Polarforschung 64 (1): 1–7, 1994 (erschienen 1995)

Pedologic, Isotopic and Microbiological Properties of Antarctic Soils

By Manfred Bölter[1], Hans-Peter Blume[2] and Helmut Erlenkeuser[3]

Summary: Soils from the maritime (Arctowski Station, King George Island) and coastal continental (Casey Station, Wilkes Land) Antarctic region are described with respect to pedology, isotopic and microbial environments. They are classified as leptosols, regosols, podzols, and histosols. Only surface layers (1-3 cm) contain sufficient organic material to provide a favourable environment for microbial communities and, further, for accumulations of organic matter. Variability of biological and chemical properties is high on a centimeter scale with depth and in the range of decimeters in horizontal scales.

Zusammenfassung: Es werden verschiedene Böden der maritimen (Arctowski Station, King George Island) und kontinentalen Antarktis (Casey, Wilkes Land) hinsichtlich pedologischer, isotopischer, und mikrobieller Aspekte beschrieben. Die Böden konnten als Leptosole, Regosole, Podsole und Histosole klassifiziert werden. Nur Oberflächenhorizonte (1-3 cm) enthalten hinreichend organisches Material, um mikrobiellen Gemeinschaften gute Lebensbedingungen zu schaffen und organisches Material langfristig anzureichern. Die Variabilität der biologischen und chemischen Eigenschaften ist hoch und vertikal auf Zentimeterskalen, horizontal im Dezimeterbereich nachweisbar.

INTRODUCTION

Soils in Antarctica are restricted to very limited areas. Only 2-3 % of the continent is ice-free and is exposed to active soil forming and biological processes, thus providing favourable habitats for animals, plants, and microbes. These ice-free environments are influenced by extreme cold and aridity which pose a severe test for all biological components. Studies of soil science and soil microbiology in these areas have been carried out for many years, and various soils and microbial or plant communities are described in the literatur (e.g. CAMPBELL & CLARIDGE 1987, VINCENT 1988, VISHNIAC 1993).

Subdivisions for Antarctic soils have been proposed on ecological and climatological criteria (WEYANT 1966, WALTON 1984). The soils were regarded mainly as intrazonal or azonal soils with properties related to their low evolutionary state. They represent levels of a very primary stage - at least in the zones of the Antarctic cold desert. Soils of this zone were described as frigic by CAMPBELL & CLARIDGE (1969).

Due to the harsh climatic conditions and prevailing permafrost, most soil forming results from weathering processes (CAMPBELL & CLARIDGE 1969, 1987) or microbial activities on the sparsely produced organic material (SMITH 1985, WYNN-WILLIAMS 1990). Freeze-thaw cycles are common, influencing both biological and biogeochemical processes as a result of extreme shifts in temperature and humidity.

A recent description of the pedogenic zonation of the soils of the southern circumpolar regions has been given by BOCKHEIM & UGOLINI (1990). A great variety of soil forms is found in the milder coastal regions of the continent and in the zone of the maritime Antarctic (UGOLINI 1970). In the latter, the Antarctic Brown-Earth (ALLEN & HEAL 1970) (Cambisols, after FAO 1990) occurs beneath the lichen-moss tundra and the Deschampsia-grasslands with accumulation of organic matter from higher plants and some humic material. Soils with high amounts of organic matter are also described as histosols (LEONARDI et al. 1987). FABISZEWSKI & WOJTUN (1993) describe those soils from Arctowski as peat mounds overgrown by various mosses, *Deschampsia antarctica* and *Colobanthus quitensis*. Wet areas even tend to accumulate high amounts of organics from moss beds and often form deep peat horizons. Unexpectedly, podzols have been observed in both, the coastal continental and the maritime Antarctic (BLUME & BÖLTER 1993a, b, and unpublished results).

This paper describes properties of soil covers of the two Antarctic areas with particular respect to the habitats for microorganisms and their possible influences on soil forming processes. A further point of high interest considers the question whether podzolization can occur under the climatic and chemical conditions in Antarctic environments. Stable organic carbon isotopes were studied to recognize possible effects of Antarctic environmental conditions on the isotopic composition of plants and on the isotopic alteration of organic matter during microbial degradation in Antarctic soils.

ENVIRONMENTAL DESCRIPTION

The data of soils and microbial communities presented here were collected from areas of the coastal continental Antarctic (Casey Station, Wilkes Land) and the maritime Antarctic (Arctowski Station, King George Island, Fig. 1). Mean annual ground air temperatures for Casey and Arctowski are -9.2 °C and -2.7 °C, respectively (WALTON 1984, VINCENT 1988). A 30

[1] Dr. Manfred Bölter, Institut für Polarökologie, Universität Kiel, Wischhofstr. 1-3, D-24148 Kiel, Germany.

[2] Prof. Dr. Hans-Peter Blume, Institut für Pflanzenernährung und Bodenkunde, Universität Kiel, Olshausenstr. 40, D-24098 Kiel, Germany.

[3] Dr. Helmut Erlenkeuser, C^{14}-Labor, Institut für Kernphysik, Universität Kiel, Olshausenstr. 40, D-24098 Kiel, Germany.

