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James G. Bockheim *Editor*

The Soils of Antarctica

Springer

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The Soils of Antarctica

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Preface

Soils have been studied in Antarctica for nearly 100 years. The first soils study in Antarctica was by Jensen (1916) who analyzed soil samples collected during the 1907–1909 Shackleton expedition. It is of interest that no soils investigations were undertaken in Antarctica during the International Geophysical Year in 1957. However, in 1959 a New Zealand field party that included J.D. McCraw and G.G.C. Claridge went to Antarctica with the intention of preparing a soil map of the Ross Dependency, an area claimed by New Zealand that includes much of the Transantarctic Mountains. In the 1960s, F.C. Ugolini examined the role of biota in soil-forming in the McMurdo Dry Valleys. Edited by J.C.F. Tedrow, *Antarctic Soils and Soil Forming Processes* was published by the American Geophysical Union in 1966 as part of the Antarctic Research Series.

During 1964 to 1999, G.G.C. Claridge and I.B. Campbell spent 15 field seasons together in Antarctica describing and sampling over 900 pedons. In 1987 they published *Antarctica: Soils, Weathering Processes and Environment*, which provided detailed information on soil-forming factors, weathering, soil distribution, glacial history, classification, and environmental considerations. This book has remained the key reference to Antarctic soils over the past 27 years.

Satellite imagery has shown that only 0.35 % (45,000 km^2) of Antarctica is ice-free. The present book was initiated as a result of the large proportion (93 %) of literature on Antarctic soils that has been generated since the mid-1980s, particularly in ice-free regions for which soils data were unavailable. The book was prepared at the request of A.E. Hartemink, who is coordinating Springer's World Soils Book Series. This book divides Antarctica into 12 ice-free regions and subregions. Although the chapters vary in structure, they generally include an introduction reviewing the literature and a description of the ice-free region. The results section presents soil maps, where they are available, a description of soil-map units and analytical soil properties. The discussion includes the soil-forming factors and soil-forming processes. We have used *Soil Taxonomy* as the basic scheme for soil classification. The final three chapters deal with management and climate change impacts on Antarctic soils and a summary of the distribution of soil taxa in Antarctica.

This book is intended to complement Campbell and Claridge's *Antarctica: Soils, Weathering Processes and Environment* and to contribute to our understanding of the global distribution of soils.

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Editor and Contributors

About the Editor

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Tatiana V. Alekseeva Ph.D. in Biogeochemistry, is a leading researcher in the laboratory of Geochemistry and Soil Mineralogy IPCBPSS RAS. She is the author of about 120 publications (papers, book chapters, and a book). Her main research field is soil mineralogy, particularly—clay mineralogy; mineral weathering and "mineral"—"soil organic matter" interactions, the effect of these interactions on organic matter preservation in soils and paleosols (including Paleozoic ones).

Megan Balks teaches Soil, Earth, and Environmental Sciences at the University of Waikato in New Zealand. Megan was brought up on a remote hill country sheep farm and studied Soil Science at Massey University. She worked for several years undertaking soil survey work for irrigation development, then completed her Ph.D. on effects of effluent irrigation on soil physical properties. Megan has been involved in Antarctic Soil Research since 1990 and has undertaken 18 Antarctic field expeditions.

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James G. Bockheim is a professor of Soil Science, University of Wisconsin, Madison. He has spent 19 field seasons in Antarctica, including Victoria Land, Ellsworth Land and the Antarctic Peninsula. He has over 80 refereed publications on soils of Antarctica.

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Abbreviations

ANTPAS	Antarctic Permafrost and Soils Working Group
AWS	Automatic Weather Station
CALM-S	Circumpolar Active-Layer Monitoring—South
CDW	Circumpolar Deep Water
CEC	Cation-Exchange Capacity
EAIS	East Antarctic Ice Sheet
EC	Electrical Conductivity
GIS	Geographic Information System
GPR	Ground-Penetrating Radar
GPS	Geographic Positioning System
IPY	International Polar Year (2007–2008)
IUSS	International Union of Soil Science
KGI	King George Island
LGM	Last Glacial Maximum (ca. 18–24 ka BP)
MAAT	Mean Annual Air Temperature
MAP	Mean Annual Precipitation
MBL	Marie Byrd Land
MDV	McMurdo Dry Valleys
QML	Queen Maud Land
SCAR	Scientific Committee on Antarctic Research
SOC	Soil Organic Carbon
SOI	South Orkney Islands
SSI	South Shetland Islands
ST	*Soil Taxonomy* (Soil Survey Staff, 1999)
TAM	Transantarctic Mountains
WAIS	West Antarctic Ice Sheet
WAP	Western Antarctic Peninsula
WRB	World Reference Base for Soil Resources (IUSS, WRB, 2006)

1 Soils of Antarctica: History and Challenges

James G. Bockheim

1.1 History

The first soil study in Antarctica was by Jensen (1916) who analyzed soil samples collected during the 1907–1909 Shackleton expedition. It is of interest that no soil investigations were undertaken in Antarctica during the International Geophysical Year in 1957. However, in 1959 a New Zealand field party that included J.D. McCraw and G.G.C. Claridge went to Antarctica on the request of N.H. Taylor, Director of the Soil Bureau, with the intention of preparing a soil map of the Ross Dependency, a slice of the Antarctic pie claimed by New Zealand that includes much of the Transantarctic Mountains. McCraw (1967) published a soil map of the lower Taylor Valley, an early version of which was presented at the International Society of Soil Science Congress in Madison, WI, in 1960.

McCraw (1960) classified soils of Taylor Valley according to topography and parent material. This also launched the career of G.G.C. Claridge, and subsequently I.B. Campbell; Claridge and Campbell spent 15 field seasons together in Antarctica during the period 1964–1999 describing and sampling over 900 pedons. They published 28 articles in refereed journals, as recorded in the Web of Knowledge (Web of Science). Their data are available on the Land Care Research website: http://soils.landcareresearch.co.nz/contents/SoilData_RossSeaSoils_About.aspx?currentPage=SoilData_RossSeaSoils&menuItem=SoilData.

The next comprehensive soil studies were initiated by F.C. Ugolini under the auspices of J.C.F. Tedrow. Ugolini's early studies (1963, 1964) focused on the effects of organic matter (moss polsters, penguins) on soil formation and movement of salts in Ahumic soils. In 1966, Tedrow edited the eighth volume of the American Geophysical Union's Antarctic Research Series, entitled "Antarctic Soils and Soil Forming Processes." The book outlined soil-forming factors in Antarctica, including geomorphology, climate, preliminary measurement of patterned ground activity, vegetation, and soil microorganisms. The book concluded with a chapter classifying Antarctic soils into those of the cold desert: (1) ahumic soils; (2) evaporate soils; (3) protoranker soils; (4) ornithogenic soils; (5) regosols; and (6) lithosols (rockland). In 1977, Tedrow included a chapter on Antarctic soils in his book, *Soils of the Polar Landscapes*, in which he summarized soil information for various parts of Antarctica.

In 1969, Campbell and Claridge proposed a soil classification scheme for Antarctica that was based on the zonal system then in use in many countries, including Russia and New Zealand. Zonal (frigic) soils were subdivided according to available moisture status into ultraxerous, xerous, and subxerous, degree of soil development, and parent material deposit and composition. Intrazonal soils included evaporite soils, algal peats, avian soils (ornithogenic soils), and hydrothermal soils. Azonal soils included recent soils on beaches, fans, stream beds, etc.

Tedrow (1977) identified several soil zones in the polar regions, which included from low latitude to high latitude, the Tundra soil zone, the polar desert soil zone, the subpolar desert soil zone, and the cold desert soil zone. In 1987, Campbell and Claridge published their book, *Antarctica: Soils, Weathering Processes and Environment*, which provided detailed information on soil-forming factors, weathering, soil distribution, glacial history, classification, and environmental considerations.

To this point, Antarctic pedologists were unsure as to whether or not surficial deposits in Antarctica were indeed soils, did not use standard soil horizonation nomenclature, and were not using global soil classification systems such as *Soil Taxonomy* (ST) (1999). On the request of R.L. Simonson, editor of the journal *Geoderma*, Bockheim (1982) clearly enunciated why the weathered surficial deposits of Antarctica were indeed soils, and his definition of soils was eventually incorporated into ST as the standard definition of soils.

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Bockheim (1979) also began using standard soil horizon nomenclature to delineate soil horizons in Antarctic soils, including D for desert pavement, Bw for oxidized (stained) B horizons, Cox for slightly oxidized parent materials, and Cn for unoxidized parent materials. He later recommended (Soil Survey Staff 1999) that ice-cemented permafrost be differentiated from dry-frozen permafrost by the symbols, fm and f, respectively, that cryoturbation be recognized with the symbols "jj," and that glacic horizons be designated "Wfm". To date Bockheim has spent 19 field seasons in Antarctica describing and sampling over 1,000 pedons throughout the Transantarctic and Ellsworth Mountains and along the Antarctic Peninsula. Part of his soils data from the McMurdo Dry Valleys is contained on the website: http://nsidc.org/data/ggd221.html. In addition, he has published 33 articles in refereed journals pertaining to Antarctic soils.

Until the introduction of the Gelisol order, soils of Antarctica could not be classified using ST. During the First International Conference on Cryopedology in 1992, there was a discussion regarding the need to revise ST so as to include soils of the polar regions. J.G. Bockheim was appointed chair of the International Committee on Permafrost-Affected Soils (ICOMPAS) to achieve this goal. In 1993, the Alaska/Yukon Society of Professional Soil Scientists organized a Meeting on the Classification, Correlation, and Management of Permafrost Affected Soils to test different classification schemes in the field. During this meeting a team of American cryopedologists proposed a new order for permafrost-affected soils, the Gelisols (Bockheim et al. 1994). In 1997, the Gelisol order was accepted by the US Department of Agriculture with three suborders, Histels, Turbels, and Orthels. Anhydrous conditions were recognized as typical of the McMurdo Dry Valley region in the mean annual water-equivalent precipitation is less than 50 mm yr^{-1}, ice-cemented permafrost is not present in the upper 70 cm, the soil moisture content averaged over the 10–70 cm layer is <3 % by weight, and the dry consistence of the 10–70 cm layer is loose to slightly hard except where a salt-cemented horizon is present.

Meanwhile the World Reference Base for Soil Resources was revising the FAO soil map legend into a comprehensive soil classification system somewhat paralleling ST. The Cryosol soil group was established, but it does not include organic soils or lithic soils with permafrost, nor does it address Antarctic soils (IUSS, WRB 2007). Likewise, the Russian soil classification system (Shishov et al. 2007) does not allow classification of Antarctic soils. Bockheim prepared a key for classifying Antarctic soils using ST, which is available from the website: http://erth.waikato.ac.nz, which has been widely used for classifying Antarctic soils.

In November of 2004 the International Conference on Antarctic Permafrost and Soils, sponsored by the USA National Science Foundation, was held at the University of Wisconsin, Madison. Thirty-four invited cryopedologists and permafrost scientists from 14 countries made the following recommendations, among others (Bockheim 2005): (i) a common, web-accessible repository for permafrost and soils data and (ii) the production of thematic maps on Antarctic permafrost and soils.

During the Eighth International Conference on Permafrost, the Antarctic Permafrost and Soils (ANTPAS) group was established, with J.G. Bockheim and M. Guglielmin (Italy) as co-chairs. ANTPAS was recognized as a working group by the International Permafrost Association (IPA) and as an expert group by the Scientific Committee on Antarctic Research (SCAR).

In 2008, a special issue of the journal, *Geoderma*, was devoted to "Antarctic Soils and Soil Forming Processes in a Changing Environment." Edited by J.G. Bockheim and M.R. Balks, the issue contained 13 articles on Antarctic soils primarily from the Ross Sea region, but also including the South Orkney Islands and the South Shetland Islands along the Antarctic Peninsula.

In 2007–2008 and 2008–2009 a team of Russian cryopedologists studied diversity, geography, and genesis of soils at six Russian stations in East Antarctica, including Novolazarevskaya, Molodezhnaya, Progress, Mirnyi, Leningradskaya, and Russkaya, thereby adding to our understanding of soils in that part of the continent. Three of the chapters in this book summarize this work.

Finally, the McMurdo Long-Term Ecological Research (LTER) project has contributed substantially to our understanding of the relation of soils to biota in the McMurdo Dry Valleys (http://www.mcmlter.org).

1.2 Challenges

A number of challenges regarding Antarctic soils must be addressed in subsequent studies. The mapping phase of research in Antarctic is over; funding organizations are no longer interested in mapping activities. However, there is interest in applying modern technologies such as satellite imagery and spectrometers to mapping objects such as soils. These tools may eventually enable preparation of detailed soil maps in Antarctica

Only 0.36 % (45,000 km^2) of Antarctica is ice-free. These ice-free areas are dispersed around the periphery of the continent and along the 3500 km long Transantarctic Mountains, creating issues of scale and map-display of soils. This problem is compounded by the lack of data in numerous remote areas, e.g., the Thiel Mountains, the Pensacola Mountains, the Prince Charles Mountains, Edward V Land, and along the western Antarctic Peninsula.

Soil Taxonomy will require a number of changes to better accommodate Antarctic soils. Some of these revisions include (i) quantifying cryoturbation; (ii) revising the Gelisol order to include Aridi-suborders and additional great groups and suborders; (iii) including more Geli suborders and great groups in ST; (iv) improving the soil temperature and soil moisture regimes to accommodate soils outside North America; (v) stressing that permafrost depths (1 or 2 m) should be taken or adjusted to end-of-season conditions; and (vi) specifying the amount of gelic materials to meet Gelisols and turbic subgroups in various orders (Bockheim et al. 2014).

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2 Soil-Forming Factors in Antarctica

James G. Bockheim

2.1 Introduction

Only 0.35 %, or 45,000 km^2, of Antarctica is ice-free. The distribution of these ice-free areas is shown in Figs. 2.1 and 2.2 and in Table 2.1. With an ice-free area of 25,700 km^2 (53 % of the total), the Transantarctic and Pensacola Mountains (regions 5b and 5a, respectively) constitute the largest ice-free area of Antarctica. The Antarctic Peninsula and its offshore islands (region 8) is the next largest ice-free area (10,000 km^2, or 20 % of the total), followed by Mac-Robertson Land and the Princess Elizabeth Coast (region 3) at 5,400 km^2 (11 % of the total) and Queen Maud Land at 3,400 km^2 (7 % of the total). Ice-free areas comprising <2,500 km^2 include the Ellsworth Mountains (region 6), Enderby Land (region 2), Wilkes Land (region 4), and Marie Byrd Land (region 7).

2.2 Elevation and Ice Sheets

Antarctica is divided by the Transantarctic Mountains into what is commonly known as East Antarctica, which contains the massive East Antarctic ice sheet (EAIS) over bedrock, and West Antarctica, which contains the marine-based West Antarctic ice sheet (WAIS). These two ice sheets contain 70 % of the Earth's freshwater and have mean elevation of over 3,000 m. While the EAIS generally has been stable during the Pleistocene, the WAIS disintegrated during Northern Hemisphere glaciations (Denton et al. 1991).

2.3 Climate

The extreme variation in Antarctica's climate has important effects on soil properties and distribution. Ice-free areas bearing soils range in elevation from sea-level to over 3,000 m in the southern Transantarctic Mountains (Fig. 2.3). The mean-annual water-equivalent precipitation varies from less than 10 mm year^{-1} in the McMurdo Dry Valleys to over 600 mm year^{-1} along the Antarctic Peninsula (Fig. 2.4; Table 2.2). Whereas rainfall occurs along the Antarctic Peninsula and in East Antarctica, i.e., at low elevations and latitudes <67° S, mountainous and interior areas receive only snow. Much of this snow either blows away or it sublimates. Campbell et al. (1997) measured moisture content of the active layer and near-surface permafrost in several areas of the McMurdo Dry Valleys, reporting values of 0.2–16 % in the active layer and 1–15 % in the underlying dry permafrost.

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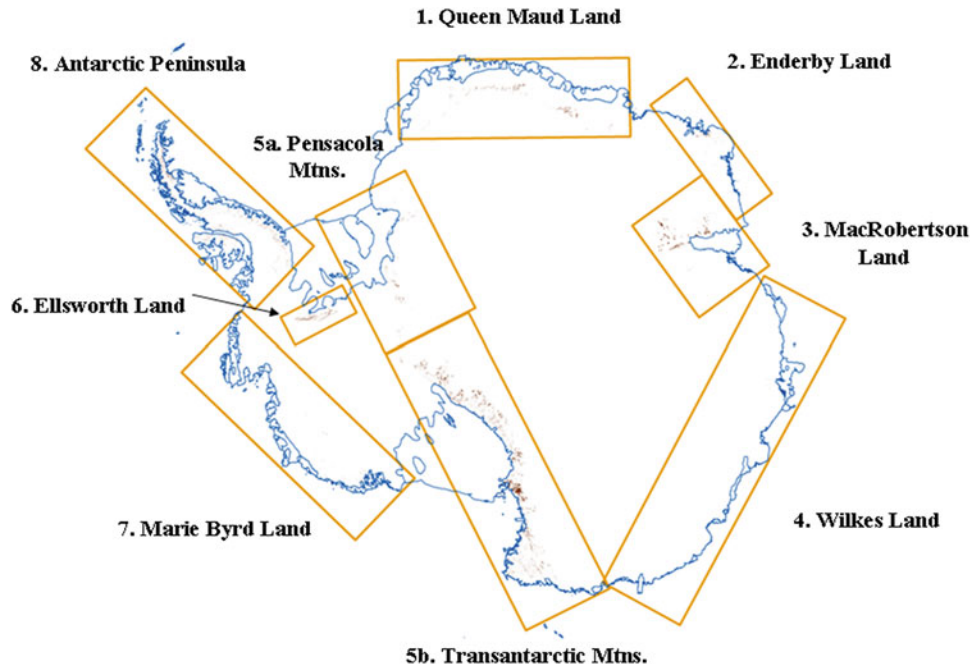

Fig. 2.1 Ice-free regions of Antarctica

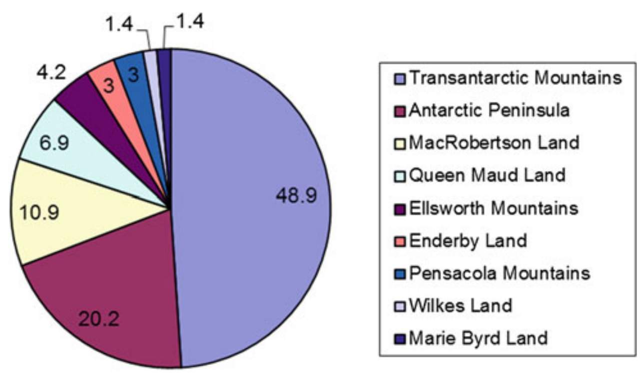

Fig. 2.2 Distribution (percent) of ice-free areas by region in Antarctica

Mean-annual air temperatures range from −2 to −4 °C in the South Orkney and South Shetland Islands to −45 °C in the southern Transantarctic Mountains (Fig. 2.5). The mean summer (December and January) temperature, which controls the amount of available water for soil formation and the existence of biota, is above 0 °C in the South Orkney and South Shetland Islands, near 0 °C in coastal locations of East Antarctica, and below 0 °C elsewhere (Table 2.2).

Permafrost is continuous in continental Antarctica and discontinuous in the South Shetland Islands (Fig. 2.6). From limited data, the permafrost thickness in Antarctica ranges from less than 100 m in the South Shetland Islands to more than 1,000 m in the MDV (Bockheim 1995). Active-layer (seasonal thaw layer) depths are dependent on the regional climate. In the South Orkney and South Shetland Islands, the active-layer depth commonly ranges between 1.0 and 2.0 m (Table 2.3). From limited data, the active-layer depth in East Antarctica ranges between 0.5 and 1.0 m. In the Transantarctic Mountains, active-layer depths range between 0.1 and 1.0 m, depending on elevation and proximity to the McMurdo coast. The present Circumpolar Active-Layer Monitoring-South (CALM-S) stations are depicted in Fig. 2.7. Active patterned ground is present throughout ice-free areas of Antarctica.

2.4 Biota

Plant life is restricted to mosses, lichens, and algae in continental Antarctica, with vascular plants limited to the Antarctic island north of 67° S, particularly in the South Orkney

Table 2.1 Ice-free areas in Antarctica

Region		Approximate area (km^2)
1	Queen Maud Land	
	Muhlig-Hoffmann	900
	Wohlthat Mtns.	900
	Sør Rondane Mtns.	900
	Queen Fabiola Mtns.	200
	Ahlmann Ridge	50
	Schirmacher Oasis	35
	Others	390
		3400
2	Enderby Land	
	Scott Mtns.	750
	Tala Mtns.	740
	Molodezhnaya	10
		1500
3	MacRobertson Land	
	Prince Charles Mtns.	3100
	Mawson Escarpment	1400
	Grove Mtns.	400
	Vestfold Hills	400
	Rauer-Bolingen Is.	50
	Larsemann Hills	50
		5400
4	Wilkes Land	
	Windmill Islands-Casey	500
	Bunger Hills	200
		700
5a	Pensacola Mtns.	**1500**
5b	Transantarctic Mtns.	
	McMurdo Dry Valleys	6700
	Queen Maud Range	4200
	North Victoria Land	3900
	Horlick Mtns.	3000
	Britannia-Darwin	2200
	Queen Alexandra-Eliz.	1200
	Thiel Mtns.	1200
	Other	1800
		24,200
6	Ellsworth Mtns.	
	Sentinel Range	1000
	Heritage Range	1100
		2100
7	Marie Byrd Land	
	Rockefeller Mtns.	480

(continued)

Table 2.1 (continued)

Region		Approximate area (km^2)
	Alexandra Mtns.	220
		700
8	Antarctic Peninsula	
	Palmer Land	4300
	Trinity Peninsula	2000
	Alexander Island	2000
	Palmer Archipelago	500
	S. Shetland Islands	500
	E. Antarctic Islands	500
	S. Orkney Islands	200
		10,000
	Grand total	**49,500**

and South Shetland Islands (Greene et al. 1967). There are 427 species of lichens in Antarctica, 40 % of which is endemic (Nayaka and Upreti 2005).

