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Soil organic matter composition, transformation, and microbial colonisation of Gelic Podzols in the coastal region of East Antarctica

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Abstract

During recent soil geographical expeditions to Casey Station (Coastal Antarctica), soils with the morphological features of Gelic Podzols (WRB: Spodic Haplic Cryosols) were found to be widespread. The purpose of this paper is to provide further information on these unique soils with respect to soil organic matter (SOM), microbiology, and soil formation. Antarctic Podzols develop on solid rock, outwash sediments, and abandoned penguin rookeries. A comparison of different SOM depth profiles, however, revealed carbon (C) and nitrogen (N) of unknown origin. The SOM composition was characterised by a mean C/N ratio of 10, with a high content of carboxyl-C units, probably derived from amino acids, organic acids, and oxidised carbohydrates. Pyrolysis-GC/MS and NMR showed a notable variation between SOM in depth profiles and the horizons within each profile. Microbial colonisation was affected by the surface vegetation, content of organic C, and the influence of seabirds. Correlations between selected SOM compounds and bacteria on the vegetated soils suggested that algal and moss C influence SOM to a great extent. Most of the long-chain C moieties in the antarctic Podzols appeared to contain multiple oxygen- and N-containing functional groups, cyclic ionised and heterocyclic structures, and alkylations. Data suggest that, along with the podzolisation process, organic acids, non-humified carbohydrates, and N-containing moieties migrated from the topsoil into the spodic horizons. The results are discussed with respect to (*i*) soil formation and (*ii*) microbial colonisation in the cold climate. The Gelic Podzols hold huge amounts of C and N but their origin is poorly understood. Explaining the origin of the SOM should be a focus for future research in antarctic soil biogeochemistry.

Additional keywords: microbial counts and abundance, CPMAS carbon-13 NMR spectroscopy, pyrolysis-GC mass spectrometry, soil ecology, soil formation, podzolisation.

Introduction

Antarctic Podzols contain high concentrations of carbon (C) and nitrogen (N) (Blume *et al.* 1996; Beyer *et al.* 1998). Blume *et al.* (1997) and Beyer *et al.* (2000*a*) suggested that the occurrence and intensity of podzolisation is determined by microclimate, parent materials, and soil microbial effects. However, coherent and confirmed information on podzolisation processes is still missing. In previous work, the soil organic matter (SOM) of the spodic horizons was characterised by a narrow C/N ratio (<10) with potentially high bioavailability, probably derived from amino acids, other organic acids, and oxidised carbohydrates (Beyer *et al.* 1997). Compared with similar soils from temperate climates, the SOM profiles with depth suggested atypical C and N moieties of unknown origin (Post *et al.* 1988). Knowledge on antarctic soils and especially on the SOM of these soils is still scarce (Seppelt and Broady 1988). More information on SOM in terrestrial ecosystems of East Antarctica is desirable since biological observations suggest that SOM transfer may play an important role in nutrient cycles in the terrestrial Antarctic ecosystem (Smith 1985).

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For this reason, some antarctic Podzols from different parent material were investigated with respect to SOM quality using cross polarisation magic angle spinning ^{13}C nuclear magnetic resonance spectroscopy (CPMAS ^{13}C NMR) and pyrolysis gas chromatography mass spectrometry (Py-GC/MS). The results are discussed with respect to SOM quality, transformation, and translocation in the cold climate of Antarctica.

Materials and methods

Site

Soils were collected near the Australian Casey Station on Bailey Peninsula (66°18´S, 110°32´E) at Wilkes Land in coastal East Antarctica about 700 m from the shore (Fig. 1). Soil C11 and D3 are located on specific observation sites close to the main station building (Fig. 1: squares C and D). Soil WP5 is located on Clark Peninsula somewhat further north from Bailey (Fig. 1). The parent material is composed of weathered gneiss and schist, moraine deposits, outwash sediments (e.g. Paul *et al.* 1995), and marine deposits by seabirds (Campbell and Claridge 1987). The coastal landscape was partly deglaciated between 5000 and 6000 years BP (Goodwin 1993) and an elevation of terraces occured. The annual precipitation (180 mm) falls mainly as snow. Because of strong drift due to persistently strong winds (Pickard 1986), seawater is heterogeneously distributed on land (Beyer *et al.* 2000*b*). The mean annual ambient temperature is –9.3°C. During the antarctic summer of nearly 6 weeks, temperatures are above the freezing point (e.g. the mean January temperature is +0.2°C). Plant communities of mosses (e.g. *Bryum pseudotriquetrum, Ceratodon pupureus, Schistidium antarcticum*), lichens (e.g. *Usnea sphacelata, Pseudephebe minuscula, Umbilicaria decussata*), and soil algae have become established (Seppelt 1984; Smith 1990).

Sampling, soil survey, and general soil investigations

Sampling was carried out during January and February 1996. The soils were originally classified as Sandy or Loamy Mixed Lithic or Pergelic Haplocryods (Beyer *et al.* 2000*a*) according to the 7th edition of Soil Taxonomy (Soil Survey Staff 1996). However, using the new Gelisol order for permafrost-affected soils in the recently adopted 8th edition of Soil Taxonomy no adequate classification seemed possible (Beyer *et al.* 2000*a*). According to the World Reference Base of Soil Resources (WRB) these soils have to be classified as Spodic Haplic Cryosols because they are characterised by permafrost within the first metre (Deckers *et al.* 1998). Because only the recently rejected FAO classification includes the name Podzol, a soil type most geoscientists are familar with, the name *Gelic Podzol* has been used (i.e. a Podzol having permafrost in the first 2 m) (FAO 1997) in this paper.

Most soil properties were analysed according to Schlichting *et al.* (1995) on air-dried soil samples. Soil mineral particle composition was determined after sieving at 2 mm by a combination of sieve and elutriate analysis. Soil texture was estimated by using the soil texture chart of the Keys to Soil Taxonomy (Soil Survey Staff 1996: p. 631). The pH was measured in 10 mM $CaCl_2$ with a commercial glass electrode. Electrical conductivity (EC) was measured in a 1 : 2.5 water extract. Loss-on-ignition (LOI) was determined gravimetrically after combustion at 650°C in a muffle furnace. Total organic carbon (TOC) was calculated after dry combustion in a Coulomat 702 (Ströhlein, Germany). The samples were heated (600°C) in an induction furnace under oxygen; CO_2 was trapped in $Ba(OH)_2$ and the remaining $Ba(OH)_2$ was neutralised by titration. Total nitrogen (N_t) was digested by the classical Kjeldahl method and determined as nitrate in a flow injection analyser. Pedogenic iron and aluminium oxides were determined after extraction with dithionate–citrate (Fe_d, Al_d) and oxalate (Fe_o, Al_o). The iron and aluminum bonded to organic matter was determined in an alkaline (NaOH) extract. Alkaline extract was used because sodium pyrophosphate extract overestimates organic iron species by destruction of certain minerals such as olivine (Grimme and Wiechmann 1969; Wiechmann and Grimme 1969). The extinction of the oxalate extract was measured at 472 nm (optical density of oxalate extract, ODOE) according to Daly (1982). The cations Na^+, K^+, Mg^{2+}, and Ca^{2+} were extracted with unbuffered $BaCl_2$. Potential H^+ and Al^{3+} were extracted with Ca^{2+}-acetate and measured as pH and converted into H^+ and Al^{3+}. The sum of the cations and potential $H^+ + Al^{3+}$ is the potential cation exchange capacity (CEC_p). The percentage of Na^+, K^+, Mg^{2+}, and Ca^{2+} from CEC_p is the base saturation (BS). The bio-available potassium (K_l), magnesium (Mg_l), and phosphorus (P_l) were extracted with 0.04 N Ca^{2+} lactate + 0.02 N HCl at pH 3.7. K_l and Mg_l were determined in an AAS (Perkin Elmer). P_l was determined colorimetrically as the blue-coloured molybdate–phosphate complex. The immobile P fraction (P_c) was extracted with 2% citric acid (modified, original 1%) (Van Reeuwijk 1993).