Manuscript received 11 May 1994; accepted 9 November 1994

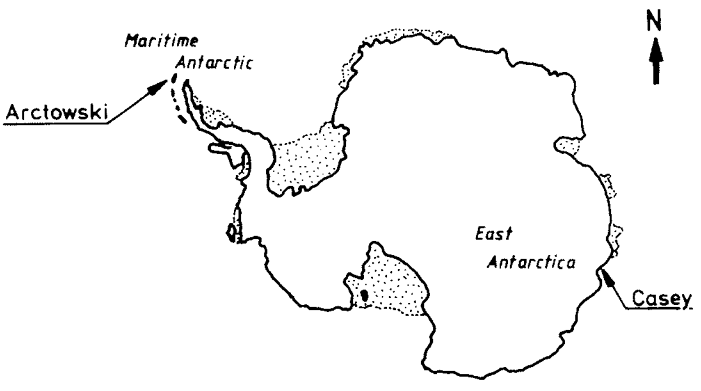

Fig. 1: Map of Antarctica and locations of the sampling stations Arctowski (King George Island) and Casey (Wilkes Land).

Abb. 1: Lage der Stationen Arctowski auf King George Island und Casey in Wilkes Land, Antarktis.

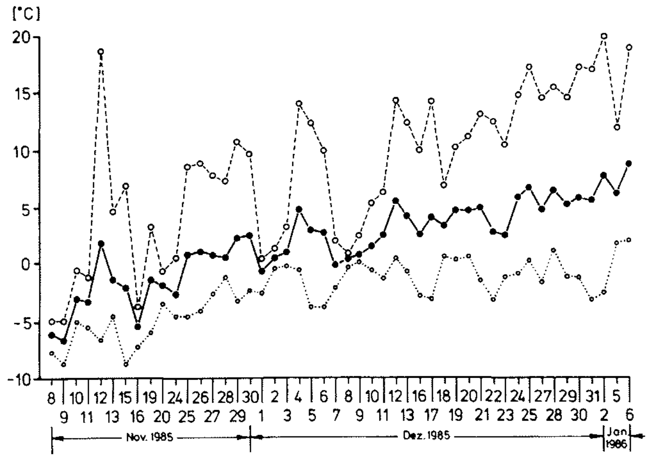

Fig. 2: Temperature data of a soil surface (0-1 cm, leptosol) from Casey (11 Nov. 1985 - 6 Jan. 1986). Presented are daily mean values (dots, full line), maxima (circles, dashed line), and minima (circles, dotted line).

Abb. 2: Temperaturdaten der Bodenoberfläche (0-1 cm, Leptosol) auf Casey (11. Nov. 1985 - 6. Jan. 1986). Dargestellt sind Tagesmittel (Punkte und durchgezogene Linie), Tagesmaxima (Kreise und gestrichelte Linie) und Tagesminima (Kreise und gepunktete Linie).

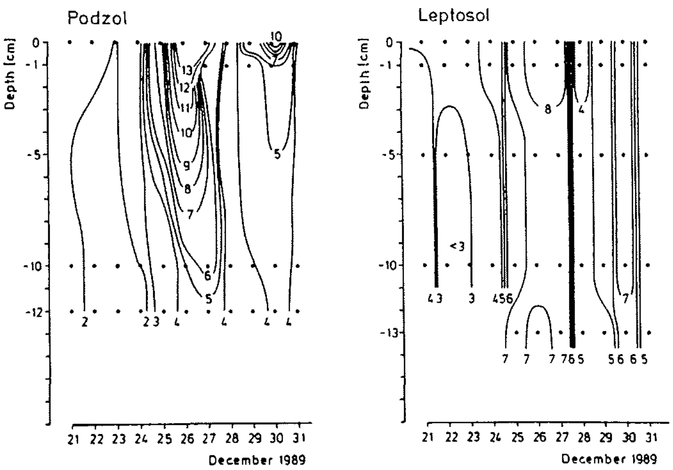

Fig. 3: Temperature profiles in a podzol and a leptosol from Casey (21 - 31 Deceember 1989; after Bölter 1992a).

Abb. 3: Temperaturprofile eines Podsols und eines Leptosols von Casey (21.-31. Dezember 1989; nach Bölter 1992a).

years mean for Casey shows for January a maximal mean value of +2.6 °C and a minimal mean value of -2.1 °C (Meteorological Station Casey, pers. comm.). Mean temperatures are -0.1 °C and -14.6 °C for January and July, respectively (Vincent 1988). Novosielski (1980) and Niemiec & Rawa (1989) show for 1978 and 1987, respectively, maximal values for January at +8.0 °C and +6.3 °C, minimal values at -1.4 °C and -2.3 °C, while mean temperatures were +2.1 °C and +1.6 °C, respectively. Vincent (1988) presents long-term mean temperatures for January and July as +1.2 °C and -8.3 °C, respectively. Soils are dominated by permafrost at both locations.

In the maritime Antarctic (King George Island) stock phytomass from lichens may reach about 1900 g dry matter m^{-2}, in the continental Antarctic (Bailey Peninsula, Wilkes Land) it may reach values of about 900 g dry matter m^{-2} (Kappen 1993, Smith1986). Phytomass from mosses may be even more than 2000 g m^{-2} (Signy Island, Smith 1984), that of moss banks may exceed 10000 g m^{-2} (Longton 1988).