Birds play an important in modifying soils of coastal Antarctica. Seabirds and nesting birds constitute the dominant factor influencing SOC and nutrient levels in Antarctic soils (Beyer 2000; Beyer et al. 2000; Park et al. 2007). The mechanism whereby seabirds influence soil development is depicted in Fig. 2.8. Ice-free areas with large deposits of seabird manure undergo phosphatization, the process whereby a suite of phosphate minerals is precipitated resulting in the formation of ornithogenic soils. Ornithogenic soils are best expressed directly under active Adélie (*Pygoscelis adeliae*), chinstrap (*P. antarctica*), or gentoo (*P. papua*) penguin rookeries but are also commonly found at abandoned rookeries, where ornithogenic soils remain hundreds to thousands of years later (Myrcha and Tatur 1991). About 200 million kg of C and 20 million kg of P are deposited annually in rookeries of maritime Antarctica from Adélie and Chinstrap penguin excrement (Pietr et al. 1983; Myrcha and Tatur 1991). The high levels of seabird manure are a function of nutrient upwelling at the Antarctic Convergence. Along the continental shelf of the Antarctic Peninsula, nutrients feed large blooms of phytoplankton to sustain Antarctic krill, which are subsequently consumed and excreted by seabirds to develop the soils of maritime Antarctica.

The effects of the high levels of soil C (>4 %), N (>2 %), and P (>1 %) in ornithogenic soils are not isolated to areas with direct manure inputs. The two main transport mechanisms whereby nutrients are removed from rookeries are wind erosion and water solution. Bird trampling and unfavorable chemical conditions result in rookeries that are almost entirely devoid of vegetation, leaving nutrient rich

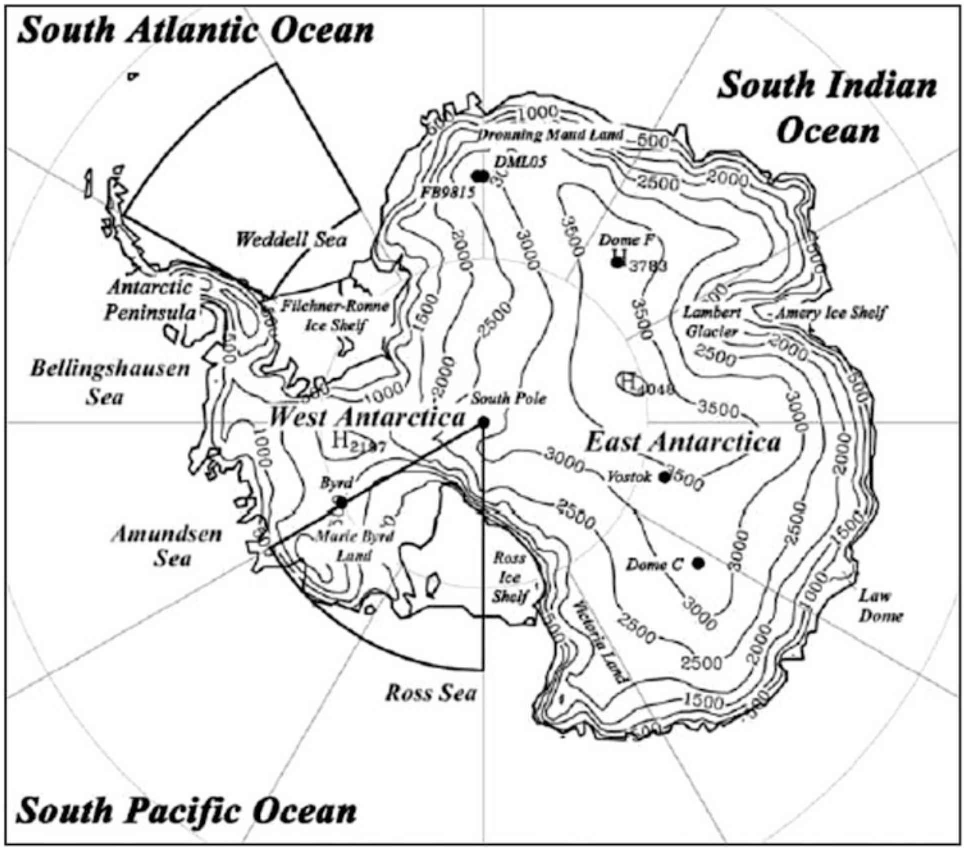

Fig. 2.3 Elevation map of Antarctica (500 m contour interval) (Bromwich et al. 2004)

surface soils susceptible to wind and water erosion. Nutrient rich solutions have been observed moving down-slope at several abandoned rookeries in the South Shetland Islands where geologic uplift has stranded marine terraces at higher elevations (Myrcha and Tatur 1991). The effects of these allochthonous nutrients can be either direct (deposition of organic acids and detritus) or indirect as the nutrients stimulate vegetative growth (algae, mosses, and vascular plants).

2.5 Parent Materials

Ice-free regions 1 through 4 in East Antarctica feature primarily Precambrian gneisses and schists (Fig. 2.9). The Transantarctic Mountains (region 5b) contain the Jurassic to Devonian age Beacon Group (sandstones intruded by dolerite) fronted by the Cambrian-Ordivician Granite Harbour Intrusives. The northern Transantarctic Mountains contain Upper and Older Precambrian metasedimentary rocks. The Pensacola Mountains (region 5a) are derived from Jurassic basaltic rocks, Upper Precambrian metasediments, and Paleozoic strata. The Ellsworth Mountains (region 6) contain Paleozoic strata. Ice-free areas in Marie Byrd Land are composed of Cenozoic volcanic rocks and Cretaceous intrusive rocks (granitic rocks). The Antarctic Peninsula is made up of a wide variety of rocks that are dominated by volcanic and granitic types.

The soil parent materials of Antarctica are primarily of glacial origin and include tills of various forms, outwash, and limited areas of glaciofluvial and glaciolacustrine deposits. Colluvium, talus, and other mass-movement

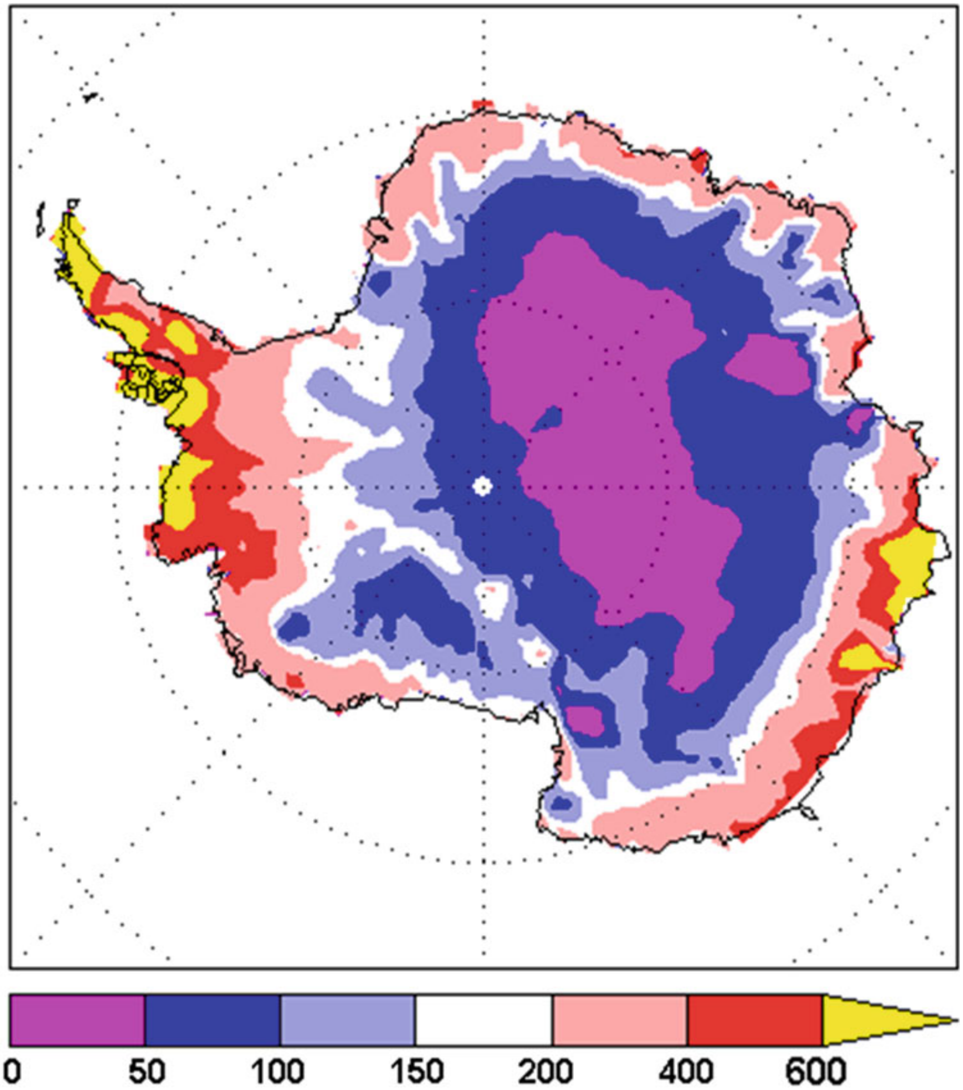

Fig. 2.4 Distribution of mean-annual precipitation (mm/year, water equivalent) in Antarctica (Connolley unpublished)

deposits occur throughout Antarctica. Debris flows and gelifluction deposits are common along the Antarctic Peninsula and in East Antarctica. Aeolian deposits include sand dunes, mega-ripples, but not loess. Volcanic ash and lapilli are common in the SSI and SOI; and scoria and other tephra occur in the MDV. Residuum is common in the high mountains and nunataks of interior Antarctica.

2.6 Time

All of Antarctica has been glaciated. In coastal areas (regions 1, 2, 3, 4, 5b, 7, 8), glacial deposits are of Holocene and Late Glacial Maximum (LGM) age. Deposits of LGM age are also present in the interior mountains (regions 1, 3, 5a, 5b, 6, 7), but glacial deposits dating back to the early Quaternary,

Table 2.2 Climate data for selected stations in ice-free subregions of Antarctica

Subregion	Station	Latitude (S)	Longitude	Elev. (m)	MAAT (°C)	Mean temperature Dec, Jan (°C)	MAP (mm)
1	Neumayer	70.683°	8.266° W	40	−17	−4.7	~400
	Sanae	71.687°	2.842° W	805	−17.1	−4.7	~100
2	Syowa	69.000°	39.583° E	15	−10.5	−1	
	Molodezhnaya	66.275°	100.160° E	42	−11	−1	250
	Mawson	67.000°	62.883° E	8	−11.2	−0.1	~200
3	Davis	68.583°	77.967° E	12	−10.3	−0.3	~200
	Mawson	67.600°	62.867° E	10	−11.2	0	
	Zhong Shan	69.367°	76.367°	15	−9.2	0.8	~200
	Grove Mtns.	73.25°	74.55° E	2160		−18.5	
4	Casey	66.279°	110.536° E	12	−9.2	−0.4	223
	Mirny	66.55°	93.01° E	30	−11.4	−2	379
5a	Halley Bay	75.500°	26.650° W	42	−18.7	−5.3	~150
5b	Lake Bonney	77.733°	162.166° W	150	−17.9	nd	<100
	McMurdo	77.880°	166.730° E	24	−17.4	−3.6	202
	Lake Vanda	77.517°	161.677° E	85	−19.8	0.8	5
6	Ellsworth	77.700°	41.000° W	42	−22.9	−8	~150
	Sky-Blu	74.79°	71.48° W	1510	−19.8	nd	nd
8	Signy Island	60.700°	45.593° W	90	−3.4	0.9	400
	Orcadas	60.750°	44.717° W	12	−2.8	−0.1	486
	King George I.	62.233°	58.667° W	12	−2	1.1	635
	Livingston I.	62.650°	60.350° W	35	−1.7	nd	800
	Esperanza	63.4°	56.98° W	13	−5		423
	Palmer	64.767°	64.005° W	8	−2.4	2	679
	Rothera	67.567°	68.013° W	33	−3.4	0.8	768
	Fossil Bluff	71.333°	68.283° W	55	−8.6	nd	nd
	Marambio	64.234°	56.625° W	5	−8.9	−1.7	250

Source Schwerdtfeger (1994); various station climate summaries

Pliocene, and Miocene occur in the Sør Rondane Mountains (region 1), the Prince Charles Mountains (region 3), the Thiel-Pensacola-Shackleton Mountains (region 5a), and the central and southern Transantarctic Mountains (region 5b) (Barrett 2009). Soils constitute a powerful tool in relative dating and correlating drifts in Antarctica (Chaps. 9 and 10).

Two key soil properties that have enabled relative dating and correlation of glacial deposits have been weathering stages and morphogenetic salt stages. Weathering stages were first established in Antarctica by Campbell and Claridge (1975) and included surface boulder frequency and weathering, relative abundance and form of soil salts, distinctiveness of soil horizons, and depth of the profile (Table 2.4).

The other key soil property used in relating dating of glacial deposits in Antarctica is the morphogenetic salt stage (Table 2.5; Fig. 2.10). This approach not only delineates soils from the maximum expression of morphogenetic salt stage (encrustations, flecks, patches, and saltpans), but also assigns an electrical conductivity value (measured in the laboratory)

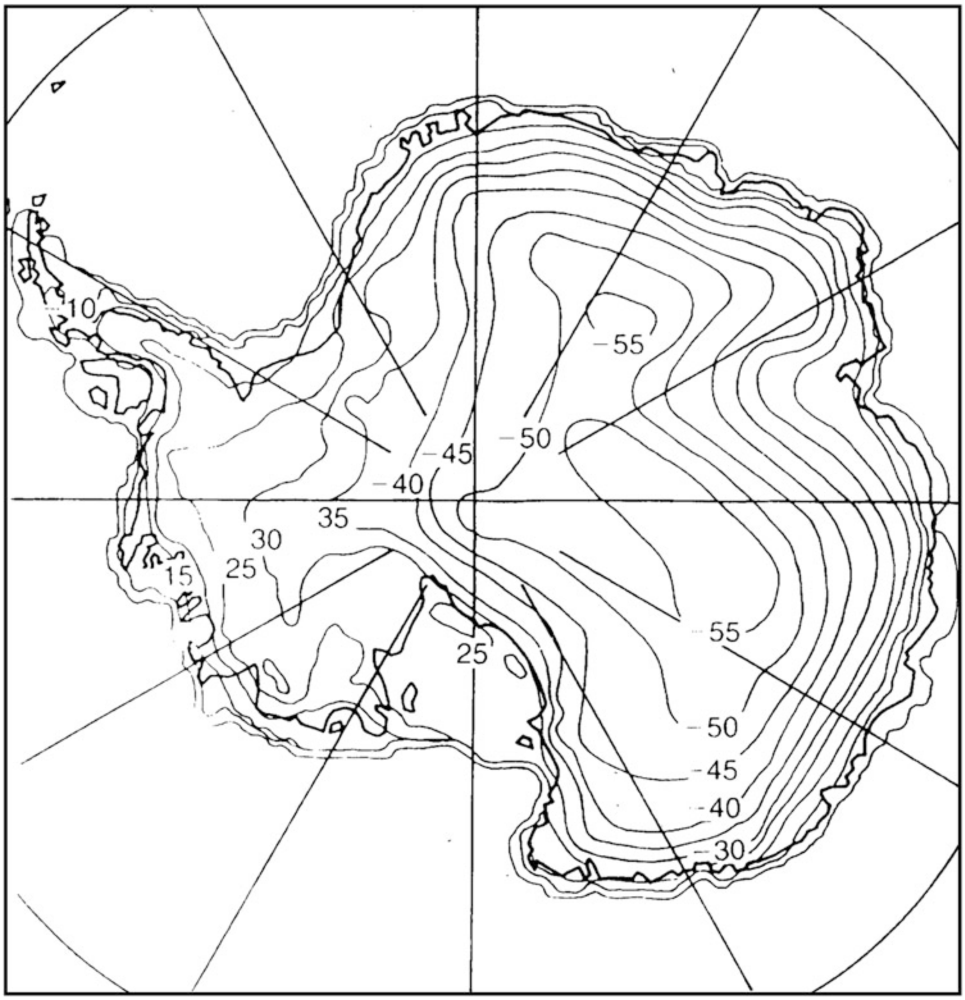

Fig. 2.5 Mean annual air temperature of the surface of Antarctica (Connolley and Cattle 1994)

and an age from numerical dating techniques. Examples of soil chronofunctions will be given in Chaps. 8 and 9.

2.7 Antarctic Soils Database

More than 2,300 pedons are reported from Antarctica in the published literature and constitute the database for this book (Table 2.6). More than 75 % of the soils have been sampled in the Transantarctic Mountains of Victoria Land. About 16 % of the pedons are from the Antarctic Peninsula. Only limited soils data are available for Enderby Land, MacRobertson Land, and the Thiel Mountains-Pensacola Mountains-Shackleton Range (region 5a). More details on the composition of the database are provided in the individual chapters.

The Antarctic Permafrost and Soils (ANTPAS) working group developed a sampling protocol for Antarctic soils that is included here as Appendix 1.

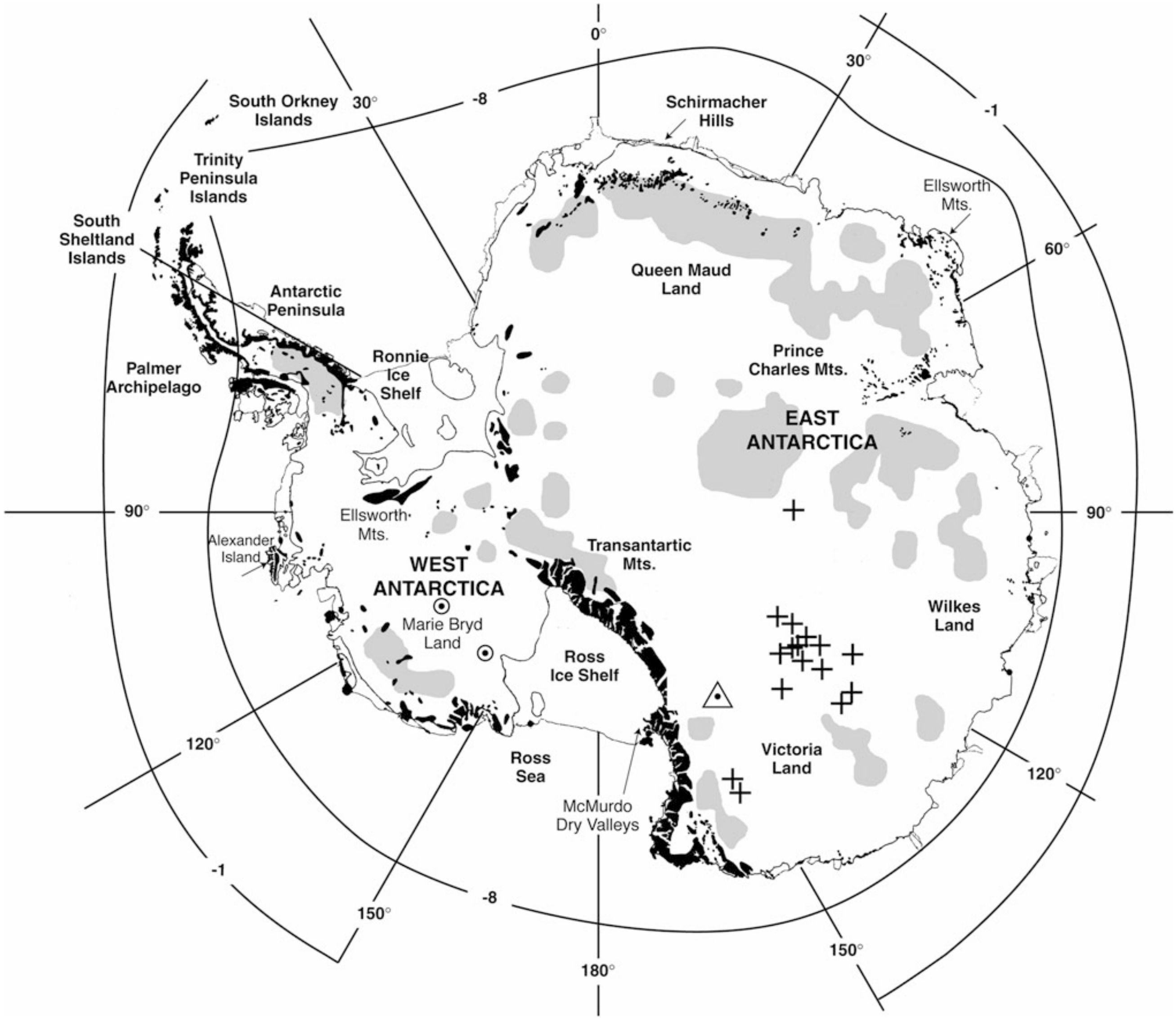

Fig. 2.6 Permafrost distribution in Antarctica (Bockheim 1995)