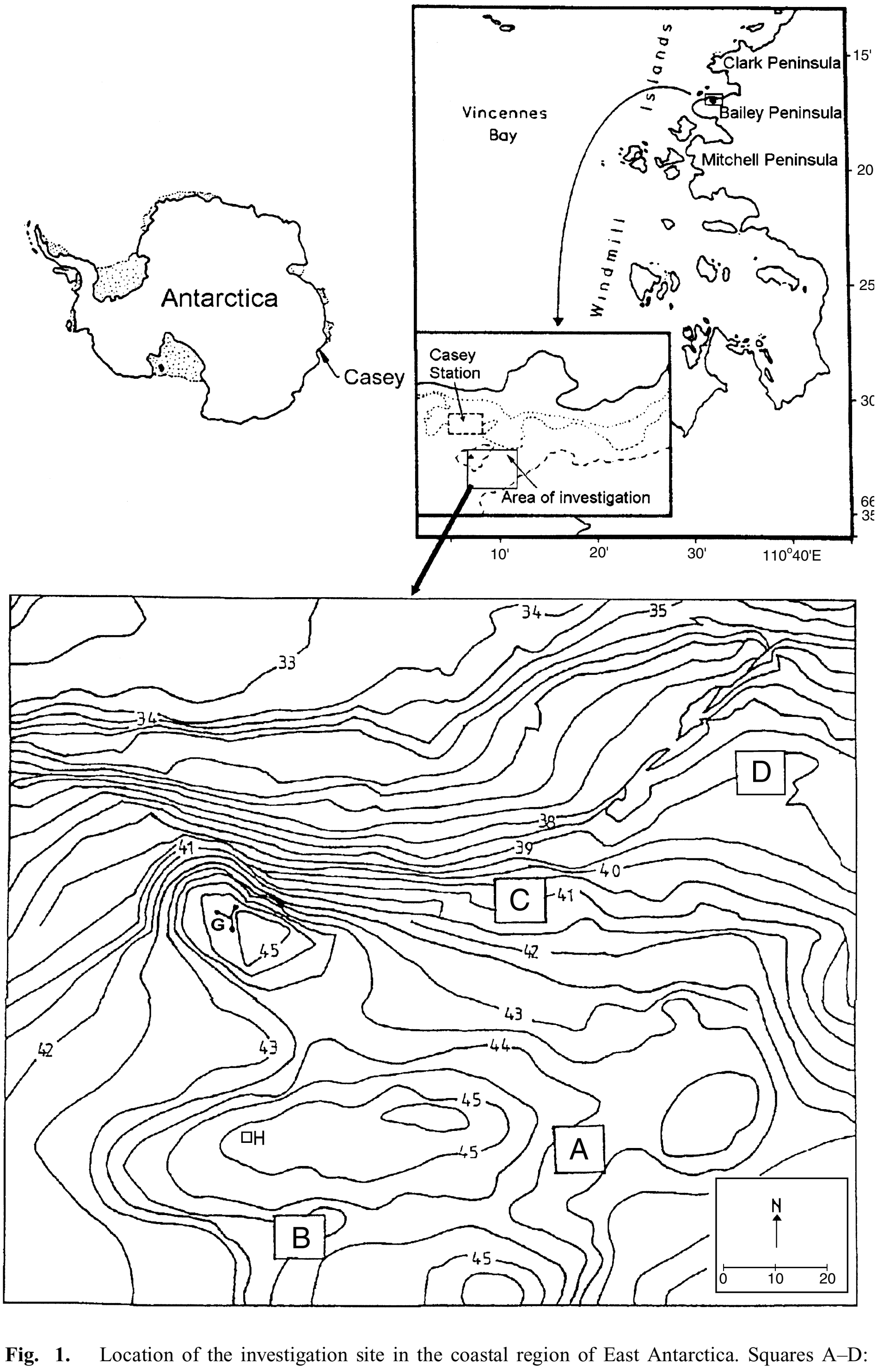

Fig. 1. Location of the investigation site in the coastal region of East Antarctica. Squares A–D: specific monitoring sites.

CPMAS ^{13}C NMR

The CPMAS ^{13}C NMR were taken at 2.3 tesla (25.2 MHz) with a Bruker MSL 100 equipped with a commercial 7-mm CPMAS probe at a rotation frequency of 4 kHz. A contact time of 1 ms was used. Due to short relaxation times (T_{1H}) in SOM, a recycle delay of 0.3 s was chosen. The chemical shift is given relative to tetramethylsilane (TMS = 0 ppm) scale. The quantitative data were obtained with the integration routine of the spectrometer. For further details see Fründ and Lüdemann (1989).

Py-GC/MS

Subsamples with a mass of 25 mg were placed in quartz tubes (2 cm by 2 mm ID) and quantified using a Mettler microbalance. In preliminary research it was determined that samples with a mass <10 mg did not give a signature greater than the baseline and samples >30 mg did not fit entirely within the quartz tube (White and Irvine 1998). The samples were held in place by a plug of quartz wool at each end of the tube. Py-GC/MS was conducted on each sample and used to identify as many compounds as possible. Py-GC/MS was conducted with a CDS Model 1000 pyrolyser and a Model 1500 GC interface. The interface temperature was set at 280°C. During pyrolysis, the sample was heated from 280°C to 700°C in 0.1 s and held at 700°C for 9.9 s. The pyrolysis reactor was mounted on an HP 5890 Series II GC with a Hewlett Packard HP-1 column (cross-linked methyl-siloxane) 25 m by 0.2 m by 0.33 µm film thickness. The GC temperature program was 35°C for 15 min, 2°C/min ramp to 250°C, and held for 10 min. The GC was plumbed directly to an HP 5971A Series Mass Selective Detector in electron impact mode. The MS scanned mass units 45–650. All mass spectra were compared to the Wiley 138 mass spectral library. Helium was used as the carrier gas at 0.5 cc/min. The sample was injected with a split ratio 1:50. For each sample, the mass spectral signals for all compounds were normalised to the compound of greatest abundance. In this study only those compounds were considered that had a normalised intensity of ≥20%. Each compound was assigned a probable parent (see Table 8). The parent represents a soil biopolymer that was present in the sample prior to pyrolysis. The soil biopolymer classifications used were protein, phenol precursors, carbohydrates, aromatic hydrocarbon precursors (AHP), lipids, and amino-carbohydrates (Bracewell *et al.* 1989). All long-chain hydrocarbons, alcohols, aldehydes and ketones were classified as having lipid parents. Any compound with no assignment to a probable parent was considered unresolved. The relative intensities for all soil biopolymers in each sample were added. Each soil biopolymer class is presented as a percentage of the total on the assigned compounds.

Microbial determinations

Determination of chlorophylls and phaeopigments were performed according to Jeffrey and Humphrey (1975) and Lorenzen (1967), respectively, in acetone extracts (90%) by spectral photometry. All values were expressed on a dry mass (DM) basis. According to the current literature the occurence of algae is indicated by chlorophyll detection (e.g. Bölter 1990, 1995, 1997). Microorganisms were counted by epifluorescence microscopy. Samples were stained with acridine orange and filtered onto nuclepore polycarbonate membranes. Cells of bacteria and yeasts were identified and counted with respect to their size classes. Biovolumes were calculated by geometrical parameters (Bölter *et al.* 1993). Samples were taken aseptically with a clean spoon and placed in plastic containers.