METHODOLOGY

Samplings were carried out during austral summers 1989/90 (Casey), 1991/92 (Casey) and 1992/93 (Arctowski). Details about sampling and additional data regarding plants, microorganisms, organic and inorganic matter have been presented in earlier reports (Bölter 1989, 1992a, b, c, Bölter et al. 1989, Kappen et al. 1987, 1991). The description of the microbial community was carried out by epifluorescence microscopy (Bölter 1992a). Organic matter was analyzed by loss on ignition, inorganic matter by standard procedures as described by Bölter (1990, 1992b). Data on $\delta^{13}C$ refer to the total organic carbon pool.

RESULTS AND DISCUSSION

Temperature stress is mainly evident for the surface layers of soils and rocks. Temperature shows strong shifts within short times (Fig. 2) related to exposure and surface patterns. Maximal values can reach more than +30 °C on rock faces (Bölter et al. 1989) as well as in moss carpets or moss beds (Smith 1986, Bölter 1992a). Vertical temperature gradients in soil horizons depend on plant cover (Fig. 3) and soil texture. Such effects are not only important for the actual biological and chemical processes - physico-chemical processes, production and decomposition of organic matter - but also for the fate and the accumulation of particulate and dissolved organic and inorganic material (Melke & Uziak 1989, Bölter 1992a, b).

Coastal continental Antarctic soils

The soils of the Casey region, like many others from Antarctica, are strongly influenced by cryoturbation and cryoclastic weathering. This is well documented by polygons (diameter 0.3-10 m, BLUME & BÖLTER 1993a). The cryoclastic processes form particles of sand to silt and clay grain size classes, depending on the parent material and exposition. Parent materials in this region are charnockite (Ardey Charnockite) and porphyrite granite (Ford Granite). They have undergone several metamorphic sequences leading to layered schists, gneisses and migmatites (the Windmill Metamorphics, BLIGHT & OLIVER 1977).

Locations with patterned ground were found as well as those of aride nature with vesiculars and high amounts of salts in the upper centimeter. Biogenic influences are evident from acidification (pH(KCl): 4-5, BLUME & BÖLTER 1993a). Accumulation of humics and other particulate organic matter is generally restricted to the upper centimeter (BÖLTER 1992b), but not in podzols. Peat accumulations over more than 30 cm from moss carpets can only be found at places which have been permanently wet (SMITH 1990, BLUME & BÖLTER 1993a).

At Casey, we classified four main soil units: leptosols, regosols, podzols, and histosols (Tab. 1). Only poor or no plant cover was found on the lepto- and regosols. This is due to low plant cover caused by wind erosion and active cryoturbation. Podzols occur at places which are covered by lichens and mosses, or moss carpets overgrown by crustose lichens. Histosols were related to deep wet moss beds with poor drainage. Contents of organic and inorganic compounds were presented by BÖLTER (1992a, c) and are summarized for the loamy leptosols and sandy podzols in Tab. 2. It should be pointed out, that the thin top cover of the soils (0-2 cm) bears the bulk of the organic matter (as determined by loss on ignition, LOI). This has consequences for the actual water holding capacity and the microbial biomass (as determined by adenosine triphosphate, ATP, BÖLTER 1992c). Due to remineralization processes in the top layers, higher amounts of inorganic products were found concomitant to distinct gradients in organic matter.

The content of organic matter is considerably higher in the podzol due to its direct production from the surficial plant cover and a partly translocation into the subsoil by podzolisation (Fig. 4a). The even profiles of organic matter and stable organic carbon content in all depths of the leptosol can be related to cryoturbation.

Maritime Antarctic soils

Solifluction and cryoturbation are features of soils at slopes and on fjells of this area (O'BRIEN 1979, BARSCH et al. 1985). This results in a characteristic differential movement of fine material within the soils (O'BRIEN et al. 1979) and cryogenic zonations (grain size separations and enrichments of gravel on surfaces) are often found. However, the soils do not show significant differentiation into horizons by transport processes of materials. BARSCH et al. (1985) did not find clay migration or tra-

a) Leptosols with gelundic and often saline phase:
(Ah ≤ 1cm, stony loamy to silty)
Lithic leptosols (solum ≤ 10 cm)
Dystri-gelic leptosols (solum 10-30 cm)

b) Regosols with gelundic and often saline phase:
(Ah ≤ 1 cm, stony loamy to silty)
A-C- soils (solum > 30 cm, subsoil with permafrost)

c) Podzols with gelundic and often saline phase:
(AE ~ 1cm, sandy to gravelly, spodic B)
Lithic podzols (solum ≤ 10 cm)
Lepti-gelic podzols (solum 10-30 cm)
Hapli-gelic podzols (solum > 30 cm)
Gravelly-gelic podzols (solum > 30cm)

d) Histosols:
Fibri-gelic histosols

Tab. 1: Dominant soils (taxonomy according to FAO 1990) on metamorphics and moraines from Casey (Wilkes Land, Antarctica, after BLUME & BÖLTER 1993).