2.8 Soil Classification in Antarctica

Tedrow (1977) offers a detailed history of soil classification in the polar regions. Early approaches were bioclimatic zonation schemes. Tedrow (1977) divided the Southern Circumpolar Region into four bioclimatic or pedological zones that included, from north to south, tundra, polar desert, sub-polar desert, and cold desert. Bockheim and Ugolini (1990) depicted changes in pedologic processes along this gradient, showing a reduction in rubification (reddening), melanization or humification (accumulation of organic matter), pervection (cryoturbation), and podzolization from the Antarctic Peninsula to coastal East Antarctica, and then to the mountainous interior of the continent. In contrast,

Table 2.3 Active-layer depths and permafrost temperatures for selected stations in ice-free subregions

Subregion	Station	Latitude (°S)	Longitude (°)	Elev. (m)	Active-layer depth (m)	Permafrost temp. (°C)[a]
1	Troll	72.011	2.533° E	1335	0.08	−17.8
	Sanae	71.687	2.842° W	805	0.15	−16.8
	Novozalarevskaya	70.763	11.795° E	80	0.7	−9.7
	Aboa	73.033	13.433° W	450	0.6	nd
	Farjuven Bluffs	72.012	3.388° W	1220	0.25	−17.8
	Sør Rondane Mtns.	71.500	24.5° E	1250	0.1–0.4	nd
2	Syowa	69.000	39.583° E	15	nd	−8.2 (6.8)
	Molodezhnaya	66.275	100.760° E	7	0.9–1.2	−9.8
3	Progress	69.404	76.343°	96	>0.5	−12.1
	Grove Mtns.	79.920	74° E	1200	0.2	nd
	Larsemann Hills	69.400	76.27° E	50	1.0–1.1	nd
4	Casey Station	66.280	110.52° E	10–100	0.3–0.8	nd
5a						
5b	Simpson Crags	74.567	162.758° E	830	0.35	nd
	Oasis	74.700	164.100° E	80	1.6	−13.5
	Mt. Keinath	74.558	164.003° E	1100	nd	nd
	Boulder clay	74.746	164.021° E	205	0.25	−16.9
	Granite Harbour	77.000	162.517° E	5	0.9	nd
	Marble Point	77.407	163.681° E	85	0.4	−17.4
	Victoria Valley	77.331	161.601° E	399	0.24	−22.5
	Bull Pass	77.517	161.850° E	150	0.5	−17.3
	Minna Bluff	78.512	166.766° E	35	0.23	−17.4
	Scott Base	77.849	166.759° E	80	0.3	−17
6	Ellsworth Mtns.	78.500	85.600° W	800–1300	0.15–0.50	nd
7	Russkaya	74.763	136.796°	76	0.1	−10.4
8	Signy Island	60.700	45.583° W	90	0.4–2.2	−2.4
	King George Island	62.088	58.405° W	37	1.0–2.0	−0.3 to −1.2
	Deception-Livingston Is.	62.670	60.382° W	272	1.0	−1.4 to −1.8
	Cierva Point	64.150	69.950° W	182	2.0–6.0	−0.9
	Amsler Island, Palmer	64.770	64.067° W	67	14.0	−0.2
	Rothera	67.570	68.130° W	32	1.2	−3.1
	Marambio Station	64.240	56.670° W	5-200	0.6	nd

Source Vieira et al. (2010); various reports
[a]Depth of measurement in parentheses where available

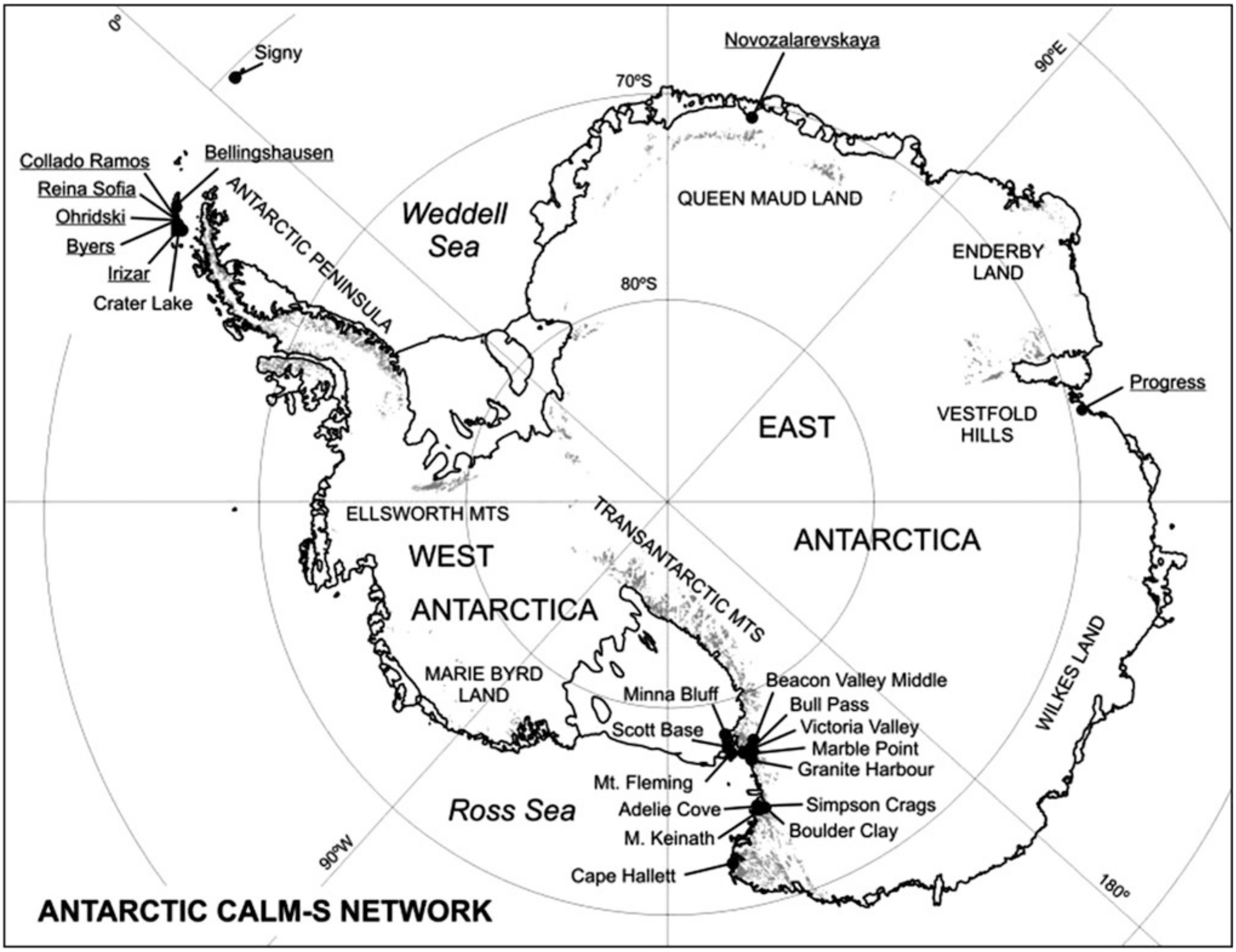

Fig. 2.7 Distribution of circumpolar active-layer monitoring-south sites (Vieira et al. 2010)

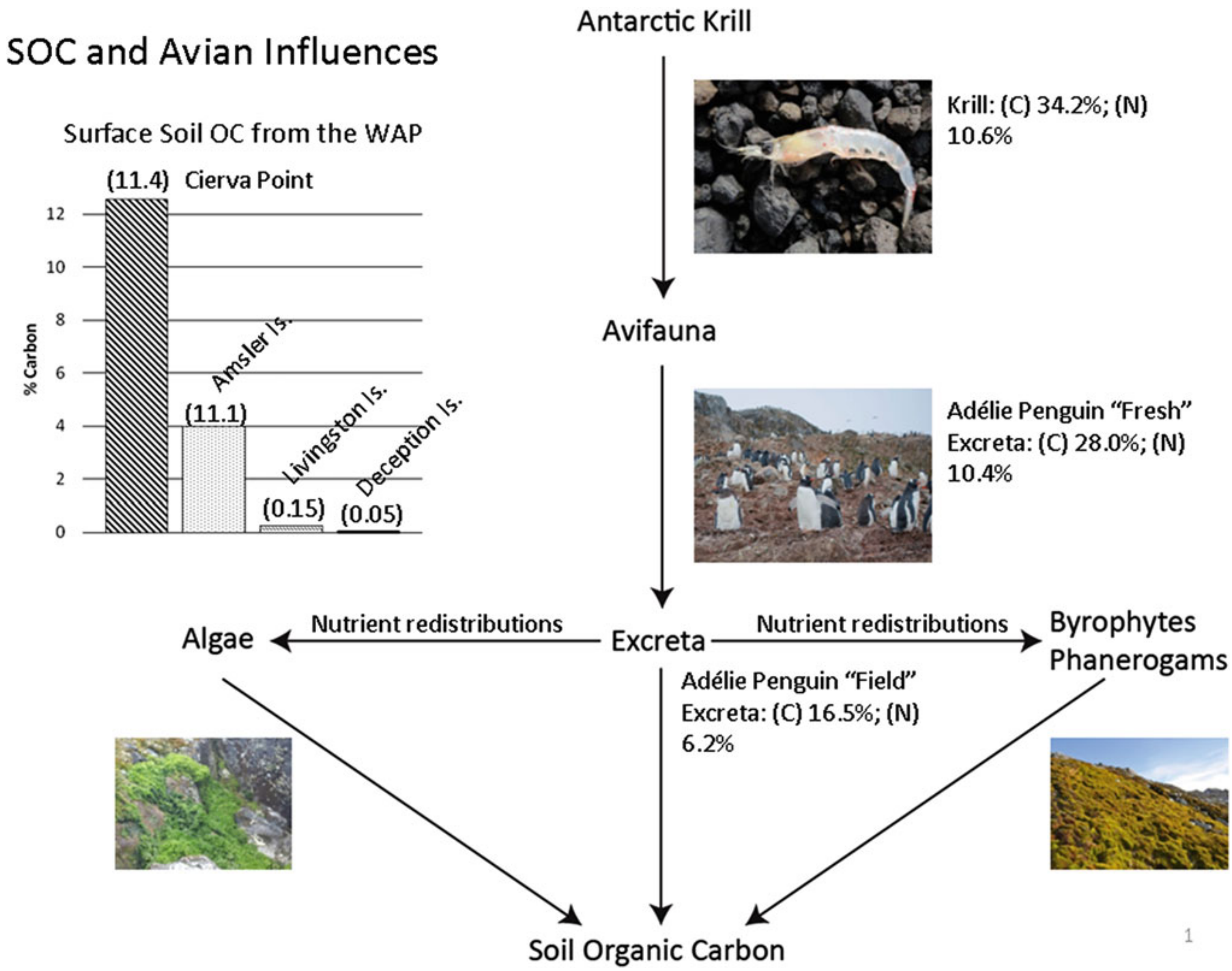

Fig. 2.8 Avian influences on nutrients and soil organic carbon (SOC) in maritime Antarctica (Bockheim and Haus 2014)

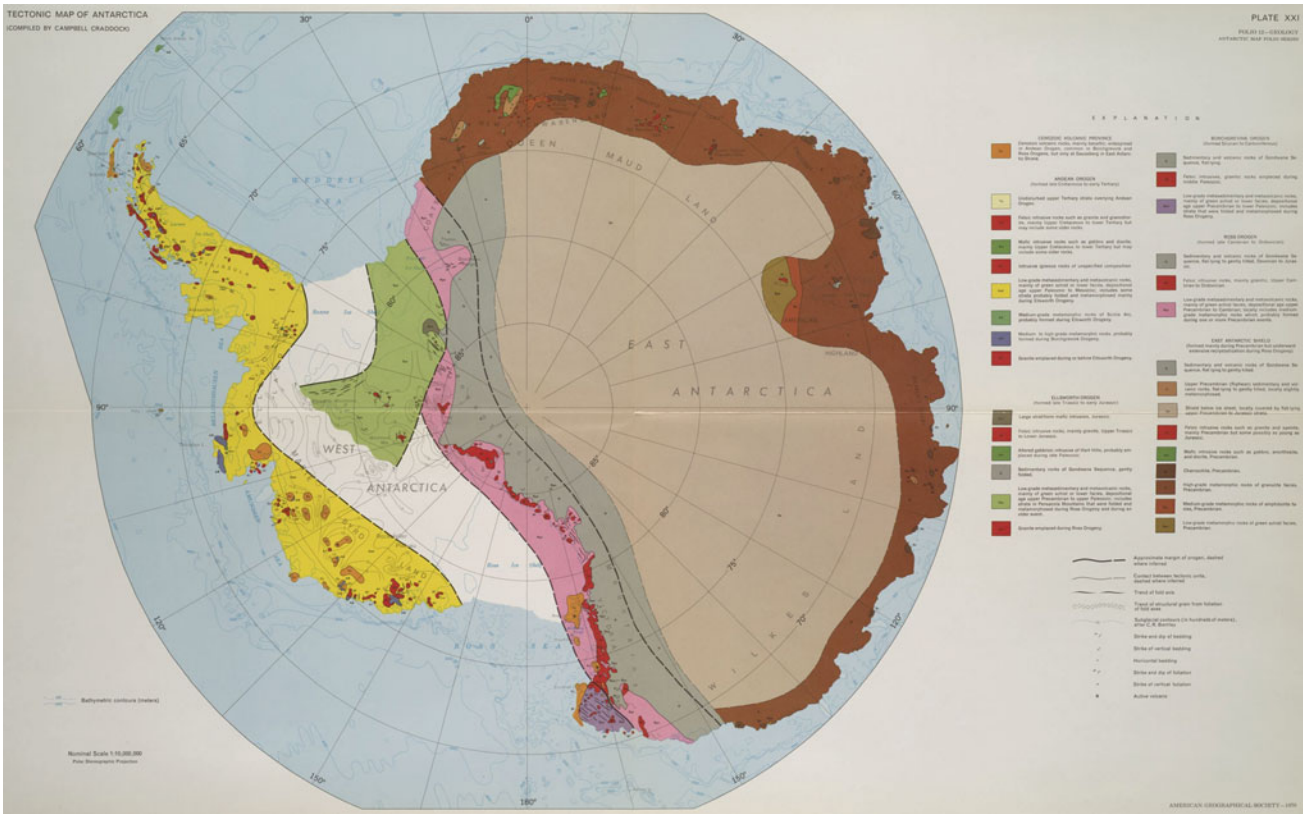

Fig. 2.9 Bedrock geology of Antarctica (Craddock et al. 1969). The major rock units from left to right (low-grade metasedimentary and metavolcanic rocks mainly of green schist of upper Paleozoic to Mesozoic age (*yellow*); low-grade metasedimentary and metavolcanic rocks mainly of green schist of upper Precambrian to upper Paleozoic age (*green*); low-grade metasedimentary and metavolcanic rocks mainly of green schist of probably Precambrian age (*pink*); sedimentary and volcanic rocks of Gondwana Sequence of Devonian to Jurassic age (*gray*); shield below ice sheet locally covered by flat-lying upper Precambrian to Jurassic strata (*light brown*); and medium-grade metamorphic rocks of amphibolite facies of Precambrian age (*dark brown*)

processes such as salinization, desert pavement formation, and permafrost accumulation increased along this gradient (Figs. 2.11 and 2.12).

Campbell and Claridge (1969) offered a similar scheme that emphasized decreasing soil moisture availability from the coast inland. Zonal (Frigic) soils of Antarctica included strongly developed subxerous soils in coastal areas, moderately developed xerous soils in dry valleys, and weakly developed ultraxerous soils along the polar plateau. Evaporite soils, algal peats, avian soils, and hydrothermal soils were recognized as intrazonal and recent soils as azonal. Since their initial zonal soil classification scheme, we have come to recognize that soils in coastal areas often contain a shallow permafrost table and are subject to considerable cryoturbation, and some of the most strongly developed soils occur not only in the valleys but also on Miocene-aged surfaces along the edge of the polar plateau.

The *Seventh Approximation* (Soil Survey Staff 1960) was a precursor to *Soil Taxonomy* (ST). It was not until 1999 (Soil Survey Staff 1999) that weathered materials in

Table 2.4 Weathering stages following Campbell and Claridge (1975)

Weathering stage	Surface rock characteristics	Soil color	Horizon development	Soil salts
1	Fresh, unstained, coarse and angular	Pale olive to light gray 5Y 6/3–7/2	Nil	Absent
2	Light staining, slight rounding, some disintegration	Pale brown gray 10YR 6/3–2.5Y 6/2	Weak	Few flecks
3	Distinct polish, staining and rounding, some cavernous weathering some ventifacts	Light yellowish brown 10YR 5/3–2.5Y 6/4	Distinct	Many salts flecks in upper part of profile and beneath the surface
4	Boulders much reduced by rounding, crumbling and ventifaction, strongly developed cavernous weathering; staining and polish well developed; some desert varnish	Yellowish brown in upper horizons (10/YR 5/4) paler in lower horizons	Very distinct	In discontinuous or continuous horizon beneath surface
5	Few boulders, many pebbles forming pavement, extensive crumbling, staining, rounding, pitting and polish	Dark yellowish brown to yellowish red 10YR 4/4–5YR 5/8	Very distinct	In horizon 20–30 cm from surface and scattered throughout profile
6	Weathered and crumbled bedrock, very strongly stained mainly residual	Strong brown to yellowish red and dark red 7.5YR 5/6–2.5R 3/6	Very distinct	In horizon 20–30 cm from surface and scattered throughout profile

Table 2.5 Morphogenetic salt stages in Antarctic soils (Bockheim 1997)

Salt stage	Morphogenetic form	EC (dS/m)	Approx. age
0	None	<0.6	<10 ka
1	Coatings beneath stones	0.6–5.0	10–18 ka
2	<20 % of horizon with flecks 1–2 mm	5.0–18	18–90 ka
3	>20 % of horizon with flecks 1–2 mm	18–25	90–250 ka
4	Weakly cemented salt pan	25–40	250 ka to ~1.7 Ma
5	Strongly cemented salt pan	40–60	−1.7 to 3.9 Ma
6	Indurated salt pan	60–100+	≳3.9 Ma

Antarctica were recognized as soils, and these soils were incorporated into ST. As will be seen in individual chapters, most of the soils in Antarctica are classified as permafrost-affected soils, or in the Gelisol order. The Gelisols are subdivided into three suborders, the Histels (organic soils underlain by permafrost), Turbels (cryoturbated mineral soils underlain by permafrost within 2 m of the surface), and Orthels (non-cryoturbated mineral soils underlain by permafrost within 1 m of the surface). The Turbels and Orthels are furthered separated into Hist-, Aqu-, Anhy-, Moll-, Umbr-, Psamm-, and Hapl-great groups, based on key soil features. Anhyorthels and Anhyturbels are particular importance in the interior mountains of Antarctica because of anhydrous conditions. Soils with anhydrous conditions typical receive less than 50 mm year^{-1} of water-equivalent precipitation and have "dry-frozen" permafrost and

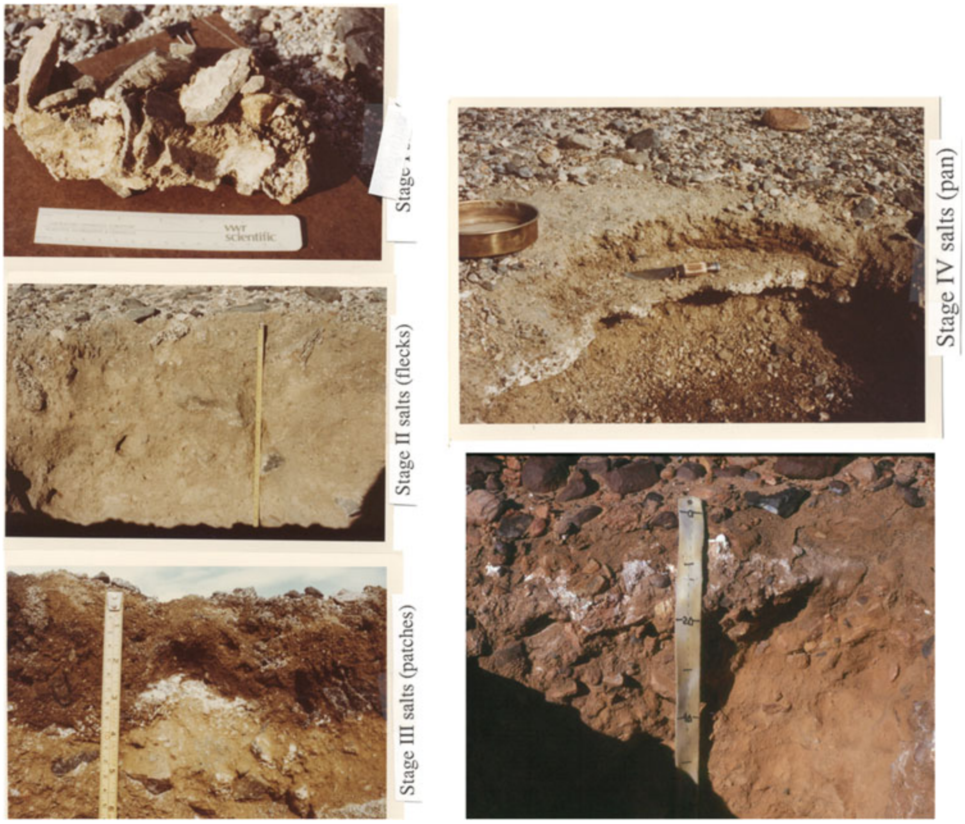

Fig. 2.10 Morphogenetic stages of salt development in Antarctic soils: *Stage I* coatings beneath stones (*upper*, *left*); *Stage II* salt flecks covering less than 20 % of soil area (*middle*, *left*); *Stage III* salt flecks covering more than 20 % of soil area (*lower*, *left*); *Stage IV* weakly cemented salt pan (*upper*, *right*); *Stage V* strongly cemented salt pan at 5–30 cm depth (*lower*, *right*; see also Table 2.5). Photos by J. Bockheim