Results and discussion

General properties

All three Podzols showed the typical horizon sequence of AE-Bh(Bhs,Bs)-C with a strong acidification and a Fe_o/Fe_d ratio that exceeds 0.5 (Tables 1–3), indicating the existence of short-range-order pedogenic iron compounds (Schlichting *et al.* 1995). Maximum values for most aluminium and iron fractions, the ODOE, LOI, TOC, and total nitrogen (N_t) occurred in the spodic Bh/Bhs horizons (Tables 1–3). The depth profile for these parameters suggests a translocation of SOM into the subsoil (McKeague *et al.* 1983). Both metals were mainly located in non-crystalline pedogenic oxides (Fe_o, Al_o) or in organic complexes (Fe_{NaOH}, Al_{NaOH}). However, the high Al_{NaOH} values suggest an overestimation of the organically bonded aluminium (Kaiser and Zech 1996) and confirmed the results of Jacobsen (1991) who showed that Fe_o and Al_o were higher than Fe_d and Al_d. A large amount

Table 1. Selected properties of a shallow Antarctic Gelic Podzol (C11) from weathered gneiss rock under mosses and lichens in a small depression (sampling date 10 February 1996)

EC, electrical conductivity; TOC, total organic carbon; LOI, loss-on-ignition; N_t, total nitrogen; Fe_d, Al_d, dithionate-citrate-extractable; Fe_o, Al_o, oxalate-extractable iron and aluminum; Fe_{NaOH}, Al_{NaOH}, alkaline (NaOH)-extract; ODOE, optical density of oxalate extract; sg, single grain; sab, subangular blocky; ab, angular blocky; S, sand, LS, loamy sand; SL, sandy loam; CEC_e, effective cation exchange capacity; CEC_p, potential CEC; BS, base saturation; K_l, lactate-extractable potassium; Mg_l, lactate-extractable magnesium; P_l, lactate-extractable phosphorus; P_c, citrate-extractable P

	Depth (cm)	Fraction >2 mm (g/kg)	Colour moist	pH $(CaCl_2)$	pH (H_2O)	EC (dS/m)	TOC (mg/g)	LOI (mg/g)	TOC/LOI	N_t (mg/g)	C/N_t
AE	0–2.5	640	10YR4/1	3.83	4.73	1.9	23.7	53.8	0.44	2.21	10.7
Bh	–10	570	10YR2/1	3.73	4.55	2.7	38.5	75.5	0.51	2.52	15.3
BsC	–20	480	10YR4/3	3.88	4.79	1.1	9.7	19.9	0.49	0.99	9.8
IIC	–25	380	2.5Y5/3	4.01	4.85	0.6	5.4	12.1	0.44	0.53	10.3
R	>25 gneiss rock										

	Texture & structure	Sand	Silt	Clay	Fe_d (mg/g fine-earth fraction)	Al_d	Fe_o	Al_o	Fe_{NaOH}	Al_{NaOH}	ODOE
AE	S, sg	911	51	38	2.16	0.76	1.09	0.84	0.61	0.99	246
Bh	LS, sab	867	93	40	3.08	1.30	1.74	1.58	0.90	1.42	377
BsC	LS, sab	868	101	31	2.76	0.78	1.16	0.99	0.34	1.06	246
IIC	SL, ab	706	244	50	4.14	1.31	1.51	1.44	0.38	1.56	164

	Ca	Mg	K	Na ($mmol_c$/kg)	H	Al	CEC_e	CEC_p	BS (%)	K_l	Mg_l (mg/kg)	P_l	P_c
AE	8	7	1	2	0.7	6	25	99	18	44	85	78	324
Bh	9	7	1	3	0.6	10	31	140	15	44	87	124	392
BsC	3	2	0.5	2	0.4	4	11	57	11	33	28	139	747
IIC	2	0.9	0.5	2	0.5	4	9	54	9	33	39	157	1270

Table 2. Selected properties of an Antarctic Gelic Podzol (WP5) from glacial outwash sediments under mosses at a dried-up melt-water lakeside (sampling date 6 February 1996)

EC, electrical conductivity; TOC, total organic carbon; LOI, loss-on-ignition; Nt, total nitrogen; Fed, Ald, dithionate–citrate-extractable iron and aluminum; Fe_o, Al_o, oxalate-extractable; Fe_{NaOH}, Al_{NaOH}, alkaline (NaOH)-extract; ODOE, optical density of oxalate extract; sg, single grain; (f)sab, (fine)subangular blocky; S, sand, LS, loamy sand; CEC_e, effective cation exchange capacity; CEC_p, potential CEC; BS, base saturation; K_l, lactate-extractable potassium; Mg_l, lactate-extractable magnesium; P_l, lactate-extractable phosphorus; P_c, citrate-extractable P; n.d., not determined

	Depth (cm)	Fraction >2 mm (g/kg)	Colour moist	pH $CaCl_2$	pH H_2O	EC (dS/m)	TOC (mg/g)	LOI (mg/g)	TOC/LOI	N_t (mg/g)	C/N_t
AE	0–4	680	10YR4/1	3.83	4.81	2.3	39.5	92.5	0.43	2.96	13.4
Bh	–7	530	10YR2/1	3.83	4.40	2.1	64.7	133.9	0.44	4.99	13.0
C	–20	440	10YR4/3	4.09	4.80	1.0	19.0	36.5	0.52	1.75	10.9
Cf	>20 permafrost										

	Texture & structure	Sand	Silt	Clay	Fe_d (mg/g fine-earth fraction)	Al_d	Fe_o	Al_o	Fe_{NaOH}	Al_{NaOH}	ODOE
AE	S, sg	926	67	7	1.50	0.61	0.84	0.78	0.70	0.95	146
Bh	S, sg	855	103	42	2.23	2.20	1.43	2.06	1.33	2.30	414
C	LS, sg-fsab	933	50	17	1.30	1.04	0.71	0.99	0.51	1.18	165

	Ca	Mg	K	Na (mmol$_c$/kg)	H	Al	CEC_e	CEC_p	BS (%)	K_l	Mg_l (mg/kg)	P_l	P_c
AE	13	11	2	5	2	7	41	163	19	83	150	49	167
Bh	12	8	1	4	2	16	44	222	12	48	114	133	412
C	4	2	0.3	2	0.6	5	14	84	10	17	27	102	n.d.

Table 3. Selected properties of an unvegetated Antarctic Gelic Podzol (D3) under a gravel pavement at an abandoned penguin rookery (sampling date 6 February 1996)

EC, electrical conductivity; TOC, total organic carbon; LOI, loss-on-ignition; Nt, total nitrogen; Fed, Ald, dithionate-citrate-extractable iron and aluminum; Fe_o, Al_o, oxalate-extractable; Fe_{NaOH}, Al_{NaOH}, alkaline(NaOH)-extract; ODOE, optical density of oxalate extract; sg, single grain; (f)sab, (fine)subangular blocky; ab, angular blocky; S, sand, LS, loamy sand; SL, sandy loam; coh, coherent, c, coatings; CEC_e, effective cation exchange capacity; CEC_p, potential CEC; BS, base saturation; K_l, lactate-extractable potassium; Mg_l, lactate-extractable magnesium; P_l, lactate-extractable phosphorus; P_c, citrate-extractable P; n.d., not determined

