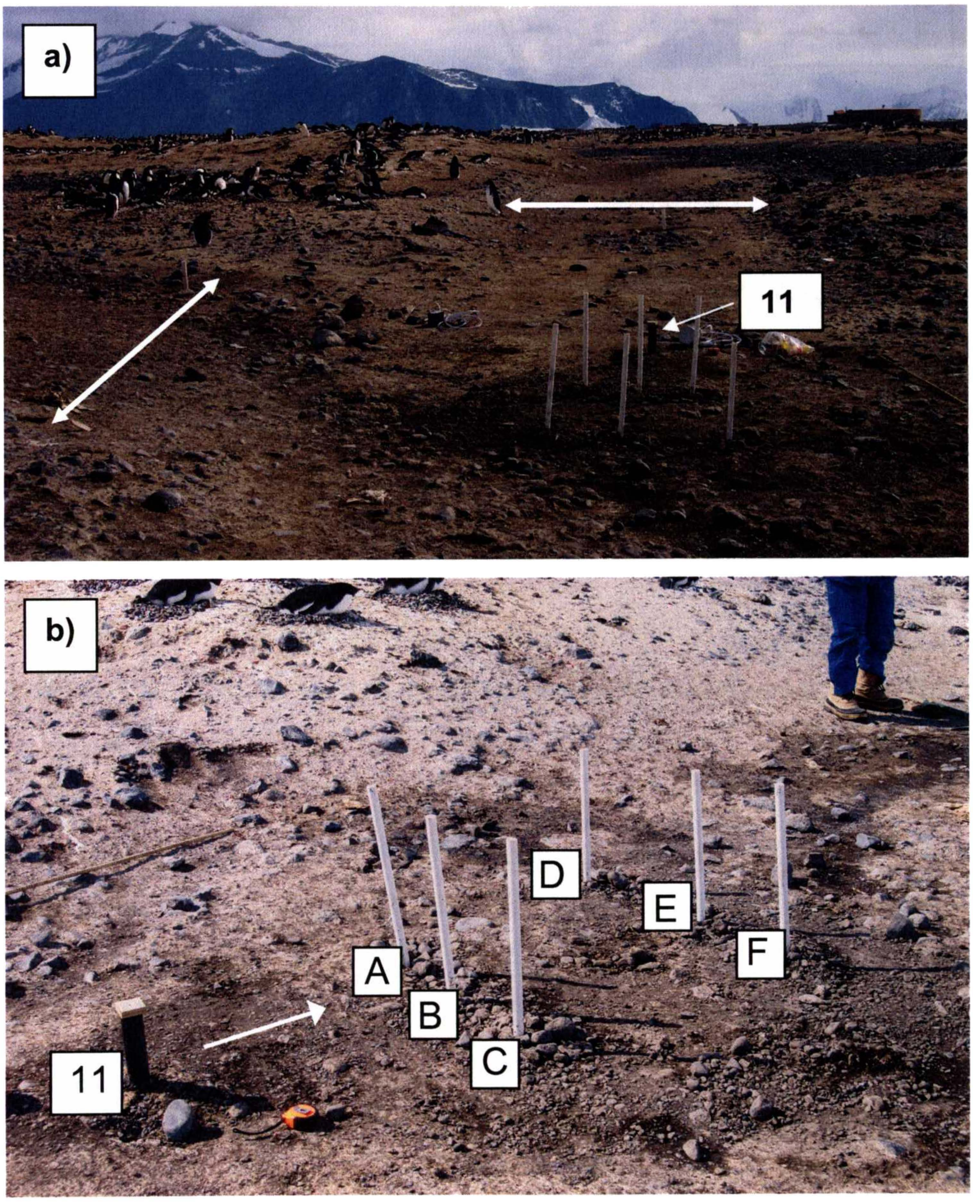

Figure 6: a) Location of tracer test at site 11, at the convergence of two shallow valleys at Seabee Hook. Arrows indicate the cross sections of the two valleys and the injection well, site 11. **b)** Dipwell 11 and sampling wells A-F. The arrow indicates general direction of groundwater flow.

During the first tracer test on 11 December 2004 a breakthrough curve of bromide concentrations within the sampling wells (Figure 7a), shows that there were clear peaks of bromide as the tracer traveled downslope within the flowing groundwater.

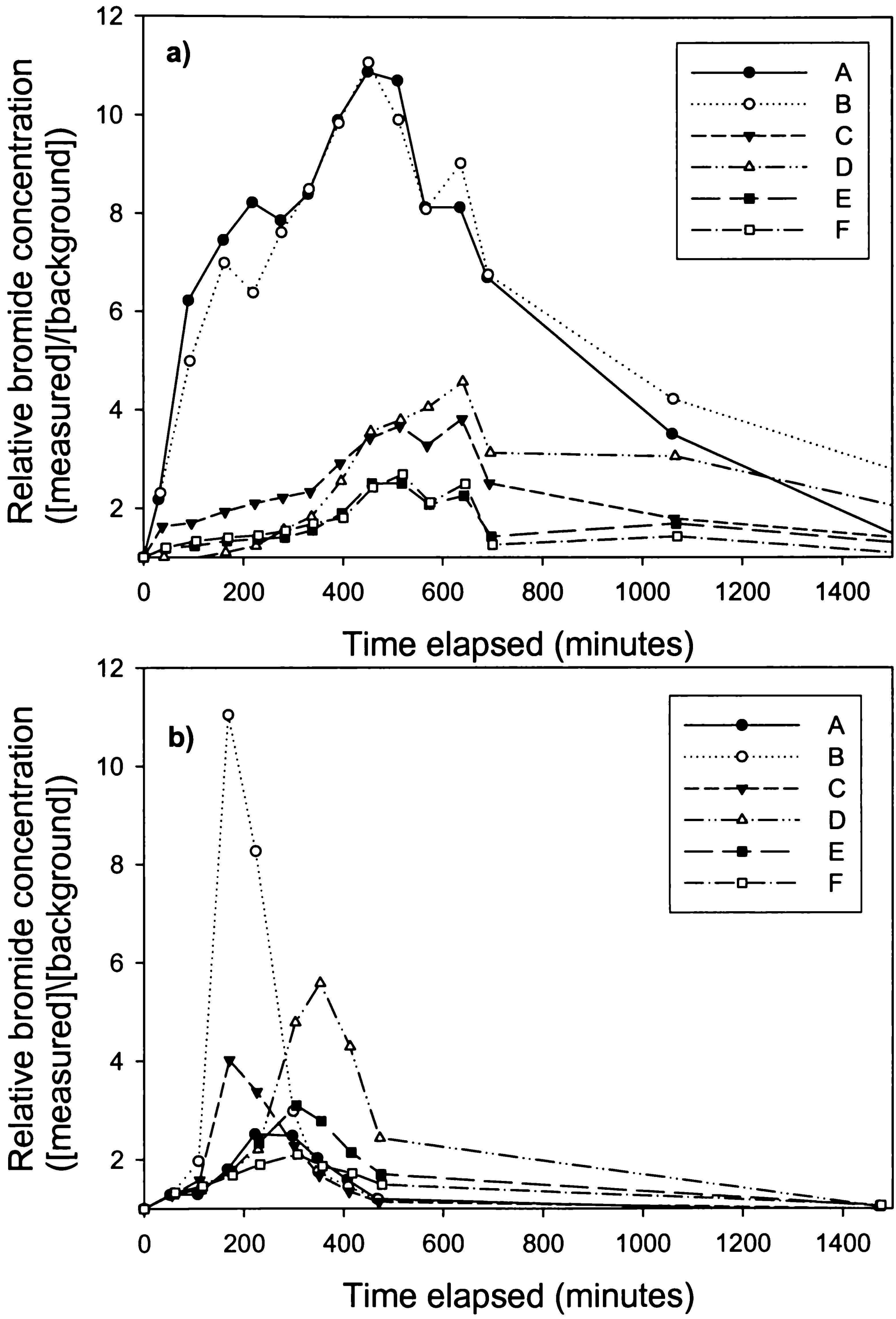

Figure 7: Breakthrough curves of bromide concentrations in sampling wells near site 11 from tracer tests on **a)** 11 December 2004. **b)** 3 January 2005.

The breakthrough curves of bromide concentrations in the two January tracer tests were similar, one example is shown in Figure 7b.

The differences between the tracer test conditions in December 2004, compared to January 2005, were reflected in the different groundwater velocities (Table 1), with similar velocities during the 3 January and 6 January 2005 tests (3.79–7.84 m day^{-1}), and a slower groundwater velocity during the 11 December tracer test (2.09–3.2 m day^{-1}).

Table 1: Groundwater velocity and aquifer hydraulic conductivity between site 11 and the sampling wells during tracer tests in December 2004, and January 2005.

Sampling	**Velocity (m day^{-1})**			**Hydraulic conductivity (m s^{-1})**		
well	11 Dec	3 Jan	6 Jan	11 Dec	3 Jan	6 Jan
A	3.20	-	-	6.3×10^{-5}	-	-
B	2.93	7.84	7.20	5.4×10^{-5}	3.6×10^{-4}	3.4×10^{-4}
C	2.10	7.83	7.20	3.7×10^{-5}	3.6×10^{-4}	3.3×10^{-4}
D	2.09	3.79	3.54	1.0×10^{-4}	4.7×10^{-4}	4.7×10^{-4}

In December 2004 groundwater flowed between 10.5 and 26 cm depth, whereas in January 2005 the groundwater flowed between 37 and 47 cm depth (Figure 5a). The shallower soil material may have had a greater concentration of organic matter derived from penguin activity (Hofstee *et al.* submitted) [Chapter 2] which would block soil pores and slow the water flow. Tracer test results indicated hydraulic conductivity of the soil material of the 11 December tracer was (3.7×10^{-5} m s^{-1} to 1.0×10^{-4} m s^{-1}) lower than the hydraulic conductivity of the soil material of the 3 and 6 January tracer tests (3.3×10^{-4} m s^{-1} to 4.7×10^{-4} m s^{-1}) (Table 1).

During the 11 December 2004 tracer test, the majority of the groundwater flowed towards sampling wells A and B, as can be seen by the largest peaks in Figure 7a. The smaller peaks in the remaining sampling wells relate to lesser flow past these wells. During the subsequent tracer tests on 3 January and 6 January 2005, groundwater levels had dropped (Figure 5a) and resulted in different flow paths being followed. Flow was initially towards wells B and C and no longer towards well A. It is probable that changes in the topography of the ice cement surface dictated the direction of groundwater flow.

A tracer test was also conducted near site 29, however no tracer was picked up in the sampling wells, and it was later found that the hydraulic head sloped away from Willett Cove near site 29 during January 2005. However it is probable that during wet years, there is considerable flow of groundwater towards Willett Cove in broad, shallow valleys, like the valley where site 29 was located. The report by Raytheon Polar Services Company (2003), suggested the hydraulic gradient was sloping towards Willett Cove from site 29, presumably from measurements taken during a year of greater groundwater volumes than 2004-05.

Groundwater chemistry

The groundwater in area D (within the penguin colony) generally had a strong dark reddish brown colour (5 YR 3/6) and tended to form froth on the surface when disturbed by digging. Groundwater from area D had increased salt and nutrient concentrations compared to groundwater sourced away from the colony (area B) (Table 2). Groundwater from area D was higher in nutrients, including total phosphorus, (33 times higher) and both ammonia-nitrogen (416 times higher) and nitrate-nitrogen (7 times higher) than groundwater from area B. Both organic (54 times higher) and inorganic (134 times higher) carbon contents and total dissolved solids (17 times higher) were elevated in area D compared to area B.

Table 2: Chemistry data for groundwater sampled at Seabee Hook in January 2005 and water chemistry reported at other Antarctic locations. All concentrations in mg L^{-1} and EC in $\mu S\ cm^{-1}$.

Location	pH	EC	TDS	Total C	Inorg. C	Org. C	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	NO_3^{-}	NH_3	Reactive P	Total P
Cape Hallett, Area D	7.6	14000	7691	622	134	488	18	96	1205	332	2653	1526	193	833	7	10
Standard Deviation		3401.8	1871	105.6	49.2	113.2	10	38.6	288.7	99.9	801.1	511.8	115.2	254.5	3.8	5
Cape Hallett, Area B	4.6	816	450	10	1	9	19	22	85	8	170	38	29	2	0.3	23
King George Island penguin colony soil solution (a)	2.9	1311					33.2	20	48	37			140			
King George Island penguin colony surface water (b)							5-35	3-20	10-110				0-59			
Streams in Northern Victoria Land (c)	6.4-8.5	41-200					1.1-8	0.8-3.2	5-10	0.4-8	5.7-30	2-16	0.2-3.4			
Coastal lakes (c)	9.2	541					23	28	276	16	439	117	1.7			
Lake Bonney (d)							34-2558	21-36272	131-68852	7-2986	244-191044	83-5151				
Lake Hoare(d)							9.2-23	11.6-38	55-184	10-31	75-239	40-109				
Lake Fryxell (d)							22-147	10-371	77-2695	9-196	108-3733	20-206				
Dry Valley Streams (d)							1.7-93	0.3-272	0.6-1871	0.3-63	0.8-95	0.7-380				
Dry Valley glaciers (d)							0.0023-5.3	0.002-0.5	0.03-2	0.004-0.5	0.02-4	0.025-3.1				
Seawater (e)	8.2	40000					412	1291	10768	399	19353	2712				

(a) Juchnowicz-Bierbasz & Rakusa-Suszczewski 2002, (b) Tatur & Myrcha 1983, (c) Borghini, & Bargagli 2004, (d) Welch *et al.* 1996, (e) Chang 1994.

Salt (sodium, potassium, sulphate, chloride and magnesium) concentrations were also elevated in area D compared to area B while calcium concentrations were similar in both areas. Salt probably originates from guano and penguin nasal excretions (Janes 1997) as well as sea water. Sea water is able to mix with groundwater from sea spray, especially during storms when the effect of breaking waves and high winds can carry large volumes of seawater a long distance inland.

The higher nutrient content in area D compared to area B is attributed to the water flowing through soil rich in guano, penguin remains, feathers, egg shells and nasal excretions. Nitrate is most likely reduced to ammonia in anaerobic conditions within the soil and groundwater. The high nutrient content is mirrored by the soils in area D, where nitrogen, phosphorus and carbon contents were also high (Hofstee *et al.* submitted) [Chapter 2].

The chemistry of Antarctic fresh waters has been reported in a number of studies (Table 2). Groundwater from area B had similar chemical properties to other non-ornithogenic groundwaters reported in Antarctica. Coastal lakes have been reported to have similar calcium, magnesium, sodium and potassium levels (Borghini & Bargagli 2004) to groundwater in area B at Seabee Hook. However sulphate and nitrate levels were higher at Seabee Hook (area B) than in coastal lakes (Borghini & Bargagli 2004). Streams in northern Victoria Land had lower nutrient and salt concentrations (Borghini & Bargagli 2004) than the groundwater from area B. Some inland lakes, such as Lake Bonney, have considerably higher salt concentrations (Welch *et al.* 1996) than area B at Seabee Hook due to concentration by evaporation.

Groundwater chemistry in area D had similarities to groundwater reported under other ornithogenic soils in Antarctica, with nitrate concentrations from Seabee Hook (193 mg L^{-1}) similar to nitrate concentration in waters from penguin colonies at King George Island (140 mg L^{-1}) (Juchnowicz-Bierbasz & Rakusa-Suszczewski 2002). pH in area D is slightly alkaline, whereas the pH from water at King George Island was reported as 2.9. The concentrations of sodium, potassium, magnesium and also the electrical conductivity were higher in area D at Cape Hallett than those reported from within a penguin colony at King George Island, possibly due to more sea spray reaching the Seabee Hook area D than the King George Island sample sites.

Conclusions

Four distinct hydrological zones were identified at Seabee Hook. Area A, a steep slope, had subsurface flows of meltwater from a glacier and snow drifts. Within area B, meltwater flowed through subsurface materials to form ground and surface water as ephemeral streams and ponds on the low-lying areas at the base of the slope. Area C is a relatively large intermittent stream receiving meltwater from areas A and B. Area E was a current penguin nesting site and is located on a steep slope near area A. Groundwater was not observed in area E but subsurface flow within the steep slope was presumed to occur. Area D hosts the large penguin colony, and formed the majority of the land on Seabee Hook.

Three distinct groundwater and ice cement conditions were present at Seabee Hook during the 2004-05 summer. Depth to ice cement increased throughout most of Seabee Hook during the summer as a result of melting ground ice. In higher elevation areas, including the area around the old fuel tank and penguin mounds, groundwater was not present above the ice cement possibly because it was able to run down slope as it melted, or the ice cement had a moisture content of less than field capacity. In areas with no groundwater accumulation, depth to ice cement increased during the 2004-05 summer. In some higher elevation areas, a shallowing of the ice cement of up to 30 cm occurred within one week in mid-December 2004, the same time as ice cement was deepening at other locations and soil temperatures were rising above 0°C at depths up to 32 cm. The shallowing of the ice cement in the higher elevated areas could be due to groundwater flowing into frozen but non-ice cemented ground. The ice cement deepened until the end of January 2005 after the initial shallowing at the higher elevated areas. In low-lying areas between penguin mounds, groundwater accumulated above the ice cement and the depth to ice cement and groundwater increased from early December 2004 to the end of January 2005.

Groundwater conditions at Seabee Hook in area D vary interanually. The summer of 2004-05 was observed to be drier than the summer of 2003-04, due to fewer summer snowfall events. The groundwater within valleys, for instance where site 29 was located, may have been a separate hydrological system, with no link to Willett Cove during the 2004-05 summer. The valleys may act as a pool for any meltwater from snow or ground ice during dry seasons. During the 2003-04 summer these large pools of groundwater may have been hydrologically connected and area D would have effectively been one large groundwater mound with all of the valley systems linked and flowing towards the sea.

Groundwater flow velocity can be rapid at Seabee Hook (area D) due to the highly permeable material through which it is flowing, with hydraulic conductivities ranging from 3.7×10^{-5} m s^{-1} to 4.7×10^{-4} m s^{-1}. Due to the high hydraulic conductivity, any contaminants within the groundwater from previous use of Hallett Station, will have already moved out to either Willett Cove or Edisto Inlet. However if hydrocarbons remain within the soil, it is possible that over time they will become mobilized and able to move within the groundwater.

The chemistry of groundwater at Seabee Hook shows that concentrations of both salts and nutrients were higher in groundwater from within area D, where there was a large penguin influence, than in area B (within the Skua colony) and also higher than values reported from other locations in Antarctica.

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Chapter 4
Conclusions

The aims of this thesis were to charaterise and map the soils in the Seabee Hook area and to determine the spatial and temporal extent of meltwater at Seabee Hook. This chapter discusses and elaborates on some aspects that were not discussed in detail in the previous chapters.

Human impacts

The presence of Hallett Station at Seabee Hook and its use over 16 years has led to contamination of the soil and groundwater by debris and hydrocarbons. If hydrocarbons do not degrade, they remain within the soil and groundwater, or are able to reach the coast. The mapping of the soils at Seabee Hook and the characterisation of the groundwater near the contaminated sites has provided information on the soil types present and also on the presence and movement of groundwater and therefore the potential movement of contaminants at Seabee Hook.

The hydraulic conductivity values estimated from tracer tests suggest that hydrocarbons present in the groundwater at the time of the use of Hallett Station would have long since moved off Seabee Hook into Willett Cove, Edisto Inlet or the Ross Sea. Hydrocarbons present within soil near the old fuel tank may still be able to be mobilized into groundwater and potentially be carried to other areas of Seabee Hook.

Soils in areas that were previously disturbed by bulldozing and that have been recolonised by penguins have developed a guano-rich horizon about 10 cm deep. Given the relatively recent and undeveloped nature of the soils in the Seabee Hook area, with active processes associated with penguin activity in a relatively warm and moist environment, recovery is relatively rapid.

Latitudinal Gradient Project

The soil map of Seabee Hook characterizes the soils of the northern-most location of the LGP programme, and establishes a baseline with which to compare other ornithogenic soils. Similar studies need to be carried out further south, for example at Cape Royds, to find if latitude has any effect or if the penguin influence over-rides any effects that latitude might bring about. The soils of Seabee Hook would be expected to be similar, but possibly wetter, than soils within other Adelie penguin colonies around the Ross Sea region that are based on basalt beach gravels and sands.

The availability of free water has been monitored over two summer seasons at the northern-most location of the LGP programme. If similar studies of groundwater volume and movement were conducted in penguin colonies further south it is expected that ice cement would be shallower further south. The volume of groundwater would likely be less in penguin colonies to the south of Seabee Hook.

One soil sample was taken from the western coastline of Edisto Inlet, well away from any penguin influence (see CH18, Appendices 1 and 5). The texture of the Luther Lake soil became finer further down the profile. A coarse desert pavement was present on the soil surface. Soil electrical conductivity was low (0.04–0.23 mS cm^{-1}), with a relatively high pH (up to 8.05). Nutrient levels were low, with total nitrogen undetectable and organic carbon percentages of <1%.

Classification of ornithogenic soil

The ornithogenic soils at Cape Hallett were classified as Gelisols in USDA Soil Taxonomy (Soil Survey Staff 2003) due to the occurrence of permafrost within 100 cm of the soil surface.

The soils at Cape Hallett were classified as Orthels, but belong to different Great Groups, with soils within the penguin mounds classified as Haplorthels and soils within the wet intermound areas classified as Aquorthels. The current classification system did not differentiate them, and therefore Cape Hallett ornithogenic soils classify within the Typic Subgroups, giving Typic Aquorthels and Typic Haplorthels.

The ornithogenic soils did not fall within the Histel Suborder as they have less than the required 20% organic carbon content. However, as the highest organic carbon content was up to 17.6% at Seabee Hook, it is not inconceivable that some ornithogenic soils would have over 20% organic carbon content and therefore make it into the Histel Suborder.

The ornithogenic soils at Cape Hallett are distinctly different to other soils in Antarctica that fall within the Gelisol classification, due to the high nutrient content and the guano-rich organic material. Therefore there is a case for a new Suborder in Gelisols to accommodate soils where the input of bird activity dominates soil properties, I suggest it be called Ornels to recognize Gelisols with ornithogenic material. Ornels would need to key out of Gelisols before Histels in order to include ornithogenic soils with organic carbon contents higher than 20%. In addition to an Ornels Suborder, a Subgroup should be added Great Groups within the Turbel and Orthel Suborders to encompass ornithogenic soils which do not fit into the Ornel Suborder. The following definitions are suggested:

AA. Gelisols that have 50 percent or more, by volume, "ornithogenic soil materials" from the soil surface to a depth of 50 cm or to a glacic layer or a densic, lithic, or paralithic contact. Ornels

Ornithogenic soil materials can be defined as "soil materials derived from the activities of birds consisting of guano, bird remains, eggshells, feathers, and stones used for nest building brought to the soil ex situ by birds".