Table 2.6 Soil profile dataset for Antarctica

Region	Name	Investigator (pedons)	Total
1	Queen Maud	Matsuoka (19); Gajanda (14); Zazovskaya et al. (34)	67
2	Enderby Land	MacNamara (11); Dolgikh et al. (80)	91
3	MacRobertson Land	Mergelov et al. (50); Zhu et al. (9)	59
4	Wilkes Land	Bolter et al. (23)	23
5a	Victoria Land (TAM)	Campbell and Claridge (898); Bockheim (731); McLeod and Bockheim (132); NRCS (8)	1769
5b	Victoria (Pensacola)	Cameron and Ford (6); Parker et al. (7)	13
6	Ellsworth Mtns.	Bockheim (22); Campbell and Claridge (23); Schaefer (30)	77
7	Marie Byrd Land	Lupachev et al. (15)	15
8	Antarctic Peninsula	Schaefer et al. (220); Navas (15); Haus and Bockheim (88); Bölter et al. (17)	–
		O'Brien (3); Everett (18); Holdgate (17)	378
Total			2492

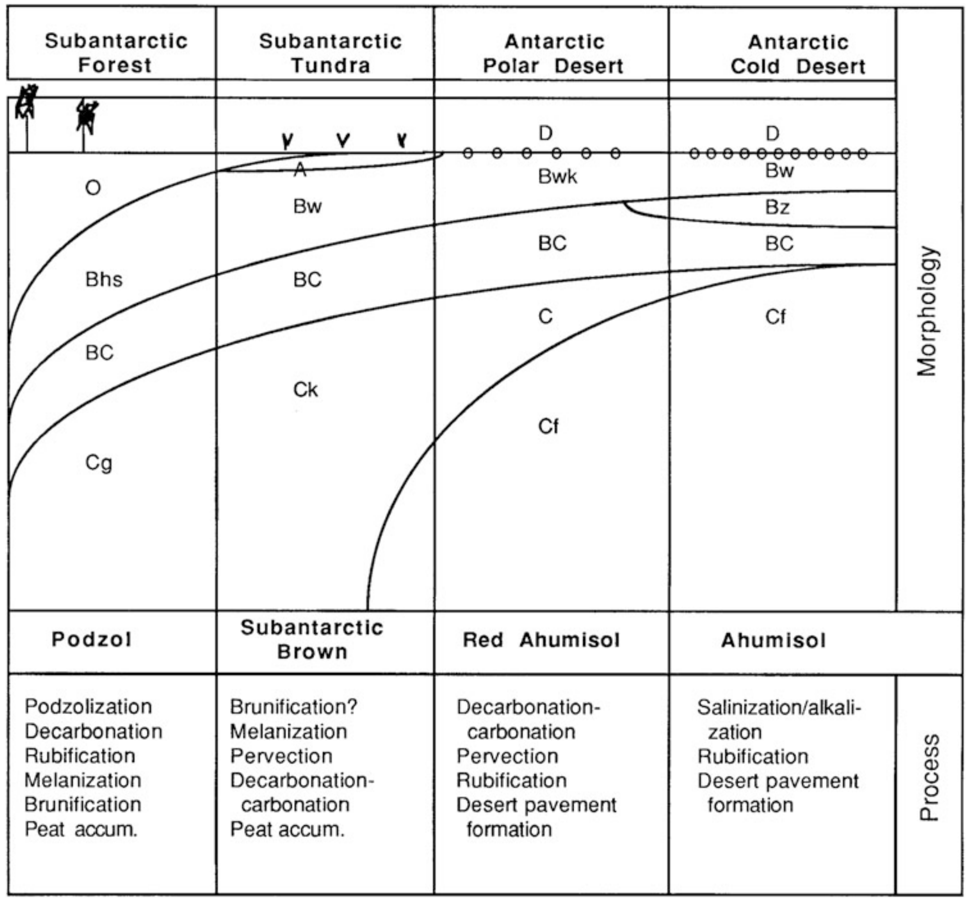

Fig. 2.11 Generalized soil horizonation and soil-forming processes in the Southern Circumpolar Region (Bockheim and Ugolini 1990)

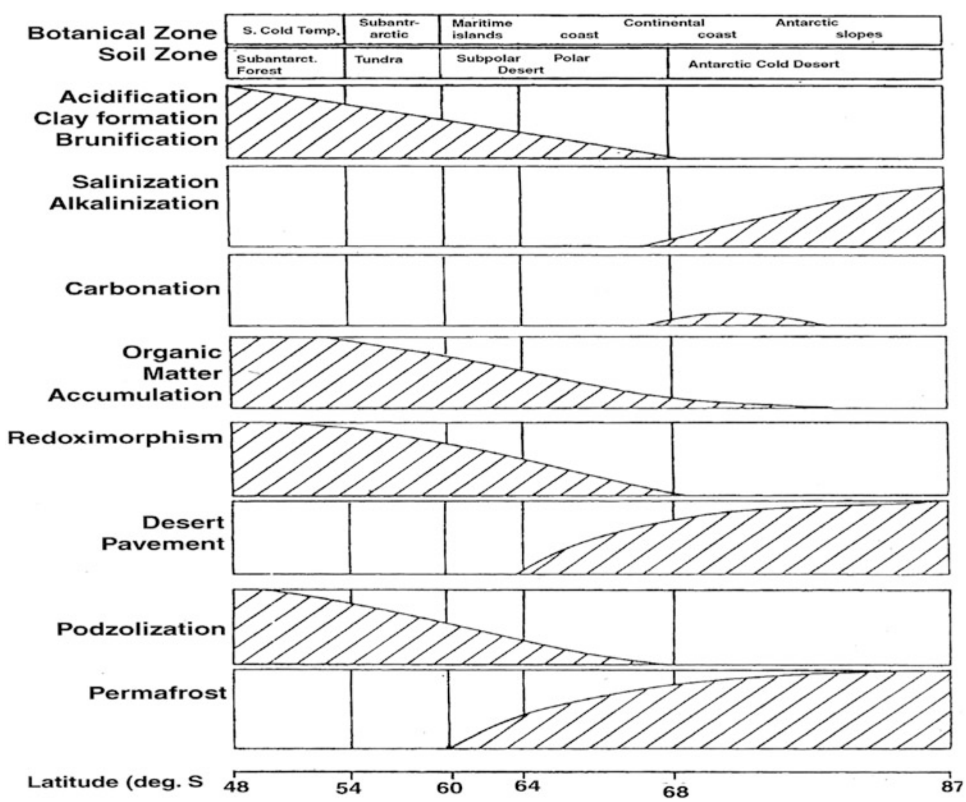

Fig. 2.12 Changes in pedogenic processes along a latitudinal transect in the Southern Circumpolar Region (Bockheim and Ugolini 1990; modified by Blume et al. 1997)

a moisture content of less than 3 % by weight. Although Gelisols are ubiquitous in Antarctica, other soil orders occur along the western Antarctic Peninsula, including Entisols, Inceptisols, Histosols, and Spodosols.

A key for classifying soils of Antarctica in ST was developed by the ANTPAS group and is contained in Appendix 2.

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3 Soils of Queen Maud Land

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3.1 Introduction

Queen Maud Land (QML) or Dronning Maud Land is that part of Antarctica between longitudes 20° W and 45° E (region 1; Fig. 2.1). QML is the fourth largest ice-free territory of Antarctica, comprising 3,400 km^2 (6.9 % of total ice-free area). The predominant ice-free areas are the Mühlig-Hoffmann and Wohlthat Mountains (Fimbulheimen) and the Sør Rondane Mountains, each comprising 900 km^2 (Table 2.1). The most studied areas of QML in terms of soils include the Sør Rondane Mountains and Schirmacher Oasis (35 km^2). The main research stations in QML are Neumayer (Germany), Sanae (South Africa), Maitri (India), and Novolazerevskaya (Russia).

The first soil scientist to visit this region was E.E. MacNamara, who concluded that soils of the Schirmacher Oasis were poorly expressed (Campbell and Claridge 1987). German scientists began to systematically research landscape geochemistry and chemical weathering at Schirmacher Oasis in the 1980s (Krüger 1987, 1989; Balke 1988; Balke et al. 1991; Bormann and Fritzsche 1995). Russian soil research in the oasis began in 2009 and is ongoing. The Sør Rondane Mountains were studied during the 1990s by Matsuoka and his colleagues (1995, 1996). The Gjelsvikfjella and Mühling-Hofmannfjella Mountains have been studied by Norwegian scientists (Engelskjøn 1986).

The objectives of this chapter are to assemble soils data from QML and interpret these data regarding the likely soil taxa and the factors controlling their distribution. Results of a detailed soil study in the Schirmacher Oasis (70°45′S, 11°37′ E) are presented here (Zazovskaya et al. unpublished). We also used published data from the Sør Rondane Mountains (71° 50′−72° 20′ S, 24–24° E) and the Gjelsvikfjella and Mühling-Hofmannfjella Mountains (72° 00′ S, 05° 20′ E).

3.2 Study Area

3.2.1 Location and Topography

Schirmacher oasis is located in the central part of the QML along the Princess Astrid Coast 90 km south of the Lazarev Sea (Figs. 3.1 and 3.2). The total length of oasis is 18 km and its width varies from 0.6 to 3.5 km. The territory stretches in a sub-latitudinal direction along the slope of the continental ice shelf. From the north the oasis borders the Lazarev Ice Shelf, which separates it from the sea. The Schirmacher oasis contains hummocky terrain, with the hills ranging from 10 to 110 m in relief. The highest point is Mt. Rebristaya at 228 m.

The Sør Rondane Mountains are located 200 km inland from the Haakon VII Sea. The mountains rise up to 1,500 m above the ice sheet surface. The highest point is Mt. Gjelsvikfjella (3,000 m a.s.l.), which is located 220 km from ice shelf margin and 100 km inside the hinge line of the ice shelf. Other high peaks are in the Risemedet Range, with summits between 2,471 and 2,704 m a.s.l. The lowest exposed ground is in the bottom of the Jutulsessen Amphitheatre, 1,080 m a.s.l., which is the most extensive non-glaciated area on this part of the Antarctic slope.

The Mühling-Hofmannfjella Mountains extend west to east approximately 200 km from the ice shelf margin and 130 km inside the hinge line. The highest summit is Mt. Kyrkjeskipet (3,083 m a.s.l.). The lowest rock exposures are nunataks to the north, which range between 1,334 and 1,661 m a.s.l.

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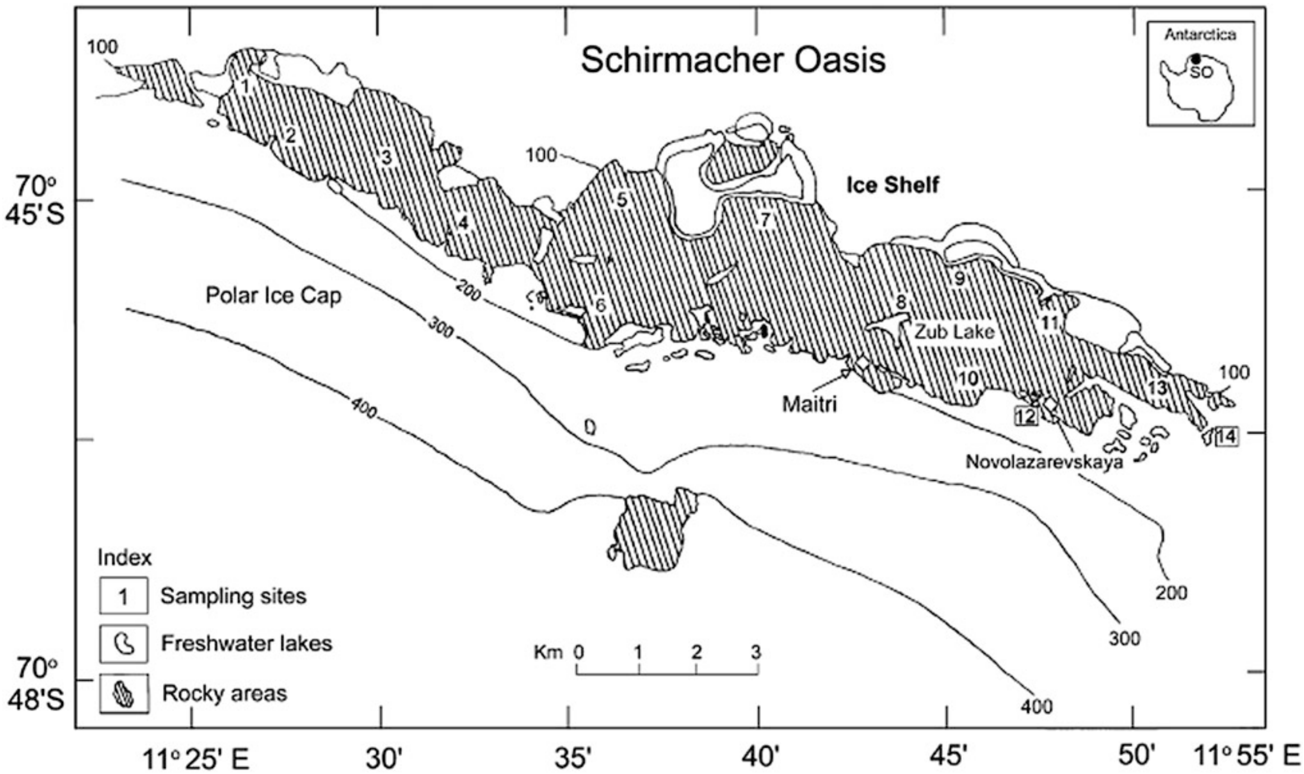

Fig. 3.1 Schirmacher Oasis, East Antarctica (Gajananda 2007)

Fig. 3.2 Novolazarevskaya (Russia) station at the Schirmacher Oasis

3.2.2 Climate

Schirmacher oasis is one of the coldest Antarctic oases, because of its high latitude and trans-shelf location and because it is surrounded by ice. The mean annual air temperature at Novolazarevskaya station is −10.3 °C; the temperature of the coldest month (August) is −17.9 °C, and the temperature of the warmest month (January) is −0.4 °C. In warmer years the monthly mean temperatures of December and/or January can be positive. The absolute minimum temperature over the period of observation (1961 to present) was −44.4 °C, and the maximum was 9.9 °C. At low temperatures during the summer period, the soil surface is warmed from the intensive solar radiation. On north-facing slopes, rock temperatures of 41.0–42.6 °C were recorded (Kruchinin and Simonov 1967; Bormann and Fritzsche 1995). We observed soil surface temperatures between 25.5 and 35.9 °C.

The mean annual wind speed is about 10 m s^{-1}. During the summer wind speeds can reach 30–35 m s^{-1} and in winter 50–55 m s^{-1}. The mean annual precipitation is 240 mm, but it is only 10 mm during the summer months of December and January. Evaporation rates vary from 350 to 590 mm $year^{-1}$ (Verkulich et al. 2011; Bormann and Fritzsche 1995). The aridity of the region is due to the positive radiation balance, the low amounts of precipitation and humidity, strong winds, and high evaporation rates.

The mean annual air temperature at Asuku Station (Japan) near the north end of the mountain massif is −18.4 ° C, with extremes of slightly above 0 and −40 °C. The adiabatic temperature lapse rate is about 10 °C km^{-1}. The mean annual air temperature on the highest mountain is presumed to be close to −40 °C (Matsuoka et al. 2006; see also Fig. 2.5). Katabatic winds from the polar plateau are strong in the mountains.

Based on measurements at Camp Norway 5, the average temperature in January in the Mühling-Hofmannfjella Mountains is −8 °C. From a few observations, the adiabatic lapse rate is 0.65 °C 100 m^{-1} in the Mühling-Hofmannfjella Mountains (Engelskjøn 1986). Environmental factors which contribute to a special mountain climate include the modest cloud cover, high altitudes, and intensive solar radiation.

3.2.3 Parent Materials and Age

The bedrock of the QML is part of the East Antarctic Shield, which is characterized by the predominance of Precambrian metamorphic and magmatic rocks (Fig. 2.10). Schirmacher oasis comprises Precambrian metamorphic rocks, including gneisses and crystalline shale. Ultramafic intrusive bodies and numerous pegmatite veins, including rarely aplite, are locally found.

Schirmacher Oasis was glaciated at least three times (Makeev 1972). Sediments in large lake depressions have been radiocarbon dated at 18–30 ka (Schwab 1998). However, soil development suggests that geomorphic surfaces are only several thousand years old. The recession of ice began in the early Holocene and had three phases, with the main phase at 6.7–2.2 ka BP (Verkulich 2011).

The Mühling-Hofmannfjella and Gjelsvikfjellaa Mountains are derived from an Archean basement complex of gneiss and charnockite (Ravich and Soloviev 1966). Metamorphic rocks range from an amphibolite facies in the west to a mainly granulite facies in the east; the lithology varies from granitic to gabbroid.

The Sør Rondane Mountains consist predominantly of metamorphic and plutonic rocks of the Late Proterozoic to Early Paleozoic age, including gneisses, granites, amphibolites, and diorites. The mountains are mantled with glacial deposits that have been subdivided into five stages, based on weathering features, elevation, and numerical dating. From cosmogenic dating (^{3}He, ^{10}Be, ^{26}Al, ^{36}Cl), the tills are <0.25, 0.5–1.6, 1.6–3, 3–4, and >4 Ma in age (Moriwaki et al. 1992).

The study area is underlain by continuous permafrost. The mountains are underlain by thick permafrost; and active layer ranges from 8 to 40 cm in depth (Matsuoka 1995). The active layer in the Schirmacher oasis ranges from 30 to 120 cm in depth.

3.2.4 Biota

The terrestrial flora in the Schirmacher Oasis has received considerable attention (Richter 1990; Bormann and Fritzsche 1995; Ochyra et al. 2008). The biota has been studied in other areas of the QML, including the Mühling-Hofmannfjella and Gjelsvikfjellaa Mountains (Engelskjøn 1985, 1986), the Syowa station area (Yamanaka and Sato 1977), and the Sør Rondane and Vestfjella Mountains (Dodge 1962; Lindsay 1972). Flora of the Schirmacher oasis comprises 57 species of lichens (Olech and Singh 2010), 13 species of mosses, and numerous soil algal species (Kurbatova and Ochyra 2012). The mountain flora is composed of isolated algae, lichens, and mosses.

3.3 Methods

3.3.1 Field

We described and sampled soils in the Schirmacher Oasis (70° 45′ S, 11° 37′ E) in accordance with the ANTPAS guidebook (Bockheim et al. 2006). Field measurements included single determinations of soil-moisture content during the summers of 2009 and 2010 at seven sites; end-of-season active-layer depth using a probe at 15 stationary points during the summers 2009 through 2012; and soil temperature was monitored for a period of 3 years (March 2009–February 2012) on six different landscapes using data loggers installed at depths of 0, 10, 20, and 50 cm and at the bottom of the active layer.

The reaction with a 10 % solution of potassium hexacianoferrate (III) was used as a field test to identify FeII compounds in soil. The redox potential was determined in the field or on fresh samples immediately returned to the Novolazorevskaya Station using a millivoltmeter with an EPL-02 platinum electrode for measurement and an EVL-1M4 silver chloride electrode as a reference.

3.3.2 Laboratory

Laboratory analyses included particle-size distribution of the fine-earth (<1 mm) (Kachinsky method), loss-on-ignition at 900 °C, total organic carbon (AN-2 device), pH in water and KCl, residual acidity, exchangeable bases (Ca, Mg, Na, K), $CaCO_3$ equivalent, and gypsum content (Vorob'eva 1998; Page et al. 1994).

Macro- and microelement concentrations were measured using an X-ray crystal-diffraction spectrometer (Spectroscan-MAKS GV). Minerals were detected with X-ray diffraction. The surfaces of quartz grains from fine and medium sand fractions (100–250 and 250–500 μm) were studied under a CamScan scanning electronic microscope (Alekseeva 2005). We studied 25 randomly selected quartz grains from each sample; their chemical composition was confirmed by an X-Ray microanalyzer. Three groups of features were compared: (1) morphological (grain shape), (2) mechanical defects on the grain surface, and (3) features of chemical origin. Micromorphological observations were carried out using an Axioplan 2 (Karl Zeiss) polarizing microscope. The radiocarbon dating was conducted in the radiocarbon dating laboratory at the Institute of Geography, Moscow.