	Depth	Fraction >2 mm (g/kg)	Colour moist	pH $CaCl_2$	H_2O H_2O	EC (dS/m)	TOC (mg/g)	LOI (mg/g)	TOC/LOI	N_t (mg/g)	C/N_t
D[A]	0–6	1000	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
AE[B]	–9	900	10YR4/1	3.47	4.77	1.9	27.6	61.7	0.45	0.96	28.9
Bh[B]	–11	850	7.5YR2.5/1	3.65	4.64	1.4	36.5	86.2	0.42	3.41	10.7
Bhs[B]	–16	880	7.5YR4/3	4.00	5.03	1.0	30.6	66.3	0.46	3.95	7.8
IIBs	–35	840	7.5YE5/4	4.70	5.48	0.9	25.7	53.2	0.48	3.51	7.3
IIICw	–71	690	10YR5/4	4.90	5.73	0.8	10.5	18.3	0.57	4.57	2.3

	Texture & structure	Sand	Silt	Clay	Fe_d (mg/g fine-earth fraction)	Al_d	Fe_o	Al_o	Fe_{NaOH}	Al_{NaOH}	ODOE
AE	S, sg	880	74	46	3.06	0.96	2.15	1.04	1.15	1.05	211
Bh	LS, fsab + c	798	135	67	6.58	2.71	6.11	2.99	6.00	3.01	641
Bhs	SL, sab + c	655	230	115	7.86	4.30	6.28	4.55	1.48	3.79	418
IIBs	SL, sab–coh + c	582	223	195	4.83	2.55	4.74	2.62	0.24	3.47	202
IIICw	LS, sg	826	108	66	4.40	1.88	2.90	1.73	0.24	2.23	108

	Ca	Mg	K	Na ($mmol_c$/kg)	H	Al	CEC_e	CEC_p	BS (%)	K_l	Mg_l (mg/kg)	P_l	P_c
AE	17	7	2	4	0.8	5	35	137	21	66	103	119	1638
Bh	32	7	1	6	0.9	8	56	229	20	51	89	276	5503
Bhs	50	5	2	9	1	3	70	241	27	63	75	360	5850
IIBs	186	9	2	10	0.8	0.2	208	364	57	84	128	1544	6151
IIICw	47	4	2	4	0.6	0.1	58	118	48	72	69	1245	5681

[A] Term see Bockheim (1997). [B] Sponge needles.

of P indicated the influence of guano input (Blume *et al.* 1997), and was seen at soil D3 for both P fractions (Table 3). The increase of the P fractions in the subsoil of the Podzol from solid rock (Table 1) also indicates guano input in earlier stages of soil formation.

All suggested spodic Bh/Bhs horizons comply with the criteria of US Soil Taxonomy (Soil Survey Staff 1998). For this reason Blume *et al.* (1997) classifed these soils as Gelic Podzols and Beyer *et al.* (2000*a*) as Haplocryods, recognising unique properties compared to Podzols (Spodosols) in temperate and/or boreal climate regions. The C/N ratios of Podzols in Antarctica were much narrower than those of their temperate counterparts due to their extremely high N_t contents. This was of course most striking in the Podzol at an abondoned penguin rookery (Table 3).

Microbial abundance

Tables 4 and 5 show the microbiological properties of the antarctic sites. Chlorophyll *a* content ranges between 0.2 and 9 μg/g depending on soil depth and the recent vegetation cover (Table 4). For a comparable site, Roser *et al.* (1993) reported values from 5 μg/g on control sites to 11.2 μg/g on extinct penguin rookeries at Whitney Point. Comparable data of total chlorophyll content (Table 4: chlΣ) were obtained at King George Island in the Maritime Antarctic (Bölter 1997). Here chlorophyll content was within a similar range except in surface horizons with dense cover of higher plants and mosses. At Casey, the same was found in soil with recent vegetation (soil C11, soil WP5). Surprisingly, in soil WP5 the chlorophyll data were highest not in the surface horizon, but in the spodic subsurface horizon, which had the highest value of TOC and chlorophyll of all horizon samples (Table 4). Data of Ohtani *et al.* (1991) from the Yukidori Valley and those of Davey (1988, 1991) from Signy Island also showed similar ranges of total chlorophyll content. The degraded chlorophyll, or phaeopigments (Table 4), however, were much higher in the present Casey data set. In the Maritime Antarctic—at King George Island—phaeopigment content ranged only between 0 and 3.8 μg/g dry mass (DM) (Bölter 1997). The high chlorophyll content in the spodic subsurface horizon of soil WP5 (sample no. WP5.2) suggests that chlorophyll is translocated with the organic matter within the podzolisation process or that the much higher current water content (Table 4) has a direct positive impact on chlorophyll-producing organisms.

Bacterial counts ranged between 91 and 1058 10^6/g DM, decreasing with depth (Table 4: TBC), consistent with the distribution of TOC at sites C11 and D3, but not site WP5. This is in agreement with the estimation of the bacterial biovolumes (Table 4). At King George Island, bacterial counts in a Podzol under *Deschampsia antarctica* were found at similar levels (Bölter 1995; Bölter *et al*. 1994, 1997). At Casey, however, no higher plants were present. Roser *et al.* (1993) found high bacterial counts in ornithogenic soils of the Windmill Islands with no vegetation. This is in agreement with the present observations, since soil D3, an abandoned penguin rookery site with no vegetation, showed the highest bacterial counts. In addition, the surface horizon of D3 was the only layer where yeasts were detected (Table 4: TYC).

The mean cell volumes of the bacterial communities range from 59 to 72 nm^3 at site C11, from 55 to 112 nm^3 at site D3 and from 106 to 193 nm^3 site WP5, indicating statistically significant differences between the soils (Table 5). Comparable data from King George Island show values between 50 and 70 nm^3 (Bölter *et al.* 1994, 1997). The situation at Whitney Point (WP5) on Clark Peninsula can be attributed to high amounts of large rod-shaped bacteria (length 2–3 μm), which contribute between 17% and 34% of the community's biovolume (Table 5). In comparison to other sites, these values are extremely

Table 4. Microbial properties of Gelic Podzols in East Antarctica

TOC, total organic carbon; Chl, chlorophyll; Phaeo, phaeopigment; TYC, total yeast counts in 10^6/g dry mass; TBC, total bacterial counts in 10^6/g dry mass; TBV, total bacterial biovolume in 10^6 μm^3/g dry mass; n.s.d., not significantly detected

Sample no.	Horizon	TOC (mg/g)	H_2O (mg/g)	Chl.*a* (µg/g)	Chl.*b* (µg/g)	Chl.*c* (µg/g)	ChlΣ (µg/g)	Phaeo. (µg/g)	TYC	TBC	TBV
Soil C11 with 100% mosses and lichens											
C11.1	AE	23.7	153	6.00	5.50	5.97	17.46	12.88	n.s.d.	211	15
C11.2	Bh	38.5	190	6.32	4.69	3.88	14.88	12.90	n.s.d.	475	31
C11.3	BsC	9.7	85	0.85	0.98	0.56	2.40	1.86	n.s.d.	135	9
C11.4	IIC	5.4	104	0.20	0.49	0.08	0.77	0.42	n.s.d.	114	6
Soil WP5 with 100% mosses											
WP5.1	AE	39.5	259	6.26	0.36	1.79	11.50	13.39	n.s.d.	387	75
WP5.2	Bh	64.7	423	9.28	6.67	5.62	21.56	20.97	n.s.d.	278	29
WP5.3	C	19.0	118	0.56	0.94	0.23	1.71	1.34	n.s.d.	197	25
Unvegetated soil D3											
D3.1	AE	27.6	186	2.88	1.83	0.33	5.04	5.92	5.6	1058	119
D3.2	Bh	36.5	205	1.82	1.26	0.02	3.10	3.48	n.s.d.	344	25
D3.3	Bhs	30.6	178	0.53	1.32	0.49	2.33	1.53	n.s.d.	91	5