The Great Groups suggested within the Ornels should follow the same definitions as used for the same Great Groups within other suborders and include the following;

Ornels

AAA. Histornels

AAB. Aquornels

AAC. Psammornels

AAD. Haplornels

I suggest that an Ornic Subgroup be added to the following Great Groups;

Aquorthels

Anhyorthels

Psammorthels

Haplorthels

Aquiturbels

Anhyturbels

Psammoturbels

Haploturbels

The Subgroup should be the first Subgroup for the particular Great Group and should be defined as "[Great Groups] that have 5 percent or more, by volume, ornithogenic soil materials from the soil surface to a depth of 50 cm or to a glacic layer or a densic, lithic, or paralithic contact".

Further research

A more detailed study of the hydrology of other areas at Seabee Hook could be carried out. The area beneath the steep slope (Area B and C on Figure 2, Chapter 3) was a hydrologically active area, with large groundwater fluctuations throughout the season, due to the different meltwater sources present near the steep slope compared to the land spit area of Seabee Hook studied in this thesis. Conducting tracer tests and monitoring dipwells installed into the area beneath the steep slope over a summer season would give data to compare to those in this thesis. A clearer picture of the spatial variability of groundwater at Seabee Hook would result.

A detailed study on the movement of hydrocarbon contaminants present in the soil around the old fuel tank could be a worthwhile undertaking. Installing and monitoring a dense dipwell network over a longer period may be useful to note any contaminant movement over time.

Research at other LGP sites to the south should be compared to this research at Seabee Hook to determine the effects latitude has on soils and hydrology in Antarctica.

Appendices

APPENDIX 1
Soil Chemistry data

Table 1: Soil pH, Electrical conductivity (EC), moisture factor, and gravimetric moisture content for soil samples from Cape Hallett.

Sample	Depth	Electrical Conductivity (mS cm^{-1})	Total Soluble salts %	Moisture factor	Gravimetric moisture content	pH
CH1/2	0	1.81	0.63	1.04		5.25
CH1/3	5	0.6	0.21	1.03		5.22
CH1/4	15	0.33	0.12	1.03		5.11
CH1/5	30	0.05	0.02	1.01		5.81
CH1/6	50	0.08	0.03	1.01		6.13
CH3/1	10	1	0.35	1.05		7.04
CH3/2	30			1.08		
CH3/3	40			1.05		
CH3/4	60	0.26	0.09	1.01		6.84
CH3/5	70	0.44	0.15	1.02		7.48
CH4/1	18	0.34	0.12	1.01		5.43
CH4/2	45	0.22	0.08	1.01		6.53
CH5/1	20	2.85	1.00	1.13		7.15
CH5/2	12			1.06		
CH5/3	30	0.65	0.23	1.02		7.48
CH5/4	35	0.91	0.32	1.10		7.38
CH5/5	50	0.56	0.20	1.03		7.46
CH6/1	10	1.35	0.47	1.03		7.11
CH6/2	50	0.19	0.07	1.01		6.39
CH7/1	5	1.24	0.43	1.05		7.16
CH7/2	20	0.17	0.06	1.01		6.11
CH7/3	30			1.07		
CH9/1	0			1.18		
CH9/2	10	16.04	5.61	1.22		6.11
CH9/3	25	16.38	5.73	1.20		6.22
CH9/4	40	1.75	0.61	1.01		6.84
CH9/5	50	0.53	0.19	1.01		7.43
CH18/1	5	0.23	0.08	1.00	0.001	6.97
CH18/2	15	0.06	0.02	1.00	0.018	7.43
CH18/3	30	0.04	0.01	1.01	0.031	8.05
CH44/1	20	0.03	0.01	1.02	0.137	6.33
CH45/1	5	22.6	7.91	1.24	0.059	7.23

CH45/2	20	8.96	3.14	1.21	0.025	
CH46/1	2	2.01	0.70	1.06	0.111	7.92
CH46/2	4	0.41	0.14	1.01	0.022	6.73
CH46/3	63	0.67	0.23	1.01	0.076	6.93
CH47/1	4	23.4	8.19	1.24	0.228	6.73
CH47/2	16	21.4	7.49	1.26	0.347	6.54
CH47/3	28	16.78	5.87	1.19	0.182	6.13
CH47/4	49	8.12	2.84	1.12	0.254	6.8
CH47/5	80	0.82	0.29	1.01	0.036	7.78
CH48/1	4	32.8	11.48	1.23	0.355	6.91
CH48/2	10	8.52	2.98	1.05	0.254	6.79
CH48/3	30	1.97	0.69	1.03	0.078	7.12
CH49/1	4	39	13.65	1.27	0.286	7.12
CH49/2	20	37.2	13.02	1.27	0.663	6.89
CH49/3	30	24.2	8.47	1.18	0.315	6.18
CH49/4	50	5.41	1.89	1.08	0.056	7.43
CH49/5	70	0.59	0.21	1.01	0.011	7.98
CH49/6	80	1.9	0.67	1.05	0.158	7.68
CH50/1	2	2.83	0.99	1.05	0.069	7.15
CH50/2	10	0.59	0.21	1.01	0.063	7.16
CH50/3	70			1.09	0.037	
CH51/1	4	23.5	8.23	1.17	0.338	5.84
CH51/2	20	43	15.05	1.23	0.588	6.56
CH51/3	60	32.6	11.41	1.22	0.685	6.16
CH51/4	70	2.72	0.95	1.03	0.058	7.64
CH51/5	80	1.41	0.49	1.05	0.033	8.09
CH51/6	90	0.56	0.20	1.01	0.011	8.28
CH51/7	95	2.26	0.79	1.05	0.140	7.44
CH52/1	4	2.87	1.00	1.04	0.066	7.15
CH52/2	10	0.56	0.20	1.01	0.031	6.37
CH52/3	30	1.04	0.36	1.02	0.092	6.36
CH52/4	50	1.2	0.42	1.03	0.113	7.16
CH52/5	60	1.83	0.64	1.24	0.200	6.97
CH53/1	2	22.8	7.98	1.20	0.349	
CH53/2	10			1.28	0.282	
CH53/3	20			1.30	0.192	
CH53/4	40	25.1	8.79	1.26	0.382	6.26
CH53/5	50			1.10	0.098	
CH54/1	5	0.97	0.34	1.02	0.367	6.37
CH54/2	30	1.23	0.43	1.06	0.313	4.36
CH54/3	60	0.59	0.21	1.10	0.376	5.83
CH55/1	2			1.39	0.005	
CH55/2	25	18.2	6.37	1.21	0.499	6.69
CH55/3	35	11.31	3.96	1.12	0.172	6.89

CH55/4	55			1.07	0.316	7.13
CH55/9	80			1.03		
CH55/10	100	1.24	0.43	1.02		7.46
CH56/1	2	0.45	0.16	1.03	0.035	5.07
CH56/2	5	0.25	0.09	1.04	0.092	4.9
CH56/3	40	0.08	0.03	1.02	0.199	4.36
CH58	15			1.02	0.017	
CH60/1	2	1.75	0.61	1.02	0.034	6.87
CH60/2	20	0.55	0.19	1.02	0.047	4.68
CH60/3	45	0.22	0.08	1.04	0.129	3.8
CH61/1	2	0.39	0.14	1.01	0.037	6.03
CH61/2	25	0.12	0.04	1.01	0.056	5.3
CH62/1	2	0.47	0.16	1.01	0.019	6.74
CH62/2	10	0.28	0.10	1.02	0.063	5.28
CH62/3	25	0.17	0.06	1.02	0.028	3.95
CH62/4	65	0.08	0.03	1.01	0.028	5.53
CH63/1	5	3.76	1.32	1.07	0.058	6.61
CH63/2	20	4.22	1.48	1.09	0.122	6.45
CH63/3	35	1.57	0.55	1.04	0.119	5.42
CH63/4	50	0.57	0.20	1.01	0.036	6.53
CH64/1	2	0.04	0.01	1.01	0.032	6.33
CH64/2	10	0.02	0.01	1.02	0.116	6.82
CH64/3	50	0.01	0.00	1.02	0.072	7.2
CH65/1	2	0.34	0.12	1.02	0.041	6.08
CH65/2	35	0.13	0.05	1.02	0.036	6.05
CH65/3	40	0.04	0.01	1.02	0.110	6.38
CH66/1	4	21.7	7.60	1.21	0.193	7.14
CH66/2	20	5.68	1.99	1.10	0.162	7.65
CH66/3	40	1.75	0.61	1.01	0.068	7.39
CH67/1	4			1.21	0.229	
CH67/2	15	27.4	9.59	1.26	0.392	7.52
CH67/3	25	13.36	4.68	1.23	0.244	6.99
CH67/4	55	5.21	1.82	1.13	0.477	7.3
CH67/5	70	0.97	0.34	1.02	0.089	7.75
CH68/1	2	2.06	0.72	1.02	0.105	7.24
CH68/2	20	0.96	0.34	1.01	0.078	7.15
CH69/1	10	0.35	0.12	1.01	0.046	6.35
CH71/1	2	0.29	0.10	1.04	0.106	4.67
CH71/2	2	0.09	0.03	1.04	0.265	5.35
CH71/3	2	0.1	0.04	1.04	2.455	6.4
CH71/4	2	0.03	0.01	1.03	0.267	6.25

CH72/1	2	0.17	0.06	1.02	0.229	6.93
CH72/2	2	0.29	0.10	1.03	0.562	6.82
CH72/3	2			1.20	2.822	
CH72/4	2			1.03	0.846	

Table 2: Soil total organic carbon, total nitrogen for soil samples from Cape Hallett.

Sample	Corrected Nitrogen %	Corrected Nitrogen%	Average Nitrogen%	Average Abs.	Corrected Carbon %
CH3/1	1.9	2.0	2.0	0.281	11.19
CH3/2	2.0	2.0	2.0	0.148	5.18
CH3/3	1.3	1.5	1.4	0.544	22.81
CH3/4	0.6	0.7	0.6	0.407	17.3
CH3/5					
CH18/1	0.0	0.0	0.0	0.034	0.45
CH18/2	0.0	0.0	0.0	0.022	0.22
CH18/3	-0.1	-0.1	-0.1	0.020	0.18
CH46/1	2.6	2.3	2.5	0.185	12.99
CH46/2	0.7	0.6	0.7	0.102	6.39
CH46/3	0.6	0.4	0.5	0.215	3.77
CH47/1	9.0	8.8	8.9	0.279	9.4
CH47/2	3.5	3.1	3.3	0.242	7.87
CH47/3	3.2	3.0	3.1	0.206	6.93
CH47/4	2.5	3.0	2.8	0.123	3.97
CH47/5	1.2	1.5	1.3	0.105	0.56
CH48/1	9.6	10.6	10.1	0.258	8.68
CH48/2	3.6	3.5	3.5	0.164	6.01
CH48/3	2.0	1.7	1.8	0.093	2.97
CH51/1	13.3	12.0	12.7	0.278	9.87
CH51/2	5.5	4.2	4.9	0.295	10.03
CH51/3	5.2	3.6	4.4	0.329	11.45
CH51/4	2.3	2.5	2.4	0.149	5.51
CH51/5	2.7	2.7	2.7	0.189	7.15
CH51/6	0.5	0.7	0.6	0.065	0.17
CH51/7	3.0	2.9	3.0	0.161	5.91
CH52/1	3.0	2.7	2.9	0.749	6.76
CH52/2	0.4	0.4	0.4	0.214	1.65
CH52/3	1.4	1.4	1.4	0.139	5.07
CH52/4	2.8	3.2	3.0	0.069	1.91
CH52/5	3.0	3.1	3.0	0.052	0.94
CH53/1	14.5		14.5	0.319	11.25
CH53/2	4.6		4.6	0.283	9.21
CH53/3	4.2		4.2	0.351	11.55
CH53/4	4.0		4.0	0.203	6.45
CH53/5	2.8		2.8	0.215	7.92

CH54/1	0.4	0.5	0.4	0.270	2.17
CH54/2	0.8	0.8	0.8	0.185	6.89
CH54/3	1.0	1.0	1.0	0.194	7.04
CH55/1	2.3		2.3	0.281	8.41
CH55/2	4.0		4.0	0.200	6.62
CH55/3	2.6		2.6	0.113	3.56
CH55/4	2.1		2.1	0.123	4.15
CH55/9	0.9		0.9	0.312	2.56
CH55/10	0.7		0.7	0.155	1.05
CH56/1	0.9		0.9	0.566	5.02
CH56/2	0.9		0.9	0.561	4.94
CH56/3	0.2		0.2	0.088	0.39
CH58	1.2		1.2	0.153	5.27
CH60/1	1.1	0.9	1.0	0.222	1.71
CH60/2	0.9	0.2	0.5	0.151	1.01
CH60/3	0.1	0.3	0.2	0.103	0.53
CH61/1	0.1	0.2	0.1	0.111	0.62
CH61/2	0.0	0.0	0.0	0.069	0.21
CH62/1	0.6		0.3	0.358	3.21
CH62/2	0.4		0.2	0.057	0.89
CH62/3	0.2		0.1	0.087	0.6
CH62/4	0.1		0.0	0.036	0.11
CH64/1	0.1		0.1	0.102	0.75
CH64/2	0.1		0.1	0.133	1.03
CH64/3	0.1		0.1	0.096	0.68
CH65/1	0.5		0.2	0.057	0.89
CH65/2	0.5		0.2	0.071	1.53
CH65/3	0.2		0.1	0.025	-0.57
CH67/1	8.8	9.0	8.9	0.272	17.61
CH67/2	3.8		1.9	0.271	16.83
CH67/3	3.6		1.8	0.183	11.03
CH67/4	3.2		1.6	0.070	3.22
CH67/5	1.3		0.7	0.174	3
CH68/1	1.3		0.7	0.970	42.42
CH68/2	0.6		0.3	0.308	2.72
CH69/1	0.1		0.0	0.016	-0.08
CH71/1	0.7		0.4	0.091	2.4
CH71/2	1.6		0.8	0.195	7.02
CH71/3	1.9		1.0	0.288	11.18
CH71/4	0.6		0.3	0.097	2.69
CH72/1	0.8		0.4	0.066	1.3

CH72/2	0.9		0.5	0.101	2.88
CH72/3	3.6		1.8	0.306	10.41
CH72/4	1.4		0.7	0.162	5.62

Table 3: XRF analysis data for samples from Cape Hallett.

	67/2a	67/2b	67/3a	67/3b	67/5	46/2	46/3	69/1	60/1	60/2	60/3
Na %	2.95	3.16	2.49	2.17	4.30	4.34	4.56	4.51	3.85	3.82	3.71
Mg %	4.28	4.44	6.37	6.54	2.58	1.82	1.98	3.26	1.52	1.50	1.51
Al %	0.36	0.36	0.62	0.63	8.84	9.05	9.30	9.27	9.16	9.55	9.15
Si %	2.39	2.47	3.24	3.28	22.79	23.07	24.08	23.90	23.53	23.84	24.70
P %	9.80	10.10	12.31	12.57	1.06	0.81	0.72	0.37	1.43	1.45	1.17
S ppm	12150	12400	11570	11800	585	570	590	285	755	670	690
Cl ppm	10510	10680	17280	17670	1360	880	1030	1300	1310	900	750
K %	0.66	0.69	0.80	0.81	1.90	1.91	1.96	1.86	1.84	1.82	1.82
Ca %	8.84	9.11	11.73	11.99	5.86	5.58	5.51	5.70	5.63	5.20	5.40
Ti %	0.04	0.04	0.10	0.11	1.39	1.38	1.39	1.41	1.35	1.35	1.44
V ppm	3.5	4.2	11.0	11.1	185	185	174	157	147	147	158
Cr ppm	4.2	4.3	11.3	10.9	142	107	95	216	36	27	35
Mn %	0.02	0.02	0.03	0.03	0.18	0.17	0.18	0.19	0.19	0.20	0.20
Fe %	0.51	0.53	0.99	1.02	7.91	7.91	7.93	8.08	8.06	8.19	8.51
Co ppm	< 4.4	< 3.1	7.4	6.1	17.3	24	33	40	21	11.8	21
Ni ppm	9.2	9.2	14.3	13.9	72	38	37	132	15.2	15.0	12.6
Cu ppm	377	391	381	394	32	31	29	30	28	26	29
Zn ppm	515	530	575	590	130	128	122	116	136	126	130
Ga ppm	0.5	1.2	1.9	2.2	22.1	22.8	22.3	21.8	23.2	22.5	24.5
Ge ppm	1.0	0.8	1.0	0.7	0.4	< 0.7	< 0.8	< 0.9	< 0.6	0.5	0.6
As ppm	13.0	13.4	9.7	9.7	< 0.3	1.3	1.7	0.3	4.4	4.9	5.8
Se ppm	43	45	41	42	1.3	1.0	0.5	< 0.4	0.9	0.7	0.9
Br ppm	431	445	433	444	9.0	5.4	5.1	4.8	7.7	5.8	6.2
Rb ppm	7.7	8.3	11.6	11.6	56	57	57	54	52	55	54
Sr ppm	1440	1500	1600	1655	965	970	960	890	1050	1040	1090
Y ppm	1.9	1.7	4.5	4.5	34	35	35	33	34	34	35
Zr ppm	17.6	18.4	48	49	390	400	404	378	401	410	433
Nb ppm	7.0	7.5	16.2	16.6	122	126	126	124	132	134	143
Mo ppm	0.7	1.0	1.5	1.6	5.4	5.6	5.8	5.4	5.0	5.4	6.0
Ag ppm	13.3	12.4	12.5	12.3	< 0.4	< 0.4	< 0.4	< 0.4	< 0.4	< 0.4	< 0.4
Cd ppm	16.2	14.7	14.2	12.6	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
In ppm	< 0.7	< 0.7	< 0.7	< 0.7	< 0.7	< 0.7	< 0.7	< 0.7	< 0.7	< 0.7	< 0.7
Sn ppm	< 0.7	< 0.7	< 0.7	0.5	2.2	2.2	1.6	1.4	1.6	1.9	1.5
Sb ppm	0.7	< 0.9	< 0.9	< 0.9	< 0.9	< 0.9	< 0.9	< 0.9	< 0.9	< 0.9	< 0.9
Te ppm	1.4	< 1.2	< 1.2	< 1.2	< 1.2	< 1.2	< 1.2	< 1.2	< 1.2	< 1.2	< 1.2
I ppm	23	18.5	16.0	14.2	< 1.5	< 1.5	< 1.5	< 1.5	< 1.5	< 1.5	< 1.5
Cs ppm	4.3	< 2.6	< 2.6	< 2.6	< 2.6	< 2.6	< 2.6	< 2.6	< 2.6	< 2.6	< 2.6
Ba ppm	122	103	149	133	645	670	660	610	670	680	715
La ppm	12.0	< 4.9	7.8	5.8	76	79	75	74	77	78	81
Ce ppm	6.8	5.4	17.0	14.3	144	149	144	134	150	151	156
Pr ppm	< 8.0	< 8.0	< 8.0	< 8.0	10.3	8.2	< 8.0	< 8.0	< 8.0	7.2	< 8.0
Nd ppm	< 10	< 10	9	< 10	59	60	54	47	57	61	61
Hf ppm	< 7.2	< 5.1	< 7.7	< 5.2	9.1	7.5	9.4	8.7	6.8	8.2	7.1
Ta ppm	< 13	< 8.5	< 13	< 9.0	8.0	9.1	11.0	9.0	7.0	7.7	7.5
W ppm	< 4.3	< 2.9	< 4.6	< 3.1	132	146	168	215	79	94	92
Hg ppm	< 0.6	< 0.4	< 0.7	< 0.4	< 1.0	< 1.0	0.9	0.8	< 0.8	< 0.9	< 0.9
Tl ppm	2.5	1.7	2.4	2.3	0.6	0.6	0.6	0.5	< 0.6	0.3	< 0.7
Pb ppm	3.9	4.2	5.7	5.8	5.8	5.8	5.4	5.7	6.3	5.4	5.8
Bi ppm	0.8	< 0.4	1.5	0.4	< 0.6	< 0.5	< 0.5	< 0.6	< 0.5	< 0.6	< 0.6
Th ppm	3.5	4.6	6.2	7.1	12.5	12.6	12.4	11.4	12.4	13.0	12.7
U ppm	< 1.5	< 1.5	1.1	< 1.5	2.9	1.5	3.5	3.1	2.4	2.0	2.1

APPENDIX 2
Tracer test data

Table 1: Bromide concentration (mg L^{-1}) in sampling wells after tracer test at CH11 on December 11, 2004. Relative bromide concentrations are actual concentration/background concentration (time =0).

Time Minutes from start	0	30	90	160	218	275	330	390	450	510	565	635	690	1060	1575
A actual [Br-]	69	150	429	514	567	542	579	683	751	739	561	561	462	242	78
A relative [Br-]	1	2.2	6.2	7.4	8.2	7.9	8.4	9.9	10.9	10.7	8.1	8.1	6.7	3.5	1.1
B actual [Br-]	69	159	344	482	440	525	586	679	764	684	558	623	466	291	175
B relative [Br-]	1	2.3	5	7	6.4	7.6	8.5	9.8	11.1	9.9	8.1	9.0	6.8	4.2	2.5
C actual [Br-]	69	112	117	133	145	153	161	201	236	253	226	263	173	123	92
C relative [Br-]	1	1.6	1.7	1.9	2.1	2.2	2.3	2.9	3.4	3.7	3.3	3.8	2.5	1.8	1.3
D actual [Br-]	95	95	93	104	117	148	173	242	338	360	385	434	297	290	177
D relative [Br-]	1	1	1	1.1	1.2	1.6	1.8	2.5	3.6	3.8	4.1	4.6	3.1	3.1	1.9
E actual [Br-]	95	112	117	126	130	133	147	180	238	238	197	214	135	160	116
E relative [Br-]	1	1.2	1.2	1.3	1.4	1.4	1.5	1.9	2.5	2.5	2.1	2.3	1.4	1.7	1.2
F actual [Br-]	95	113	126	133	137	146	160	171	230	255	201	237	119	135	97
F relative [Br-]	1	1.2	1.3	1.4	1.4	1.5	1.7	1.8	2.4	2.7	2.1	2.5	1.3	1.4	1.0

Table 2: Bromide concentration (mg L^{-1}) in sampling wells after tracer test at CH11 on January 3, 2005. Relative bromide concentrations are actual concentration/background concentration (time =0).