Tab. 1: Dominante Böden (Taxonomie entsprechend FAO 1990) auf metamorphem Gestein und Moränen von Casey (Wilkes Land, Antarktis, nach BLUME & BÖLTER 1993).

	Depth cm	H_2O %	pH	LOI %	ATP ng g^{-1}	Cl ---	PO_4 µg g^{-1}	Ca ---	Mg
Podzols									
1A	0-1.5	29.4	5.9	8.4	437	391	9.3	289	19.8
1B	1.5-3	5.7	5.7	2.0	22	47	5.6	219	16.3
2A	0-1	16.2	5.3	10.9	204	416	4.8	127	12.4
2B	1-2	3.3	5.6	7.6	74	100	3.6	129	7.2
7A	0-0.5	22.2	5.0	8.4	330	0	22.0	213	143.3
7B	0.5-2	14.0	5.6	3.3	249	0	9.7	145	22.4
Leptosols									
8A	0-0.5	13.7	5.6	2.6	94	25	6.2	125	22.0
8B	0.5-2	14.6	5.8	2.0	10	37	6.2	0	21.7
9A	0-0.5	18.9	7.7	3.4	99	337	11.7	0	7.9
9B	0.5-2	13.2	6.5	2.1	96	109	10.3	0	15.2

Tab. 2: Chemical and microbial properties of soils from Casey Station (Wilkes Land) with respect to soil types (from BÖLTER 1992a). Mineral constituents and pH were analyzed in water solution (1:5). Soil surfaces are covered by dry moss cushion (sample 1A), moss cushion and microlichens (mainly *Candelariella sp.*) (2A), moss cushion and microlichens (mainly *Buellia sp.*) (7A), no visible plant cover (8A), and soil algae (mainly *Prasiola crispa* and cyanobacteria) (9A). Podzols on leuco gneiss, partly with thin moraine cover: lithic to lepti-gelic podzols with gelundic phase; leptosols on shist: dystri-gelic leptosols with gelundic phase. Texture of podzols is stony sand, texture of leptosols is gravelly sandy loam.

Tab. 2: Chemische und mikrobielle Eigenschaften von Böden (Casey Station, Wilkes Land) unter Berücksichtigung der Bodentypen (nach BÖLTER 1992a). Mineralgehalte und pH wurden in wäßriger Lösung (1:5) gemessen. Bodenoberflächen waren bewachsen mit trockenem Moosteppich (Probe 1A), Moos mit Krustenflechtenaufwuchs, hauptsächlich *Candelariella sp.* (2A) oder *Buellia sp.* (7A). Standort 8A hatte keine sichtbaren Pflanzen, Standort 9A zeigte Bodenalgen, hauptsächlich *Prasiola crispa* und Cyanobakterien. Podsole auf Leukogneis, teilweise mit dünner Moränendecke, Leptosole auf Schist. Textur der Podsole: steiniger Sand, Textur der leptosole: sandiger Lehm.

ces of pseudogleying, but also found an even distribution of iron in profiles causing the brownish soil colours. Only in well drained soils at the Fildes Peninsula (King George Island) with plant covers by mosses and fruticose lichens, BARSCH et al. (1985) found red colored horizons derived from iron in a depth of 20 cm, which might be indicative of podzolization. A recent study of soils from Arctowski region showed podzols below *Deschampsia*-mats and at other places (BLUME & BÖLTER unpubl. data). Some chemical properties of a regosol and a podzol underneath a *Deschampsia* mat are presented in Tab. 3.

	Depth cm	H_2O %	LOI %	EC µS/cm	pH (H_2O)	pH ($CaCl_2$)	C - mg/kg -	Fe
I-1	0-4	30	25.0	808	6.05	5.57	296	933
I-2	4-8	24	6.3	285	5.95	5.38	172	868
I-3	8-12	21	5.6	145	6.13	5.30	189	997
I-4	12-16	24	5.1	96	6.23	5.24	211	1176
I-5	16-20	20	5.0	40	6.64	5.26	219	1131
I-6	25-29	14	2.6	27	7.09	5.55	51	693
I-7	42-46	20	3.1	31	7.25	5.80	48	570
II-1	0-4	14	3.2	24	6.93	5.15	19	427
II-2	4-8	16	3.2	20	7.07	5.25	25	518
II-3	8-12	15	3.3	18	7.11	5.34	31	556
II-4	14-18	14	3.0	18	7.29	5.45	27	531
II-5	20-24	14	2.9	17	7.34	5.50	49	587
II-6	28-32	15	3.5	16	7.33	5.57	28	556
II-7	35-39	18	3.7	17	7.32	5.60	31	518
II-8	50-54	17	3.9	18	7.39	5.64	23	552

Tab. 3: Chemical analyses of two soil profiles from Arctowski (King George Island). Profile I(1-7) = Podzol, profile II (1-8) = Regosol. Electrical conductivity (EC) and pH values were analyzed in soil solutions (1:2.5) with water and 0.01n $CaCl_2$, mobile C and Fe were extracted by Na-pyrophosphate and measured via optical density of the extract and AAS, respectively. Al was not detectable.