Table 5. Structure and size classes of bacterial colonies of Gelic Podzols in East Antarctica

TBC, total bacterial counts in 10^6/g dry mass; TBV, total bacterial biovolume in 10^6 μm^3/g dry mass; BCV, mean bacterial cell volume; n.s.d., not significantly detected; cocci and rods are expressed as a percentage of TBC

Hori-zon	TBC	Cocci <0.5 μm	Cocci –1 μm	Rods 0.5–1 μm	Rods –2 μm	Rods –3 μm	TBV	Cocci <0.5 μm	Cocci –1 μm	Rods 0.5–1 μm	Rods –2 μm	Rods –3 μm	BCV (nm^3)
Soil C11 with 100% mosses and lichens (C11.1–4)													
AE	211.16	51.1	n.s.d.	40.0	8.9	n.s.d.	15.21	9.9	n.s.d.	51.4	38.7	n.s.d.	72
Bh	474.86	52.6	n.s.d.	41.1	6.3	n.s.d.	30.96	11.3	n.s.d.	58.4	30.3	n.s.d.	65
BsC	135.50	47.1	n.s.d.	46.9	6.0	n.s.d.	9.32	9.6	n.s.d.	63.0	27.4	n.s.d.	69
IIC	114.25	56.0	n.s.d.	39.5	4.5	n.s.d.	6.69	13.4	n.s.d.	62.4	24.2	n.s.d.	59
Soil WP5 100% mosses (WP5.1–3)													
AE	387.15	29.8	n.s.d.	30.5	30.3	9.5	74.54	2.2	n.s.d.	15.7	49.4	33.8	193
Bh	278.60	41.0	n.s.d.	44.0	11.8	3.3	29.43	5.4	n.s.d.	38.5	35.0	21.0	106
BsC	196.73	24.0	n.s.d.	57.5	15.3	3.3	24.9	2.7	n.s.d.	42.0	37.9	17.5	127
Unvegetated soil D3 (D3.1–3)													
AE	1058.45	40.5	n.s.d.	41.3	15.3	3.0	118.89	5.1	n.s.d.	34.0	42.7	18.3	112
Bh	344.05	52.3	n.s.d.	38.8	8.8	0.3	24.91	10.1	n.s.d.	49.5	38.0	2.4	72
Bhs	90.63	57.3	n.s.d.	39.5	3.3	n.s.d.	4.96	14.6	n.s.d.	66.7	18.7	n.s.d.	55

high. Elsewhere such high values are mostly found for nutrient-rich microsites such as plant tissue surfaces (Bölter 1995). Similarly, Roser *et al.* (1993) reported cell volumes ranging between 130 and 250 nm^3 for communities in the ornithogenic soils of the Windmill Islands. However, at site WP5 no recent or relic penguin influence was detectable (Tables 1–3). Another explanation for this phenomenon might be the high TOC content of the AE horizons, which was 1.4–1.7× that of soil D3 or C11 (Table 4).

Finally, we suggest that in the coastal region of Continental Antarctica both vegetation and the influence of seabirds affected soil bacterial colonisation. This is discussed in detail by Beyer *et al.* (2000*b*).

Soil organic matter composition

Table 6 shows the SOM composition according to the carbon-13 NMR experiments. The increase in alkyl C and simultaneous decrease of O-alkyles is comparable to the pattern observed in Podzols in temperate regimes (Post *et al.* 1988). However, the high level of carboxyl-C in all soil horizons was unexpected. This might be the reason for the somewhat higher CEC_p in the soil at the abandoned penguin rookeries (Table 3). The abrupt change of the SOM composition within the subsurface Bhs, the IIBs and the IIICw horizons of the Podzol on the penguin rookery (D3) is probably due to different concentrations and quantities of droppings and deposits by penguins in different layers. Beyer *et al.* (1997) suggest for the spodic horizons that, in contrast to those in Germany, the SOM is characterised by a high percentage of amino derivates from proteins, polysaccharides, urates, and chitin, resulting in a mean C/N ratio of 10 and a high content of carboxyl-C units, probably derived from amino and other organic acids. The podzolic soil from solid rock under mosses and lichens (C11) showed an aromatic-C pattern comparable to Podzols in temperate climate regions. However, the aromatic C in the AE was very high and cannot be explained with residual preservation from the recent vegetation. It was unclear if another source of SOM in the area, such as relic organic matter or an input by eolian transport, was contributing. An input by seabirds can be discarded because P contents were low (Table 1). The most substantial similarity of SOM composition with that of Podzols from temperate climates was found in the podzolic soil from outwash sediments under mosses (WP5). However, the comparison of the AE horizons under mosses (WP5-1 and C11-1) confirms the assumption that, in the shallow Podzol from gneiss and schist (C11), a C source other than recent vegetation is likely. Comparing the SOM composition of the soil horizons with the SOM composition (Beyer *et al.* 1995, 1997; White and Beyer 1999) of selected organic parent materials (Table 7) suggests that in soil WP5 the algal and mossy C sources influence SOM to a great extent, whereas in soil D3 and C11 the influence is smaller.

Table 8 shows the major ions found by using Py-GC/MS. In general, there were no indications of lignin in any of the samples. A variety of methylphenols were present, which indicate either protein or lignin. If the methylphenols were derived from lignin, however, methoxylphenols, which were not observed, would have been present (Hempfling and Schulten 1990). The phenols, therefore, were assumed to be derived from proteins. Most of the long carbon-chain molecules in the Antarctic soil samples appeared to contain multiple O- and N-containing functional groups, cyclic ionised and heterocyclic structures, and alkylations. However, the complex and easily ionised compounds and the low C content made mass spectral identification difficult.

In all 3 soils the signal pattern was more detailed in the AE and Bh horizons than in the deeper layers (see example given in Fig. 2), which indicates the direct influence of local vegetation or microbial colonisation, consistent with the NMR data. In soil C11 from

Table 6. Soil organic matter composition according to CPMAS carbon-13 spectroscopy of Gelic Podzols soils in coastal East Antarctica (signal range in ppm shift to the reference tetramethylsilane, TMS)

Hori-	Alkyl-C			O-alkyl-C				Aromatic C			Carboxyl-C		
zon	0–25	–45	Σ	45–60	–90	–110	Σ	110–140	–160	Σ	160–190	–220	Σ
	(% of total organic carbon)												
C11: Soil from weathered gneiss rock under mosses and lichens in a small depression													
AE	6	10	16	5	15	12	33	19	11	30	14	7	21
Bh	11	13	24	6	15	8	29	11	11	22	15	10	25
WP5: Soil from glacial outwash sediments under mosses at a dried-up melt water lake side													
AE	10	15	25	8	25	12	45	10	6	16	11	3	14
Bh	11	17	28	8	25	11	14	9	5	14	10	4	14
C	10	15	25	7	20	10	37	14	9	23	12	3	15
D3: Unvegetated soil under gravel pavement at an abandoned penguin rookery													
AE	8	11	19	5	19	12	36	14	10	24	15	6	21
Bh	11	14	25	5	16	9	32	13	10	23	15	5	20
Bhs	9	14	23	5	12	10	27	14	11	25	18	7	25
IIBs	15	18	34	6	15	7	28	11	7	18	15	5	20
IIICw	7	19	12	5	11	6	22	22	6	36	18	5	23
Organic parent materials													
Mosses[A]	n.d.	n.d.	23	8	24	20	52	9	5	13	n.d.	n.d.	12
Algae[A]	n.d.	n.d.	20	9	32	23	64	6	2	8	n.d.	n.d.	8
Guano[B]	n.d.	n.d.	29	n.d.	n.d.	n.d.	37	n.d.	n.d.	20	n.d.	n.d.	14

n.d., not determined.
[A] Adapted from Beyer *et al.* (1995).
[B] Adapted from Beyer *et al.* (1997).