Time Minutes from start	0	50	105	165	220	295	345	405	465	1465
A actual [Br-]	98	125	126	176	246	242	198	154	117	90
A relative [Br^-]	1	1	1	2	3	2	2	2	1	1
B actual [Br^-]	98	126	192	1079	808	291	170	141	116	92
B relative [Br^-]	1	1	2	11	8	3	2	1	1	1
C actual [Br^-]	98	125	154	393	330	222	164	132	111	97

C relative [Br⁻]	1	1	2	4	3	2	2	1	1	1
D actual [Br⁻]	98	127	142	170	215	466	545	418	237	102
D relative [Br⁻]	1	1	1	2	2	5	6	4	2	1
E actual [Br⁻]	98	127	136	172	228	302	271	209	166	102
E relative [Br⁻]	1	1	1	2	2	3	3	2	2	1
F actual [Br⁻]	98	130	142	164	185	205	182	168	145	104
F relative [Br⁻]	1	1	1	2	2	2	2	2	1	1

Table 3: Bromide concentration (mg L^{-1}) in sampling wells after tracer test at CH11 on January 6, 2005. Relative bromide concentrations are actual concentration/background concentration (time =0).

Time Minutes from start	0	65	120	180	235	315	370	450	540	1440
A actual [Br-]	24	7	21	22	53	73	81	56	25	24
A relative [Br⁻]	1	0	1	1	2	3	3	2	1	1
B actual [Br⁻]	26	13	257	1013	346	72	36	34	24	24
B relative [Br⁻]	1	0	10	39	13	3	1	1	1	1
C actual [Br⁻]	24	23	38	148	69	42	37	34	25	25
C relative [Br⁻]	1	1	2	6	3	2	2	1	1	1
D actual [Br⁻]	24	16	32	36	30	168	343	262	122	35
D relative [Br⁻]	1	1	1	1	1	7	14	11	5	1
E actual [Br⁻]	23	17	29	30	27	63	86	68	54	31
E relative [Br⁻]	1	1	1	1	1	3	4	3	2	1
F actual [Br⁻]	22	25	30	32	16	34	46	42	39	25
F relative [Br⁻]	1	1	1	1	1	2	2	2	2	1

Table 4: Bromide concentration (mg L^{-1}) in sampling wells after tracer test at CH29 on December 21, 2004. Relative bromide concentrations are actual concentration/background concentration (time =0).

Time Minutes from start	0	30	85	285	350	400	510	690	1350	1470
A actual [Br-]	55.3	56.6	53.7	60.6	55.8	53.1	54.5	62.8	81.7	79.5
A relative [Br^-]	1.0	1.0	1.0	1.1	1.0	1.0	1.0	1.1	1.5	1.4
B actual [Br^-]	67.4	57.4	55.2	67.8	64.5	55.8	60.8	69.4	76.1	75.9
B relative [Br^-]	1.0	0.9	0.8	1.0	1.0	0.8	0.9	1.0	1.1	1.1
C actual [Br^-]	66.7	54.4	70.8	64.3	57.5	66.8	70.1	77.1	76.9	64.8
C relative [Br^-]	1.0	0.8	1.1	1.0	0.9	1.0	1.1	1.2	1.2	1.0
D actual [Br^-]	68.3	57.8	70.7	68.1	60.3	70.5	71.2	73.4	80.8	64.0
D relative [Br^-]	1.0	0.8	1.0	1.0	0.9	1.0	1.0	1.1	1.2	0.9
E actual [Br^-]	68.5	56.6	69.7	69.9	66.5	70.3	72.1	74.5	87.4	65.9
E relative [Br^-]	1.0	0.8	1.0	1.0	1.0	1.0	1.1	1.1	1.3	1.0
F actual [Br^-]	70.0	57.1	75.0	72.1	70.0	78.3	76.3	74.4	94.0	70.3
F relative [Br^-]	1.0	0.8	1.1	1.0	1.0	1.1	1.1	1.1	1.3	1.0

Table 5: Bromide concentration (mg L^{-1}) in sampling wells after tracer test at CH29 on December 28, 2004. Relative bromide concentrations are actual concentration/background concentration (time =0).

Time Minutes from start	0	40	110	175	235	305	375	435	500	570	1480	1540
G actual [Br-]	128.0	161.0	123.2	87.4	104.4	97.8	125.1	129.8	125.1	123.2	106.3	109.1
G relative [Br^-]	1.0	1.3	1.0	0.7	0.8	0.8	1.0	1.0	1.0	1.0	0.8	0.9
A actual [Br-]	117.6	128.9	120.4	98.7	106.3	107.2	111.0	129.8	102.5	115.7	108.1	
A relative [Br^-]	1.0	1.1	1.0	0.8	0.9	0.9	0.9	1.1	0.9	1.0	0.9	
B actual [Br^-]	120.4	131.7	120.4	106.3	111.0	99.7	108.1	122.3	108.1	108.1	103.4	
B relative [Br^-]	1.0	1.1	1.0	0.9	0.9	0.8	0.9	1.0	0.9	0.9	0.9	
C actual [Br^-]	120.4	134.6	127.0	104.4	108.1	108.1	110.0	127.0	97.8	124.2	107.2	

C relative [Br⁻]	1.0	1.1	1.1	0.9	0.9	0.9	0.9	1.1	0.8	1.0	0.9
H actual [Br⁻]	117.6	129.8	129.8	108.1	108.1	104.4	119.5	131.7	94.9	77.6	104.4
H relative [Br⁻]	1.0	1.1	1.1	0.9	0.9	0.9	1.0	1.1	0.8	0.7	0.9
D actual [Br⁻]	120.4	120.4	122.3	111.0	100.6	105.3	114.7	133.6	103.4	78.3	106.3
D relative [Br⁻]	1.0	1.0	1.0	0.9	0.8	0.9	1.0	1.1	0.9	0.6	0.9
E actual [Br⁻]	125.6	133.3	130.4	113.3	113.3	124.7	132.3	109.4	83.7	109.4	
E relative [Br⁻]	1.0	1.1	1.0	0.9	0.9	1.0	1.1	0.9	0.7	0.9	
F actual [Br⁻]	139.3	124.2	137.4	114.7	111.9	123.2	135.5	107.2	89.3	109.1	
F relative [Br⁻]	1.0	0.9	1.0	0.8	0.8	0.9	1.0	0.8	0.6	0.8	

Table 6: Bromide concentration (mg L^{-1}) in sampling wells after tracer test at CH29 on January 9, 2005. Relative bromide concentrations are actual concentration/background concentration (time =0).

Time Minutes from start	0	30	105	190	220	300	370	450	520	580	1405
G actual [Br-]	81.7	91.2	98.7	117.6	118.5	110.0	111.0	104.4	99.7	98.7	92.1
G relative [Br⁻]	1.0	1.1	1.2	1.4	1.4	1.3	1.4	1.3	1.2	1.2	1.1
A actual [Br-]	84.6	89.3	100.6	119.5	122.3	118.5	110.0	100.6	103.4	100.6	85.5
A relative [Br⁻]	1.0	1.1	1.2	1.4	1.4	1.4	1.3	1.2	1.2	1.2	1.0
B actual [Br⁻]	89.3	90.2	94.0	112.9	117.6	109.1	108.1	94.0	97.8	99.7	88.3
B relative [Br⁻]	1.0	1.0	1.1	1.3	1.3	1.2	1.2	1.1	1.1	1.1	1.0
C actual [Br⁻]	80.8	84.6	89.3	113.8	110.0	100.6	101.5	91.2	94.9	97.8	91.2
C relative [Br⁻]	1.0	1.0	1.1	1.4	1.4	1.2	1.3	1.1	1.2	1.2	1.1
H actual [Br⁻]	85.5	81.7	98.7	99.7	94.9	99.7	100.6	96.8	95.9	88.3	82.7
H relative [Br⁻]	1.0	1.0	1.2	1.2	1.1	1.2	1.2	1.1	1.1	1.0	1.0
D actual [Br⁻]	85.5	89.3	94.0	89.3	84.6	89.3	109.1	88.3	89.3	94.9	86.5
D relative [Br⁻]	1.0	1.0	1.1	1.0	1.0	1.0	1.3	1.0	1.0	1.1	1.0

E actual [Br-]	84.6	85.5	94.9	90.2	85.5	94.0	95.9	87.4	92.1	99.7	91.2
E relactive [Br-]	1.0	1.0	1.1	1.1	1.0	1.1	1.1	1.0	1.1	1.2	1.1
F actual [Br-]	89.3	90.2	91.2	100.6	81.7	84.6	84.6	94.0	93.1	88.3	81.7
F relative [Br-]	1.0	1.0	1.0	1.1	0.9	0.9	0.9	1.1	1.0	1.0	0.9

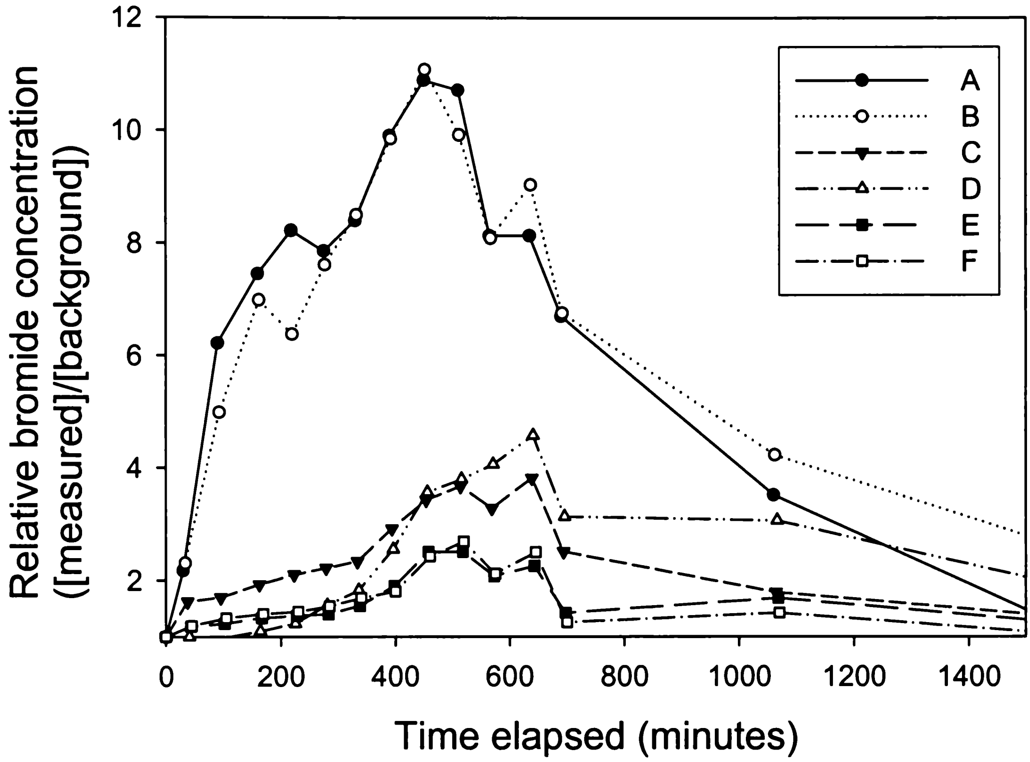

Figure 1: Breakthrough curve of bromide concentrations in sampling wells near CH11 after tracer test on 11 December 2004.

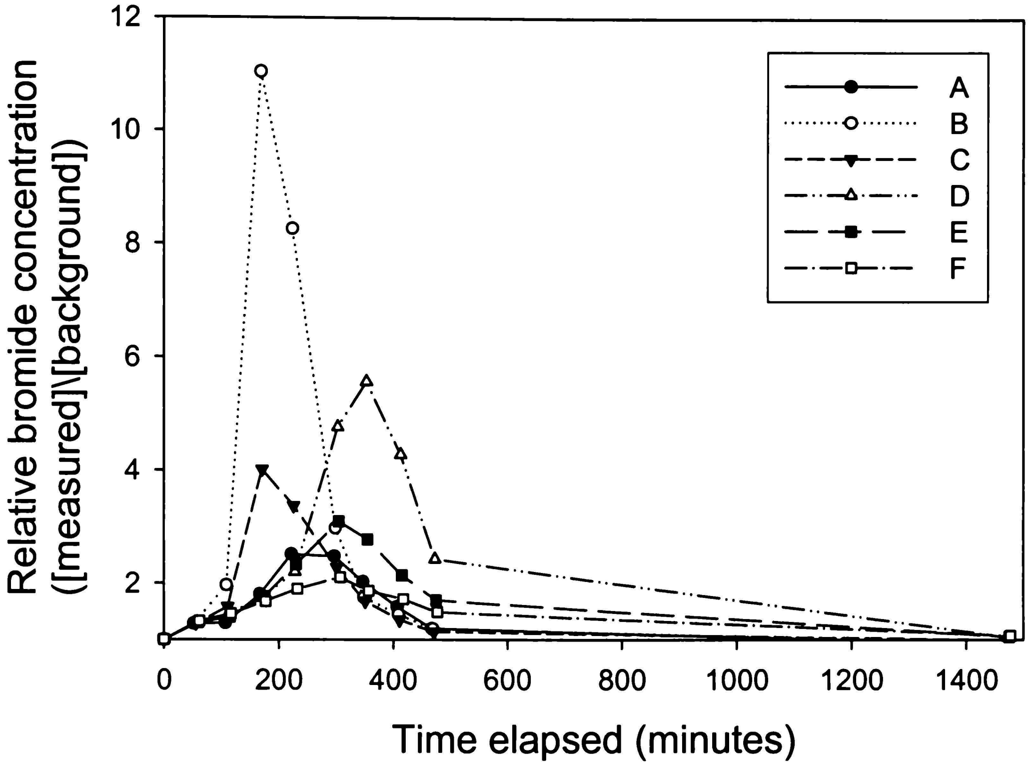

Figure 2: Breakthrough curve of bromide concentrations in sampling wells near CH11 after tracer test on 3 January 2005.

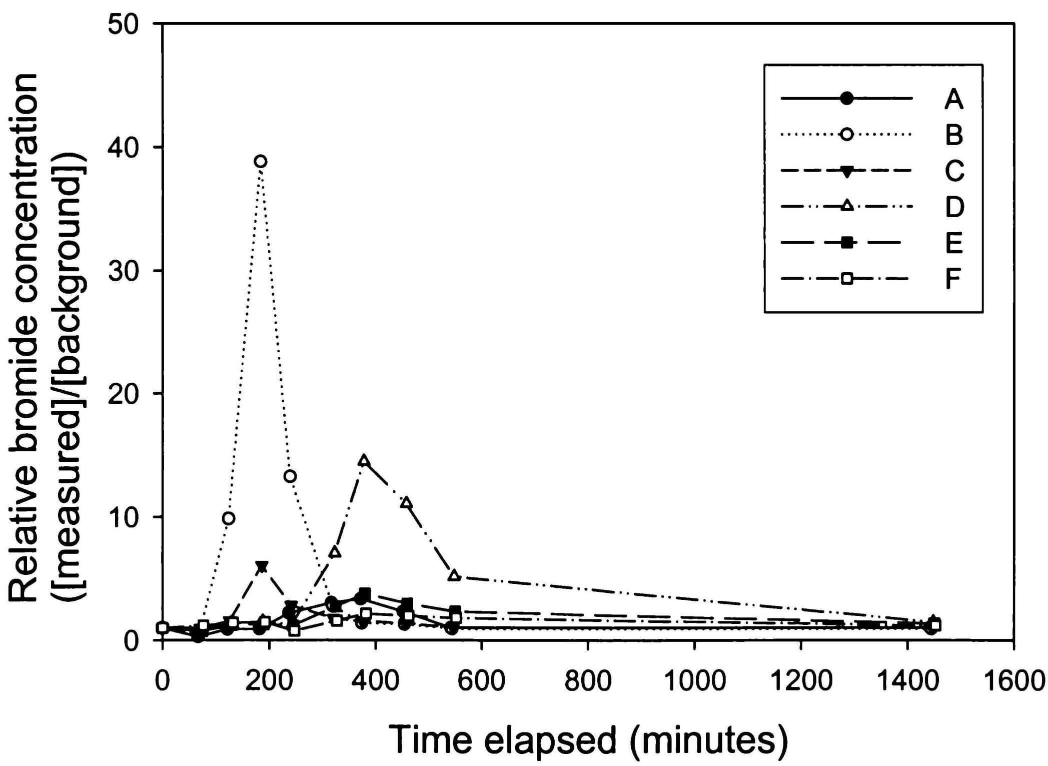

Figure 3: Breakthrough curve of bromide concentrations in sampling wells near CH11 after tracer test on 6 January 2005.

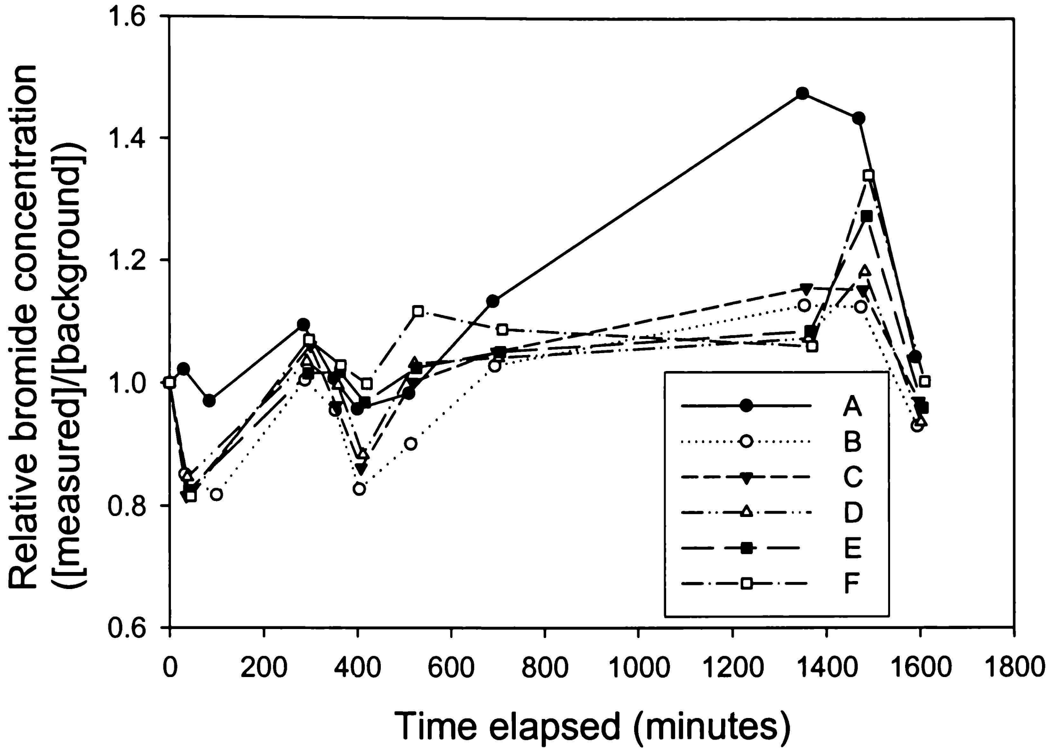

Figure 4: Breakthrough curve of bromide concentrations in sampling wells near CH29 after tracer test on 21 December 2004.

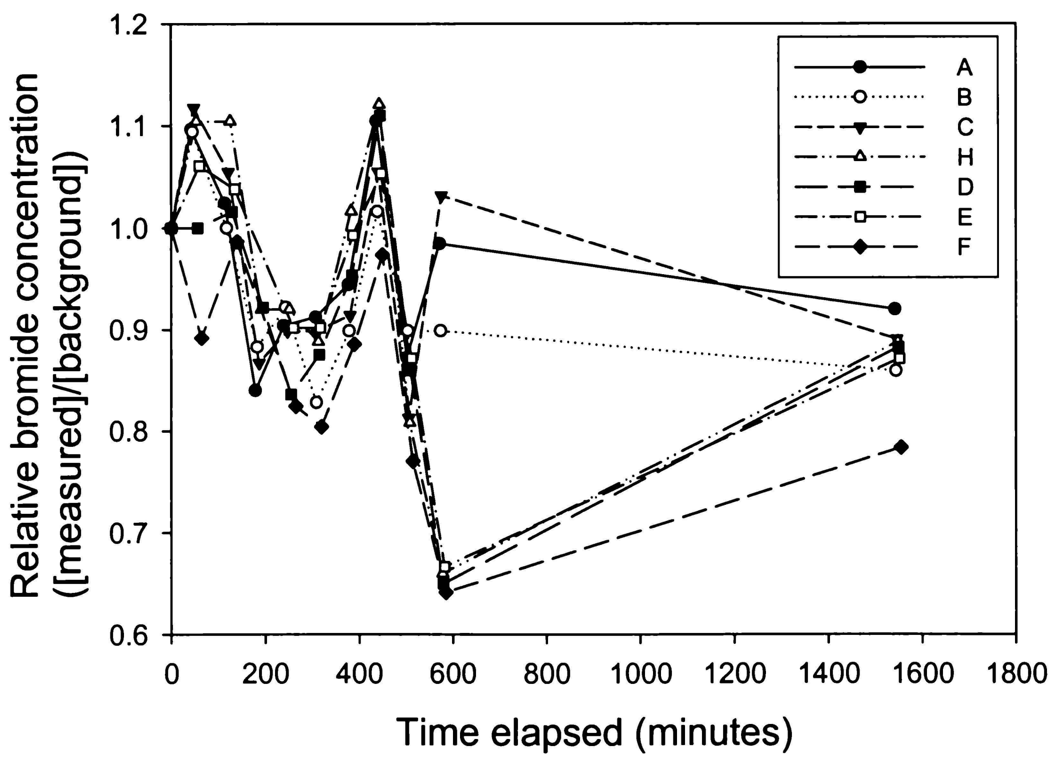

Figure 5: Breakthrough curve of bromide concentrations in sampling wells near CH29 after tracer test on 28 December 2004.