Tab. 3: Chemische Analysen zweier Bodenprofile von Arctowski (King George Island). Profil I(1-7) = Podsol, Profil II (1-8) = Regosol. Elektrische Leitfähigkeit (EC) und pH-Werte wurden in Bodenlösungen (1:2,5) mit Wasser und 0,01n $CaCl_2$ gemessen, mobiler C und mobiles Fe wurden extrahiert mit Na-Pyrophosphat und als optische Dichte bzw. AAS in den Extrakten gemessen; Al war nicht nachweisbar.

Similar to the soils of the continental Antarctic, biological activity in the maritime Antarctic is strongly related to environmental properties (BÖLTER 1992b, c). Relief, parent material, temperature and humidity are basic controlling factors for the plant cover and related biogeochemical cycles. Due to the milder oceanic climate and the growth of higher plants, the matrix of the organic matter, which provides a high water holding capacity, is an important biogeochemical characteristic. The feature of the soil cover is a prominent key factor for the carrying capacity of the living microbial biomass. Close relationships can be seen between total organic material (LOI, Fig. 4a) and the total bacterial number (TBN, determined by epifluorescence microscopy, Fig. 4b). Microorganisms are determining the actual turnover rates of organic matter and possible accumulation (BÖLTER 1992c). Layers below 3 cm in the podzol profile show similar LOI and TBN values as those typical of the total

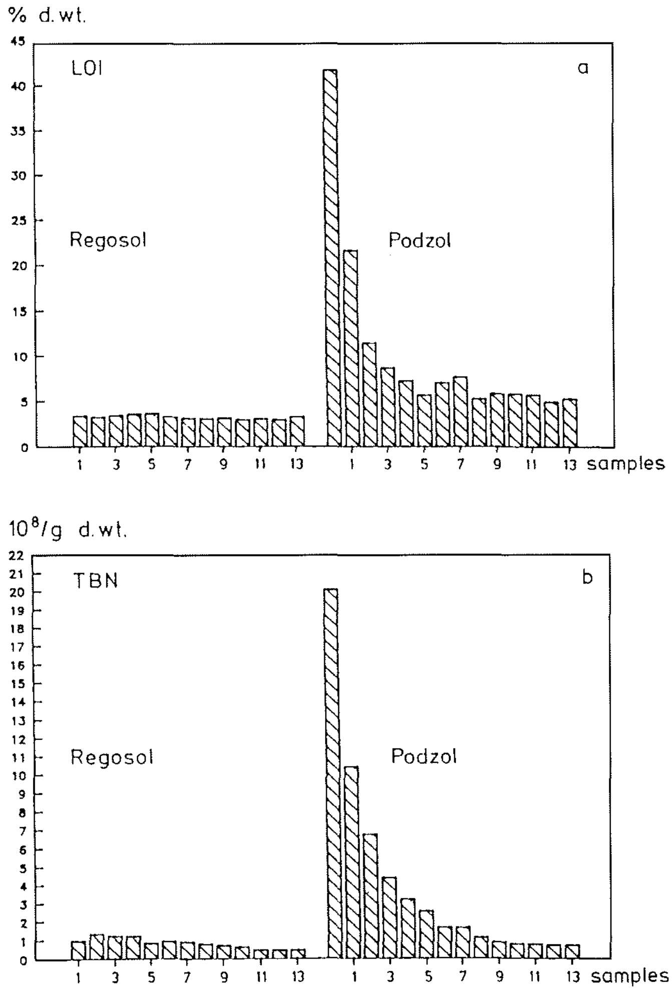

Fig. 4: Organic matter (LOI, % loss on ignition of d.wt.) = (a) and total bacterial number (TBN, n•10^8 g^{-1} d.wt.) = (b) in samples of two soil profiles from Arctowski. Samples are taken in 1 cm intervals (sample 1 = horizon 0-0.5 cm, sample 2 = 0.5-1.5 cm etc., the uppermost sample of the podzol is from the plant cover (*Deschampsia antarctica*).

Abb. 4: Organisches Material (LOI, % Glühverlust des TG) = (a) und bakterielle Gesamtzellzahl (TBN, n•10^8 g^{-1} TG) = (b) in Proben zweier Profile von Arctowski. Die Probennahme erfolgte in 1 cm Abständen (Probe 1 = Horizont 0-0,5 cm, Probe 2 = 0,5-1,5 cm, usw., die obere Probe des Podsols ist die pflanzliche Deckschicht (*Deschampsia antarctica*).

depth range of the leptosol profile. This suggests that comparable processes prevail in these habitats for microbial life.

Stable carbon isotopes

The stable carbon isotope composition of the vegetation at Casey is typical of the C3-plant category (SMITH & EPSTEIN 1971). $\delta^{13}C$ ranges about 19.5 to 23 ‰ PDB for various lichen taxa - the subsamples analysed were taken from the upper zone of the soil plant cover - and between 24.5 to 26 ‰ PDB for samples from the moss cushion covering the podzols (Fig. 5). A special $\delta^{13}C$ signature related to the extreme environment of this Antarctic habitat is not indicated.