Table 7. Linear correlation coefficients (*r*) between NMR subunits of the SOM in Gelic Podzols of coastal East Antarctica and the organic matter composition of mosses and algae (data see Table 6, *n* = 9)

Soil	Horizon	r value$_{algae}$	r value$_{mosses}$
C11	AE	0.488	0.589
	Bh	0.480	0.610
WP5	AE	0.931***	0.966***
	Bh	0.911***	0.950***
	C	0.800**	0.856**
D3	AE	0.789**	0.807**
	Bh	0.613	0.730*
	Bhs	0.356	0.500
	IIBs	0.498	0.624
	IIIC	0.041	0.149

*$P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

weathered gneiss rock under mosses and lichens, only the C11-1 (AE) and C11-2 (Bh) horizons contained smaller molecules such as phenols and single-ring aromatics (Fig. 2: e.g. peaks no. 28, 37), whereas in the deeper C11-3 (BsC) and C11-4 (IIC) horizons, long-chain acids, alcohols and ketones were present (Fig. 2; peaks no. 87, 93, 101). Protein precursors (e.g. peaks no. 9, 75) were found only in C11-1 and C11-2, which was in line with a higher occurrence of bacterial microorganisms (Table 4). However, at the same time, peak no. 109 suggested the significance of unresolved compounds, which might have some aromatic structure as suggested by peak 79 (Fig. 2, Table 8) and the NMR data (Table 6).

In Table 9 the semi-quantitative data are summarised in per cent of assigned signals. The SOM of the C11-1 (AE) and C11-2 (Bh) horizons were composed of a large percentage of unresolved compounds, but contained some carbohydrates, protein, and/or phenol precursors as well as aromatic hydrocarbon precursors (AHP). For all samples, most of the compounds comprising the unresolved fraction appeared to be heterocyclic or cyclic molecules (Table 8). In addition, NMR data suggested 20–30% aromatic C nature in soil C11 (Table 6). The decrease of phenol precursors and AHP was in agreement with the decrease of aromatic-C units determined by NMR (Table 6). The increase of alkyl-C from AE to Bh, as evaluated from NMR, was not detectable in the lipid fraction of Py-GC/MS.

In soil WP5 from glacial outwash sediments under mosses, lipids were abundant in all samples (Table 9). As observed in soil C11, in soil WP5 the SOM patterns of the upper WP5-1 (AE) and WP5-2 (Bh) horizons were similar, consisting of protein, phenol precursors, carbohydrates, trace amounts of amino carbohydrates, and low amounts of unresolved compounds. In contrast, the SOM in the WP5-3 (C) horizon had an abundance of unresolved carbon units, lipids, and, in contrast to the C horizon of the Podzol C11, amino carbohydrates (Table 9). As observed in soil C11, proteins were found only in the 2 topsoils, probably as a consequence of a higher microbial activity due to more favourable conditions (light, temperature, etc.) in the surface layers (Beyer *et al.* 2000*b*; Bölter 1990; Bölter *et al.* 1997). On the other hand, there might be a certain impact of the vegetation, because no proteins were found in the surface soil in soil D3, which had no plants.

In unvegetated soil D3 at an abondoned penguin rookery there was an abundance of amino carbohydrates in all but the D3-4 (IIBs) horizon. None of the other Podzols contained nearly as high a concentration of amino carbohydrates. This might be due to some degradation products of uric acids (White and Beyer 1999). Uric acid itself might be

Table 8. Major ions detected with Py-GC/MS in Gelic Podzols in coastal East Antarctica and their assignment to probable parent compounds
Ions in highest abundance underlined

Peak no.	Major ions	Most probable chemical compound (probable parent compound)
9	95, 96	Dimethylpyrole (protein)
15	50, 78, 103, 104, 105	Styrene (aromatic hydrocarbon percursors)
23	51, 61, 109, 110	Furancarboxaldehyde (carbohydrate)
28	66, 94, 95	Phenol (phenol precursors)
30	40, 41, 47, 91, 92	Toluene (aromatic hydrocarbon percursors)
31	63, 69, 83, 84, 112	Fluorophenol (carbohydrate)
34	43, 65, 82, 107, 108, 137	Benzeneacetonitrile (amino carbohydrate)
35	51, 90, 97, 117	2-methylphenol (phenol precursor)
36	42, 53, 68, 69, 70, 96, 97, 98	Heptanol (carbohydrate)
37	42, 51, 59, 77, 79, 90, 107, 108	4-methylphenyl (phenol precursor)
38	42, 47, 55, 62, 97, 126	Carbohydrate (carbohydrate)
42	42, 43, 53, 57, 58, 60, 69, 70, 85, 95, 116	Polysaccharide (carbohydrate)
45	42, 43, 51, 57, 60, 69, 71, 97, 98, 10	(Unresolved)
46	42, 59, 69, 91, 131	Alkylbezene aromatic (hydrocarbon precursors)
48	45, 51, 83, 91, 111, 115	(Unresolved)
50	43, 44, 56, 57, 90, 117	Indole (protein)
56	41, 49, 59, 65, 75, 114, 122	(Unresolved)
60	42, 71, 87, 98	Long chain 'arrangement' (lipid)
65	43, 54, 60, 69, 116	(Unresolved)
67	42, 55, 60, 63, 71, 73, 78	Long chain carboxylic acid (lipid)
75	53, 92, 93, 186	Alkylpyridine (protein)
77	44, 51, 54, 60, 82, 96, 97, 124	Long chain (lipid)
78	41, 50, 63, 77, 78, 91, 143, 221, 236	Heterocyclic (unresolved)
79	42, 67, 77, 91, 115, 128, 205, 220	Alkylnaphthalene (unresolved)
82	55, 70, 101, 115, 128, 203, 205	Long chain 'arrangement' (lipid)
83	42, 48, 52, 91, 119	Phenylalkyl 'arrangement' (unresolved)
85	43, 205, 220	(Unresolved)
87	44, 58, 81, 91, 117, 195	Long chain 'arrangement' (lipid)
88.2	41, 42, 58, 91, 92, 221	(Unresolved)
88.4	42, 100	Alkylated acetamide (aminocarbohydrate)
88.6	43, 55, 69, 83, 96, 97, 110, 124, 138	Alkenylcyanide (aminocarbohydrate)
89	43, 57, 73, 81, 82, 91, 94, 95, 110, 141	(Unresolved)
93	42, 55, 69, 85, 97, 115, 129, 256	Hexadecanoic acid (lipid)
97	55, 56, 60, 68, 72, 73, 81	Polysaccharide (carbohydrate)
98	41, 57, 70, 83, 96, 97, 110, 124, 180, 208	Alkenylcyanide (carbohydrate)
99.2	48, 57, 62, 73, 85, 99, 141	Cycloalcohol (unresolved)
99.4	41, 55, 69, 83, 91, 109	Long chain ketone (lipid)
101	89, 103	Long chain alcohol (lipid)
103	41, 42, 56, 83, 122	Long chain acid, alcohol or ketone (lipid)
108	43, 5, 71, 83, 97, 111, 123, 310	Thiaphenyl 'arrangement' (unresolved)
109	43, 77, 83, 280	(Unresolved)

hidden in the unresolved fraction and its occurence is suggested to be correlated with the occurrence of heterocyclic moieties (White and Beyer 1999 and Table 8, peaks 78, 79), which could be found in most of the horizons of soil D3 (spectra not shown). This probably reflects the influence of the organic input from guano. In contrast to the other Podzols, miscellaneous carbohydrates are abundant in all 5 horizons without having the clear