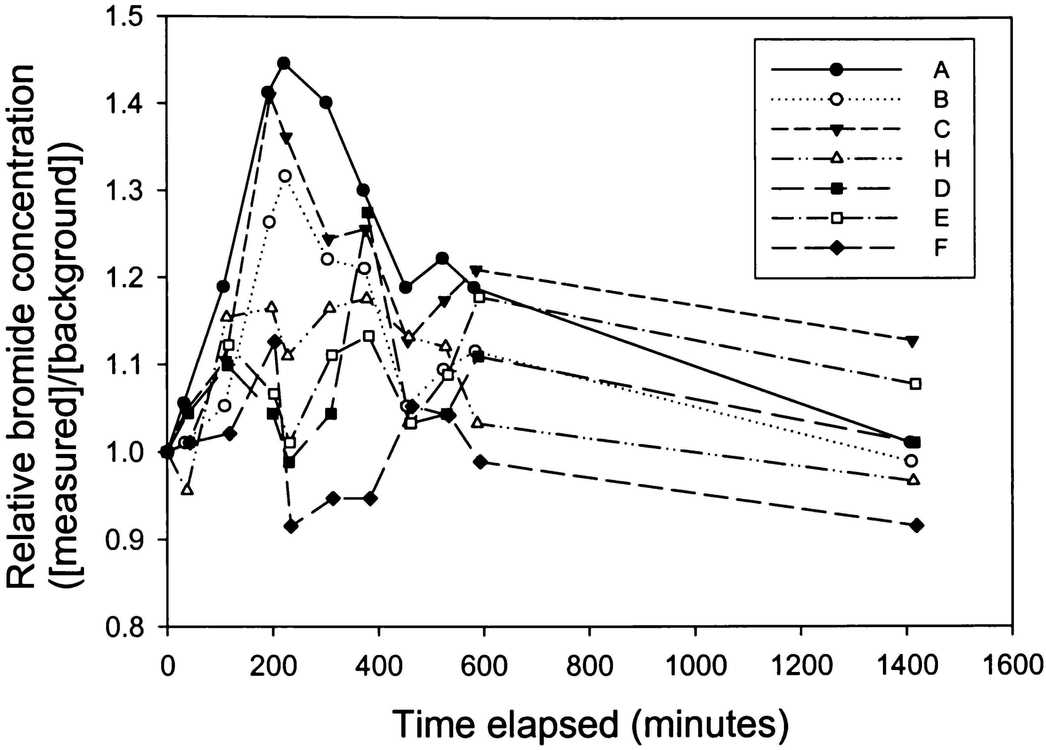

Figure 6: Breakthrough curve of bromide concentrations in sampling wells near CH29 after tracer test on 9 January 2005.

APPENDIX 3
Radiocarbon dating data

The University of Waikato
Radiocarbon Dating Laboratory

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Ph +64 7 838 4278
email c14@waikato.ac.nz
Head: Dr Alan Hogg

Report on Radiocarbon Age Determination for Wk- 16685

(AMS measurement by IGNS [NZA-22846])

Submitter	E Hofstee
Submitter's Code	CH67/6 40cm
Site & Location	Cape Hallett, Victoria Land, Antarctica
Sample Material	Penguin bone
Physical Pretreatment	Sample was cleaned, ground and visible contaminants were removed.
Chemical Pretreatment	Sample was decalcified in 2% HCl, rinsed and dried. Then gelatinised at pH=3 with HCl at 90 degrees for 4 hours. Rinsed and dried.

$d^{14}C$	-244.0 ± 2.7	‰
$\delta^{13}C$	-22.9 ± 0.2	‰
$D^{14}C$	-251.3 ± 3.1	‰
% Modern	74.9 ± 0.3	%
Result	**2325 ± 33 BP**	

Comments

AG Hogg

18/8/05

- Result is *Conventional Age or % Modern* as per Stuiver and Polach, 1977, Radiocarbon 19, 355-363. This is based on the Libby half-life of 5568 yr with correction for isotopic fractionation applied. This age is normally quoted in publications and must include the appropriate error term and Wk number.
- Quoted errors are 1 standard deviation due to counting statistics multiplied by an experimentally determined Laboratory Error Multiplier of 1
- The isotopic fractionation, $\delta^{13}C$, is expressed as ‰ wrt PDB.
- Results are reported as *% Modern* when the conventional age is younger than 200 yr BP.

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Report on Radiocarbon Age Determination for Wk- 16684

Submitter	E Hofstee
Submitter's Code	CH63/5 35cm
Site & Location	Cape Hallett, Victoria Land, Antarctica
Sample Material	Penguin bone
Physical Pretreatment	Sample was cleaned, ground and visible contaminants were removed.
Chemical Pretreatment	Sample was decalcified in 2% HCl, rinsed and dried. Then gelatinised at pH=3 with HCl at 90 degrees for 4 hours. Rinsed and dried.

$d^{14}C$	-206.5 ± 15.5	‰
$\delta^{13}C$	-26.4 ± 0.2	‰
$D^{14}C$	-204.3 ± 15.6	‰
% Modern	79.6 ± 1.6	%
Result	**1835 ± 159 BP**	

Comments

AG Hogg
18/8/05

- Result is *Conventional Age or % Modern* as per Stuiver and Polach, 1977, Radiocarbon 19, 355-363. This is based on the Libby half-life of 5568 yr with correction for isotopic fractionation applied. This age is normally quoted in publications and must include the appropriate error term and Wk number.
- Quoted errors are 1 standard deviation due to counting statistics multiplied by an experimentally determined Laboratory Error Multiplier of 1
- The isotopic fractionation, $\delta^{13}C$, is expressed as ‰ wrt PDB.
- Results are reported as *% Modern* when the conventional age is younger than 200 yr BP.

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Report on Radiocarbon Age Determination for Wk- 16679

Submitter	E Hofstee
Submitter's Code	CH51/8 70-80cm
Site & Location	Cape Hallett, Victoria Land, Antarctica
Sample Material	Penguin bone
Physical Pretreatment	Sample was cleaned, ground and visible contaminants were removed.
Chemical Pretreatment	Sample was decalcified in 2% HCl, rinsed and dried. Then gelatinised at pH=3 with HCl at 90 degrees for 4 hours. Rinsed and dried.

$d^{14}C$	-162.1 ± 5.4	‰
$\delta^{13}C$	-25.7 ± 0.2	‰
$D^{14}C$	-160.9 ± 5.5	‰
% Modern	83.9 ± 0.5	%
Result	**1409 ± 52 BP**	

Comments

AG Hogg
18/8/05

- Result is *Conventional Age or % Modern* as per Stuiver and Polach, 1977, Radiocarbon 19, 355-363. This is based on the Libby half-life of 5568 yr with correction for isotopic fractionation applied. This age is normally quoted in publications and must include the appropriate error term and Wk number.
- Quoted errors are 1 standard deviation due to counting statistics multiplied by an experimentally determined Laboratory Error Multiplier of 1
- The isotopic fractionation, $\delta^{13}C$, is expressed as ‰ wrt PDB.
- Results are reported as *% Modern* when the conventional age is younger than 200 yr BP.

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Report on Radiocarbon Age Determination for Wk- 16680

Submitter	E Hofstee
Submitter's Code	CH51/9 90cm
Site & Location	Cape Hallett, Victoria Land, Antarctica
Sample Material	Penguin bone
Physical Pretreatment	Sample was cleaned, ground and visible contaminants were removed.
Chemical Pretreatment	Sample was decalcified in 2% HCl, rinsed and dried. Then gelatinised at pH=3 with HCl at 90 degrees for 4 hours. Rinsed and dried.

$d^{14}C$	-195.5 ± 13.3	‰
$\delta^{13}C$	-26.5 ± 0.2	‰
$D^{14}C$	-193.1 ± 13.3	‰
% Modern	80.7 ± 1.3	%
Result	**1723 ± 134 BP**	

Comments

AG Hogg
18/8/05

- Result is *Conventional Age or % Modern* as per Stuiver and Polach, 1977, Radiocarbon 19, 355-363. This is based on the Libby half-life of 5568 yr with correction for isotopic fractionation applied. This age is normally quoted in publications and must include the appropriate error term and Wk number.
- Quoted errors are 1 standard deviation due to counting statistics multiplied by an experimentally determined Laboratory Error Multiplier of 1
- The isotopic fractionation, $\delta^{13}C$, is expressed as ‰ wrt PDB.
- Results are reported as *% Modern* when the conventional age is younger than 200 yr BP.

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Report on Radiocarbon Age Determination for Wk- 16678

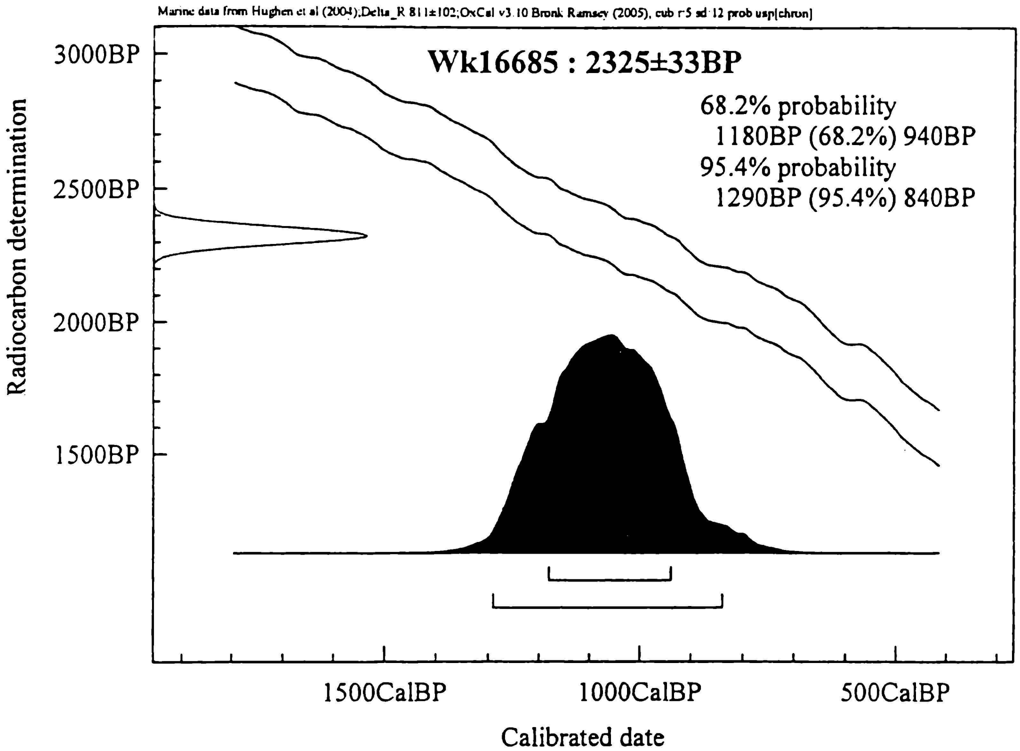
Submitter	E Hofstee
Submitter's Code	CH49/7 70-80cm
Site & Location	Cape Hallett, Victoria Land, Antarctica
Sample Material	Penguin eggshell
Physical Pretreatment	Fresh shell was selected for dating.
Chemical Pretreatment	Sample was acid etched in 2M HCl for 100 seconds, rinsed and dried.

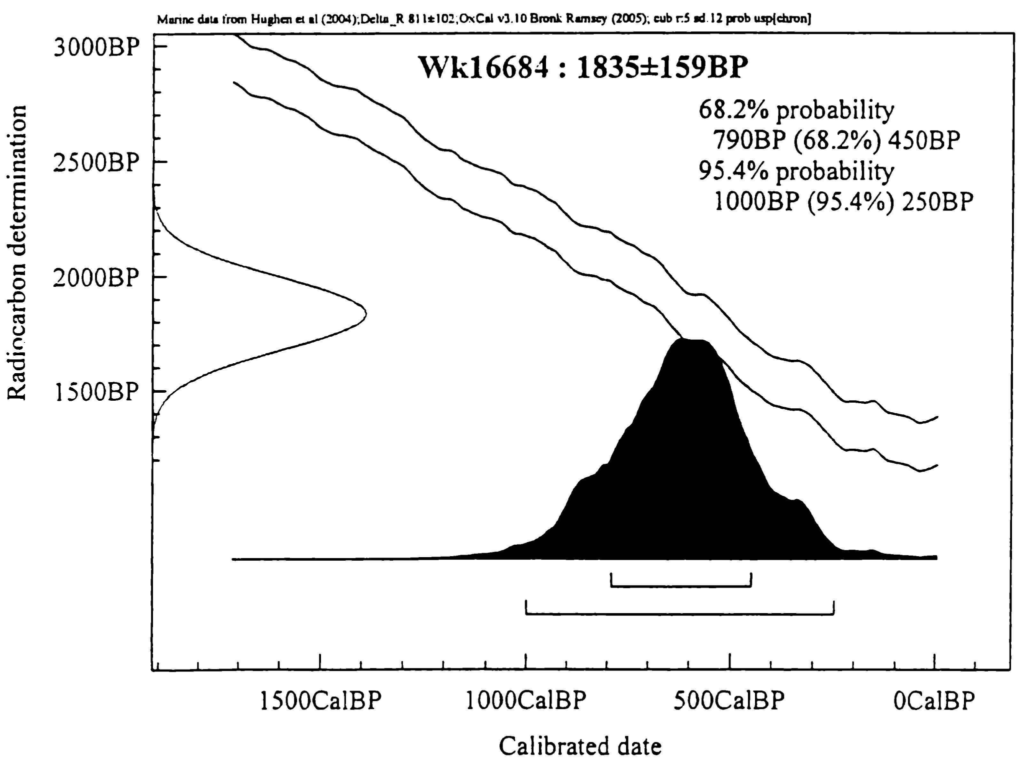
$d^{14}C$	-119.4 ± 23.3	‰
$\delta^{13}C$	-19.3 ± 0.2	‰
$D^{14}C$	-129.4 ± 23.0	‰
% Modern	87.1 ± 2.3	%
Result	**1113 ± 215 BP**	

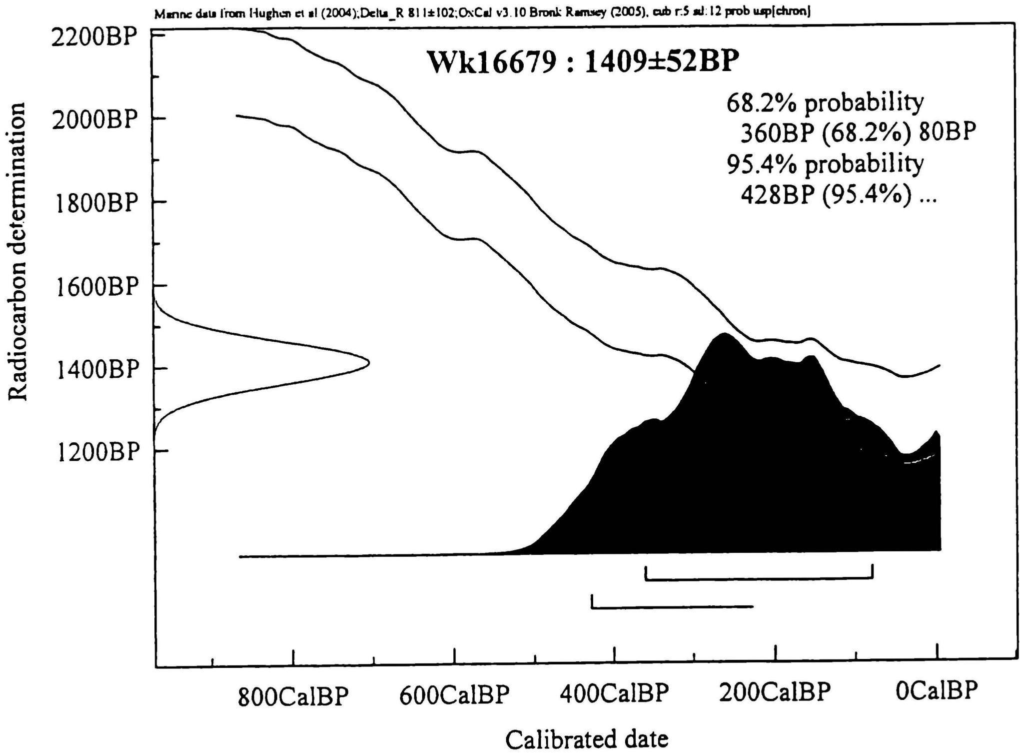
Comments

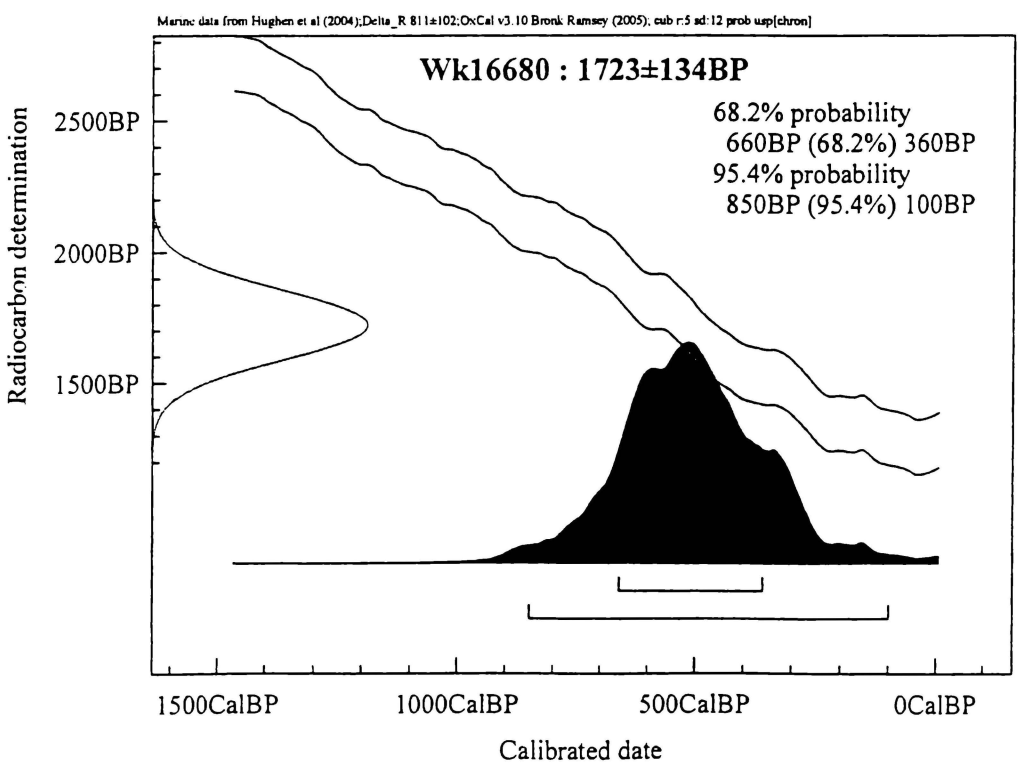
AG Hogg
18/8/05

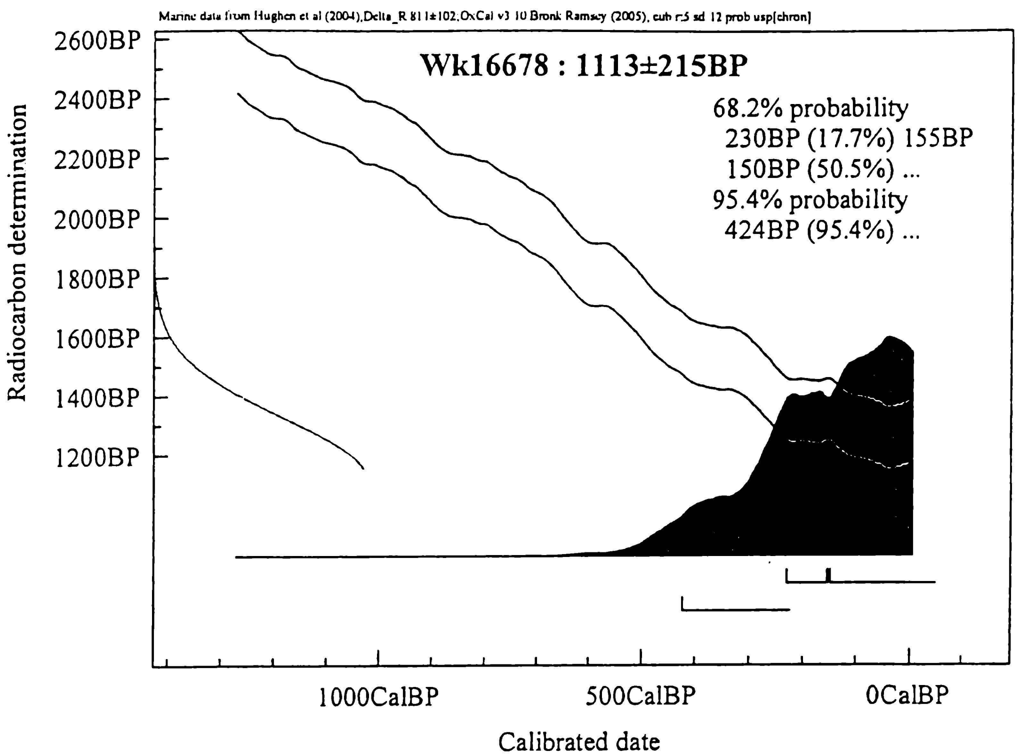
- Result is *Conventional Age or % Modern* as per Stuiver and Polach, 1977, Radiocarbon 19, 355-363. This is based on the Libby half-life of 5568 yr with correction for isotopic fractionation applied. This age is normally quoted in publications and must include the appropriate error term and Wk number.
- Quoted errors are 1 standard deviation due to counting statistics multiplied by an experimentally determined Laboratory Error Multiplier of 1
- The isotopic fractionation, $\delta^{13}C$, is expressed as ‰ wrt PDB.
- Results are reported as *% Modern* when the conventional age is younger than 200 yr BP.