The isotope composition of the soil detrital organic fraction is close to that of the living source, a result established for other environments as well (e.g. MARIOTTI & PETERSCHMITT 1994). Degradation of the organic matter, which slightly increases $\delta^{13}C$ by microbial attack (NADELHOFFER & FREY 1988), or the secular decrease in $\delta^{13}C$ of atmospheric CO_2 from fossil fuel burning in modern times (MARINO & MCELROY 1991), may explain the $\delta^{13}C$ gradient in the upper podzol profile (Fig. 5). Interestingly, the $\delta^{13}C$ change occurs in the upper 2 cm, a range which particularly correlates to biological activity as measured by other methods (BÖLTER 1992c).

The organic carbon stable isotope characteristics in the maritime Antarctic at Arctowski closely resemble those from the coastal continental environment at Casey. The podzol 2 (Fig. 6) shows a dense plant cover (Deschampsia mat) with grasses and mosses. This sample revealed a $\delta^{13}C$ figure of 24.7, i.e. a C3-vegetation, which is source of the high organic content in the podzol established below. In contrast, the regosol (Fig. 6) is barren of any plant cover and organic matter is low in this profile. In both soils, however, the $\delta^{13}C$ distributions show a similar isotopic enrichment with depth. The slightly higher enrichment in the podzol could reflect a more thorough degradation related to conditions where substrates of microbial activity are available at higher concentration. Fermentation of organic matter accompanied by the release of highly ^{13}C-depleted methane gas is not likely in the environment to contribute to the isotopic enrichment of the organic matter left in the soil RASK & SCHOENAU 1993). On the other hand, lateral mixing of the regional $\delta^{13}C$ facies by wind-borne long distance transport or stronger vertical mixing by cryoturbation in the unprotected leptosol (see below) may have affected the $\delta^{13}C$ signature of the organic matter accumulation at site 1 and could have weakened the vertical isotope gradient.

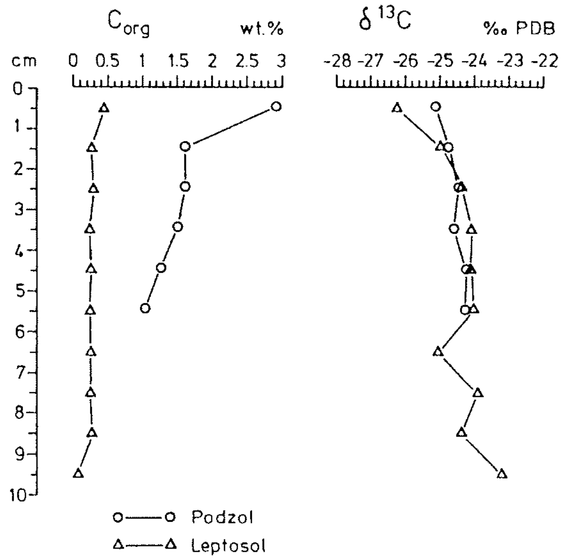

Fig. 5: Organic matter content (C_{org}) and $\delta^{13}C$ (‰ PDB) of the total organic fraction in a leptosol and a podzol from Casey.

Abb. 5: Gehalt an organischem Material (C_{org}) und $\delta^{13}C$ (‰ PDB) des organischen Materials eines Leptosols und eines Podsols von Casey.

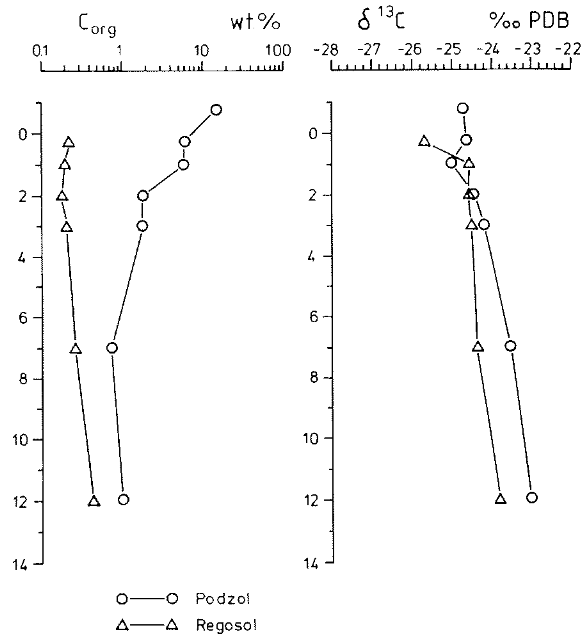

Fig. 6: Organic matter content (C_{org}) and $\delta^{13}C$ (‰ PDB) of the total organic fraction in a regosol and a podzol from Arctowski.

Abb. 6: Gehalt an organischem Material (C_{org}) und $\delta^{13}C$ (‰ PDB) des organischen Materials eines Regosols und eines Podsols von Arctowski.

Podzolisation in Antarctic soils

The detailed description of podzols at Casey Station is given by BLUME & BÖLTER (1993a, b). In brief, these are sandy lepti-gelic podzols with salic and gelundic phase on acid gneiss. They show a stony sand in the epipedon and stony sand to stony silt loam in the subsoil. The profiles have AE, Bh, and Bhs horizons. High electric conductivity (375 µS) in the surface results from salt accumulations. Low amounts oxalate and dithionite extractable aluminium, iron and manganese are controverse to high contents of these compounds in the subsoil corresponding with high contents of mobile humic substance (ODOE). The B-horizons fit to the criterions of a spodic horizon after FAO (1990) and of the spodic material after SOIL SURVEY STUFF (1992).