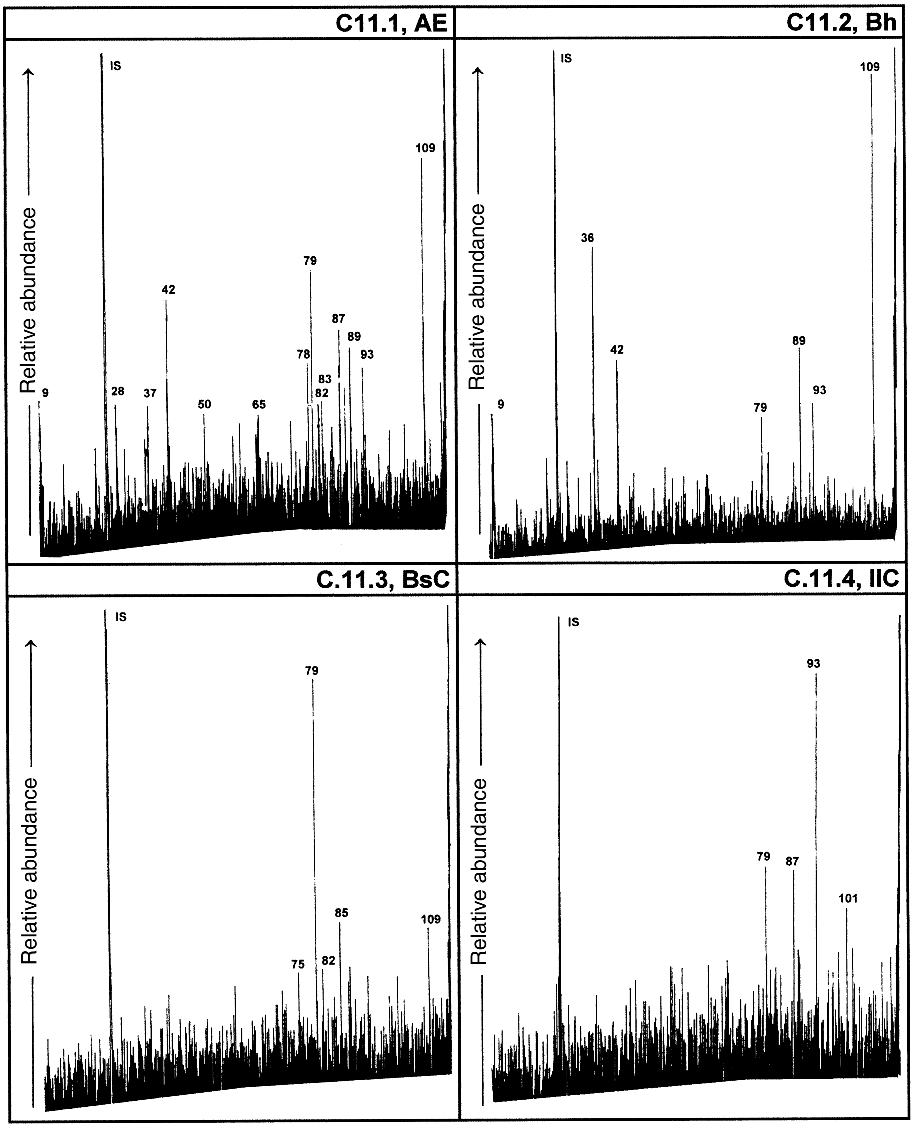

Fig. 2. Ion chromatograms of pyrolysis GC/MS of a Gelic Podzol (C11) from weathered gneiss rock under mosses and lichens.

differentiation from the upper soil horizons and the subsoil. NMR and Py-GC/MS suggest the occurrence of a very specific SOM pattern in the D3-4 (IIBs) horizon. The strong decrease of O-alkyl-C units within the soil profile observed by NMR was not found with Py-GC/MS. The minimum of aromatic C in the D3-4 horizon might be correlated to the occurrence of carbohydrates. However, the observed maximum in carbohydrates was in contrast to the NMR data. This suggests that pyrolysis data do not reflect total SOM due to the occurrence of high amounts of unresolved compounds and the undetected SOM fractions (>20%, compare methods). In any case, the data combination suggest that a large amount of aromatic C was hidden in the unresolved fraction of Py-GC/MS.

Table 9. Soil organic matter compound classes (% of assigned signals) according to the pyrolysis GC/MS experiments in Gelic Podzols in coastal East Antarctica

Horizon	Protein	Phenol precursors	Carbo-hydrates	Aromatic hydro-precursors	Lipids	Amino-carbo-hydrates	Unresolved
Soil from weathered gneiss rock under mosses and lichens in a small depression (C11.1-4)							
AE	9	9	14	3	20	n.d.	46
Bh	8	n.d.	30	n.d.	15	n.d.	48
BsC	11	n.d.	n.d.	n.d.	11	n.d.	78
IIC	n.d.	n.d.	n.d.	n.d.	79	n.d.	21
Soil from glacial outwash sediments under mosses at a dried-up melt water lake side (WP5.1-3)							
AE	5	14	23	n.d.	22	4	32
Bh	8	10	33	n.d.	25	3	21
C	n.d.	n.d.	n.d.	n.d.	39	20	42
Unvegetated soil under a gravel pavement at an abondoned penguin rookery (D3.1–5)							
AE	n.d.	n.d.	19	n.d.	16	33	32
Bh	9	13	24	4	10	10	29
Bhs	7	n.d.	30	n.d.	n.d.	22	41
IIBs	n.d.	n.d.	43	n.d.	34	n.d.	23
IIICw	n.d.	n.d.	27	n.d.	n.d.	17	56

n.d., none detected.

Soil ecology and soil formation

Frequently the measured microbial properties are highest in the uppermost AE horizons, although TOC was less than in the underlying spodic horizons (Bh/Bhs). The reason may be the rapid temperature decrease over the first few centimeters below the soil surface (Bölter *et al.* 1994), and temperature is more important than TOC for biological activity (Beyer *et al.* 1998). Overall, the microbiological data show values lower than those commonly observed. In cryptogamic crusts on Signy Island, Wynn-Williams (1985) found larger populations of 450–2180× 10^6/g soil DM. This can be attributed to the much milder climate and higher temperatures in Maritime Antarctica. For soils on the Windmill Islands, Roser *et al.* (1993) gave total bacterial counts of 4.6×10^{10}/g for active and 3.4×10^9/g DM for extinct penguin colonies. The latter is greater than in the penguin-affected soil D3. The non-penguin affected control sites of Roser *et al.* (1993) contained 2.6×10^9/g DM, which is greater than in soil D3. For abandoned and active penguin colonies on Ross Island, Ramsay and Stannard (1986) gave bacterial counts similar to those of this study, but the bacterial cell volumes were much greater, indicating a better substrate supply in terms of available organic matter (Bölter 1990). The higher bacterial counts of Roser *et al.* (1993) and the larger bacterial cell volumes described by Ramsay and Stannard (1986) (in a similar climate to Casey) suggest that conditions for bacterial colonisation of soils at Casey are less favourable than elsewhere in the coastal region of Antarctica. However, using the same methods, Bölter (1990) and Bölter *et al.* (1993, 1994) obtained counts near Casey Station of between 10^6 and 10^8/g DM in non-podzolic soils, suggesting that the antarctic Podzols have smaller colonies of microbes than other soils in the area.