Marine data from Hughen et al (2004);Delta_R 811±102;OxCal v3.10 Bronk Ramsey (2005), cub r5 sd 12 prob usp[chron]
Wk16685 : 2325±33BP
68.2% probability
1180BP (68.2%) 940BP
95.4% probability
1290BP (95.4%) 840BP
3000BP
2500BP
2000BP
1500BP
Radiocarbon determination
1500CalBP
1000CalBP
500CalBP
Calibrated date


Marine data from Hughen et al (2004);Delta_R 811±102;OxCal v3.10 Bronk Ramsey (2005); cub r:5 sd.12 prob usp[chron]
Wk16684 : 1835±159BP
68.2% probability
790BP (68.2%) 450BP
95.4% probability
1000BP (95.4%) 250BP
3000BP
2500BP
2000BP
1500BP
Radiocarbon determination
1500CalBP
1000CalBP
500CalBP
0CalBP
Calibrated date


Marine data from Hughen et al (2004);Delta_R 81 1±102;OxCal v3.10 Bronk Ramsey (2005); cub r:5 sd:12 prob usp[chron]
Wk16679 : 1409±52BP
68.2% probability
360BP (68.2%) 80BP
95.4% probability
428BP (95.4%) ...
Radiocarbon determination
2200BP
2000BP
1800BP
1600BP
1400BP
1200BP
800CalBP
600CalBP
400CalBP
200CalBP
0CalBP
Calibrated date


Marine data from Hughen et al (2004);Delta_R 81 1±102;OxCal v3.10 Bronk Ramsey (2005); cub r:5 sd:12 prob usp[chron]
Wk16680 : 1723±134BP
68.2% probability
660BP (68.2%) 360BP
95.4% probability
850BP (95.4%) 100BP
Radiocarbon determination
2500BP
2000BP
1500BP
1500CalBP
1000CalBP
500CalBP
0CalBP
Calibrated date


Marine data from Hughen et al (2004),Delta_R 81 1±102,OxCal v3 10 Bronk Ramsey (2005), cub r:5 sd 12 prob usp[chron]
Wk16678 : 1113±215BP
68.2% probability
230BP (17.7%) 155BP
150BP (50.5%) ...
95.4% probability
424BP (95.4%) ...
2600BP
2400BP
2200BP
2000BP
1800BP
1600BP
1400BP
1200BP
Radiocarbon determination
1000CalBP
500CalBP
0CalBP
Calibrated date

APPENDIX 4
Dipwell graphs

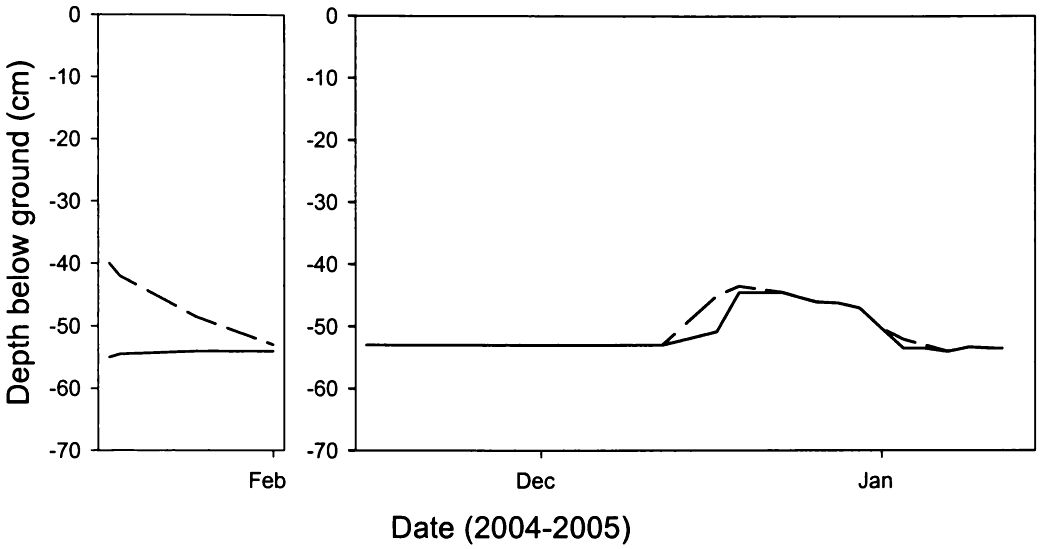


Figure 1: Ice cement (solid) and groundwater (dashed) depths over the 2003-04 and 2004-05 summers at groundwater monitoring site 4.

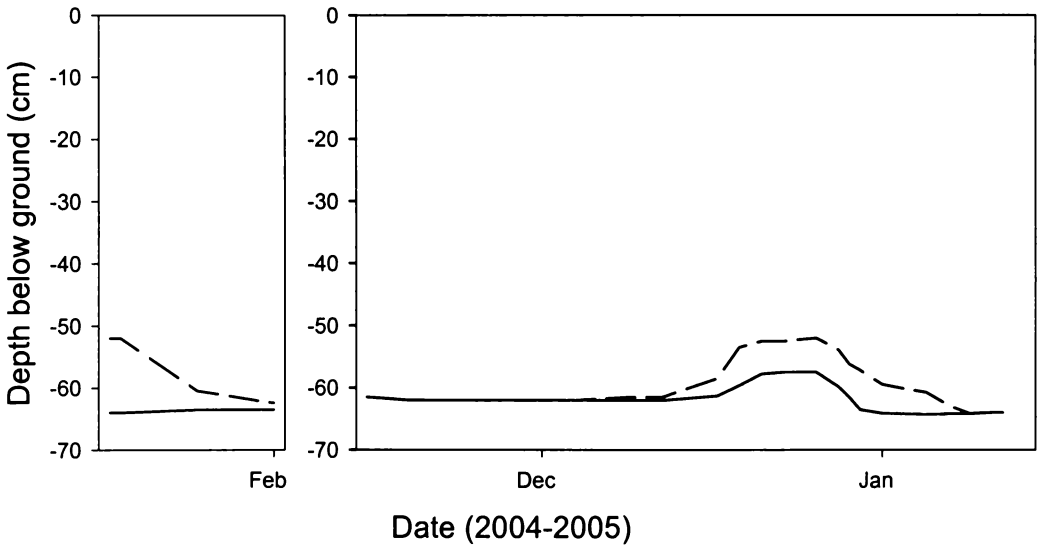


Figure 2: Ice cement (solid) and groundwater (dashed) depths over the 2003-04 and 2004-05 summers at groundwater monitoring site 5.

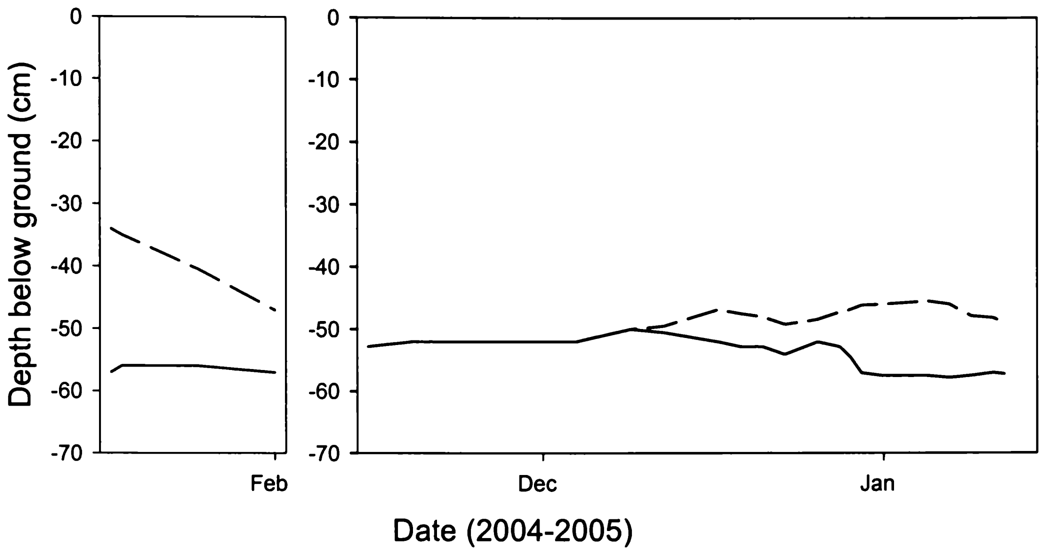


Figure 3: Ice cement (solid) and groundwater (dashed) depths over the 2003-04 and 2004-05 summers at groundwater monitoring site 6.

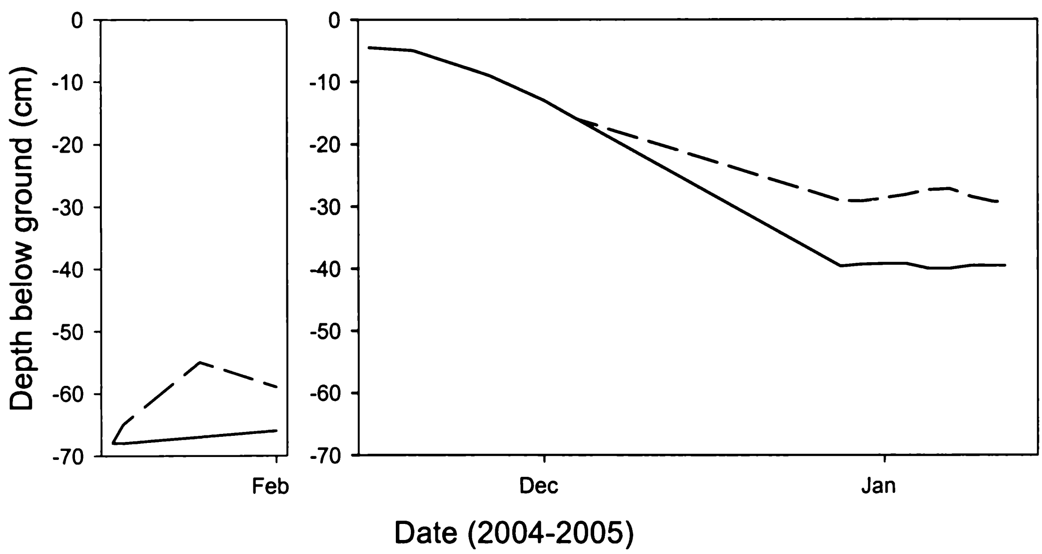


Figure 4: Ice cement (solid) and groundwater (dashed) depths over the 2003-04 and 2004-05 summers at groundwater monitoring site 8.

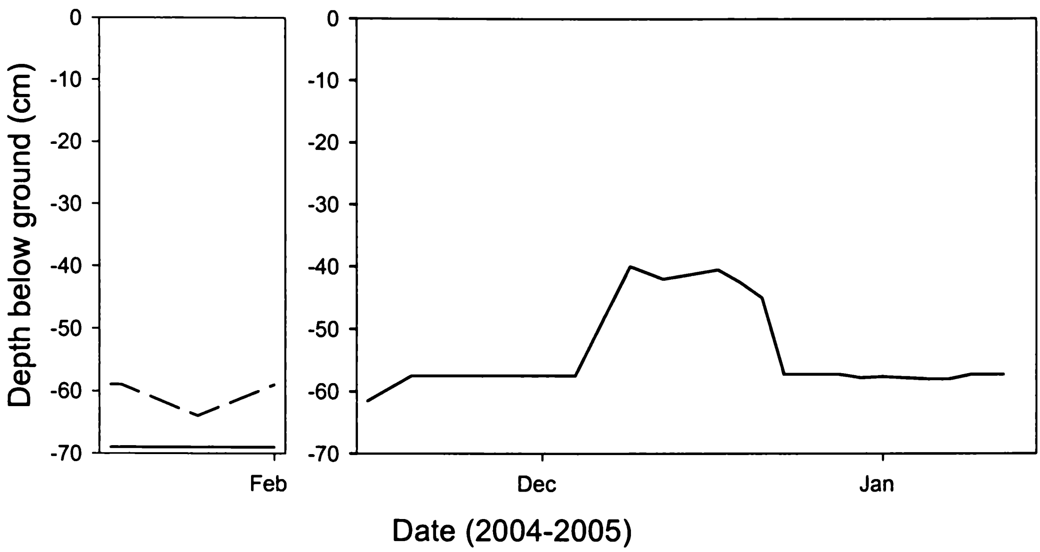


Figure 5: Ice cement (solid) and groundwater (dashed) depths over the 2003-04 and 2004-05 summers at groundwater monitoring site 9.

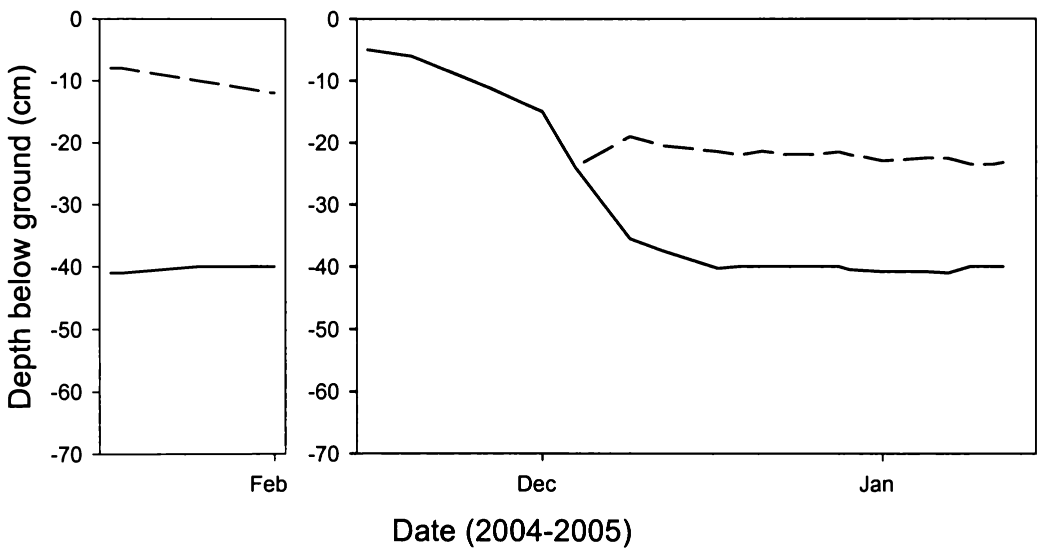


Figure 6: Ice cement (solid) and groundwater (dashed) depths over the 2003-04 and 2004-05 summers at groundwater monitoring site 10.

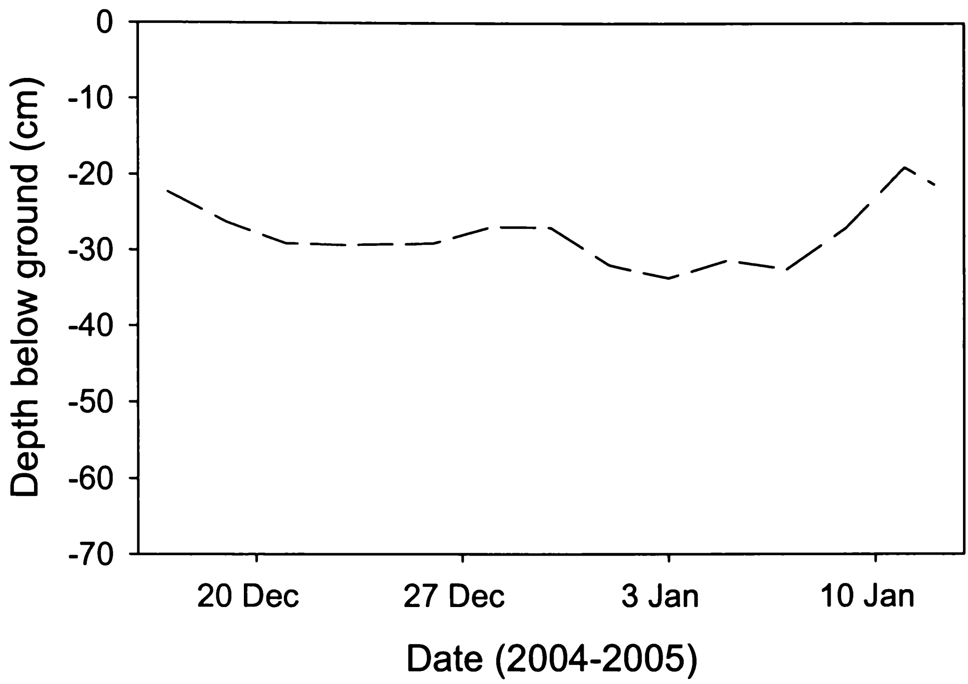


Figure 7: Groundwater depths over the 2004-05 summer at groundwater monitoring site 17.

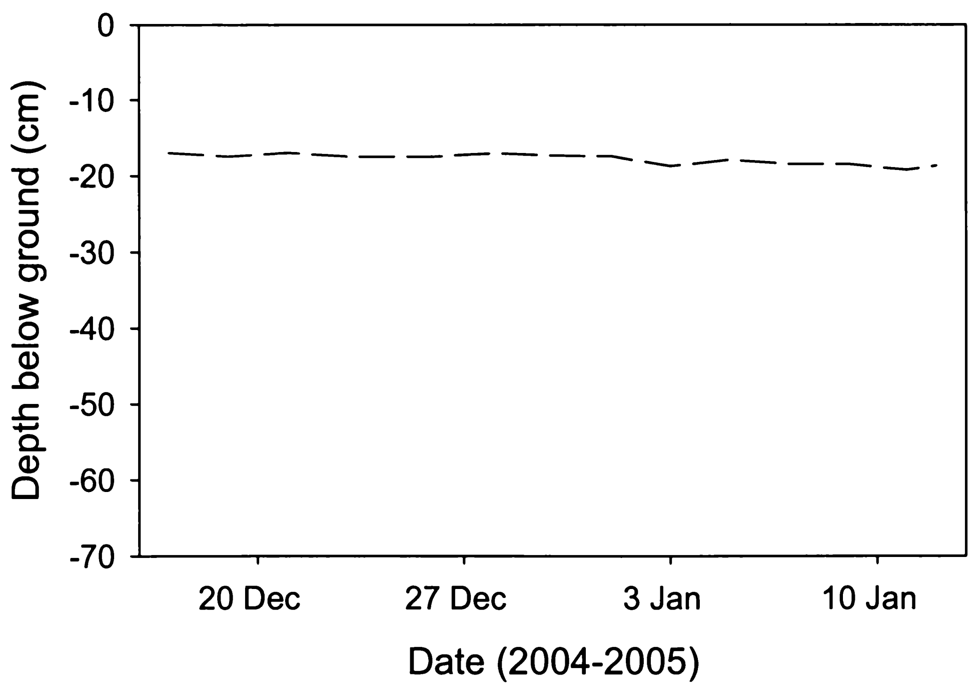


Figure 8: Groundwater depths over the 2004-05 summer at groundwater monitoring site 19.

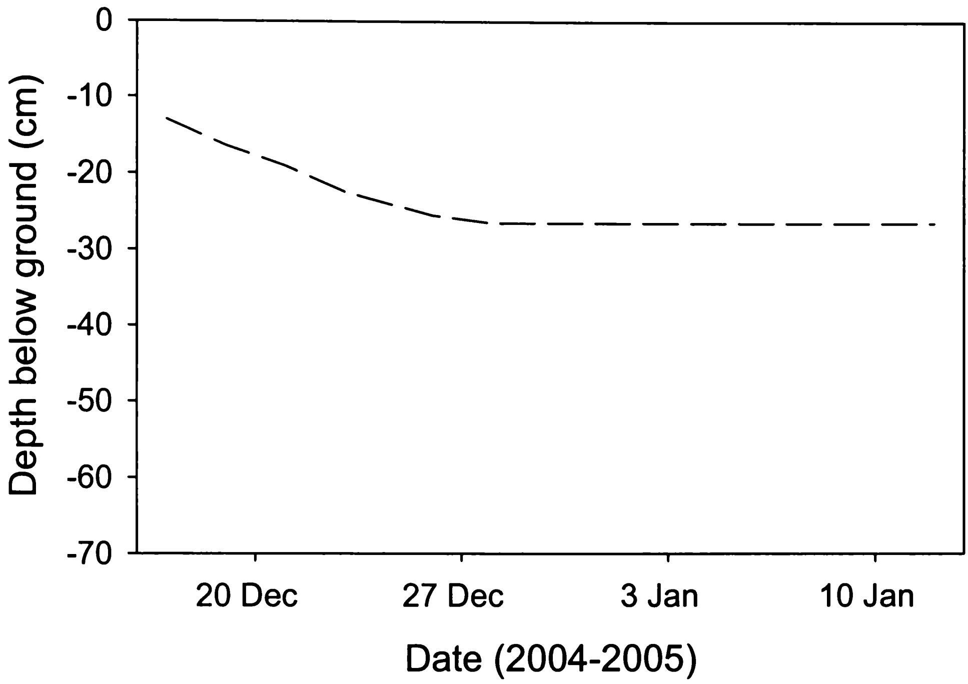


Figure 9: Groundwater depths over the 2004-05 summer at groundwater monitoring site 20.

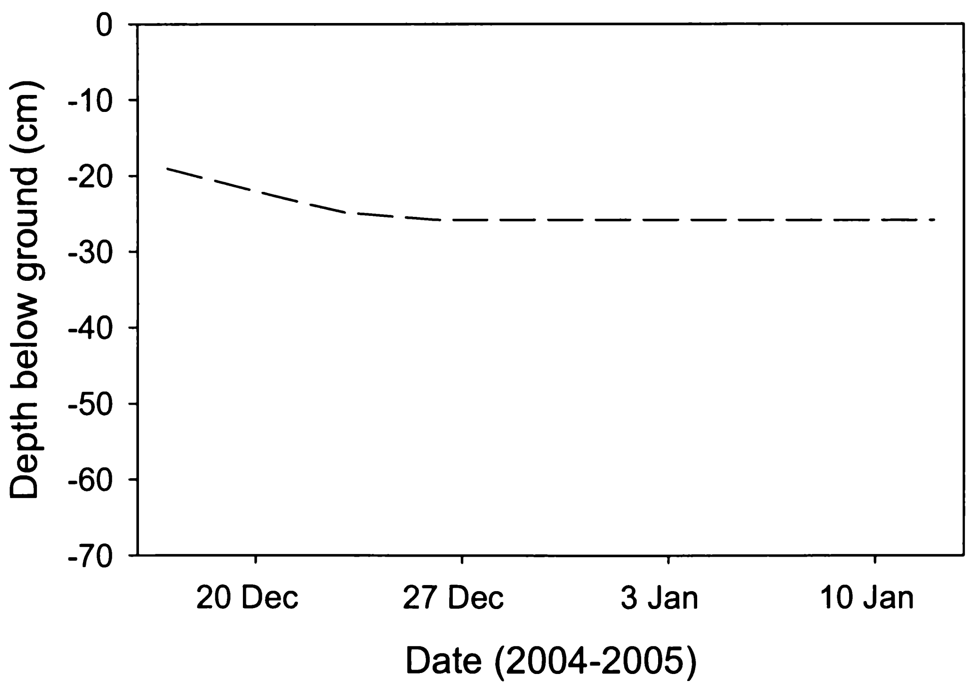


Figure 10: Groundwater depths over the 2004-05 summer at groundwater monitoring site 21.