3.4 Results

3.4.1 Soil Moisture Regimes

Soil moisture was monitored at four sites arrayed along a slope leading into a depression in a small valley at Lake Krasnoe (moist site), including the lake basin (Point 1), a terrace immediately above the lake (Point 2), a moss-covered site above the terrace (Point 3), and a moss-covered side-slope (Point 4). Soil moisture was also monitored at three dry sites (Points 5, 6, and 7). The soils at these sites had a comparable particle-size distribution and were sands or sandy loams with a low water-holding capacity.

The moist areas of the oasis (P1–P4) experienced a gradual increase in moisture and reached a maximum in the middle of January at the time of maximal snowmelt. The highest moisture values were registered at the bottom of the hollow (P1): 10–20 % in December and 25 % and more, i.e., up to the maximal water-holding capacity in January. There was a slight decrease in moisture content in February. Perched water appeared during the beginning of thaw and persisted until complete freezing. High soil moisture values were due not only to snowmelt but also to a rise in the lake level. In January the perched water table rose up to 19–25 cm from the surface. As freezing progressed, the water concentrated within the top layer of the soil, where the ice content reached 170 %.

The soil on the terrace (P2) was drier than P1. The moisture content reached 9–12 % in December and 15–18 % in January. Perching of water occurred at a depth of 24–25 cm in the second half of January. There was a lower ice content (37 %) at P2 than at P1. The moss-covered site adjacent to a large snow patch above the lake terrace at Lake Krasnoe (P3) had moisture contents between 60 and 70 % in the organic horizons and 33–36 % in the mineral horizons of the soil in the middle of summer. Perched water appeared at 6–15 cm from the soil surface for 3 weeks in mid-January. As thawing slowed down by the end of January, the moisture content in the mineral horizons dropped to 9–13 %. At the end of thawing in mid-February, some features of drought developed with the moisture content falling to 13 % in the organic horizons and 6–9 % in mineral horizons.

The soil under moss on a side-slope (P4) also contained perched water during a short period from late December to early January, with the water table rising to a maximum of 12 cm from the soil surface. Following thawing of a small snow patch during the middle of January, the soil underwent dramatic desiccation with the organic horizons drying even quicker than the mineral horizons. From 9 to 22 January, the moisture content decreased from 91 to 9 % in organic horizons and from 25–28 to 6–15 % in mineral horizons. Later, the soil moisture content increased following a snowfall on February 7, 2010.

In all four moist profiles there was an excess of moisture during the summer periods in 2009 and 2010. The duration of these periods depended on topography, with an increase from the hill slope position to the bottom of the lake basin. Moreover, soils at the higher elevations lost moisture more quickly when snowmelt ceased and were more variable in moisture content over the seasons. At the bottom of the valleys and hollows, seasonal fluctuations in soil moisture were minimal, as was reported in previous studies (Bormann and Fritzsche 1995). Drainage was enhanced at the moss-covered sites (P3 and P4) due to a high stone content in soils, which contrasted with the terrace site (P2). The difference between the P3 and P4 was determined by not only the topographic position but also by the size of thawing snow patches.

The moisture content within the dry parts of the oasis (P5–P7) was at 0.7–2.5 % in early December. Following the snow fall on the 10 December 2009, the moisture content rose to 2.5–4.4 %; it remained at that level for several weeks until mid-January on the lake terrace (P5), late January at the top of the hill (P7) and early February on the steep slope (P6). The February snowfall resulted in an increase in soil-moisture content in the dry-ground areas. The other snowfall (07.02.2010) was lighter and did not lead to significant change in the soil moisture. The lake terrace contained permafrost that influenced moisture distribution within the active layer. The moisture content at the bottom of the active layer reached 7 %. Indeed, even dry soils are not absolutely dry and can provide a temporary medium for chemical and biochemical processes.

Differences in moisture conditions predetermined the variations in the active layer thickness and the temperature regime of soils and grounds within the Schirmacher Oasis. The seasonal thaw of permafrost began in late November and ended in late January to early February. Freezing of the active layer began in the middle of February. Then in late February to early March, the joining of freezing fronts takes place. The summer thaw and autumn freeze were rapid because of the absence of vegetation and snow cover over the dominant part of the land.

During the warm season the upper part of the active layer occasionally underwent overnight freezing. On sunny days in the second half of February the soils thawed in a day's time to a depth from 1–2 to 12–13 cm.

3.4.2 Active-Layer Dynamics

The average thickness of the active layer on wet sites during the summers of 2009–2011 varied from 63 to 94 cm. The deepest seasonal thaw of the wet grounds occurred within the lake basin. The maximal thickness of the active layer of 119 cm was registered on unconsolidated sediments of a rocky terrace with a northern aspect. Generally, the active layer thickness tended to decrease with increased elevation. The active layer reached its maximal thickness in late January to early February.

At the same time each summer, the dry parts of the oasis had temperatures above 0 °C within a depth range of 47–54 cm. A small amount of ice present within the profile melted by the middle of summer. Later in summer the permafrost table position did not change, due to the low thermal conductivity of dry ground as well as due to the absence of convectional heat influx, as there was no snow thaw water.

Positive temperatures at a depth of 20 cm stabilized in the rocky ground by the end of November, in the patterned ground of the lake terrace by late November to early December and in the dry grounds in the middle of December. In soil under moss the zero-degree isotherm reached the 20 cm depth even later, in the second half of December and in the second half of January in the summer of 2009–2010. Positive temperatures at a depth of 50 cm were observed in the rocky ground from the first half of December, in the moist patterned ground and the dry loam in early January, and in the dry sandy ground during a short period (5–6 days) in mid-January in two of the three years. The moist soil under moss did not thaw to the depth of 50 cm.

Negative temperatures at the 20 and 50 cm depths frequently occurred for several days during the summer in the dry grounds where the rocks have a low thermal capacity. That phenomenon was observed usually in December but also in January. At the beginning of the cold summer of 2011–2012, the negative temperatures at the 20 cm depth were registered on two occasions on the lake terrace with patterned ground (P2). Freezing to this depth in December could be caused by desiccation of the ground over the winter and also by the permafrost influence on the shallow active layer at that time of year. A similar phenomenon was reported during the summer of 1981–1982 (Vturin 1990).

The autumnal freezing at the sites began during the second half of February, but developed at different rates. In the dry grounds and rock there was a rapid establishment of negative temperatures by middle to late February. In wet soils under moss (P3, P4), the period of the autumnal "zero curtain" lasted from 10 to 15 days, and freezing was completed by the end of February to the beginning of March. In the wet patterned ground site (P2) with a thick active layer, the "zero curtain" persisted for 9–15 days at the 20 cm depth and up to 3 weeks at the 50 cm depth. Freezing was not complete at P2 by the first half of March. In all of the profiles except for the rock, there was an annual freezing (subzero temperatures) in the lower part of the active layer, as was previously observed by Vturin (1990). This freezing was related to a low average temperature of the permafrost registered at the 2 m depth in January at the two boreholes: from −3.0 to −3.9 °C and from −2.6 to −3.2 °C. The active layer began to freeze from underneath in January, i.e., much earlier than freezing from above and continued to join the freezing fronts.

At the 20 cm depth in rock (P1), the patterned ground site (P2), and the dry loam site (P5), there were positive mean temperatures in December, January, and February for the 3 years of observation. In the soil under moss (P3) only the mean temperature of January and February remained positive, while the mean December temperature could be either positive or negative. In the dry sandy ground (P6) there were alternating positive and negative temperatures both in December and February. At the 50 cm depth, a positive mean monthly temperature was found only within the rock profile (P1), only in December, and not every year. In the patterned ground site, the mean January and February temperatures were positive, while in dry loamy ground (P5) only the mean January temperature was positive. In other cases (P3 and P6) the mean temperature values were negative for all the 3 months.

Positive temperatures at the 20 cm depth lasted for the following periods: 75–84 days in the rock, 67–84 days in the wet ground, 59–76 days in the dry ground, and only 27–56 days in soil under moss. Positive temperatures at the 50 cm depth lasted for 63–73 days in the rock, 35 days in the wet ground, 32 days in the dry loamy ground, and 0–6 days in the dry sandy ground.

Because of its high thermal conductivity, the rock at the top of the hill (P7) was the warmest during the summer. The mean temperatures of the three summer months (December through February) at the 20 cm depth were as follows: 2.3 °C on the rock, 2.2 °C in the wet patterned ground, 1.6 °C in dry loamy ground, and 0.6 °C in dry sandy ground as well as in soil under moss. The mean temperatures of the three summer months at the 50 cm depth were negative in all the cases except for the rock.

January was the warmest month of the year with the mean monthly temperatures varying by 2.2 °C at the 20 cm depth and 3.3 °C at the 50 cm depth. There was little difference between the mean January temperatures in the wet and dry loamy grounds. There was a higher temperature at 20 cm in the wet soil under moss than in the dry sandy ground.

Mean daily temperatures above 5 °C at the 20 cm depth were observed in December and January in the rock, wet patterned ground, and for two of the three summers in dry loamy ground. The mean number of days with temperatures above 5 °C was as follows: 13 in the rock, 9 in wet areas, and 5 in the dry loamy ground. These temperatures did not occur in the dry sandy ground and in the soil under moss, although they were registered in the latter at the 10 cm depth in the summer of 2010–2011. Temperatures at the 50 cm depth did not rise above 5 °C at any of the sites. However, temperatures above 10 °C were registered at the 10 cm depth at some sites and even at the 20 cm depth according to other investigators (Balke et al. 1991; Richter 1990; Bormann and Fritzsche 1995).

Our study of the temperature regime revealed that the dry grounds were colder than the wet grounds within the Schirmacher oasis. The dry grounds varied markedly in temperature. The loamy ground was warmer than the sandy ground, because it had a higher density and, hence, higher thermal conductivity.

3.4.3 Soil Formation

Pedogenic transformations were compared and contrasted among moss-covered soils, algae-influenced soils, soils with patterned ground and variable amounts of vegetation cover, and soils on dry ground within the Schirmacher Oasis.

3.4.3.1 Soil Formation Under Moss Cover

Large areas of moss covering from 45 to 95 % of the surface were, as a rule, found close to snow patches that occurred on the hill slopes and within the upper reaches of the valleys. Therefore, the moss communities were usually found at the periphery of the valleys, by the foothills and less commonly at the slopes. The parent rocks were stony sands and two-layered deposits consisting of sand and sandy loam layers. Even on the most homogeneous substrates there were coarser particles concentrated within the upper part of the profile, which could be explained by aeolian input as well as by cryogenic sorting of the particles.

The mineralogical analysis of one of the profiles (pit FDG-09-14) revealed that the main components of the 50–100 μm fraction were as follows (in order of decreasing abundance): quartz, plagioclases (anorthite and oligoclase), amphiboles (riebeckite and crocidolite), vermiculite, and mica (biotite). The mineral composition of the <50 μm fraction was generally similar with higher proportions of clay minerals (mica and vermiculite) and also a small amount of kaolinite. Microscopic analysis of quartz grains in one of the profiles (Fig. 3.3) shows a dominance of grains with very angular and angular outline (70–95 % in total). There were conchoidal fractures of various sizes, straight and arcuate steps as well as fracture-plates on the grain surfaces. Some grains (up to 30 % of the total) also had straight grooves. Most of the grains had pre-weathered surfaces. Grains with features of fluvial or aeolian transport were extremely rare. Judging from the combination of features revealed, the sand particles were the products of weathering of the bedrock partly altered by glacial processes.

The mineralogical data were comparable to micromorphological observations. Minerals in thin sections were represented by sand particles with some fine gravel, mostly angular, derived from granite and gneiss: quartz, acid plagioclase, potassium feldspar, biotite, and garnet. All of these minerals except for biotite, were intact. A lack of sorting and the angular shape of the grains were indicative of a short-term and short-distance transport. Biotite had typical weathering features—splitting along cleavage and bending edges of plates (Fig. 3.4).

Soils under moss communities were the only soils with a well-developed organogenic profile within the Oasis, despite the summer temperatures under the moss being significantly lower than in the wet bare ground, and the period of time suitable for pedogenesis being significantly shorter.

The soil profile under moss included several horizons (Fig. 3.5). The 'litter' horizon (O) was from 0.2–0.3 to 1.0–1.5 cm thick and consisted of dead parts of mosses that still retained their anatomic structure and abundant sand grains of

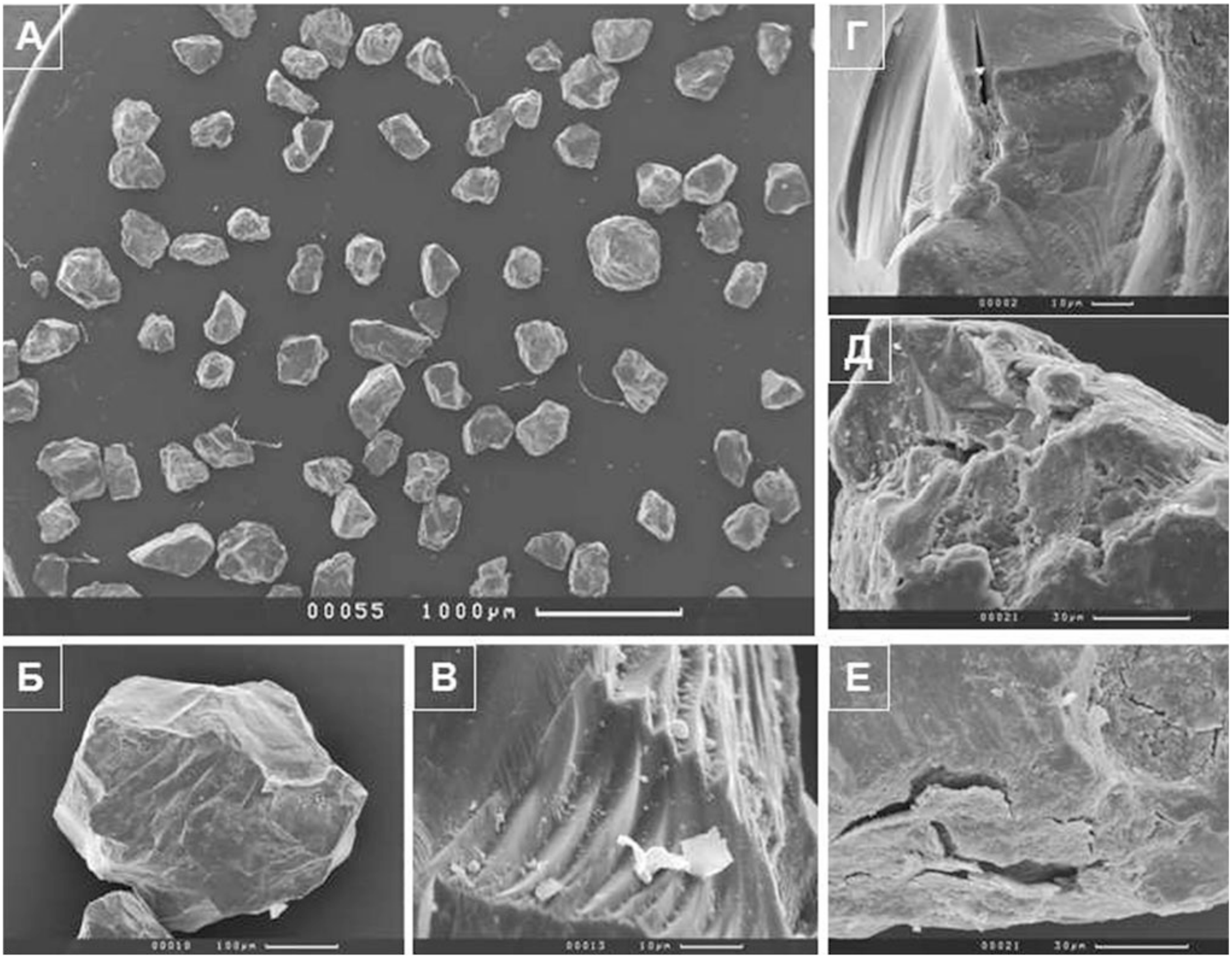

Fig. 3.3 Morphology of quartz grains from soils of the Schirmacher Oasis

Fig. 3.4 Weathering of biotite in a soil from Schirmacher Oasis

aeolian origin. The litter was usually underlain by fragmentary (separate lenses and pockets) dry peat, the TJmr horizon, from several millimeters to 2.5–3.0 cm thick, which was also rich in mineral matter. These organogenic horizons were underlain by an organo-mineral TB horizon that consisted of sand with living and dead rhizoids of moss. The TB horizon often filled in the spaces between the fragments of the TJmr horizons or, more rarely, occurred under the latter. The O, TJmr, and TB horizons usually contained sand-sized grains of light-colored minerals devoid of iron oxide films. In half of the studied profiles these bleached grains formed fragmentary layers and lenses 3–5 mm thick between the organogenic horizons and sand layer, i.e., primitive albic horizons. The TB and B horizons often contained small lenses of peat from moss residues. The B mineral horizon and the mineral component of the TB horizon were differentiated from the parent material by a browner color or more intensive yellow hue. Similar profile differentiation by color

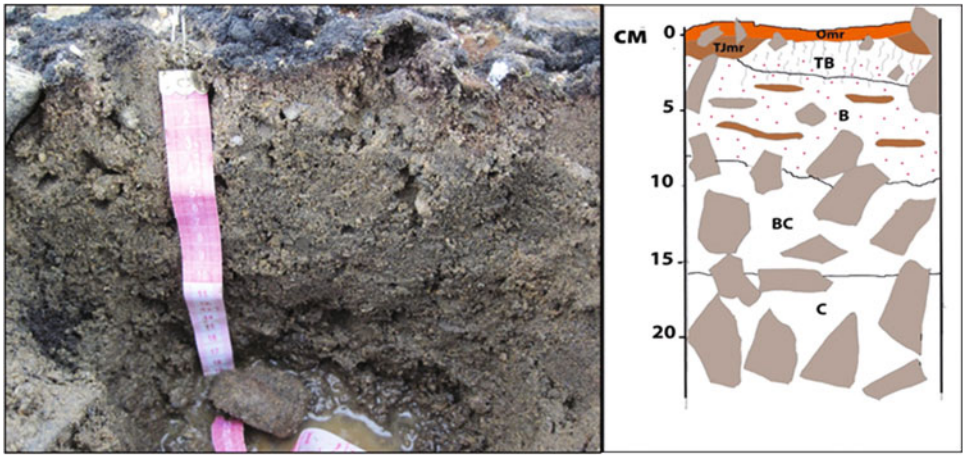

Fig. 3.5 Soil under moss cover at Schirmacher Oasis

was described in earlier studies (Balke et al. 1991; Bormann and Fritzsche 1995). Further down the profile there was a BC mineral horizon that is transitional to the bedrock. The boundaries between the mineral horizons were usually gradual and rarely clear, in some profiles only the BC horizon was distinguishable. The TB, B, and BC horizons often contained sand grains covered by thick brown and yellow-brown films that sometimes accumulated in form of lenses. The total thickness of soils under moss varied from 9–11 to 25–30 cm.

The soils under moss have a micromorphological feature of particular interest. That feature is the spatial arrangement of organic (living and dead) and mineral components within specific bio-abiotic microstructures. Moss tissues form a porous matrix with the cells filled by mineral matter (Fig. 3.6). This organo-mineral mat has microzones where moss tissues are dead and partly decomposed with features of fragmentation, loss of cellular structure and darkening in color. Dark brown isotropic organic films develop over the mineral films within those microzones. The formation of such structures is probably important for stabilizing the fine earth under extremely severe climatic conditions with intense erosion and re-deposition processes. Sometimes such structures concentrate not only sandy but also clay material. Similar observations earlier (in the 1940s and 1950s) probably led to a hypothesis of clay mineral synthesis by lichens (Glazovskaya 1958). In our opinion, clay minerals occur within lichen crusts and moss due to more favorable conditions for ferruginous clay material fixation and stabilization at the surface of sand particles immobilized by the lichen and moss tissues. The terms "organogenic" and "organo-mineral" horizons are used conventionally. The organic component proportion by weight is low because of the high content of sand. The losses on ignition within the O horizon are from 6.5 to 28.7 %, TJmr—from 3.0 to 9.4 % and TB—from 0.7 to 4.9 % (Fig. 3.7). It should be also emphasized that non-decomposed moss residues determine the nature of these horizons and their processes.

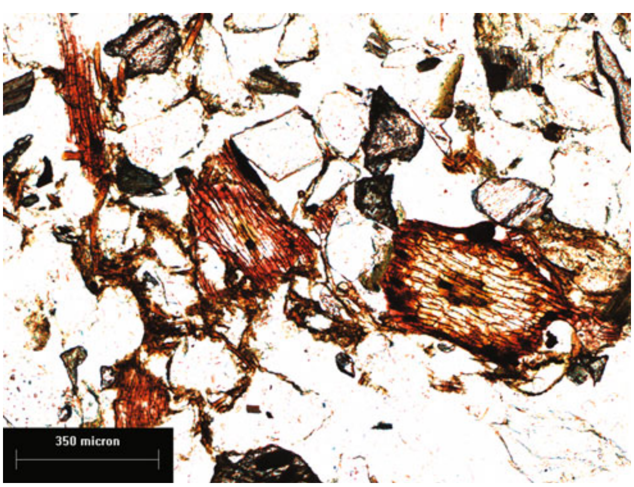

Fig. 3.6 Moss tissues form a porous carcass with the cells filled by minerogenic matter

The organic carbon distribution is as follows: 2.7–13.6 % in the litter, 0.4–2.1 % in the TB horizon, 0.17–0.62 % in the B horizon, and 0.02–0.25 % in the BC horizon (Fig. 3.7). The bedrock usually does not contain organic matter. Three radiocarbon dates were obtained for the lower part of the organogenic layer, with the deepest dry peat horizon dated at 400 ± 30 BP.