It seems to be the first time that podzols of the Antarctic mainland are described, they are not mentioned by CAMPBELL & CLARIDGE (1987) or by BOCKHEIM & UGOLINI (1990) during their reviews of Antarctic soils. The data shown in Figure 4 were obtained from a regosol and a podzol. It should be mentioned, however, that the soils from Arctowski show relatively high pH-values (Tab. 3), a fact which generally is considered to be unfavourable for podzolisation processes. But other parameters, such as high amounts of organically bound Fe (>1100 mg kg^{-1}), mobile humic substances (ODOE >200 mg kg^{-1}) in deep layers (12-20 cm) on the one hand, and salt accumulation in the top layer on the other hand, show clear features of podzolisation which are unambiguously evident in these soils. This is comparable to the observations of BARSCH et al. (1985) from the Fildes Peninsula at King George Island. The pH-levels at Casey are significantly lower providing a generally acid soil environment (BÖLTER 1990c, BLUME & BÖLTER 1993a, b). This question, how podzolisation can occur under elevated pH needs to be studied in more detail.

CONCLUSION

The structure of the Antarctic soil surfaces is strongly related to the basic parent material, the relief, micro-climate and the soil type - which in turn is influenced by biological processes. These environmental factors span the frame for the microbiological community and its activity, which influences the composition of organic and inorganic compounds (e.g. via acidification from nitrifying processes) and by the „production“ of typical refractive material, such as lichen acids.

Biological variability in terms of plant cover by higher plants as well as cryptogams is high on a scale of centimeters in the vertical and within decimeters on horizontal scales. The distribution patterns of plants leads to different habitats for microbial populations. Interspersed rocks, gravels or sand further prevent direct exchange of organisms and biochemical materials and is in favour of high patchiness of these Antarctic soil biotopes.

ACKNOWLEDGEMENTS

We thank the Australian Antarctic Division and the Polish Academy of Science for their permits to work at Casey Station and Henryk Arctowski Station, respectively, and the kind cooperations during logistics and field work. We also thank Mr. W. Dzomla for preparing the graphs. The projects were funded by the Australian Antarctic Research Program (Project Nos. 36 (CA/01/90) and 475 and the German Research Council (DFG, Bo 918/4).

References

Allen, S.E. & Heal, O.W. (1970): Soils of the maritime Antarctic.- In: M.W. HOLDGATE (ed.), Antarctic Ecology, Vol. II, 693-696, Academic Press, London,

Barsch, D., Blümel, W.-D., Flügel, W.-A., Mäusbacher, R., Stäblein, G. & Zick, J. (1985): Untersuchungen zum Periglazial auf der König-Georg-Insel, Südshetlandinseln/ Antarktika.- Ber. Polarforsch. 24: 1-75.

Blight, D.F. & Oliver, R.L. (1977): The metamorphic geology of the Windmill Islands, Antarctica: a preliminary account.- J. Geol. Soc. Australia 24: 239-262.

Blume, H.-P. & Bölter, M. (1993a): Soils of Casey Station, Antarctica.- In: D. GILICHINSKI (ed.), Proc. 1st Int. Symp. Cryopedol., 96-103, Pushchino.

Blume, H.-P. & Bölter, M. (1993b): Podsole, Leptosole und Regosole der Antarktis.- Mitt. Dtsch. Bodenkundl. Gesellsch. 72: 843-846.

Bockheim, J.G. & Ugolini, F.C. (1990): A review os pedogenic zonation in well-drained soils of the southern circumpolar region.- Quatern. Res. 34: 47-66.

Bölter, M. (1989): Microbial activity in soils from Antarctica (Casey Station, Wilkes Land).- Proc. NIPR Symp., Polar Biol. 2: 146-153.

Bölter, M. (1990): Evaluation - by cluster analysis - of descriptors for the establishment of significant subunits in Antarctic soils.- Ecol. Model. 50: 79-54.

Bölter, M. (1992a): Environmental conditions and microbiological properties-from soils and lichens from Antarctica (Casey Station, Wilkes Land).- Polar Biol. 11: 591-599.

Bölter, M. (1992b): Organic matter and its availability to microorganisms in Antarctic soils.- In: D. GLICHINSKY (ed.), Proc. 1st Int. Conf Cryopedology,189-199, Pushchino.

Bölter, M. (1992c): Vergleichende Untersuchungen zur mikrobiellen Aktivität in Böden und an Kryptogamen aus der kontinentalen und maritimen Antarktis.- Habil.Schrift, Universität Kiel, 203 pp.

Bölter, M., Kappen, L. & Meyer, M. (1989): The influence of microclimate on potential photosynthesis of *Usnea sphacelata*: a model.- Ecol. Res. 4: 297-307.

Campbell, I.B. & Claridge, G.G.C. (1969): A classification of frigic soils - the zonal soils of the Antarctic continent.- Soil Sci. 107: 75-85.

Campbell, I.B. & Claridge, G.G.C. (1987): Antarctica: Soils, weathering processes and environment. – Elsevier, Amsterdam, 368 pp.