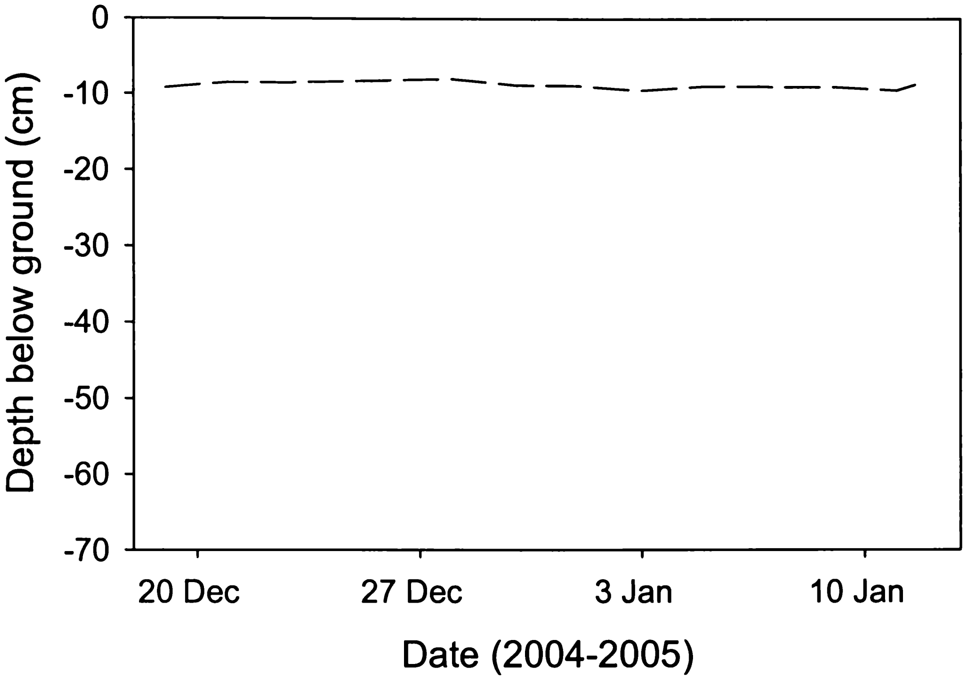


Figure 11: Groundwater depths over the 2004-05 summer at groundwater monitoring site 28.

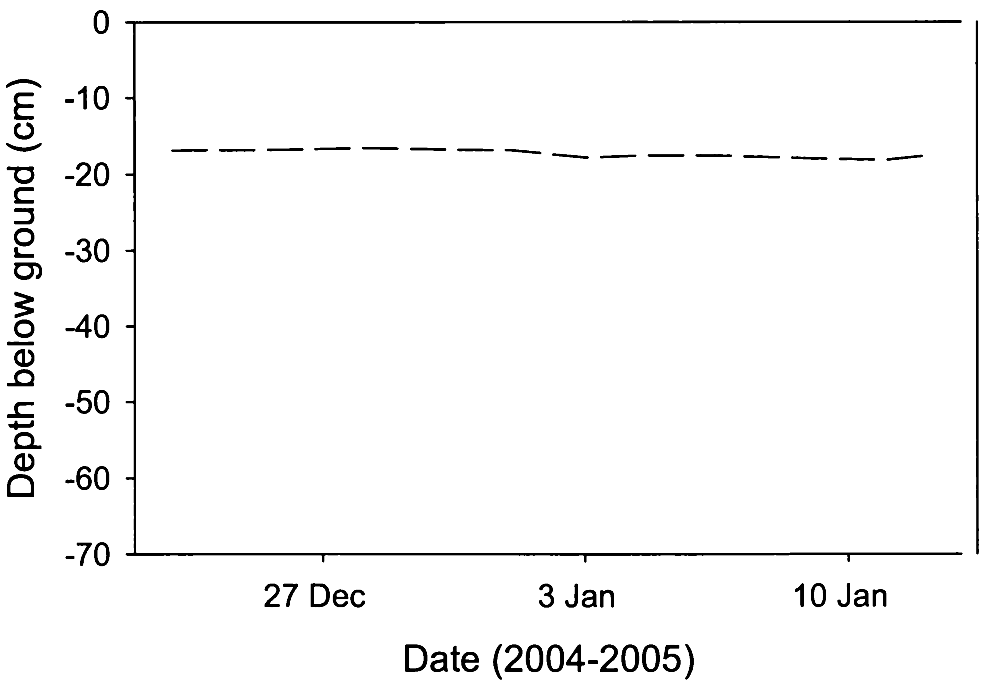


Figure 12: Groundwater depths over the 2004-05 summer at groundwater monitoring site 29.

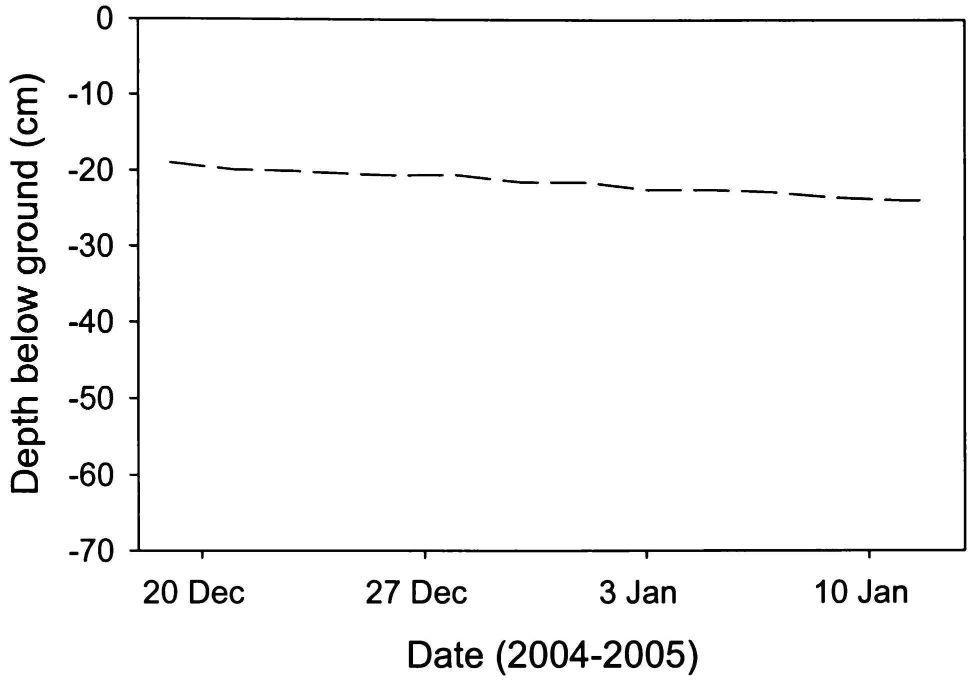


Figure 13: Groundwater depths over the 2004-05 summer at groundwater monitoring site 30.

APPENDIX 5
Soil descriptions

Note: where information is missing e.g. depth to ice cement or groundwater, it was not observed.

CH1

Date:	15 January 2004.
Location:	S 72° 19.200' E 170° 13.604'
Elevation:	4m (GPS) 2m (observed)
Slope:	5°
Aspect:	E
Weather:	Calm, lightly snowing

Location description: Cape Hallett climate station site, immediately below the NIWA climate station. TDR probe installed here. Site is approximately 15m from ice edge. Site is located on the eastern shoulder of a low mound. The mound is evenly sloping.

Drainage: Well drained.

Geologic substrate: Basalt dominated sand and gravel.

Temperatures:

Air	Surface	5cm	15cm	25cm	40cm
+2°C	+4.5°C	+3.5°C	+2.2°C	+1.8°C	-0.1°C

Samples taken:

	Depth (cm)	Notes
CH1/1	5-0	
CH1/2	0-5	
CH1/3	5-15	
CH1/4	15-30	
CH1/5	30-50	
CH1/6	65-75	
CH1/7	5-15	Skua or penguin legbone for ^{14}C dating.

Horizons	1	2	3	4	5	6
Base (cm)	5-0	5	15	30	50	80+
Thickness	5	5	10	15	20	30+
Sample no.	CH1/1	CH1/2	CH1/3	CH1/4	CH1/5	CH1/6
Field moisture	Dry	Moist	Moist	Very moist	Ice cemented	Very moist
Boundary distinctness	Sharp	Diffuse	Distinct	Distinct	Diffuse	
Boundary Shape	Irregular	Smooth	Irregular	Smooth	Smooth	
Colour	-10R 2/1 Reddish black	-7.5YR 4/4 Brown.	7.5YR 4/4	10YR 3/2 Brownish	2.5YR 2/1 Reddish	2.5YR 2/1 Reddish

	-Red scoria 10R 3/3 Reddish brown	-Stones 7.5 YR 4/1			black	black
Texture	Stony gravel. 99% > 6.7mm.	Stony gravely. 95% sand	Stony gravely. 98% sand.		Gravelly Coarse sand, 100%.	Gravelly Coarse sand, 100%.
Gravel	100% abundance 1-8cm. no weathering. Sub rounded, sub angular. Basalt, scoria and lava	80% abundance Very weak weathering. Rest same as horizon 1.	60% abundance Rest same as horizon 2.			
Boulders	0%	0%	20%	10% 10-20cm.	10%	

Notes: Lots of penguin remains. Bones found in various stages of decomposition. Feathers found. Few fibres present from bones.

CH2

Date:	14 January 2004.
Location:	5m East of CH1

Notes: This soil was not sampled, but pit dug to see if the depth to frozen ground is deeper on a NW aspect compared to a SE (CH1) aspect. Frozen ground was found here at 45cm.

The soil profile was essentially similar to CH1 but simpler.

Description:

3-0cm	Desert pavement. Dry and clean grey subrounded to subangular highly porous basalt and basalt scoria. As for CH1, 99% of the stones were 2-10cm diameter with a distinct and irregular boundary.
0-6cm	Air dry rocks as above but coated with pale grey guano material. Fibrous and fine material coats top but not the bottom of stones. Common coarse voids? Indistinct, irregular boundary.
6-15cm	Similar as above but stones are >10cm diameter and guano is bright brown in colour. Common fine voids? Sharp wavy boundary.
15-45+cm	Dark grey iron sand with common stones similar to above. Very moist soil, similar to 15-80+ in CH1.

CH3

Date: 15 January 2004.
Location: S 72° 19.069'
E 170° 12.798'
Slope: 5
Aspect: SE
Weather: Calm, cloudy. No sun for the past couple of days.
Location description: Cape Hallett, on the "hook". Site is located 8m SE of the tank. Most likely dug up a previously excavated site (USA 2003?), seen by some disturbance within the profile.
Contour: Flat even slope.
Depth to ice-cemented ground: 70cm
Temperatures (°C):

Air	1cm	5cm	15cm	30cm	55cm	75+cm
+0.1	+6.2	+4.1	+4.0	+3.3	+2.1	+0.1

Samples taken:

	Depth (cm)	Notes
CH3/1	0-10 cm	All samples taken for soil characterisation
CH3/2	10-30cm	
CH3/3	30-40 cm	
CH3/4	40-60 cm	
CH3/5	60-70 cm	

Horizons	1	2	3	4	5
Base (cm)	10	30	40	60	70+
Thickness (cm)	10	20	10	20	10+
Sample no.	CH3/1	CH3/2	CH3/3	CH3/4	CH3/5
Field moisture	Moist	Moist	Wet	Wet	Wet
Boundary distinctness	Sharp	Sharp	Indistinct	Indistinct	
Boundary Shape	Irregular	Irregular	Wavy	Smooth	
Colour	10YR 4/3 Dull yellowish brown	10YR 1/1 Black	Colour of basalt stones	7.5YR 1.7/1 Black	7.5YR 1.7/1 Black
Texture	Gravelly coarse loamy sand. Smelly guano.	Stony gravelly coarse sandy loam. Dead penguin smell	Gravel with no fines. Sample seems gungy but appeared as clean permeable gravels in profile.	Gravelly coarse sand. Dead penguin smell.	Gravelly coarse sand.
Gravel	70% abundance 1-10cm	90% abundance. 1-5cm	95% abundance. 1-5cm	60% abundance. 1-5cm	20% abundance. 1-5cm

	diameter. Low weathering. Rounded to subangular. Basalt scoria and lava.	diameter. Rest same as CH3/1	diameter. Rest same as CH3/1	diameter. Rest same as CH3/1	diameter. Rest same as CH3/1
Boulders	n/a	n/a	2% abundance. 10-20cm diameter. Low weathering rounded basalt lava.	20% abundance. 10-40cm diameter. Rest same as CH3/3	20% abundance. 10-20cm diameter. Rest same as CH3/3

Notes: The profile was made up of very wet unconsolidated material over hard solid ice. A lot of sticky gravel guano was found, typical of the mounds. No real desert pavement found on this site, but a gravel pavement found intermittently. Water table was around 65cm. Piezometer installed here. 88 cm put in, with a total of 2cm above the ground surface. Located in uphill end of the hole. Once installed, the piezometer was surrounded by sand material and then the hole back-filled with wet sticky gravel that came from it. A layer of this sticky gravel was placed around the top of the piezometer to create a less permeable seal around is so that the water flows from undisturbed ground through the gravel to the pipe.

The soil is distinctly black in colour. This is likely to be due to hydrocarbon contamination.

CH4

Date:	Presume 15 January 2004.
Location:	72°19.077S
	170°12.793E

Location description: Located roughly 15 m south of CH3, on the other side of a small penguin mound. The site is 6 m downhill of this mound in a hollow area.
Depth to ice-cemented ground: 65cm

Temperatures:

Water	soil adj 2 water	0cm	10cm	30cm
+1.8°C	+1.3°C	+7.2°C	+3.8°C	+2.2°C

Samples taken:

	Depth (cm)	Notes
CH4/1	0-18 cm	All samples taken for soil characterisation
CH4/2	18-45 cm	

Description:

2-0 cm	Desert pavement. 1-10cm basalt stones (photo)
0-18 cm	Penguin goo layer. Brown in colour.
18-45 cm	Gravelly sand, grey. Both layers contain common rounded 10-20cm stones.
45-60+ cm	Same as 18-45 but under saturated conditions.

Notes: Inter mound low guano content soil. There is no sign of hydrocarbon contamination, water has a reddish brown colour of penguin goo. Soil has a weak penguin smell but no hydrocarbon smell. Some wood was found in the upper 10 cm.

Piezometer installed. 72 cm was able to be put in. Water table was at 50 cm at time of piezometer installation.

CH5

Date: 15 January 2004, 3 pm
Location: 72°19.076 S
170°12.847 E
Slope: 5°
Aspect: E
Weather: Fine, calm and sunny.
Location description: 35 m to the east of the oil tank. On a wide gently sloping to east in middle of plain and as far from penguin mounds as possible.
Contour: Side slope in a slight hollow.
Drainage: Well drained.
Depth to ice cemented ground: 68cm.
Depth to groundwater: 52cm.
Parent lithology: Basalt and guano.
Temperatures:

1cm	10cm	20cm	30cm	40cm	In water
+15.3°C	+5.9°C	+3.5°C	+3.0°C	+2.1°C	+1.7°C

Samples taken:

	Depth (cm)	Notes
CH5/1	0-20 cm	Avoiding black lens
CH5/2	10-14 cm	Sampled black lens
CH5/3	20-30 cm	
CH5/4	30-35 cm	
CH5/5	35-50 cm	

Horizons	1 (Guano layer)	2 (Black discontinuous lens)	3 (Gravelly sand)	4 (Guano layer)	5 (Diesel smelling sand)
Base (cm)	20	14	30	35	15?
Thickness (cm)	20	4	10	5	50+
Sample no.	CH5/1	CH5/2	CH5/3	CH5/4	CH5/5
Field moisture	Slightly moist	Moist	Moist	Moist	Wet
Boundary distinctness	Distinct	Distinct (top and bottom)	Distinct	Distinct	
Boundary Shape	Irregular	Irregular	Irregular	Irregular	
Colour	10YR 4/3 Dull yellowish brown	7.5YR 1.7/1 Black	7.5YR 1.7/1 Black	10YR 3/3 Dark brown	7.5YR 1.7/1 Black
Texture	Gravelly sandy loam	Gravelly sandy loam (possibly penguin remains)	Gravelly coarse sand	Gravelly loamy sand	Gravelly coarse sand
Gravel	80%	80%	40%	20%	10%

	abundance, 1-5 cm diameter. No weathering, subrounded basalt.	abundance, 1-3 cm diameter. Rest same as CH5/1	abundance, 1-5 cm diameter. Rest same as CH5/1	abundance, 1-5 cm diameter. Rest same as CH5/1	abundance, 1-5 cm diameter. Rest same as CH5/1
Boulders	2% abundance up to 20cm diameter. Rounded basalt and scoracious basalt.	Same as CH5/1	Same as CH5/1	Same as CH5/1	Same as CH5/1

Notes: Surface pavement is compacted guano with imbedded grey gravel, stones and occasional boulders up to 20 cm diameter. All are subrounded to subangular. A photo was also taken of a buried hunk of steel with apparently normal looking surface pavement on top. Fine materials generally accumulate around obstacles like steel cables. Sand from the base of this hole smells of diesel.
Sites CH3, CH4 and CH5 all have much less bone material than sites CH1 and CH2. Piezometer installed, length of 80cm.

CH6

Date: 15 January 2004
Location: 72°19.089 S
170°12.859 E
Slope: 5°
Aspect: E
Weather: Fine, calm and sunny.
Location description: 65 m South East of oil tank, 15m North West of the top of a penguin mound. In a low lying area at foot of slope back to oil tank.
Depth to ice cemented ground: 63 cm
Depth to groundwater: 40 cm
Samples taken:

	Depth (cm)	Notes
CH6/1	0-10 cm	
CH6/2	10-50+ cm	

Horizons	1	2
Base (cm)	10	50+
Thickness (cm)	10	40+
Sample no.	CH6/1	CH6/2
Boundary distinctness	Distinct	
Boundary Shape	Irregular	
Colour	10YR 4/3 Dull yellowish brown	7.5YR 1.7/1 Black

Notes: Piezometer installed with a length of 71 cm.

CH7

Date: 15 Jan 2004 5:30pm
Location: 72°19.096 S
170°12.775 E
Weather: Fine and sunny.
Location description: ~100 m South of the tank on a bouldery bed and the head of a "valley". ~15 m from the nearest penguin mound but mounds encircle the site on all sides.
Depth to groundwater: ~40cm.
Temperatures:

1cm	5cm	15cm	30cm	In water
+15.2°C	+14.8°C	+8.2°C	+1.4°C	+2.2°C

Samples taken:

	Depth (cm)	Notes
CH7/1	0-5 cm	
CH7/2	5-20 cm	
CH7/3	20-30+ cm	

Horizons	1	2	3	4
Base (cm)	0	5	20	35+
Thickness (cm)	5	5	15	15+
Sample no.		CH7/1	CH7/2	CH7/3
Boundary distinctness		Distinct	Distinct	
Boundary Shape		Irregular	Irregular	

Notes: Piezometer installed. Length of 70.5 cm.

CH8

Date: 16 January 2004
Location: 72°19.099 S
170°12.877 E
Slope: 3°
Aspect: E
Weather: Snowing, fairly calm.
Location description: Site on stony "river" bed. Surface water ~2 m down slope of site. Within channel.
Depth to groundwater: 25cm.
Temperatures:

Air	1cm	10cm	In water
+0.9°C	+5.1°C	+3.8°C	+1.3°C

Description:

2-0 cm	Desert pavement. Crust of pale compacted guano and small gravel. Gravelly coarse sandy loam with ~40% stone 10-40cm diameter. Stones protrude above stated pavement depth.
0-50 cm	Gravelly coarse sand. 10% large stones, loose and unconsolidated.

CH9

Date: 16 January 2004
Location: 72°19.143 S
170°12.968 E
Elevation: 8m
Slope: 5°
Aspect: NE
Weather: Snowing and wet, light wind
Location description: 200m SE of tank on guano covered ground that is currently free of penguins. Approximately 40m W of a former penguin enclosure. The site is located on a ridge or saddle between two penguin mounds and is a brown guano colour indicating former penguin habitation.
Contour: Shoulder of a mound.
Depth to ice cemented ground: 80cm.
Depth to groundwater: 75cm.
Samples taken:

	Depth (cm)
CH9/1	2-0 cm
CH9/2	0-10 cm
CH9/3	10-25 cm
CH9/4	25-40 cm
CH9/5	40-50 cm

Horizons	1	2	3	4	5
Base (cm)	0	10	25	40	50+
Thickness (cm)	2	10	15	15	10+
Sample no.	CH9/1	CH9/2	CH9/3	CH9/4	CH9/5
Field moisture	Wet/saturated	Dry	Moist	Moist	Moist
Boundary distinctness	Distinct	Diffuse	Indistinct	Diffuse	
Boundary Shape	Smooth	Smooth	Smooth	Smooth	
Colour	2.5YR 7/6 Bright yellowish brown (wet) normally 2.5YR 7/3 light yellow	5YR 4/6 Reddish brown	10YR 2/3 Brownish black		
Texture	Stony gravelly sandy loam	Stony gravelly sandy loam. Very very sticky	Stony gravelly sandy loam. Very very sticky		
Gravel	80% abundance. 1-5 cm diameter.	80% abundance. 2-5 cm diameter.	Rounded basalt	Rounded basalt	Rounded basalt

	Rounded basalt.	Rounded basalt. Penguin nest stones.			
Boulders	20% abundance. 10-40cm diameter. No weathering. Rounded basalt.	Occasional abundance. Rounded basalt.	Rounded basalt	1 boulder. 40 cm diameter. Rounded basalt.	Rounded basalt

CH10

Date:	January 2004
Location:	72°19.148 S 170°12.881 E
Slope:	2°
Aspect:	E
Elevation:	4m
Weather:	Snowing and wet.

Location description: In valley of fenced ponds, ~80m up valley of ponds. Around 80 down valley from CH8. Gently sloping valley floor.

Depth to groundwater: 5 cm.

Temperatures:

Air	8cm
+1.7°C	+4.9°C

Description:

2-0 cm	Water, guano slime and large stones (40%) strongly embedded. Compacted. Distinct smooth boundary.
0-30+ cm	Gravelly sand and stones. 40% stones with dominant (60%) sand.

Notes:

Profile very similar as CH8, no need for a full description here. Piezometer installed to ~40 cm depth.