Cold water coming from melting snow patches is usually rich in oxygen, hence oxidation conditions, weak to strong, persist within the profile despite prolonged periods of saturation. The redox potential varies from 422 to 613 mV. There are no redoximorphic features of gleying.

The presence of bleached grains of light-colored minerals is indicative of general similarity of soil formation under mosses. In comparison with bare grounds, soils under moss communities have generally higher active and exchangeable acidity (Table 3.1) with significant differences in acidity parameters between the profiles studied. The differences are

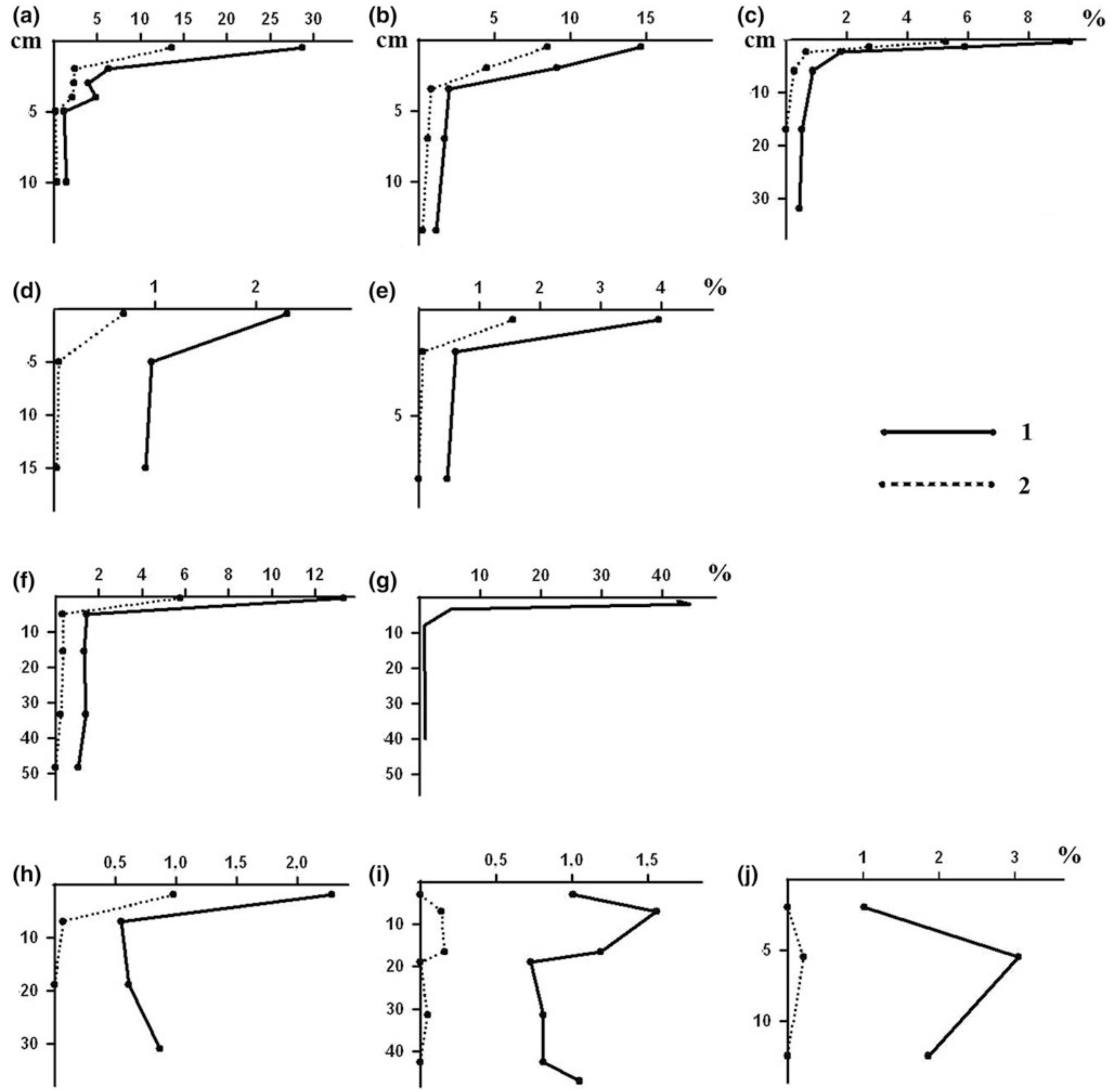

Fig. 3.7 Depth-distribution of loss-on-ignition (1) and soil organic carbon (2) for soils in the Schirmacher Oasis, including soils under moss cover (**a**–**c**), algae (**d**–**e**), a soil on a hillock (**f**), a soil in a depression (**g**), a soil on patterned ground (**h**), and soils on dry ground (**i**–**j**)

to a certain extent predetermined by the size and total cover of moss community. Besides, lower acidity and higher degree of saturation of the soil exchange complex are typical for soils derived from two-layered (bisequal) parent materials, where the lower layer of sandy loam is rich in exchangeable bases (primarily calcium) that can neutralize acidic products of pedogenesis.

Residual acidity decreases with depth, with values distributed as follows: 1.9–8.9 in the O horizon, 1.0–2.2 in the TB horizon, 0.2–1.8 in the mineral horizons, and 0.4–0.8 meq 100 g^{-1} ($cmol_c$ kg^{-1}) in the bedrock. Sandy and sandy-loam ground without features of soil formation have a residual acidity from 0.3 to 0.6 meq 100 g^{-1}.

Soil formation under mosses results in the accumulation of exchangeable bases, primarily calcium and magnesium, in the organogenic horizon. However, the base cations are leached from the mineral horizons, where their concentration decreases to minimal values found in soils and ground of the Oasis. In many profiles the upper mineral horizon (B) becomes impoverished in exchangeable bases and, therefore,

Table 3.1 Some chemical properties of Schirmacher Oasis soils

Horizon	Depth (cm)	pH		Residual acidity, mg-egv./100 g	Exchangeable bases, mg-eqv./100 g				Exchangeable cations, мг-экв./100 г	Unsaturation of the SEC (%)	CO_2 $_{carbonate}$ (%)	SO_4 gypsum (%)	K_2O (%)
		H_2O	KCl		Ca^{2+}	Mg^{2+}	Na^+	K^+					
FDG-09-03 (*soil under moss cover*)													
O	0.0–0.5	5.18	5.04	8.91	15.25	7.32	5.14	3.17	39.79	22.4	1.27	–	127.71
$TJmr_1$	1.0–2.5	5.72	5.28	–	–	–	–	–	–	–	0.84	–	–
$TJmr_2$	2.5–3.5	5.97	–	–	–	–	–	–	–	–	0.73	–	–
TB	0.8–2.0	5.72	5.11	2.23	2.51	1.00	0.17	0.31	6.22	35.9	0.62	–	19.06
B	3.5–6.0	5.84	4.67	1.57	1.10	0.60	0.03	0.10	3.40	46.2	0.62	–	6.25
BC	8–13	5.67	4.57	0.20	1.41	0.70	0.03	0.11	2.45	8.2	0.62	–	6.85
FDG-09-14 (*soil under moss cover*)													
O	0.0–0.5	4.84	4.52	5.98	9.10	3.27	2.43	1.05	21.83	27.4	0.85	–	–
TJ	0.8–2.0	5.20	4.42	–	6.49	1.62	0.36	0.54	–		0.63	–	–
TB	2–4	5.32	4.50	1.68	1.51	0.50	0.06	0.14	3.89	43.2	0.31	–	–
B	5–9	5.25	4.35	1.79	0.80	0.50	0.03	0.07	3.19	56.1	0.41	–	–
BC	11–16	5.48	4.54	–	0.40	0.30	0.03	0.05	–	–	0.31	–	–
FDG-09-25 (*soil under moss cover*)													
O	0.0–0.5	5.04	4.73	5.72	7.34	2.65	0.16	1.23	17.10	33.5	–	–	–
TJmr	0.7–2.0	5.25	4.68	–	–	–	–	–	–	–	–	–	–
TB	1.5–3.0	5.29	4.55	1.71	1.81	0.90	0.03	0.14	4.59	37.3	–	–	–
B	3.0–4.5	5.59	4.52	–	–	–	–	–	–	–	–	–	–
B	4.5–6.5	5.53	4.58	1.10	0.40	0.60	0.00	0.03	2.13	51.6	–	–	–
BC	8–12	5.65	4.61	–	0.30	0.40	0.01	0.03	–	–	–	–	–
BC	15–22	5.64	4.63	–	–	–	–	–	–	–	–	–	–
FDG-55-06 (*soil under moss cover*)													
O	0.0–0.5	5.31	4.74	4.99	7.51	2.03	0.96	0.86	16.35	30.5	0.84	–	38.49
TJ	1.0–2.5	5.42	4.53	3.36	5.05	1.92	0.32	0.62	11.27	29.8	0.63	–	–
TB	2–3	5.64	4.77	1.57	1.09	0.65	0.03	0.15	3.49	45.0	0.41	–	11.48
B	4–8	5.74	4.82	1.27	0.48	0.55	0.00	0.03	2.33	54.5	0.13	–	4.64
BC	11–20	5.79	5.00	1.08	0.58	0.65	0.00	0.00	2.31	46.8	0.41	–	3.24
C	25–34	5.88	5.25	0.83	0.85	0.45	0.00	0.00	2.13	39.0	0.41	–	3.69

(continued)

Table 3.1 (continued)

Horizon	Depth (cm)	pH		Residual acidity, mg-egv./100 g	Exchangeable bases, mg-eqv./100 g				Exchangeable cations, мг-экв./100 г	Unsaturation of the SEC (%)	CO_2 carbonate (%)	SO_4 gypsum (%)	K_2O (%)
		H_2O	KCl		Ca^{2+}	Mg^{2+}	Na^+	K^+					
FDG-55-07 (*soil under moss cover*)													
O	0.0–0.5	5.50	4.56	3.43	4.84	2.12	0.74	0.74	11.87	28.9	–	–	–
TB	1–3	6.09	4.53	1.03	0.70	1.00	0.13	0.16	3.02	34.1	–	–	–
BC	4–10	6.14	4.53	0.95	0.60	0.80	0.05	0.08	2.48	38.3	–	–	–
BC	10–22	6.06	4.97	1.08	0.50	0.70	0.04	0.08	2.40	45.0	–	–	–
FDG-55-13 (*soil under moss cover*)													
O	0.0–0.5	5.80	5.14	2.33	8.66	0.91	0.12	0.58	12.60	18.5	0.47	–	–
TB	1.5–3.0	6.67	5.37	0.63	1.91	0.50	0.04	0.12	3.20	19.7	0.62	–	–
BD	4–6	7.17	5.32	0.53	2.71	0.70	0.04	0.08	4.06	13.1	0.62	–	–
BD	7–15	7.20	5.37	0.58	3.22	0.60	0.03	0.11	4.54	12.8	0.78	–	–
FDG-55-16 (*soil under moss cover*)													
O	0–1	5.58	4.72	2.55	7.68	1.62	0.32	0.84	13.01	19.6	0.71	–	21.00
TB	1–3	5.98	4.58	1.04	1.03	0.80	0.01	0.08	2.96	35.1	0.39	0.006	7.28
B	4–6	6.40	4.60	0.61	1.05	0.85	0.00	0.05	2.56	23.8	0.54	–	5.41
BD	10–17	6.75	4.68	0.63	1.15	1.05	0.00	0.04	2.87	22.0	0.54	0.034	6.36
D	23–45	7.10	5.28	0.44	1.35	1.25	0.00	0.01	3.05	14.4	0.70	–	6.91
FDG-56-02 (*soil under moss cover*)													
O	0.0–0.5	5.70	5.09	3.44	7.58	1.52	0.53	0.37	13.44	25.3	1.02	–	17.73
TJmr	0.5–2.0	6.16	5.33	1.91	3.52	0.91	0.18	0.25	6.77	28.2	0.86	–	15.48
TB	1–3	6.35	5.29	–	–	–	–	–	–	–	0.78	–	12.19
BC	3–10	6.82	4.87	0.81	3.11	0.81	0.04	0.06	4.83	16.8	0.78	–	5.82
C	11–26	8.43	4.95	0.80	2.11	0.60	0.04	0.06	3.61	22.2	0.78	–	5.97
C	27–30	7.03	4.97	–	–	–	–	–	–	–	0.78	–	5.92
FDG-56-11 (*soil under moss cover*)													
O	0–1	6.11	5.78	4.02	14.11	3.35	1.18	1.42	24.08	16.7	0.94	–	–
TB	1–2	6.42	5.82	1.27	1.71	0.90	0.09	0.22	4.19	30.3	0.78	–	–
B	2–4	6.60	5.60	0.75	1.91	0.70	0.07	0.19	3.62	20.7	0.78	–	–
B	4–6	6.75	5.31	0.78	2.01	0.50	0.03	0.16	3.48	22.4	0.78	–	–
BC	7–11	6.75	5.14	0.76	2.31	0.40	0.03	0.14	3.64	20.9	0.62	–	–

(continued)

Table 3.1 (continued)

Horizon	Depth (cm)	pH		Residual acidity, mg-egv./100 g	Exchangeable bases, mg-eqv./100 g				Exchangeable cations, мг-экв./100 г	Unsaturation of the SEC (%)	CO_2 carbonate (%)	SO_4 gypsum (%)	K_2O (%)
		H_2O	KCl		Ca^{2+}	Mg^{2+}	Na^+	K^+					
BC	13–22	6.70	5.13	1.00	3.22	0.60	0.03	0.13	4.98	20.1	0.78	–	–
FDG-55-14 (*soil under moss cover*)													
O	0.0–0.5	–	4.46	2.70	3.92	0.81	0.08	0.36	7.87	34.3	–	–	–
TB	1.0–2.5	5.65	4.34	1.08	0.90	0.90	0.02	0.07	2.97	36.4	–	–	–
BD	3–9	9.81	4.84	0.53	1.91	0.60	0.03	0.09	3.16	16.8	–	–	–
D	10–25	7.05	5.13	0.46	1.71	0.80	0.03	0.10	3.10	14.8	–	–	–
FDG-09-07 (*soil under moss cover*)													
O	0–1	5.99	5.48	0.82	–	–	–	–	–	–	0.84	–	–
TB	1.0–2.5	6.36	5.57	0.66	0.81	0.60	0.29	0.28	3.64	18.1	0.52	–	–
BC	3–6	6.45	4.93	–	0.78	0.45	0.0	0.46	–	–	0.41	–	–
D	8–16	6.58	4.74	–	–	–	–	–	–	–	0.62	–	–
FDG-09-11 (*soil under algae*)													
K	0.0–0.5	7.40	7.49	–	–	–	–	–	–	–	1.25	–	–
O	0.0–0.5	7.39	4.21	–	–	–	–	–	–	–	0.74	–	–
TB	0.5–1.0	7.46	7.43	–	–	–	–	–	–	–	0.72	–	–
BC_1	1–3	7.13	6.82	–	–	–	–	–	–	–	0.52	–	–
BC_2	3–12	6.56	5.31	–	–	–	–	–	–	–	0.62	–	–
D	12–17	6.39	4.71	–	–	–	–	–	–	–	0.62	–	–
FDG-09-05 (*soil under algae*)													
K	0.0–0.2	7.70	7.58	0.34	7.54	14.88	7.07	2.47	32.30	1.1	0.62	–	108.54
BC	1–8	7.18	6.90	0.67	2.61	0.90	0.31	0.16	4.65	14.4	0.62	–	14.96
C	10–20	6.76	5.53	0.61	1.61	0.70	0.05	0.07	3.04	20.1	0.52	–	7.95
FDG-09-16 (*soil under algae*)													
K	0.0–0.5	6.95	6.88	0.37	5.84	3.93	2.14	0.24	12.52	3.4	0.73	–	20.32
B	0.5–2.0	7.00	5.83	0.68	3.44	1.31	0.00	0.09	5.52	12.3	0.62	–	11.48
BC	2.0–4.5	6.92	5.65	0.54	3.11	0.40	0.06	0.09	4.20	12.9	0.52	–	8.05
BC	5–10	7.17	5.69	0.60	2.86	0.23	0.02	0.07	3.78	15.9	0.62	–	10.77
C	10–15	7.33	5.60	0.61	3.12	1.51	0.07	0.14	5.45	11.2	0.62	–	11.48
FDG-09-22 (*soil under algae*)													
K	0.0–0.3	7.56	7.51	0.20	4.53	1.21	1.17	0.47	7.58	2.6	0.31	–	–
BC	0.5–4.0	7.32	6.44	0.41	0.95	0.45	0.00	0.00	1.81	20.5	0.21	–	–
C	4–12	6.66	5.67	0.46	1.13	0.75	0.00	0.00	2.34	18.4	0.31	–	–

(continued)

Table 3.1 (continued)

Horizon	Depth (cm)	pH		Residual acidity, mg-egv./100 g	Exchangeable bases, mg-eqv./100 g				Exchangeable cations, мг-экв./100 г	Unsaturation of the SEC (%)	CO_2 carbonate (%)	SO_4 gypsum (%)	K_2O (%)
		H_2O	KCl		Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}					
FDG-09-10 (*soil under algae*)													
K	0.0–0.5	6.70	6.29	–	–	–	–	–	–	–	0.40	–	–
BC	2–10	6.00	4.53	–	–	–	–	–	–	–	0.47	–	–
C	10–20	6.53	4.78	–	–	–	–	–	–	–	0.31	–	–
разрез FDG-55-11 (*soil under hillock*)													
	0–1	7.40	7.39	–	–	–	–	–	–	–	0.80	–	16.36
G1	2–9	7.65	7.09	0.46	2.89	0.71	0.11	0.44	4.61	10.0	0.63	0.052	293.18
G2	11–20	7.68	6.86	0.43	2.89	0.71	0.11	0.46	4.60	9.4	0.47	0.032	30.88
Bg	22–44	7.57	6.72	0.52	2.84	0.96	0.19	0.65	5.16	10.1	0.47	0.0	41.98
BCg	47–50	7.67	6.69	0.38	2.33	2.01	0.14	0.47	5.33	7.1	0.62	0.009	34.08
разрез FDG-55-10 (*soil at the microlow*)													
O1	0.0–1.5	8.53	7.85	0.61	37.67	40.06	72.80	12.48	163.62	0.4	–	–	481.47
O2	1.5–2.5	8.53	7.05	0.61	31.30	18.89	18.88	5.66	75.34	0.8	–	–	–
SS	2.5–4.5	7.81	7.31	0.16	2.22	1.34	0.54	0.48	4.74	3.4	–	–	48.75
G	5–10	7.69	7.01	0.22	3.93	0.61	0.22	0.77	5.75	3.8	–	–	49.52
GC	12–30	7.82	7.38	0.16	2.89	0.45	0.12	0.43	4.05	4.0	–	–	33.97
GC	35–45	8.47	7.80	0.08	4.50	0.71	0.09	0.50	5.88	1.4	–	–	37.43
разрез FDG-55-02 (*patterned ground, soil under large moss communities*)													
	0.0–1.5	5.92	5.16	0.66	0.60	0.40	0.15	0.09	1.90	34.7	0.41	–	17.73
TB	0.5–1.5	6.11	5.77	0.88	2.92	1.11	0.52	0.40	5.83	15.1	0.41	–	24.81
BC	1.5–10.0	5.25	5.03	0.75	0.55	0.63	0.00	0.00	1.93	38.9	0.21	–	3.84
C	16–30	5.89	4.77	0.93	0.94	0.60	0.00	0.00	2.47	37.7	0.52	–	5.35
B	30–32	6.05	4.70	1.00	1.76	0.53	0.00	0.02	3.31	30.2	0.62	–	5.45
разрез FDG-09-06 (*patterned ground*)													
	0–6	6.47	5.69	1.15	1.10	0.70	0.33	0.14	3.42	33.6	0.41	–	10.70
	7–16	6.29	4.70	–	1.30	0.50	0.06	0.09	–	–	0.52	–	5.94
разрез FDG-55-18 (*patterned ground,*)													
	0–5	7.15	5.88	–	–	–	–	–	–	–	0.85	–	–
	10–20	7.06	5.10	–	–	–	–	–	–	–	0.70	–	–
	20–30	7.15	5.06	–	–	–	–	–	–	–	0.70	–	–
	35–50	7.13	5.02	–	–	–	–	–	–	–	0.54	–	–
	55–65	6.96	5.06	–	–	–	–	–	–	–	0.70	–	–

(continued)

Table 3.1 (continued)