Fabiszewski, J. & Wojtun, B. (1933): Peat-forming vegetation.- In: S. RAKUSA-SUSZCZEWSKI (ed.), The Maritime Anatarctic Coastal Ecosystem of Admiralty Bay, 189-195, Department of Antarctic Biol., Polish Acad. Sci., Warsaw.

FAO (1990): Revised legend of the world soil map.- FAO, Rome, 51 pp.

Kappen, L. (1993): Lichens in the Antarctic region.- In: E.I. FRIEDMANN (ed.), Antarctic Microbiology, 433-490, Wiley-Liss, Inc., New York.

Kappen, L., Bölter, M. & Kühn, A. (1987): Photosynthetic activity of lichens in natural habitats in the maritime Antarctic.- Bibl. Lichenol. 25: 297-312.

Kappen, L., Breuer, M. & Bölter, M. (1991): Ecological and physiological investigations in continental Antarctic cryptogams. 3. Photosynthetic production of *Usnea sphacelata*: diurnal courses, models, and the effect of photoinhibition.- Polar Biol. 11: 393-401.

Leonardi, J.M., Marchetti, C., Monticelli, L. & Osterrieth, M. (1987): Characterization preliminar de un histosol antartico bajo gramineas.- Contr. Cient. Inst. Antartico Argentino 340: 1-17.

Longton, R.E. (1988): Biology of polar bryophytes and lichens. - Cambridge Univ. Press, Cambridge, 391 pp.

Marino, B.D. & McElroy, M.B. (1991): Isotopic composition of atmospheric CO_2 inferred from carbon in C4 plant cellulose.- Nature 349: 127-131.

Mariotti, A. & Peterschmitt, E. (1994): Forest savanna ecotone dynamics in India as revealed by carbon isotope ratios of soil organic matter.- Oecologia 97: 475-480.

Melke, J. & Uziak, S. (1989): Dynamics of moisture, redox potential and oxygen diffusion rates of some soils of Calypsostranda, Spitsbergen.- Polish Polar Res. 10: 91-104.

Nadelhoffer, K.J. & Fry, B. (1988): Controls of natural nitrogen-15 and carbon-13 abundances in forest soil organic matter.- Soil Sci. Soc. Am. J. 52: 1633-1640.

Niemiec, J. & Rawa, Z. (1989): Meteorological data from Polish Antarctic Station „H. Arctowski“ for 1987.- Polish Polar Res. 10: 251-254.

Nowosielski, L. (1980): Meteorological conditions at Arctowski Station 1978 (King George Island, South Shetland Islands).- Polish Polar Res. 1: 83-93.

O'Brien, R.M.G., Romans, J.C.C. & Robertson, L. (1979): Three soil profiles from Elephant Island, South Shetland Islands.- Br. Antarct. Surv. Bull. 47: 1-12.

Rask, H.M. & Schoenau, J.J. (1993): 13C natural abundance variations in carbonates and organic carbon from boreal forest wetlands.- Biogeochem. 22: 23-35.

Smith, B.N. & Epstein, S. (1971): Two categories of $^{13}C/^{12}C$ ratios of higher plants.- Plant Physiol. 47: 380-387.

Smith, R.I.L. (1984): Terrestrial plant biology of the sub-Antarctic and Antarctic.- In: R.M. LAWS (ed.), Antarctic Ecology, Vol. I, 61-162, Academic Press, London.

Smith, R.I.L. (1985): Nutrient cycling in relation to biological productivity in Antarctic and Sub-Antarctic terrestrial and freshwater ecosystems.- In: W.R. SIEGFRIED, P.R. CONDY, & R.M. LAWS (eds.), Antarctic Nutrient Cycles and Food Webs, 138-155, Springer-Verlag, Berlin.

Smith, R.I.L. (1986): Plant ecological studies in the fellfield ecosystems near Casey Station, Australian Antarctic territory, 1985/86. - Br. Antarct. Surv. Bull. 72: 81-91.

Smith, R.I.L. (1990): Plant community dynamics in Wilkes Land, Antarctica. - Proc. NIPR Symp. Polar Biol. 3: 229-244.

Soil Survey Stuff (1992): Keys to soil taxonomy.- SMSS Techn. Monogr. 19, 5th Ed., Pacohantas, Blacksburg, Virginia.

Ugolini, F.C. (1970): Antarctic soils and their ecology.- In: M.W. HOLDGATE (ed.). Antarctic Ecology, Vol. 2, 673-692, Academic Press, London.

Vincent, W.F. (1988): Microbial ecosystems of Antarctica.- Cambridge University Press, Cambridge., 304 pp

Vishniac, H.S. (1993): The microbiology of Antarctic soils.- In: E.I. FRIEDMANN (ed.), Antarctic Microbiology, 297-341, Wiley-Liss Inc., New York.

Walton, D.W.H. (1984): The terrestrial environment.- In: R.M. LAWS (Ed.), Antarctic Ecology, Vol. 1, 1-60, 344 pp., Academic Press, London.

Weyant, W.S. (1966): The Antarctic climate. Antarctic soils and soil forming processes.- Antarct. Res. Ser. 8: 47-59.

Wynn-Williams, D.D. (1990): Ecological aspects of Antarctic microbioloy.- Adv. Microb. Ecol. 11: 71-146.