The difference in SOM composition and SOM depth profile suggests that parent materials and different C sources influence the mechanisms of humification and translocation in the soil. We suggest that in addition to specific vegetation (e.g. mosses) microclimate as well as soil microbial decomposition and secondary products are also responsible for the occurrence and intensity of podzolisation and organic matter transformation. For example, total bacterial counts of vegetated soils C11 and WP5 are correlated with selected organic compounds. Total bacterial counts (TBC) and alkyl-C units in a shift range of 0–45 ppm show a weak correlation of $r = 0.639^*$. When calculated with only the terminal methyl groups (0–25 ppm) r was 0.674*. These correlations suggest that bacterial metabolism affected the SOM composition, or vice versa. For this reason the alkyl-C/O-alkyl-C ratio is correlated to TBC ($r = 0.709^{**}$). The negative correlation of TBC with the signals of the aromatic-C moieties (110–160 ppm) with an r value of –0.633*, especially with respect to olefinic and alkylaromatics (110–140 ppm) with an r value of –0.820**, suggests negative interactions between soil microbes and aromatic SOM compounds. In addition, in soil D3 without any vegetation cover, no correlations between the microbial properties and SOM compounds were present. The high numbers of bacteria may be a response to temperature because no insulating vegetation cushion mitigates a temperature increase in soil (Beyer *et al.* 2000*b*).

Formation of the podzolic soil C11 from weathered gneiss rock under mosses is characterised by a strong decrease of O-alkyl-C and an increase of aromatic- and carboxyl-C units from the recent vegetation (mosses), and probably soil algae, within the humification process. This is why White and Beyer (1999) found a strong correlation between the pyrogram of recent vegetation and the underlying soil horizons by using a Py-GC/FID technique. NMR data and partly this of Py-GC/MS data confirm a different SOM composition between the bleached AE horizon and the dark-coloured spodic Bh horizon suggested with the classification as a Podzol (FAO, 1997). Proteins were located only in the topsoils, probably due to microbial colonisation. Alkyl-C was translocated from the AE to the Bh and probably into deeper subsurface horizons, as the high abundance of lipids in the subsoil suggest. Aromatic compounds were preserved in the uppermost topsoil layer. A high protein content correlates with the extent of algal colonisation. Algae are main precursors of chlorophyll (Bölter 1995; 1997).

Soil formation of WP5 is characterised by a decrease of O-alkyl-C but only a weak increase of aromatic and carboxyl-C units from the recent soil algae colonisation (White and Beyer 1999). Surprisingly, neither NMR nor Py-GC/MS data indicate a different SOM composition between the bleached AE horizon (WP5-1) and the dark-coloured spodic Bh horizon (WP5-2) suggested by Podzol classification within the soil survey. However, both methods suggest a change in SOM quality in the WP5-3 (C) horizon. The higher carbohydrate content found with Py-GC/MS was in agreement with the somewhat higher amount of hydroxyl-C units of NMR (60–90 ppm). However, the increase of the aromatic C from WP5-2 to WP5-3 was not detected as phenol precursors or AHP. As described for the soil C11, these moieties are probably located in the unresolved fraction or in the amino carbohydrate fraction, because for soil D3 the disappearance of amino carbohydrates in the D3-4 horizon (Table 8) was well correlated with a significant decrease of the aromatic-C units (Table 6). In addition, since we are looking at the largest amount of components, some moieties occurring to a lesser extent may have been overlooked. In contrast to soil C11, the increase of the lipid fraction from WP5-1 and WP5-2 to WP5-3 was not detected with NMR. In summary, in the Podzol WP5 from glacial outwash sediments under mosses, the SOM chemistry does not reflect the soil morphology concerning the suggested chemical difference between an albic AE and a spodic Bh as known from temperate climates (Beyer *et al.* 1997). However, the Py-GC/MS data suggest a translocation of alkyl-C moieties in the podzolisation process.

For soil D3, the NMR data suggest that SOM modification from the parent organic matter material (guano) to the soil horizons by a decrease of alkyl-C and increase of carboxyl C units means a reverse relationship between both chemical units. An interpretation of the SOM data with respect to soil formation processes is complicated due to the impact of layering of different deposits by seabirds (Beyer *et al.* 2000*a*). The NMR data indicate a strong downward movement of alkyl-C with a simultaneous enrichment of O-alkyl-C, whereas aromatic and carboxyl-C moieties are stable in the profile. But an influence of layering with a different organic matter source in the deepest horizon is possible. However, Py-GC/MS shows a completely different SOM pattern in most of the 5 soil horizons, which indicates a much stronger influence of seabird-induced layering than an *in-situ* soil formation. In contrast to soil WP5, the SOM chemistry in the unvegetated soil D3 at an abandoned penguin rookery reflects the soil morphology with the assignment of a bleached AE and the dark-coloured spodic Bh horizon.

Conclusions

In permafrost-affected Podzols at the coast of East Antarctica, soil microbial colonisation with bacteria and algae as indicated by chlorophyll detection is similar to that of soils of the Maritime Antarctic. The highest bacterial colonisation was found in soil D3, the podzolic soil without any vegetation. We suggest that, in the coastal region of the Antarctic continent, not only vegetation but also the influence of seabirds on soil and the content of organic C affect microbial colonisation. The SOM composition is characterised by a high level of carboxylic C and lipidic moieties in all soil horizons, the quantity of which is uncommon compared with temperate climate regions. The correlation of selected SOM compounds and bacteria on the vegetated soils suggests that algal and moss C sources influence SOM to a great extent. The great variety in SOM composition and SOM variation with depth in the profiles suggest that parent materials and different C sources influence the mechanisms of humification and translocation. We think that not only vegetation but predominantly microclimate and soil microbial decomposition and secondary microbial products are responsible for the detailed geochemistry of these processes. The observed pattern variety of long-chain alcohols, acids, and ketones observed with the Py-GC/MS technique are not typical for well-developed soil. Most of the long chains in the Antarctic soil samples appear to contain multiple O- and N-containing functional groups, cyclic-ionised and heterocyclic structures, and alkylations, which are confirmed by the occurence of 20–40% aromatic NMR C subunits. However, the complex and easily ionised compounds and the low C content made Py-GC/MS identification very difficult, resulting in several unresolved fractions. With respect to soil formation in a Gelic Podzol from weathered gneiss rock under mosses, alkyl-C units must have been translocated from the AE to the Bh and probably into more deeply located horizons, whereas aromatic compounds have been preserved in the uppermost topsoil layer. In a Podzol from glacial outwash sediments under mosses, the SOM chemistry does not reflect the soil morphology. However, the Py-GC/MS data indicate a translocation of alkyl-C moieties within the podsolisation process. The data combination of NMR and Py-GC/MS suggests that a large amount of aromatic C is hidden in the unresolved fraction of Py-GC/MS. In contrast, in an unvegetated Podzol at an abondoned penguin rookery the SOM chemistry reflects the soil morphology with the assignment of a bleached AE and the dark-coloured spodic Bh horizon. However, from the Py-GC/MS data no translocation of lipid moieties was found. For this reason we think that podzolisation in antarctic soils is chemically an ill-defined soil formation process. The processes of formation and translocation of SOM shown are variable and are affected by the parent materials, the physical and mechanical properties, and by the microclimate and local moisture regime as well as the degree of microbial colonisation.

Regardless of the origin and location of the antarctic Gelic Podzols, these soils store huge amounts of C and N (Beyer *et al.* 1998). SOM depth functions and the comparison of the profiles suggest unknown C and N sources. This puzzle is not solved by our detailed SOM investigation of 3 typical antarctic Podzols. Finding the origin of SOM should be included in future research in antarctic soil science. The results of the analytical approaches and field observations presented in this study suggest that podzolisation and SOM transfer may play an important role in nutrient cycles in antarctic ecosystems. However, little is known about the geo-ecological correlations between soil sources and plant communities in terrestrial Antarctica

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