CH11

Date: 16 January 2004?
Location: 72°19.150 S
170°13.204 E
Slope: 8°
Aspect: E
Weather: Snowing and wet, relatively calm.
Location description: ~30 from ice edge of Willett Cove. At the junction of fenced pond valley and valley that leads to the tank. Flowing water to the sea occurs here.
Contour: Floor of low gully, concave.
Depth to groundwater: 25cm.
Description:

2-0 cm	Guano compacted desert pavement with fine gravel. 30% abundance of 10-20 cm stones. Diffuse boundary.
0-30 cm	Gravelly sand. 60+% gravel of 2-10 cm diameter. Some brown guano colour. Diffuse boundary.
30-50 cm	Gravelly coarse sand. Some black sand and 60+% gravel.

Notes: Piezometer installed. 70 cm in length.

CH12

Date: 18 January 2004
Location: 72°19.066 S
170°12.844 E
Location description: 10m N of piezometer site CH5, 30 m E of tank. Site of Aislabie microbe samples.
Samples taken:

	Depth (cm)
CH12/1	0-3 cm
CH12/2	3-15 cm
CH12/3	20-25 cm

Description:

2-0 cm	Fine gravel (1-3 cm diameter) thinly dispersed.
0-3 cm	Gravelly coarse sandy loam, surface crust. Contains a lot of whitish organic matter. Skua guano, Bird egg shell, feathers and forms a crust which is coherent and firm when dry.
3-15 cm	Stony gravelly coarse sandy loam. 90% gravel and stone but enough guano present to combine it into a coherent and firm layer, dull yellowish brown.
15-25 cm	Coarse black sand. Stones common, to for a loose and unconsolidated layer.
25-40+ cm	Dark bright reddish brown guano and penguin stones. Impermeable layer with sticky "toffee" consistency.

CH13

Date:	18 January 2004
Location:	72°19.069 S
	170°12.798 E
Weather:	Fine and calm

Location description: Hydrocarbon contaminated site near CH3 for Aislabie microbe samples.

Description:

2-0 cm	Surface stones, most sticking up through guano layer. Some desert pavement.
0-3 cm	Highly disturbed site near tank. Stones, gravel, guano crust. All is coherent and compacted.
3-15 cm	Dull yellowish brown guano layer, with gravel and penguin stones.
15-25 cm	Black penguin guano layer, with gravel and penguin stones.
25-30 cm	Brown guano layer, with gravel and penguin stones.
30-40 cm	Discontinuous sand layer with strong hydrocarbon smell. Some penguin stones present.
40-50+ cm	Reddish brown guano layer. Very sticky with low permeability and penguin stones.

CH18

Date:	14 December 2004
Location:	72°37.047 S
	169°88.978 E
Weather:	Fine and calm

Location description: ~100 m to north east of Luther Lakes on western side of Edisto Inlet. On flat surface.

Description:

10-0 cm	Surface pavement of boulders, up to 30 cm diameter.
0-10 cm	80% boulders with 10% gravel and 10% sand, dry soil in field.
10-22 cm	60% boulders with 20% gravel and 10% sand, damp soil in field
22-47 + cm	20% boulders with 10% gravel and 60% sand. Damp soil.

Parent material was sedimentary rocks (greywacke?), as opposed to all basalt at Seabee Hook. Ice cement was deeper than at the same time (early December) at Seabee Hook. Soil was dry near the surface but became damp from 10 cm.

CH36
Date: 2 January 2005, 10:30am
Weather: Overcast and light wind
GPS location: S 72.31890°, E 170.21496°.
Elevation: 2m
Location description: On ridge between two penguin sub-colonies. It is obvious that this was used for nesting in the recent past. Heavy crusts of penguin guano occur on the surface. Penguin stones are embedded in this crust. Ridge is about 45m directly N of CH10.
Slope: 2°
Aspect: E
Profile shape: top of ridge of mound.
Weathering stage: 1
Temperature:
Air: 2.8 Surface 4.9 2cm 4.5 10cm 3.9 25cm 4.2

Horizons	1 (surface guano)	2 (guano layer)	3 (gravel)	4 (sand layer)
Base (cm)	5	15	32	44+
Thickness (cm)	5	10	17	12+
Sample no.				
Field moisture	Slightly moist	Moist	Slightly moist	Slightly moist
Boundary distinctness	Indistinct	Distinct	Indistinct	
Colour	5YR 2/4 Very dark reddish brown	2.5YR 2/4 Very dark reddish brown	10YR 5/4 Dull yellowish brown	10R 1.7/1 Reddish black
Texture	Gravel	Gravel	Sandy gravel	Gravelly sand
Sand %	0	0	25	75
Silt %	10	10	0	0
Clay %	0	0	0	0
Gravel	90% abundance, 2-5 cm diameter. No weathering, subangular basalt.	90% abundance, 2-5 cm diameter. Rest same as CH36/1	70% abundance, 2-5 cm diameter. Rest same as CH36/1	20% abundance, 1-3 cm diameter. Subrounded basalt and some shist?
Boulders	2% abundance up to 20cm diameter. Rounded basalt and scoracious basalt.	Same as CH36/1	Same as CH36/1	5% abundance 10cm+

CH37
Date: 2 January 2005, 2pm
Weather: Overcast and light wind
GPS location: S 72.31825°, E 170.21716°.
Elevation: 3m
Location description: On large flat area ~70m W of the climate station. No evidence of recent penguin nests, no mound nearby.
Slope: 1°
Aspect: E
Profile shape: Surface of 'plain' between mounds.
Weathering stage: 1
Depth to groundwater: 51cm
Depth to permafrost: 53cm

Horizons	1 (surface guano)	2 (light guano layer)	3 (gravel)	4 (lighter guano layer)	5 (dark sand layer)
Base (cm)	2	13	29	35	53+
Thickness (cm)	2	11	16	6	18+
Sample no.					
Field moisture	Dry	Slightly moist	Slightly moist	Slightly moist	Moist
Colour	7.5YR 4/3 brown	7.5YR 4/3 brown	7.5YR 2/2	7.5YR 4/4 brown	5YR 2/1 brownish black
Texture	Gravel	Gravel	Gravel	Bouldery gravel	Gravelly sand
Sand %	0	0	0	0	80
Silt %	20	30	20	20	5
Clay %	0	0	0	0	
Gravel	90% abundance, 5-10mm diameter. No weathering, subangular basalt.	90% abundance, 5-10mm diameter. Rest same as CH37/1	90% abundance, 2-5 cm diameter. Rest same as CH37/1	90% abundance, 2-5mm and some 20-50mm diameter. Small ones sunangular, large ones subrounded basalt	10% abundance 20-50mm subrounded

CH38

Date: 5 January 2005, 2pm
Weather: Overcast and strong wind
Location description: On flat mound free area dominated by large stones. Around 20m NW of CH20.
Slope: 1°
Aspect: E
Profile shape: 'Valley' bottom.
Weathering stage: 1
Depth to groundwater: 43cm

Horizons	1 (surface guano)	2 (coarse sandy gravel)	3 (gravel)	4 (coarse sandy gravel)
Base (cm)	2	27	34	43+
Thickness (cm)	2	25	7	9+
Field moisture	Dry	Slightly moist	Slightly moist	Moist
Colour	10YR 7/3 dull yellowish orange	2.5Y 5/1 yellowish grey	7.5YR 4/3 brown	2.5Y 5/1 yellowish grey
Texture	Coarse gravel	Gravely sand	Gravel	Gravelly sand
Sand %	10	60	20	70
Silt %	20	0	0	0
Clay %	0	0	0	0
Gravel	60% abundance, 80-90mm diameter. No weathering, subrounded basalt.	30% abundance, 30-50mm diameter. Rest same as CH38/1	80% abundance, 20-40mm diameter. Rest same as CH38/1	20% abundance, 30-50mm diameter. Rest same as CH38/1

CH42

Date: January 8 2005, 9am
Weather: Overcast and windy
GPS location: S72.31933°, E170.21966°.
Elevation: 0.5m
Location description: On beach ~20m SE from CH17. About 10m from waters edge at low tide. Surface littered with boulders, typical of all the land directly surrounding the coast.
Slope: 5°
Aspect: E
Profile shape: slope of beach down to water.
Weathering stage: 1
Depth to groundwater: 25cm

Horizons	1 (surface sand)	2 (coarse sand)
Base (cm)	3	25+
Thickness (cm)	3	22+
Sample no.		
Field moisture	Moist	Moist to saturated
Boundary distinctness	Indistinct	
Colour	Substrate between sand: 10YR 4/3 dull yellowish brown Sand: 10R 1.7/1 reddish black	10R 1.7/1 reddish black
Texture	Coarse sand	Gravelly coarse sand
Sand %	95	80
Silt %	0	0
Clay %	0	0
Gravel	3% abundance, 20-50mm diameter. No weathering, subrounded to rounded basalt.	20% abundance, 20-100mm diameter. Rest same as CH42/1
Boulders	2% abundance 10-20cm diameter subrounded to rounded basalt	

CH43
Date: 8 January 2005, 2pm
Weather: Overcast and windy
GPS location: S 72.31860°, E 170.22824°.
Elevation: 3m
Location description: In valley on handle of hook. Reasonably thick guano crust on top. On slope towards Willett Cove, directly in line with camp.
Slope: 5°
Aspect: S
Profile shape: Slope of valley floor .
Weathering stage: 1
Depth to permafrost: 45cm

Horizons	1 (surface guano)	2 (unconsolidated gravel)	3 (surface guano-2)	4 (coarse sand)	5 (penguin stones)
Base (cm)	2	4	5	10	18
Thickness (cm)	2	2	1	5	8
Field moisture	Dry	Dry	Dry	Moist	Moist
Boundary distinctness	Distinct sharp	Distinct sharp	Indistinct wavy	Indistinct	Indistinct wavy
Colour	Dry guano- 2.5Y8/4 pale yellow	10YR 3/1 brownish black	10YR4/3 dull yellowish brown	5YR2/1 brownish black	10YR 4/6 brown
Texture	Gravelly sand	Gravel	Gravel	Coarse sand	Coarse sand
Sand %	60	10	5	100	5
Silt %	30	20	40	0	10
Clay %	0	0	0	0	0
Gravel	10% abundance, 10-20mm diameter. No weathering, subangular basalt.	60% abundance, 10-30mm diameter. Rest same as CH43/1	70% abundance, 10-30mm diameter. Rest same as CH43/1		50% abundance 20-50mm diameter. Rest same as CH43/1

Profile continued:

Horizons	6 (coarse sand and gravel)	7 (penguin sand)	8 (coarse sand	9 (penguin stones)
Base (cm)	24	30	39	45+
Thickness (cm)	6	6	9	6+
Field moisture	Moist	Moist	Moist	Moist

Boundary	Indistinct wavy	Indistinct	Indistinct	
Colour	7.5YR 3/1 brownish black	10YR 4/4 brown	7.5YR2/1 black	7.5YR5/6 bright brown
Texture	Coarse sandy gravel	Sand	Sand	Gravelly sand
Sand %	60	100	100	80
Silt %	0	0	0	0
Clay %	0	0	0	0
Gravel	30% abundance, 10-20mm diameter. No weathering, subangular basalt.			20% abundance, 20-50mm diameter. Rest same as 43/6.

CH44

Date: 10 January 2005 10am
Weather: Overcast and wind
GPS location: S 72.32082°, E 170.22637°.
Location description: On valley floor behind camp. Not in an area where a pool of water was earlier in the season, however there was water running through this entire area at some stage this season. ~20m directly behind lab tent.
Slope: 2°
Aspect: W
Profile shape: Valley floor, slightly sloping towards sea.
Weathering stage: 1
Depth to groundwater: 24cm
Samples: At 20cm for characterisation

Horizons	1 (surface pavement)	2 (stony sand)
Base (cm)	0	24+
Thickness (cm)	3	21+
Sample no.		1
Field moisture	Moist	Moist
Boundary distinctness	Sharp distinct	
Colour	Average basalt boulder: 10YR 5/1 brownish grey	Sand: 2.5YR 2/1 reddish black. Light coloured bits: 2.5Y 6/4 dull yellow
Texture	Pavement	Stony sand
Sand %	0	80
Silt %	0	0
Clay %	0	0
Gravel		20% abundance, 20-100mm diameter. No weathering sunrounded basalt
Boulders	100% abundance, 90% 5-20cm diameter. Subrounded basalt.	

CH45

Date: 10 January 2005, 11am
Weather: Overcast and wind
GPS location: S 72.32097°, E 170.22639°.
Location description: on mound at the back of camp. Directly ~40m behind workshop, and ~20m SE of CH44. Surface with small sized pavement and flakey guano.
Slope: 2°
Aspect: W
Profile shape: On side of an old mound.
Weathering stage: 1
Samples: CH45/1 at 5 cm - characterisation
CH45/2 at 20cm - characterisation
CH45/3 at 45cm – penguin bones (2)

Horizons	1 (surface pavement)	2 (consolidated stones)	3 (loose peng stones)	4 (dark sand)
Base (cm)	0	10	55	80+
Thickness (cm)	2	10	45	25+
Sample no.	1	2/3		
Field moisture	Dry	Dry	Dry	Dry
Colour	10YR 5/1 brownish grey	5YR ¾ dark reddish brown	5YR 2/4 very dark reddish brown	2.5YR 2/1 reddish black.
Texture	Gravel	Stones	Stones	Sand and boulders
Sand %	0	0	0	80
Silt %	0	20	10	0
Clay %	0	0	0	0
Gravel	100% abundance, 20-50mm diameter. No weathering, subrounded basalt.	80% abundance, 20-50mm diameter. No weathering, subrounded basalt	90% abundance, 2-10 cm diameter. Subangular to rounded balsalt.	20% abundance, 90% is >10cm diameter. Subangular basalt.

CH46

Date: 13 January 2005
Weather: Overcast and calm
GPS location: S 72.32100° E 170.21168°.
Location description: In valley approximately 20m north of CH47. In the middle of quite a wide valley, which is around 20m wide. Located on the south end of the spit.
Profile shape: Valley floor
Weathering stage: 1
Depth to groundwater: 44cm
Depth to permafrost: 63cm
Samples: CH47/1 at 0-2 cm
CH47/2 at 2-4 cm
CH47/3 at 4-63cm

Horizons	1 (surface pavement)	2 (consolidated stones)	3 (loose peng stones)
Base (cm)	2	4	63+
Thickness (cm)	2	2	60+
Sample no.	1	2	3
Field moisture	Sightly moist	Dry	Moist/Wet below 44cm
Colour	10YR6/3 dull yellowish orange	(Stones) 2.5Y2/1 black	5YR2/1 brownish black
Texture	Gravelly humic material	Gravely sand with some guano	Coarse gravely sand
Sand %	30	30	90
Silt %	0	0	0
Clay %	0	0	0
Gravel	40% abundance, 20-50mm diameter. No weathering, subrounded basalt.	40% abundance, 20-50mm diameter. No weathering, subrounded basalt	
Boulders	30% abundance 20-40cm diameter. No weathering, rounded basalt		10% abundance, 10-15cm diameter.

CH47

Date: 13 January 2005
Weather: Overcast and calm
GPS location: S 72.32096°, E 170.21126°
Location description: On a coastal mound at the south end of the spit. Inhabited currently by penguins. Heavy guano cement. Approximately 100m from beach.
Profile shape: Mound top.
Weathering stage: 1
Depth to ice cement: 80cm
Samples: CH47/1: 0-4cm
CH47/2: 4-16cm
CH47/3: 16-28cm
CH47/4: 28-49cm
CH47/5: 49-80+cm

Horizons	1	2	3	4	5
Base (cm)	4	16	28	49	80
Thickness (cm)	4	12	12	21	31
Sample no.	47/1	47/2	47/3	47/4	47/5
Field moisture	Slightly moist	Moist	Wet	Moist	Moist
Boundary	Distinct smooth	Indistinct smooth	Distinct smooth	Sharp wavy	
Colour	Majority – 7.5YR7/3 dull orange. 7.5YR8/2 light grey	5YR3/2 dark reddish brown	7.5YR4/4 brown	7.5YR4/6 brown	2.5YR2/1 reddish black
Texture	Mesic organic material	90% penguin stones 10% humic organic material, very sticky	90% penguin stones 10% humic	90% penguin stones 10% sandy humic	Bouldery gravely coarse sand.
Sand %	0	0	0	5	50
Silt %	0	0	0	0	0
Gravel		Subrounded penguin stones	Subrounded penguin stones	Subrounded penguin stones	20% abundance, 5mm size. Subrounded basalt
Boulders	0	0	0	0	30% abundance 20-30cm subrounded basalt.

CH48

Date: 13 January 2005
Weather: Overcast and calm
GPS location: S 72.31843° E 170.21043°
Location description: On top of artificial mound. Bulldozed in 1989?? Approximately 150m south of the tank.
Slope: 2°
Aspect: Slightly W
Profile shape: Top of mound
Weathering stage: 1
Samples: 48/1: 0-4cm
48/2: 4-10cm
48/3:10+cm

Horizons	1 (surface guano)	2 (penguin stones)	3 (disturbed material)
Base (cm)	3	8	?
Thickness (cm)	3	5	
Sample no.	1	2	3
Field moisture	Slightly moist	Moist	Slightly moist
Boundary distinctness			
Colour	1- 10R 6/4 dull reddish orange 2- 5Y5/4 Olive 3- 2.5Y8/3 pale yellow	2.5Y4/3 olive brown	1- 10YR5/4 dull yellowish brown Sand-5YR 2/1 brownish black
Texture	Humic material	Gravel	Gravelly sand
Sand %	0	20	50
Silt %	0	0	0
Clay %	0	0	0
Gravel		80% abundance, penguin stones, no weathering, subrounded basalt	50% abundance. 2-10cm diameter, no weathering subrounded basalt
Boulders	0	0	0

CH49

Date: 14 January 2005
GPS location: S 72.31741° E 170.21608°
Location description: On mound near main beach, 100 north east of tank.
Profile shape: mound top.
Depth to ice cement: 80cm
Samples: CH49/1: 0-4cm
CH49/2: 4-20cm
CH49/3: 20-30cm
CH49/4: 30-50cm
CH49/5: 50-70cm
CH49/6: 70-80cm
CH49/7: 80+ - bone for dating from paleopenguin layer.

Horizons	1 (surface guano)	2 (sticky dark)	3 (sticky black)
Base (cm)	4	20	30
Thickness (cm)	4	16	10
Sample no.	49/1	49/2	49/3
Field moisture	Damp	Moist	Very moist
Boundary distinctness	Defined wavy	Indistinct	Indistinct
Colour	7.5YR6/3 dull brown	7.5YR4/4 brown	7.5YR2/2 brownish black
Texture	Humic material	Gravel, penguin stones	Gravel, penguin stones
Sand %	0	0	0
Silt %	0	0	0
Clay %	0	0	0
Gravel		100% abundance, penguin stones.	100% abundance, penguin stones
Boulders	0	0	0

Profile continued:

Horizons	4 (lighter sticky)	5 (sand)	6 (paleopenguin layer)
Base (cm)	50	70	80+
Thickness (cm)	20	20	10+
Sample no.	47/4	47/5	47/6
Field moisture	Moist	Slightly moist	Slightly moist
Boundary distinctness	Indistinct	Distinct	Distinct smooth
Colour	5YR4/4 dull reddish brown	5YR2/1 brownish black	10YR6/4 dull yellowish orange
Texture	Gravel, penguin stones	Gravelly sand with some boulders	Gravel with penguin bones

Sand %	0	50	0
Silt %	0	0	0
Clay %	0	0	0
Gravel	100% abundance, penguin stones.	30% abundance, 10-50mm diameter.	100% abundance, penguin stones.
Boulders	0	20% abundance, 10-20cm diameter, no weathering, rounded basalt.	0

CH50

Date: 14 January 2005
Weather: Overcast and calm
GPS location: S 72.31762° E 170.21627°
Location description: In valley approximately 20m SE of CH49. Near coast. ON edge of a dried pond. On the main beach, about 100m NE of tank.
Profile shape: Valley bottom
Depth to groundwater: 27cm
Depth to permafrost: at least 70cm
Dissolved oxygen: 30%
Samples: 50/1: 0-2cm
50/2: 2-10cm
50/3:20-70+cm

Horizons	1	2	3	4
Base (cm)	2	10	20	70+
Thickness (cm)	2	8	10	50+
Sample no.	1	2		3
Field moisture	Moist	Moist	Moist	Wet
Boundary distinctness	Distinct	Distinct Wavy	Indistinct	
Colour	2.5YR7/3 light yellow	5YR2/1 brownish black		5YR2/1 brownish black
Texture	Humic material	Medium sand	Bouldery	Coarse gravel
Sand %	0	100	5	0
Silt %	0	0	0	0
Clay %	0	0	0	0
Gravel				100% abundance. 20-50mm diameter, no weathering, subrounded basalt.
Boulders	0	0	95% abundance, 5-10cm diameter, no weathering, rounded basalt.	

CH51

Date: 14 January 2005
Weather: Overcast and windy
GPS location: S 72.31851° E 170.23243°
Location description: On mound near coast of main beach. NE of camp, around 200m away from scree slope
Profile shape: Top of mound
Depth to permafrost: 90cm+
Samples: 51/1: 0-4cm
51/2: 4-20cm
51/3: 20-60cm
51/4: 60-70cm
51/5: 70-80cm
51/6: 80-90cm
51/7: 90cm+
51/8: 70-80cm – bones for dating
51/9: 90+cm – bones for dating

Horizons	1 (surface guano)	2 (black goo)	3 (brown goo)	4 (beach sand)
Base (cm)	4	20	60	70
Thickness (cm)	4	16	40	10
Sample no.	1	2	3	4
Field moisture	Damp	Moist	Very moist	Damp
Boundary distinctness	Diffuse	Very diffuse	Diffuse	Diffuse
Colour	1- 2.5YR6/3 dull orange 2- bright green, not on colour chart	7.5YR2/2 brownish black	7.5YR3/2 brownish black	5YR3/1 brownish black
Texture	Humic material	Penguin stones and humic material	Penguin stones and humic material	Gravelly sand
Sand %	0	0	0	70
Silt %	0	0	0	0
Clay %	0	0	0	0
Gravel	0	100%, penguin stones	100% penguin stones	30% abundance, 2-10 cm subrounded basalt.