Horizon	Depth (cm)	pH		Residual acidity, mg-egv./100 g	Exchangeable bases, mg-eqv./100 g				Exchangeable cations, мг-экв./100 г	Unsaturation of the SEC (%)	$CO_{2\ carbonate}$ (%)	SO_4 gypsum (%)	K_2O (%)
		H_2O	KCl		Ca^{2+}	Mg^{2+}	Na^+	K^+					
разрез FDG-55-19 (*patterned ground,*)													
	26–36	7.02	5.41	–	–	–	–	–	–	–	–	–	–
	40–50	7.26	5.27	–	–	–	–	–	–	–	–	–	–
разрез FDG-09-20 (*dry grounds*)													
	0–7	6.81	5.74	0.41	0.60	0.80	0.03	0.05	1.90	21.6	0.21	–	5.23
	7–12	6.75	6.08	0.38	0.95	0.75	0.00	0.00	2.08	19.3	0.52	0.015	6.23
разрез FDG-55-01 (*dry grounds*)													
	4–10	6.80	4.72	0.55	1.20	0.60	0.18	0.13	2.66	20.7	0.47	–	–
	12–20	7.09	5.06	0.48	1.20	0.60	0.25	0.13	2.66	18.1	0.47	–	–
разрез FDG-09-15 (*dry grounds*)													
	0–1	6.13	5.30	–	–	–	–	–	–	–	0.62	–	–
	1–4	6.02	5.69	–	–	–	–	–	–	–	0.26	0.001	–
	4–13	6.51	5.60	–	–	–	–	–	–	–	0.52	0.002	–
разрез FDG-55-04 (*dry grounds*)													
	0–6	6.76	6.42	0.27	2.61	0.90	0.55	0.25	4.58	5.9	1.09	–	–
	6–25	6.92	6.74	0.25	3.41	1.10	1.98	0.46	7.20	3.5	1.09	–	–
	25–38	7.02	6.49	0.31	1.91	1.00	0.27	0.12	3.61	8.6	0.93	–	–
разрез FDG-55-05 (*dry grounds*)													
	0–4	7.71	6.98	–	–	–	–	–	–	–	1.02	–	–
	4–20	7.85	6.28	–	–	–	–	–	–	–	0.85	–	–
	22–33	7.22	5.63	–	–	–	–	–	–	–	0.93	–	–
	33–44	7.27	5.75	–	–	–	–	–	–	–	0.78	–	–
разрез FDG-56-01 (*dry grounds*)													
	0–1	8.39	8.14	–	–	–	–	–	–	–	0.85	–	–
	1–5	8.75	7.74	0.20	1.98	0.73	0.13	0.00	3.04	6.6	0.70	0.008	–
	5–15	8.69	6.69	0.28	1.99	0.73	0.29	0.12	3.41	8.2	0.85	0.036	–
	15–30	7.94	6.35	0.32	2.89	0.40	0.01	0.11	3.73	8.6	0.85	0.035	–
	32–37	8.06	6.25	0.34	2.54	1.16	0.00	0.09	4.13	8.2	0.85	0.0	–
	40–52	7.87	6.24	0.37	2.44	1.16	0.00	0.11	4.08	9.1	1.01	0.013	–

(continued)

Table 3.1 (continued)

Horizon	Depth (cm)	pH		Residual acidity, mg-egv./100 g	Exchangeable bases, mg-eqv./100 g				Exchangeable cations, мг-экв./100 г	Unsaturation of the SEC (%)	CO_2 carbonate (%)	SO_4 gypsum (%)	K_2O (%)
		H_2O	KCl		Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}					
разрез FDG-09-21 (*lake terrace, dry grounds*)													
	0–4	6.49	5.45	0.46	0.90	0.60	0.47	0.09	2.52	18.3	0.41	–	7.13
	4–17	7.12	6.42	0.36	3.21	0.80	1.93	0.15	6.45	5.6	0.52	–	12.18
разрез FDG-55-09 (*lake terrace, dry grounds*)													
	0–2	6.11	6.10	0.67	–	–	–	–	–	–	0.52	0.0	13.77
	2–7	6.14	5.90	0.46	0.77	0.00	0.00	0.08	1.31	35.1	0.31	0.0	10.95
	10–17	5.59	4.83	0.75	0.45	0.90	0.60	0.03	2.73	27.5	0.52	0.0	6.45
	19–33	6.38	5.20	0.52	0.88	0.95	0.13	0.00	2.48	21.0	0.62	0.0	4.34
	35–45	6.48	5.26	0.80	2.70	1.69	0.11	0.11	5.41	14.8	0.62	0.0	10.80
разрез FDG-55-15 (*lake terrace, dry grounds*)													
Bf	2–6	6.27	6.30	0.43	3.52	4.32	8.29	0.51	17.07	2.5	0.52	0.012	29.55
BC	6–12	5.78	5.23	0.82	4.23	2.21	4.36	0.21	11.83	6.9	0.21	0.107	12.25
C	15–20	5.35	4.74	1.02	2.31	1.51	2.35	0.17	7.36	13.9	0.41	0.016	10.23
разрез FDG-55-17 (*lake terrace, dry grounds*)													
Bf_1	2.0–3.5	–	6.55	–	–	–	–	–	–	–	0.54	–	–
Bf_2	4–10	5.72	5.17	0.99	1.45	0.00	0.00	0.16	2.60	38.1	0.54	0.009	–
Bf_2	10–15	5.48	4.55	–	–	–	–	–	–	–	0.54	–	–
BD	15–25	5.87	4.59	0.93	1.58	0.45	0.23	0.00	3.19	29.2	0.54	0.044	–
D_1	25–37	6.64	4.65	1.04	1.06	1.06	0.06	0.05	3.27	31.8	0.45	0.047	–
D_2	40–46	6.87	4.81	0.81	–	–	–	–	–	24.4	0.70	0.0	–
D_2	47–50	6.95	4.84	1.02	1.76	2.06	0.09	0.10	5.03	20.3	0.70	0.032	–
разрез FDG-56-04 (*lake terrace, dry grounds*)													
	0–1	6.63	6.21	0.41	–	–	–	–	–	–	0.79	–	–
	1–3	6.84	6.26	0.47	1.64	1.15	0.23	0.27	3.76	12.5	0.79	0.004	–
	3–7	6.91	6.57	0.36	4.19	1.03	0.00	0.17	5.75	6.3	0.79	0.140	–
	7–10	6.95	6.53	–	–	–	–	–	–	–	0.79	–	–
	10–20	7.05	6.45	0.31	2.25	2.42	0.00	0.18	5.16	6.0	0.79	0.0	–
	20–25	7.23	6.74	0.27	1.08	1.58	0.16	0.13	3.22	8.4	0.93	0.012	–
разрез FDG-09-13 (*lake terrace, dry grounds*)													
Bf	1.0–2.5	5.89	4.85	0.87	2.51	0.00	0.06	0.15	3.59	24.2	0.54	0.017	–
BD	3–8	4.90	4.12	3.18	1.93	4.55	0.80	0.28	10.74	29.6	0.79	0.0	–
D	9–16	5.20	4.21	2.23	2.55	3.18	0.50	0.36	8.82	25.3	0.71	0.013	–

Editor's note the authors here and in the text use the Russian system of soil-horizon nomenclature performs as an eluvial horizon within the profile. In most cases the soil exchange complex contains more calcium than magnesium ions. The percentage of magnesium ions is greatest in horizons where residual acidity is also greatest. This can be explained by selective leaching of calcium ions under the impact of acidic products of pedogenesis.

There is a biogenic accumulation of phosphorus, sulfur, calcium, magnesium, iron, and manganese within the upper part of profiles. Phosphorus and sulfur are accumulated within the O, T, and TB horizons, while the other elements accumulate only in the O and T horizons. The bulk concentration of K_2O is distributed rather uniformly, but there is some accumulation in upper horizons: 18–128 mg 100 g^{-1} within litter and 7–19 mg 100 g^{-1} in the TB horizon.

The high total concentration of CaO (5–6 %) is related to the weak leaching process. The $(SiO_2)/(Al_2O_3)$ ratio is wide, probably because of the lithological heterogeneity of the rock with concentration of coarser particles including quartz grains within the upper layers. The heterogeneity of the substrate is also reflected in a wider $(TiO_2)/(Al_2O_3)$ ratio within the O horizon. That upper horizons are characterized also by lowest values of weathering index (Retallack 2003)—the ratios of $(Al_2O_3)/(CaO) + (Na_2O) + (K_2O) + (MgO)$—that is in agreement with the distribution of such parameters as pH and the degree of unsaturation of soil exchange complex with bases. Apparently, the weathering processes are most active not in the organogenic horizon but in mineral horizons or at their contact. That could account for a higher content of readily weatherable minerals, such as plagioclases and amphiboles, within the upper part of profile. The content of phyllosilicates, primarily vermiculite, increases with depth. At the same time, the vermiculite phase from the upper horizons is represented by interstratified vermiculite-smectite that originates from the weathering of vermiculite. However, these minerals could also be contributed by dust deposition.

The changes in weathering with depth are evidenced by morphological changes in quartz grains down the profile. The proportion of angular particles decreases from 85 to 70 % with depth; and the Khabakov index of roundness increases from 0.81 to 1.16. At the same time, the frequency of occurrence of the small fractures decreases from 40 to 20 % and that of arcuate steps and conchoidal fractures of probable cryogenic origin decreases from 50 to 25–30 %. These changes are indicative of active physical processes, such as cryogenic and thermal weathering. Moreover, down the profile there is an increasing percentage (from 23 to 40 %) of quartz grains with weathered surfaces often (up to 32 % of the grains) with etching pit and large precipitation features of amorphous silica formed as a result of silica dissolution and precipitation. These surface features are developed on sandy particles as a result of chemical weathering. It is of interest that desquamation tracks (pealed skin) were observed in thin sections, with the greatest proportion reaching 28 % in the lower part of the profile.

The concentration of dithionite-soluble Fe_2O_3 varies from 0.23 to 0.39 % within the mineral horizons and from 0.42 to 0.48 % within the organogenic horizons being almost the same in soils under moss and bare sandy grounds. However, the concentration of oxalate-soluble Fe_2O_3 in soil under moss is significantly higher, which results from the processes of iron mobilization during the course of pedogenesis. The ratio of oxalate-soluble to dithionite-soluble Fe_2O_3 in the mineral horizons of soil under moss ranges from 0.21 to 0.37; this ratio is considerably narrower in 'lifeless' ground at 0.15–0.19. The concentration of pyrophosphate-soluble Fe_2O_3 is 0.095 % in the organogenic horizon and from 0.016 to 0.023 % in mineral horizons. The ratio of pyrophosphate soluble to oxalate-soluble Fe_2O_3 is 0.23–0.55 and indicates that a part of amorphous iron is represented by organo-mineral compounds. Total Fe in vegetated soils is lower than in the 'lifeless' ground, possibly because of mobilization and leaching of organo-metallic products; however, stronger evidence is needed because of the heterogeneity of the soil parent materials.

Dithionite-soluble and oxalate-soluble forms of Fe_2O_3 are concentrated in the upper part of the profile and are apparently of biogenic origin. The middle part of one profile (B horizon of FDG-09-25) is impoverished in oxalate-soluble Fe_2O_3. In another profile (FDG-55-06) the oxalate-soluble iron distribution resembles eluvial-illuvial pattern with minimum in the TB horizon, the maximum in the BC horizon, followed a decrease with further depth. The distribution of oxalate-soluble aluminum is similar to that of iron. The concentration maximum of amorphous iron within the lower part of the profile in combination with yellowish brown coatings on some sand grains suggest illuviation of iron and possibly other elements.

Soils under moss contain the lowest amount (0.016–0.019 %) and most uniform distribution pattern of soluble salts of the soils examined (Fig. 3.8).

3.4.3.2 Soil Formation Under Algae

There is an abundant growth of algae, predominantly blue-green algae (cyanobacteria), on wet and also periodically inundated substrates near large and small water courses and lakes. The algae communities are confined to the lowest topographic positions within the valleys and lake hollows. Soils under algae are sands and sandy loams.

Depending on the degree of ground wetness (saturation) the algae can form either continuous slimy black films upon drying (organogenic soil horizons, FDG-09-10), or a distinctive type of organo-mineral K horizon (pits: FDG-09-05, FDG-09-16 and FDG-09-22; Fig. 3.9). The K horizons are often covered with salt crusts. During seasonal drying these horizons turn into crusts up to 0.5 cm thick, easily separated

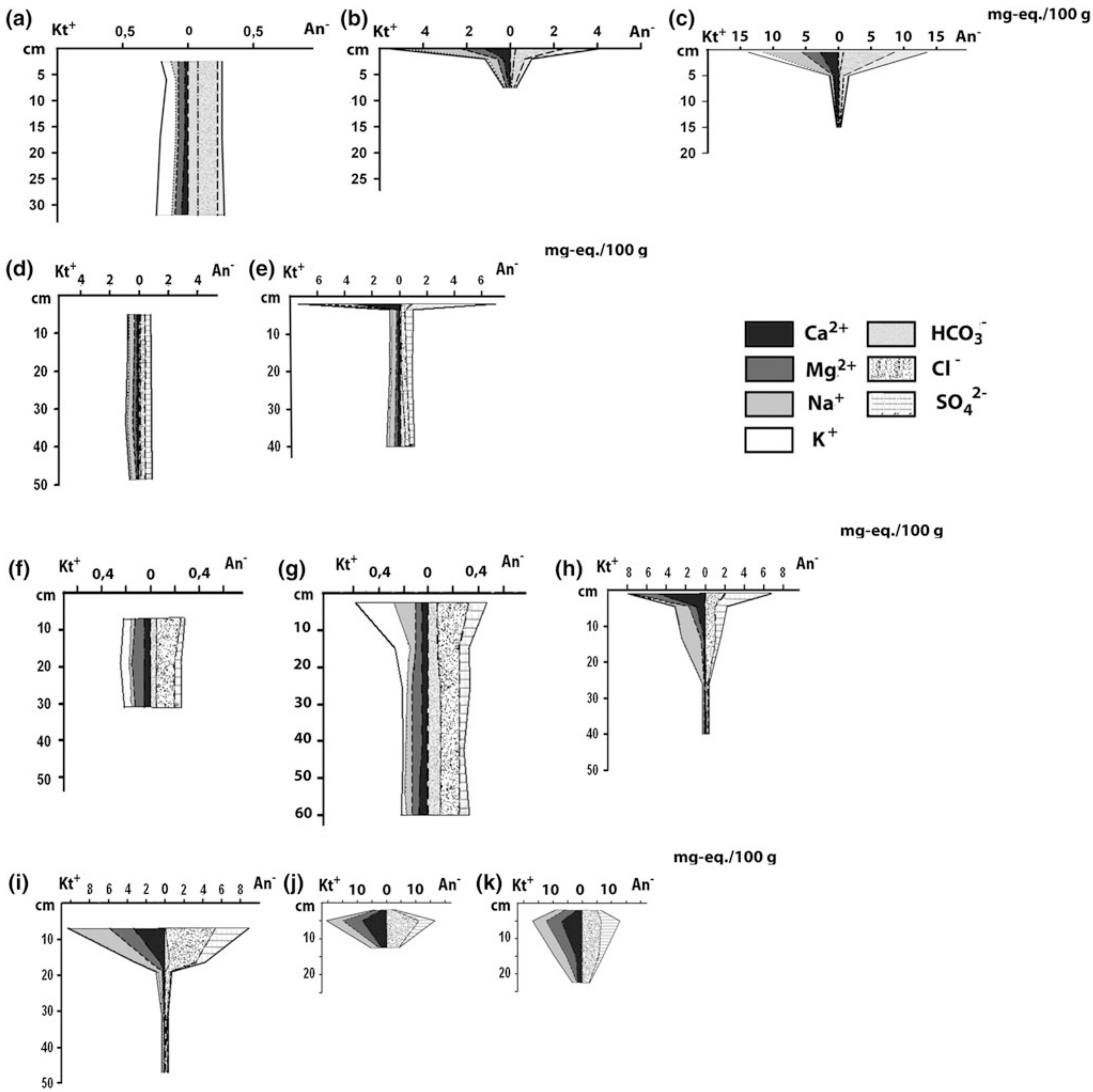

Fig. 3.8 Concentration of readily soluble salts in soils under moss cover (**a**–**c**), soils under algae (**d**–**e**), soils on a hillock (**f**), a soil in a depression (**g**), a soil on patterned ground (**h**), and soils on dry ground (**i**–**k**)

from the ground below and consisting of mineral material bound by algae threads. These horizons may have more clay than horizons below. The crust layer is underlain by a transitional BC horizon that can be distinguished by its chemical characteristics, but looks morphologically similar to the parent rock. The total thickness of these soils varies from 4 to 20 cm.

Despite a high moisture content and periodic inundation, the redox potential (472–597 mV) in most soil profiles under algae favors weak and moderate oxidation. The organic carbon content varies from 0.7 to 1.6 % within the K horizon (crust) and from 0.03 to 0.07 % within the BC horizon (Fig. 3.9). Soils under algae are characterized by increased pH values (Table 3.1) with the maximum of 7.0–7.7 (from neutral to weakly alkaline reaction) found within the K horizon. The pH varies from 6.6 to 7.3 within the BC horizon and decreases with depth to neutral or weakly acidic depending on the parent rock composition. The soil

Fig. 3.9 Soils under algae in the Schirmacher Oasis

exchange complex is completely saturated with bases represented mostly by calcium and magnesium within the upper part of the profile and calcium within the deeper part.

Apparently the alkaline pH does not result from carbonate concentration, which is at a background level (Table 3.1). Most probably, soil alkalinization results mainly from the impact of algae. It is generally known that algae, especially blue-green algae, tend to increase the pH of the substrate due to their physiological activity (release of alkalinity during photosynthesis) and biochemical processes, i.e., excretion of basic exudates (Johnston and Vestal 1989). Alkalinization can also be connected with the presence of 15–22 % of sodium on the soil exchange complex.

Soils under algae are characterized by an increased concentration of salts (Fig. 3.9) with an accumulative distribution pattern. The sum of salts can reach 0.30 % within the K horizon and 0.030–0.069 % within the transitional horizon, below which it decreases to a background level. Total amounts of phosphorus, sulfur, manganese, calcium, and magnesium in the upper K horizon are often quite high. These elements are apparently of biogenic origin. There is also an accumulation of labile K_2O (20.3–108.5 mg 100 g^{-1}) within the K horizon. Its concentration within the BC horizon is also higher (up to 15.0 mg 100 g^{-1}) than that within the parent rock (Table 3.1).

Soils under algae are richer in dithionite-soluble iron oxide than the soils under moss communities and ‘lifeless’ grounds. The concentrations of dithionite-soluble Fe_2O_3 in soils under algae are as follows: 0.37–0.54 % in sand and loamy sand varieties and 0.73–0.85 % in sandy loam varieties. The ratios of oxalate-soluble to dithionite-soluble iron are 0.28–0.68 in loamy sand and 0.04–0.07 in sandy loam soil. In the former, this ratio becomes wider in the K horizon, which indicates that an amorphous form prevails in the composition of non-silicate Fe_2O_3. It is likely that dithionite-soluble iron is concentrated in soils under algae films and that it has an allochtonous origin, i.e., it has been brought in by flowing meltwater. The same can be suggested regarding the high values for total iron, potassium, and sodium.

The mineral composition and morphology of quartz grains in these soils are principally the same as those found in soils under moss communities. The K horizon also contains interstratified vermiculite-smectite, probably, of allochtonous nature. The <50 μm fraction from this horizon is also enriched in magnesium carbonate (dolomite) that can be connected with its authigenic formation under the impact of cyanobacteria metabolism. In one of the profiles (FDG-09-16), small amounts of gypsum were identified from chemical analysis (Table 3.1).

Special attention should be given to the parts of lake hollows that regularly undergo prolonged inundation during the period when water table in lakes rises. Algae can stay under water for a while during summer or continuously for several years. Freezing within these areas is often accompanied by ground heaving which leads to a hummocky topography. Hydromorphic soils developing under such conditions are characterized at the time of their sub-aerial existence by a stagnant water regime, continuous or periodic prevalence of reduction conditions, and the development of gley processes.

An example of this pedogenesis occurs within a basin of Lake Krasnoe. The lake is enclosed and is enriched with marine salts, including sulfates. Hence the periodically inundated parts of the hollow undergo, along with gleying, the process of sulfate reduction and then a sulfide-rich horizon is formed within soil (see also Chaps. 13 and 14).

The soil profile structure varies depending on the microtopographic position. At the micro-low (FDG-55-10) there is a mat of blue-green algae 2–4 cm thick with a salt crust. Parts of the algae thallus are green and photosynthetic. Therefore, this mat has a dual ecological function: firstly, it represents an analogue of vegetation cover, and secondly, it

Table 3.2 Salt occurrence on rock surfaces, rock debris and soils as a function of weathering stage in the Sør Rondane Mountains, Antarctica (Matsuoka 1995)

Salt phase	Chemical formula	Number of identification				
		Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
Gypsum	$CaSO_4 \cdot 2H_2O$	12	14	25	25	16
Thenardite[a]	Na_2SO_4	0	0	5	0	8
Epsomite[b]	$MgSO_4 \cdot 7H_2O$	0	1	1	3	5
Jarosite	$KFe(SO_4)_2(OH)_6$	1	2	5	2	0
Bloedite	$Na_2Mg(SO_4)_2 \cdot 4H_2O$	0	1	0	1	3
Nitratite	$NaNO_3$	0	0	0	2	1
Calcite	$CaCo_3$	0	0	0	0	3
Dolomite	$CaMg(Co_3)_2$	0	0	0	0	2
Halite	NaCl	0	0	0	0	1

[a]Also mirabilite, $Na_2(SO_4)_2 \cdot 10H_2O$
[b]Also hexahydrite, $MgSO_4 \cdot 6H_2O$

is the organogenic soil horizon. The algal mat is underlain by a black sulfide (SS) horizon 2–3 cm thick, which becomes discolored upon exposure. Deeper in the profile there is a bluish gray homogeneous gley (G) horizon that gives a positive reaction when tested for a presence of Fe-II compounds. Below the G horizon down to the bottom of the active layer (45 cm), lays the GC horizon that represents a transition to the parent rock.