Profile continued:

Horizons	5 (paleo guano layer)	6 (beach sand)	7 (paleo guano layer)

Base (cm)	80	90	90+
Thickness (cm)	10	10	10+
Sample no.	5	6	7
Field moisture	Dry	Dry	Damp
Boundary distinctness	Sharp distinct	Not noted	
Colour	10YR4/6 brown	5YR2/1 brownish black	10YR 6/3 dull yellow orange
Texture	Penguin stones	Gravelly sand	Penguin stones
Sand %	0	80	0
Silt %	0	0	0
Clay %	0	0	0
Gravel	100% penguin stones	20% abundance, 2-8cm diameter, subrounded basalt.	100% penguin stones

CH52

Date: 14 January 2005
Weather: Overcast and light wind
GPS location: S 72.31863° E 170.23264°
Location description: On valley bottom around 20m S of CH51. Covers an area where flow off the mound occurs, as can be seen by the guano patterns on the surface here. NE of camp.
Profile shape: Valley bottom
Weathering stage: 2, slightly more than other places??
Depth to permafrost: 60cm
Samples: 52/1: 0-4cm
52/2: 4-10cm
52/3: 10-30cm
52/4: 30-50cm
52/5: 50-60cm
52/6: 10-30cm – bone for dating.

Horizons	1 (surface guano)	2 (black sand)	3 (guano dominated layer)	4 (gravel dominated layer	5 (guano dominated layer)
Base (cm)	4	10	30	50	60+
Thickness (cm)	4	6	20	20	10+
Sample no.	1	2	3	4	5
Field moisture	Dry	Damp	Slightly damp	Slightly damp	Damp
Boundary distinctness	Distinct	Distinct sharp	Indistinct	Indistinct	
Colour	1- 2.5Y8/2 light grey 2- 5YR2/1 brownish black 3- 10YR5/3 dull yellowish brown	5YR2/1 brownish black	1- 2.5Y6/4 dull yellow 2- 7.5YR2/1 black	1- 7.5YR2/1 black 2-2.5Y6/4 dull yellow	10YR5/4 dull yellowish brown
Texture	Humic material	Coarse sand	Gravelly bouldery sand	Gravelly sand	Gravelly sand
Sand %	0	100	50	60	30
Silt %	0	0	0		0
Clay %	0	0	0		0
Gravel	0	0	40% abundance, less than 2cm, slight weathering,	40% abundance, less than 2cm, slight weathering,	90% abundance, less than 5cm, slight weathering,

			subrounded basalt	subrounded basalt	subrounded basalt.
Boulders	0	0	10% abundance, no weathering, subrounded basalt.	0	0

Notes: Most of the profile 10-50cm is made up of a number of layers from 2 processes. 1 – in big storms wash comes over the beach and this area gets a larger than normal deposit of sand and gravel 2 – guano washes here from mounds between storms.

CH53

Date: 14 January 2005
Weather: Overcast and light wind
GPS location: S 72.31913° E 170.23573°
Elevation: about 20m
Location description: on mound located on fan of steep scree slope at back of camp.
Slope: 10°
Aspect: W
Profile shape: mound top
Weathering stage: 1
Depth to permafrost: 60cm
Samples: 53/1: 0-2cm
53/2: 2-10cm
53/3: 10-20cm
53/4: 20-40cm
53/5: 40-50cm

Horizons	1 (surface guano)	2 (dark goo layer)	3 (light brown super goo layer)	4 (chocolate brown goo)	5 (dryer brown guano)
Base (cm)	2	10	20	40	50+
Thickness (cm)	2	8	10	20	10+
Sample no.	1	2	3	4	5
Field moisture	Moist	Moist	Moist	Moist	Slightly moist
Boundary distinctness	Indistinct	Indistinct	Indistinct	Indistinct	
Colour	1- 10R5/4 reddish brown 2- 2.5YR7/3 pale reddish orange 3- bright green, not on chart	5YR3/2 dark reddish brown	7.5YR4/3 brown	10YR3/4 dark brown	10YR5/4 dull yellowish brown
Texture	Humic material	Penguin stones	Penguin stones	Penguin stones	Not penguin stones, but includes clay or organic material.
Sand %	0	0	0	0	0

Silt %	0	0	0	0	0
Clay %	0	0	0	0	5
Gravel	0	100% abundance penguin stones, no weathering, angular to subangular basalt	100% abundance penguin stones no weathering, angular to subangular basalt.	100% abundance penguin stones no weathering, angular to subangular basalt.	95% abundance, 20-40mm diameter, no weathering, angular to subangular basalt.

CH54
Date: 14 January 2005
Weather: Overcast and windy
GPS location: S 72.31921° E 170.23551°
Describe location: In valley located on steep fan. About 10m S of CH53
Slope: 5-10°
Aspect: W
Profile shape: Valley
Weathering stage: 2
Depth to permafrost: 60cm
Samples: 54/1: 0-5cm
54/2: 5-30cm
54/3: 30-60cm

Horizons	1 (surface guano)	2 (black sand)	3 (guano dominated layer)
Base (cm)	5	30	60
Thickness (cm)	5	25	30
Sample no.	1	2	3
Field moisture	Moist	Moist	Moist
Boundary distinctness	Indistinct, wavy	Indistinct	
Colour	Crust – 2.5Y7/1 light grey Stones – 7.5YR2/1 black	10YR6/3 dull yellowish orange	10YR6/4 dull yellowish orange
Texture	Medium sized gravel	Loamy gravel	Loamy gravel
Sand %	0	10	10
Silt %	0	0	0
Clay %	0	10? Or organic, not sure.	10? Or organic, not sure.
Gravel	95% abundance, 2-5mm, weathering stage2, angular basalt.	80% abundance, 60% less than 5 cm and 40% 5-20cm, angular basalt, weathering stage 2.	80% abundance, 70% less than 5cm, 30% 5-20cm. angular basalt, weathering stage 2.

CH55

Date: 16 January 2005

Weather: Overcast and windy

GPS location: S 72.31975° E 170.23100°

Location description: On old non-habitated mound at the back of camp, about 50m S of the great northern river and about 100m W of scree slope. Some guano on surface, rather than the other mound dug behind camp where there was no guano on surface.

Profile shape: Mound top

Weathering stage: 1

Depth to permafrost: 55cm

Samples: 55/1: 0-2cm
55/2: 2-25cm
55/3: 25-35cm
55/4: 35-55+cm
55/5: 0-5cm – bone for dating
55/6: 20-30cm - bone for dating
55/7: 5-10cm – bone for dating
55/8: 20-30cm? not sure. – bone for dating
55/9: 55-80cm – core
55/10: 80-100cm - core

Horizons	1 (washed penguin stone pavement)	2 (dark goo layer)	3 (light brown goo layer)	4 (lighter brown and large stones)
Base (cm)	2	25	35	55+
Thickness (cm)	2	23	10	20+
Sample no.	1	2	3	4
Field moisture	Dry	Variable, dry and moist	Moist	Moist
Boundary distinctness	Indistinct	Distinct, sharp	Indistinct	
Colour	7.5YR2/1 black	7.5YR2/2 brownish black varying to 7.5YR4/6 brown	7.5YR4/4 brown	5YR4/6 reddish brown
Texture	Penguin stones2-5cm	Penguin stones and 10% humic material	Penguin stones and 5% humic material	Larger stones 3-10cm and 2% humic material
Sand %	0	0	0	0
Silt %	0	0	0	0
Clay %	0	0	0	0
Gravel	Penguin stones, subrounded basalt	90% abundance penguin stones, no weathering,	95% abundance penguin stones, no weathering subrounded basalt	98% abundance, 3-10cm no weathering subangular basalt.

		subrounded basalt		
Boulders	0	0	0	0

Notes: Cored through the permafrost to recover samples down to 100 cm.

CH56

Date: 16 January 2005
Weather: Overcast and windy
GPS location: S 72.31977° E 170.23072°
Location description: Valley near CH55 behind camp in a dryer spot in that area.
Profile shape: Valley bottom
Weathering stage: 1
Depth to groundwater: 45cm
Depth to permafrost: 60cm
Samples: 56/1: 0-2cm
56/2: 2-5cm
56/3: 30-40cm

Horizons	1	2	3	4
Base (cm)	2	5	45	60+
Thickness (cm)	2	3	40	15+
Sample no.	1	2	3	
Field moisture	Damp	Damp	Very moist to moist	Wet
Boundary distinctness	Indistinct	Indistinct	Indistinct	
Colour	7.5YR4/1 brownish grey	10YR3/1 brownish black	5YR1.7/1 black	
Texture	Pavement coarse gravel	Fine sand	Sandy gravel	Coarse gravel
Sand %	5	100	90	60
Silt %	0	0	0	0
Clay %	0	0	0	0
Gravel	95% abundance, no weathering subrounded basalt	10% abundance, variable size, 2mm to 10cm, no weathering, subrounded basalt	40% abundance, 5-10cm, no weathering, subrounded basalt	
Boulders	0	0	0	0

CH57
Date: 16 January 2005
GPS location: S 72.32069° E 170.23347°
Elevation: around 15m
Location description: On scree slope about 200m S of the fan with penguins on it. 15m up slope.
Slope: ~30 degrees
Aspect: W
Profile shape: steep hill slope
Weathering stage: 1-2
Notes: The slope consists of angular basalt scree both lava and scoria, 5mm to 50cm. Fine material is found below the surface (<5%). Scree on the surface has many orange and yellow lichens and some moss lower down. Skua nests are dotted on some parts of the slope, usually below a large boulder which acts to protect them from any scree movement downslope.

CH58

Date: 16 January 2005
GPS location: S 72.32125° E 170.23226°
Elevation: ~20m
Location description: On scree slope ~20m N of the snow slope.
Slope: ~25 degrees (slightly less than CH57)
Aspect: W
Profile shape: steep scree slope
Weathering stage: 1-2
Depth to permafrost: 30cm
Samples: CH58/1 7.5YR 4/1 brownish grey.
Notes: This profile is very similar to CH57 apart from the fact that there is some organic matter accumulated from skuas nesting in the area.

CH59

Date: 16 January 2005

GPS location: S 72.32140° E 170.23120°

Location description: On scree slope in the snow slope which has currently melted away.

Slope: ~25 or maybe only 20.

Aspect: W

Profile shape: scree slope

Weathering stage: 1-2

Notes: This is an active fan, so not younger surface compared to CH57-58. Some fine material is found here, probably from the snow which covers this area for a large part of the year. The soil is slightly moist, contrasting what we found in the earlier scree profiles. This moisture most likely comes from the snow which is still present upslope. Fine material is 5%, if that. Entire profile is angular scoria and lava basalt scree.

CH60
Date: 16 January 2005
Weather:
GPS location: S 72.32261° E 170.22816°
Location description:: On moraine slope, on an area which looks lighter in the arial photo, above the skua pond.
Slope: 20.
Aspect: W
Profile shape: steep slope
Weathering stage: 1-2
Depth to permafrost: 45cm

Samples:	60/1	0-2cm	skua poo	7.5YR8/1 light grey 10YR4/2 greyish yellow brown
	60/2	2-20cm	dry	10YR3/2 brownish black
	60/3	20-45cm	moist	10YR4/3 dull yellowish brown

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.

CH61

Date: 17 January 2005
GPS location: S 72.32259° E 170.22497°
Elevation: 2m
Location description: In valley ~40m from coast between 'skua' mounds, ~50m from scree slope.
Slope: 1°
Profile shape: Valley bottom
Weathering stage: 1
Depth to groundwater: 65cm
Depth to permafrost: 75+cm

Samples:	61/1	0-2cm	5YR 1.7/1 black
	61/2	25cm	10R1.7/1 reddish black
	Groundwater		

Description:

0-2cm	Surface pavement of sand to boulder material <20cm. about 50% of this is coarse sand. Some moss occurs on the surface.
2-75+cm	Bouldery gravelly sand. 40% sand, 30% gravel, 30% boulders. Boulders up to 20cm diameter in size. All material is subrounded indicating rounding from the beach rather than raw material from the scree slope.

CH62

Date: 17 January 2005
Weather: Overcast and light wind
GPS location: S 72.32264° E 170.22545°
Elevation: 2m
Location description: On skua mound half way between scree slope and beach.
Profile shape: Mound top
Weathering stage: 1
Depth to permafrost: 65cm
Samples: 62/1: 0-2cm
62/2: 2-10cm
62/3: 10-25cm
62/4: 25-65cm
62/5: 35cm – salt to identify

Horizons	1	2	3	4
Base (cm)	2	10	25	65
Thickness (cm)	2	8	15	40+
Sample no.	1	2	3	4
Field moisture	Dry	Moist	Moist	Moist
Boundary distinctness	Indistinct	Indistinct	Indistinct	
Colour	2.5YR1.7/1 reddish black	5YR2/2 brownish black	10R1.7/1 reddish black	10R1.7/1 reddish black
Texture	Medium gravelly boulders with fine material	Sandy bouldery gravelly	Bouldery gravelly	Coarse gravelly
Sand %	10	30	30	20
Silt %	30	0	0	0
Clay %	0	0	0	0
Gravel	20% abundance, 1-5cm no weathering subrounded basalt	30% abundance, rest same as 62/1	30% abundance, rest same as 62/1	80% abundance, rest same as 62/1
Boulders	40% abundance, 5-40cm diameter, no weathering, subrounded basalt	40% abundance, 5-40cm diameter, no weathering, subrounded basalt	40% abundance, 5-40cm diameter, no weathering, subrounded basalt.	0

Notes: Lots of salt on bottomof boulders up to 30 cm depth.

CH63

Date: 17 January 2005
Weather: Overcast and light wind
GPS location: S 72.32220° E 170.22507°
Elevation: 2m
Location description: On penguin mound which is surrounded by skua mounds. Half way between sea and scree slope. S extent of the penguin mounds behind camp.
Profile shape: Mound top
Weathering stage: 1
Depth to permafrost: 50cm
Samples: 63/1: 2-5cm
63/2: 5-20cm
63/3: 20-35cm
63/4: 35-50cm
63/5: 35cm - bones

Horizons	1	2	3	4	5
Base (cm)	2	5	20	35	50+
Thickness (cm)	2	3	15	15	15+
Sample no.		1	2	3	4
Field moisture	Dry	Dry	Moist	Moist	Moist
Boundary distinctness	Indistinct			Distinct, sharp	
Colour		7.5YR4/3 brown	7.5YR3/2 brownish black	7.5YR3/3 dark brown	2.5YR1.7/1 reddish black
Texture	Gravel pavement of penguin stones	Penguin stones and humic material	Penguin stones and humic material	Penguin stones and humic material	Raw sandy, bouldery gravel
Sand %	0	0	0	0	40
Silt %	0	3	5	10	0
Clay %	0	0	0	0	0
Gravel	100% penguin stones 2-5cm subrounded basalt	97% penguin stones, 2-5cm, subrounded basalt.	95% penguin stones, 2-5cm subrounded basalt.	90% penguin stones 2-5cm subrounded basalt.	50% 1-3cm diameter stones, subrounded basalt.
Boulders	0	0	0	0	10% 5-10cm diameter stones, subrounded basalt.

CH64
Date: 17 January 2005
Weather: Overcast and light wind
GPS location: S 72.32202° E 170.22669°
Elevation: 3m
Location description: Skua pond at back of camp.
Profile shape: Flat land
Weathering stage: 1
Depth to permafrost: 60cm
Samples: 64/1: 0-2cm
64/2: 2-10cm
64/3: 30-50cm

Horizons	1	2	3
Base (cm)	2	10	60+
Thickness (cm)	2	8	50
Sample no.	1	2	3
Field moisture	Dry	Moist	Moist to very moist
Boundary distinctness	Indistinct		
Colour	10YR1.7/1 black	10YR2/1 black	7.5YR1.7/1 black
Texture	Bouldery gravel	Sandy gravel	Bouldery sandy gravel
Sand %	0	80	80
Silt %	0	0	0
Clay %	0	0	0
Gravel	50% 0.5-5cm subrounded basalt	20% 2-5cm subrounded basalt	15% 2-5cm subrounded basalt
Boulders	50% up to 30cm diameter. Subrounded basalt	0	5% up to 20cm subrounded basalt.

CH65

Date: 17 January 2005
Weather: Overcast and light wind
GPS location: S 72.32159° E 170.22794°
Elevation: 5-10m
Location description: On large fan to the S of the snow patch at the back of camp
Slope: 3 degrees
Aspect: W
Profile shape: Lower fan
Weathering stage: 1
Depth to permafrost: 40cm – possibly a glacic horizon
Samples: 65/1: 0-2cm
65/2: 2-35cm
65/3: 35-40cm

Horizons	1	2	3
Base (cm)	2	35	40
Thickness (cm)	2	33	5
Sample no.	1	2	3
Field moisture	Dry	Slightly moist	Moist
Boundary distinctness	Distinct irregular	Distinct smooth	
Colour	7.5YR3/3 dark brown	7.5YR2/2 brownish black	7.5YR4/3 brown
Texture	Bouldery gravel	Bouldery sandy gravel	Gravely fine sand
Sand %	0	0	0
Silt %	0	5	100%
Clay %	0	0	0
Gravel	60% abundance, 2-5cm	55% abundance 2-5 cm	0
Boulders	40%, 5-20cm	40% 5-10cm	0

CH66
Date: 19 January 2005
Weather: Calm and sunny
GPS location: S 72.32021° E 170.20753°
Location description: On mound near coast on S end of the hook.
Profile shape: Mound top
Weathering stage: 1
Samples: 66/1: 0-4cm
66/2: 4-20cm
66/3: 20+cm

Horizons	1	2	3
Base (cm)	4	20	30+
Thickness (cm)	4	16	10+
Sample no.	1	2	3
Field moisture	Dry	Moist	Moist
Boundary distinctness	Indistinct	Distinct	
Colour	10YR8/2 light grey	7.5YR3/2 brownish black	5YR2/1 brownish black
Texture	Humic gravel	Penguin stones	Gravelly sand
Sand %	0	0	80
Silt %	0	10% humic	0
Clay %	0	0	0
Gravel	0	90% penguin stones, subrounded basalt	10% up to 2cm in diameter, subrounded basalt
Boulders	0	0	0

CH67

Date: 19 January 2005
Weather: Calm and sunny
GPS location: S 72.31969° E 170.20943°
Location description: On mound near coast, on next set of ridges in from CH66. 200m in from the sea at the south end of the hook.
Profile shape: Mound top
Weathering stage: 1
Depth to permafrost: 65cm
Samples: 67/1: 0-4cm
67/2: 4-15cm
67/3: 15-25cm
67/4: 25-55cm
67/5: 55-70cm
67/6: 40cm – dating

Horizons	1	2	3	4	5	6
Base (cm)	4	15	25	55	65	70+
Thickness	4 cm	11 cm	10 cm	30 cm	10 cm	5+ cm
Sample no.	1	2	3	4	5	
Field moisture	Dry	Slightly moist	Moist	Slightly moist	Moist	Cement
Boundary distinctness	Indistinct	Indistinct	Indistinct	Distinct		
Colour	10R5/4 reddish brown 5Y8/2 light grey	5YR4/3 dull reddish brown	5YR3/2 dark reddish brown	10YR4/6 brown	7.5YR2/1 black	
Texture	Humic material	Penguin stones	Penguin stones	Penguin stones	Gravelly bouldery sand	Penguin stones
Sand %	0	0	0	0	30	0
Silt %	0	10 (humic)	10 (humic)	5 (humic)	0	0
Gravel	0	0	0	0	40% 2-5cm sub-rounded basalt	0
Boulders	0	0	0	0	30% abundance, up to 20cm diameter, sub-rounded basalt.	0

CH68

Date: 21 January 2005

GPS location: S 72.31889° E 170.22109°

Location description: Beach on sheltered Willett Cove.

Profile shape: Beach

Weathering stage: 1

Samples: 68/1: 0-2cm
68/2: 2-20cm
68/3: 2-4mm – entire profile
68/4: >4mm – entire profile

Notes: Low energy beach, with organic matter from penguin colony and tides washed up in certain areas thicker than others. Top surface 2cm has a greeny brown more organic layer. Under this is rounded gravelly sand. Throughout the profile, fine gravels predominate. Colour – all 5YR1.7/1 black except 68/1 10YR2/1 black because of organic matter.

CH69

Date: 21 January 2005

GPS location: S 72.31981° E 170.20611°

Location description: Medium energy beach on S end of hook.

Profile shape: Beach

Weathering stage: 1

Samples: 69/1: 0-20cm
69/2: <2mm – entire profile
69/3: 2-4mm – entire profile

Notes: Medium energy beach. Larger stones found here with quite a few boulders over 20cm diameter. No organic matter is found on the surface and the entire profile is bouldery, gravelly sand. All rounded basalt.

CH70
Date: 21 January 2005
GPS location: S 72.31812° E 170.22782°
Location description: Main beach, high energy.
Profile shape: Beach
Weathering stage: 1
Samples: 70/1: entire profile
Notes: This beach differs from the other because of a higher energy level, can be seen by a steeper profile and larger boulders present. Generally the large boulders are present at the back of the beach with stones and medium sands near the waters edge.

Through the profile there is little sand under the surface. But this varies greatly along the beach, as does the size of the dominant stone size. No organic matter has accumulated. Colour – 5YR 1.7/1 black.

CH71

Date: 23 January 2005

GPS location: S 72.31973° E 170.22959°

Location description: Zone behind camp where an ephemeral stream runs, S of the GNR.

Profile shape: valley bottom – wet area

Weathering stage: 1

Samples: 71/1: 0-2cm – no vegetation zone
71/2: 0-2cm – dry sparse algae zone
71/3: 0-2cm – green algae/moss zone
71/4: 0-2cm – stream, red algae zone

Notes: A graduation occurs across all of these streams. White salts occur on edge of streams. Then gradually moss abundance increases, probably due to greater water availability. Colour: 71/1: - 5YR2/1 brownish black
71/2: - 5Y3/2 olive black
71/3: - 5Y4/4 dark olive
71/4: - 2.5Y3/1 brownish black

CH72

Date: 23 January 2005

Location description: Across main wet area by penguin mounds on fan.

Samples: Four samples were taken in different zones of this wet area.

72/1: S72.31953°, E170.23425°. In penguin mound area, near the bottom of the fan, no algae present. Receives a lot of runoff from the penguin mounds here, it runs over this area. 10YR5/4 dull yellowish brown.

72/2: S72.31958°, E170.23407°. On mossy area directly below penguin mound. Abundant moss and alge here, including some black algae. 7.5Y4/3 dark olive

72/3: S72.31977°, E170.23440°. In muddy zone, slightly away from the area receiving the direct penguin runoff. 5Y3/2 olive black.

72/4: S72.32004°, E170.23393°. In runoff zone from a snow patch, should have less penguin influence. 2.5Y5/6 yellowish brown.