The soil profile on the hillock has a simpler structure. The surface layer is represented by a fragmentary, loose, and dry mat of algae mixed with mineral matter. Below there are several gleyed and weakly gleyed horizons. This soil profile (pit FDG-55-11) is less wet. There are brown concretions on a bluish gray background that are indicative of changeable oxidation-reduction conditions.

The soils are derived from lacustrine sediments and have the finest texture of all described in this study (Table 3.2). The fine earth (<1 mm) from the soil profile in micro-low contains 24.5–29.4 % of the fractions <0.01 mm and 13.3–18.5 % of clay (<0.001 mm). The profile of soil under hillock is clearly divided into two parts: upper sandy loam (to a depth of 20–22 cm) and lower loam. The upper part is stonier and contains from 44 to 63 % of coarse material (>1 mm), while the content of that in the lower part is only 14–27 %. In the micro-low there is a high degree of stoniness within a shallow sulfide horizon, i.e., the upper mineral horizon, whereas deeper the content of coarse material (>1 mm) lowers to 4–16 %. There is enough evidence to assume that such pattern of textural heterogeneity both in vertical and horizontal directions has resulted from cryogenic sorting.

The algae mat is not purely organogenic, but contains a lot of mineral matter. However, it differs from the O-TJmr horizons of soils under moss communities by a higher loss on ignition—from 42.6 to 44.6 %. The loss on ignition is 5.2 % in the sulfide horizon and 0.9–1.0 % below (Fig. 3.7). In the hillock soil, the content of organic carbon decreases with depth from 5.8 to 0.25–0.37 % and even zero within the lowest horizon of the soil.

These soils also accumulate some soluble compounds. The concentration of soluble salts is 0.46 % in the upper part of soil of the micro-low (Fig. 3.8) and decreases to 0.056–0.072 % in the lower horizons. In the soil on the hillock, the sum of salts is evenly distributed over the profile with values from 0.052 to 0.058 %.

In spite of a low concentration of carbonates in soils under algae, their pH values in water extract are the highest identified in this study. These soils are neutral and weakly alkaline (7.4–7.7) on the hillock and from weakly to medium alkaline (7.7–8.5) in the soil in the micro-low (Table 3.1). The reasons for such a high pH are not fully understood. The percentage of sodium ions in the soil exchange complex is low. Most probably, the alkalinity is caused by algae exudates and sulfides, but these are unlikely to be the only reasons, because the high pH values are not confined to the upper horizons but are spread over the whole soil microcomplex. The soil exchange complex is nearly fully saturated with bases.

The hydromorphic conditions and low redox potential determine a high concentration of labile iron in 0.1 N H_2SO_4 extract from fresh samples: 100–430 mg Fe_2O_3 100 g^{-1} in the microlow and 50–110 mg Fe_2O_3 100 g^{-1} on the hillock. In both cases FeII prevails in composition of acid-extractable iron. The highest concentration of labile K_2O among all soils studied occurs in the soil beneath algae: 393–482 mg 100 g^{-1} in the surface horizons and 31–50 mg 100 g^{-1} in the subsoil (Table 3.1). There is a slight accumulation gypsum (0.03–0.05 %) in the hillock soil (Table 3.1).

3.4.3.3 Soil Formation on Patterned Ground

Wet parts of valleys are covered almost entirely by patterned ground, which can be lifeless or vegetated along the borders of

Fig. 3.10 Patterned ground (sorted circles) at Schirmacher Oasis

sorted polygons (Fig. 3.10). Films of algae, lichens, and small turfs of mosses are found on them. Conditions for the growth of large moss communities occur rarely. If grounds are formed by sandy loams or loams, this can be caused also by active cryoturbation (Blume et al. 1996). Percentage of mosses cover on polygons reaches up to 30–40 %. Such patches are places of formation of thin soils having, in truncated variant, the same set of horizons as the soils under large moss communities: O-TB-B-C (FDG-55-02). There is no dry peat horizon. Organic and organo-mineral horizons are limited by sizes of small turfs of mosses and have fragmentary extension. The thickness of such soils ranges from 10 to 16 cm.

The content of organic carbon in the horizon TB is 0.98 %. The results of soil analysis after plant residues removal indicate that about a quarter of this value (0.26 %) is represented by humus matter. The accumulation of organic carbon (0.07 %) is found in the mineral horizon BC as well.

In this case mosses do not exercise acidifying effect upon parent substratum. In comparison with underlying layer the horizon TB is characterized by a larger value of effective cation-exchange capacity due to biogenic accumulation of exchange bases, first of all calcium. Because of this the organic-mineral horizon is characterized by minimal degree of non-saturation of soil exchanging complex and by maximal pH values in the profile.

The content of dithionite-soluble iron is slightly higher than in soils under large moss communities (0.32–0.43 %) while the ratio of oxalate-soluble iron to dithionite-soluble one is smaller (0.15–0.20). Conditions for iron mobilization do not emerge here. Biogenic accumulation of loose K_2O is noted (17.7–24.8 mg 100 g^{-1}).

The content of readily soluble salts ranges from 0.016 to 0.038 %, which is generally higher than in soils under large moss communities but significantly lower than in soils under algae and in most dry grounds.

In close vicinity to water bodies there are many polygons with algae and light moss cover. In this case the horizon K is spatially complemented by fragmentary horizons O and TB (FDG-09-11). These soils feature alkalization in that the upper layers have a pH ranging between 7.1 and 7.5. The organic horizon O has a high potential acidity, with a pH in a KCl extract of 4.2.

3.4.3.4 Soil Formation on Dry Ground

There is no vegetation in the dry parts of the Schirmacher Oasis except solitary and rare lichens; soil formation processes are indistinct here. Periodically the dry soils receive some moisture from summer snowfalls and hyperarid conditions occur. Even in these conditions periodic snowfalls may transform the initial substrate, as noted by J.D. McCraw in 1960 (cited by Campbell and Claridge 1987). The formation of an accumulative distribution profile of readily soluble salts on lake terraces, where their concentration is the largest (0.024–0.44 %), can be regarded as the simplest example. In dry areas, within active layer, surface formations with ocherous brown color of the Bw horizon attract particular attention; the thickness of this horizon laying as a rule directly under desert pavement ranges from 2–3 cm to 20 cm (FDG-09-13, FDG-55-15, FDG-55-17, FDG-56-04). These soils can be defined as "ahumic soils" (Tedrow and Ugolini 1966). Heterogeneity of their profiles is mainly the result of abiogenic processes. The presence of microorganisms gradually transforming the substrate is very probable and needs to be confirmed through laboratory research.

All described variants of such grounds are represented by loamy sands which can be underlain by finer-textured horizons. There is a very small quantity of organic carbon (0.10–0.21 %) in the upper layers of the profile (Fig. 3.7).

The Bw horizon is notable due to higher content of dithionite-soluble Fe_2O_3 (0.47–0.48 %) in comparison with underlying strata, but among other soils and grounds of the oasis there are also examples of higher concentrations without appearance of brown ocherous color. The concentration of readily soluble salts is very high (0.56–1.03 %; Fig. 3.8). The accumulation of significant quantities of gypsum (0.02–0.14 %; Table 3.1) occurs. The origin of these soils is not completely clear. It appears probable that the ocherous brown horizon is inherited from an earlier stage of the basin development when the terrace was at the same level with the lake and the terrace ground was moist or wet.

3.4.3.5 Soil Formation in Mountainous Areas

The studies by Matsuoka and his colleagues (1995, 1996, 2006) in the Sør Rondane Mountains suggest that the frequent diurnal freezing and thawing have led to rapid rock disintegration. He judged that the Sør Rondane Mountains are subject to an arid form of weathering. Salts, especially gypsum, accumulate progressively with time in the soils and play an important role in the weathering processes (Table 3.2). Thenardite and epsomite are also common salts on rock surfaces, in rock debris, and within soils. The dominant soil clays are mica and chlorite, with some talc. The relative abundances of these minerals do not vary with weathering stage, suggesting that there is minimal synthesis of clay weathering products. From 19 samples on weathering stages 3–5 surfaces, the mean concentrations of clay, silt, and sand were 0, 21 and 79 %, respectively, yielding a texture of sandy loam (Table 3.3). Since the exposure above the ice sheet, continuous weathering (mainly from salt action over 1 Ma) has led biotite gneiss to produce silty soils with a high salt content beneath a protective stone pavement without neither significant soil disturbance nor chemical alteration. During the same period, more resistant granite has changed to mushroom-like boulders as a result of cavernous weathering (Fig. 3.11). The surface of granite boulders is case of crust, hardened with Fe oxide that tends to protect the rock against weathering, whereas it also undergoes extremely slow, microscopic physical disintegration with the accumulation of sulfates.

Soil examinations in the Mühling-Hofmannfjella and Gjelsvikfjellaa Mountains (Engelskjøn 1986) suggest that the texture and weathering of rocks vary in a way significant to pedogenesis and vegetation. A Lithosol derived from feldspar-rich bedrock (charnockite and migmatite) had a pH below 7 and modest amounts of Ca and Mg. A Lithosol derived from biotite-pyroxene rocks had mean pH above 7 and abundant Ca, K, and Mg. Sandy deposits had variable pH values, presumably due to polymictic bedrock derivation and exposure to leaching. A Lithosol adjacent to a petrel nesting area showed a remarkable enrichment of P and Na. The soils of the study area were all of the frigic type, with negligible amounts of soil organic carbon. They showed a considerable range of pH and metallic cation content. Bird influence varies from excessive to virtually none. Some areas of exposed soil or stone pavements were devoid of vegetation.

3.5 Discussion

3.5.1 Soil-Forming Processes

According to the zonal division of the Southern Circumpolar Region (Bockheim and Ugolini 1990; Blume et al. 1997), the Schirmacher Oasis should be included in the polar desert zone. This zone is also referred to as the zone of Antarctic barrens (Goryachkin et al. 2004). However, the Schirmacher Oasis, as well as the entire ice-free portion of Queen Maud Land, is actually south of the southern boundary of polar desert zone as shown on the existing maps and should be part of the cold desert zone.

Within the polar desert zone, the most detailed soil studies were performed in the Grearson Oasis. The organic carbon content in this oasis ranges from 0.14 to 1.50 % in ornithogenic soils and Haplorthels under algal communities, from 2.1 to 2.9 % in Spodorthels under lichens, and from 16 to 29 % in Histels under mosses (Blume et al. 1997; Goryachkin et al. 2004). The organic carbon content in Spodorthels of King George Island in the subpolar desert zone varies from 0.21 to 4.41 % (Goryachkin et al. 2004).

In the Schirmacher Oasis, the organic carbon content in the organomineral horizons varies within 2.4–13.6 % in soils

Table 3.3 Soil properties in relation to weathering stage in the Sor Rondane Mountains, Antarctica (ranges followed by median values in parentheses; derived from Matsuoka 1995)

Weathering stage[a]	No. of samples	>2 mm (%)	Sand (%)	Silt (%)	Clay (%)	Clay minerals[b]
1	5	29–80 (29)	69–87 (79)	9–25 (18)	2–6 (3)	Mc, Ch, Ta
3	5	8–38 (31)	76–99 (82)	1–24 (16)	0	None
4	6	0–24 (14)	66–80 (77)	19–34 (20)	0–2 (0)	Mc, Ch
5	8	0–17 (9)	62–92 (76)	7–38 (23)	0–1 (0)	Mc

[a]Weathering stage after (Campbell and Claridge 1975)
[b]*Clay minerals* Ch Chlorite; Mc Mica; Ta Talc

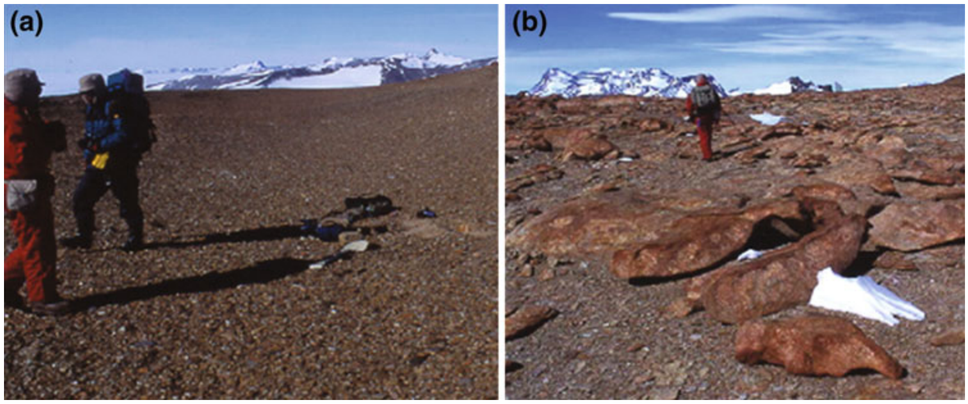

Fig. 3.11 Weathering features on a flat-top mountain on the Koyubi Plateau, Sør Rondane Mountains (weathering stage 4). **a** Stone pavement underlain by a 30 cm thick, saline-silty soil developed on biotite gneiss bedrock. **b** Granite boulders with strong desert varnish and cavernous weathering (photos by Matsuoka 2006)

under moss communities and within 0.4–2.1 % in soils under mosses and algae; in the mineral horizons of various soils, it varies between 0.02 and 0.62 %. The organic carbon content in most soils of Victoria Land dry valleys (the zone of cold deserts) is as low as 0.02 to 0.08 % (Campbell and Claridge 1987). Thus, the organic carbon content of the soils studied by us in the Schirmacher Oasis correspond to the lower level of the values typical of the soils in the polar desert zone and is considerably higher than that in the soils of cold deserts. The radiocarbon age of organic horizons is younger in our case than that in the Histels of the Grearson Oasis: 850 ± 40 and 1,420 ± 50 BP, respectively.

In QML physical (cryogenic) weathering is the main supplier of skeletal material, which locally redeposited later. Chemical transformations are insignificant; however, there is distinct chemical weathering of biotite grains. Biotite weathering in the Schirmacher Oasis is similar to that described in soils of humid temperate regions. We suspect that biotite weathering is from current processes rather than inherited from previous weathering cycles, because it is difficult to envision that cracked grains with deformed plates could “survive” re-deposition. Other minerals and rock fragments do not show recent chemical weathering. However, aggregates of clayey components in some gravel-sized and coarse-sand-sized gneiss fragments attest to rock transformation by intensive ancient weathering or by hydrothermal processes. These ancient products of gneiss transformation, as well as weathered biotite grains dispersed in the soils, serve as the source of ferruginous clayish material forming films on skeleton grains. These films can be of principal importance for the biological functioning of the soils, because they provide ecological microniches for microorganisms and supply them with nutrients in available (exchangeable) form.

The transformation of organic components proceeds very slowly and incompletely. A larger part of decomposed vegetative residues preserve elements of the initial morphology of plant tissues; the content of colloidal humus (in the form of organic films) is very small. The most significant process is the formation of specific bio-abiotic structures and microhorizons, in which skeletal material is “fixed” by organs of living plants. The formation of such structures is probably of principal importance for stabilization of the soil surface under conditions of extremely severe climate and intense processes of erosion and re-deposition.

In the Schirmacher Oasis, the soils under mosses and most of the ahumic soils are characterized by the acid reaction. The soils of sandy or loamy sandy textures are usually moderately acid to neutral, and the soils of loamy textures are slightly acid to neutral. Slightly and moderately alkaline conditions are locally developed and are usually associated with the presence of algae. This regularity is generally typical of the maritime and continental East Antarctica (Goryachkin et al. 2004) within the zone of polar deserts. At the same time, the soils of Schirmacher Oasis are less acid than the soils of Grearson Oasis (Blume et al. 1997).

Nonsilicate iron in the studied soils is mainly present in the crystallized form, except for the soils, in which the accumulation of allochthonous iron migrating in the oasis with water flows takes place. A predominance of crystallized nonsilicate iron over amorphous nonsilicate was also noted for the soils of Grearson Oasis (Goryachkin et al. 2004).

3.5.2 Soil Classification

Within the framework of *Soil Taxonomy* (Soil Survey Staff 2010), all the soils in this study belong to the Gelisol order. The soils under moss communities can be classified as Typic Haploturbels/Haplorthels and Lithic Haploturbels/Haplorthels. The soils of patterned ground belong to Typic Haploturbels. The soils under algal communities near the lakes Typic Haplorthels, and the soils of lake shores subjected to regular and long-term bonding are Typic Aquorthels. In contrast, the soils described by Matsuoka and his colleagues likely have anhydrous conditions and are classified as Anhyorthels and Anhyturbels.

A comparison with the soils of the Grearson Oasis and of the polar desert (Mid-Antarctic barrens) zone in general (Blume et al. 1997; Goryachkin et al. 2004) attests to the reduced systematic list and poor development of soils in the Schirmacher Oasis. Histels and Spodorthels have not been described in the Schirmacher Oasis. Peat accumulation and podzolization are weakly developed. As the oasis lies far from the sea, it is devoid of ornithogenic soils.

The reasons for the poor soil development in the Schirmacher oasis are related to the severity of its climatic conditions (even within the zone of polar deserts) and to the young age of its landscapes that were freed from the glaciers relatively recently. The most favorable conditions for supergene processes in the oasis are observed in places, where the active layer is subjected to normal or excessive allochthonous moistening; the same sites are highly susceptible to water erosion. As a result, a larger part of the products of weathering and pedogenesis (salts, organic substances, colloids, clay fractions, etc.) is redistributed within the oasis or discharged into the ocean rather than accumulated in situ. This is the third reason for the scarcity of pedogenic features in the studied region. The only soils of the oasis having relatively well-developed organic horizons—the soils under moss cushions—are found on slopes and are highly susceptible to erosion. Thus, during the warm summer of 2012–2013, intense melting of the glacial ice and snow patches resulted in the development of active water flows. Several plots, on which long-term monitoring of the soils under moss cushions had been performed, were completely eroded.

3.6 Summary

Queen Maud Land (QML) is the fourth largest ice-free territory of Antarctica, comprising 3,400 km^2 (6.9 % of total ice-free area). The predominant ice-free areas are the Mühlig-Hoffmann and Wohlthat Mountains (Fimbulheimen) and the Sør Rondane Mountains, each comprising 900 km^2. However, the most studied area of QML in terms of soils is the Schirmacher Oasis (35 km^2). Schirmacher oasis is one of the coldest Antarctic oases, because of its high latitude and trans-shelf location and because it is surrounded by ice.

QML is underlain by continuous permafrost. The mountains are underlain by thick permafrost; and active layer ranges from 8 to 40 cm in depth in the Sør Rondane Mountains to from 30 to 120 cm in depth in the Schirmacher Oasis. Soil moisture distribution plays an important role in pedogeneis and in controlling the distribution of vegetation. The moisture is provided primarily by melting of snowbanks.

Five broad groups of soils are described, including (i) soils with a moss cover, (ii) soils with algae, (iii) soils on patterned ground, (iv) soils on dry ground, and (v) soils in the high mountains. Soils under moss occur near snow patches, have abundant SOC, and contain etched quartz grains and chemically altered biotite. Soils under algae are wet and contain an algal crust and abundant SOC. Soils on patterned ground are strongly cryoturbated and have low amounts of SOC. Soils on dry ground have a shallow active-layer and have accumulated soluble salts. Soils in the high mountains contain a very shallow active layer, feature abundant soluble salts, and on early Pleistocene and Pliocene surfaces are strongly weathered.

Physical weathering processes, especially cryogenic processes, are predominant in QML. Chemical is limited to biotite alteration. The dominant soil-forming processes are humification in soils under mosses and to a lesser extent those with algae, desert pavement and permafrost formation, pervection/cryoturbation in areas with patterned ground, salinization in soils on dry ground and especially in the mountains, and redoximorphism and alkalization in wet soils of depressions. Rubification and podzolization are not readily apparent.

The dominant soil taxa include Typic Haploturbels-Haplorthels and Lithic Haploturbels-Haplorthels under moss cover, Typic Aquorthels-Haplorthels in soils along lake margins and those influenced by algae, Typic Haploturbels in areas of patterned ground, Typic Haplorthels in dry areas, and Typic and Lithic Anhyorthels-Anhyturbels in the mountains.

Soils of Queen Maud Land are less developed than those elsewhere in East Antarctica because they are more distant from the coast and have not been influenced by penguins and other birds.

Acknowledgments The authors commemorate the inspiration of Russian soil studies in Antarctica—David Gilichinsky. We kindly acknowledge all of the members of the Russian Antarctic Expedition and Antarctic Logistics Central International (ALCI), especially Valery Lukin and Aleksey Turchin, for invaluable help in conducting the investigations. We also thank Dr. Andrey Alekseev and Dr.Veronica Alekseeva for assistance in the investigations of quartz grain analysis and Prof. Sergey Sedov for assistance in the micromorphology researches. Investigations were partly funded by the Russian Fund for Basic Researches (12-04-01815).

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Soils of Enderby Land

4

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4.1 Introduction

Enderby Land is that portion of Antarctica extending from Shirase Glacier and Lutzow-Holm Bay from the west (38° 30′ E) to Wilma Glacier and Edward VIII Bay to the east (57° E). Enderby Land is bordered by the Cosmonauts Sea in the west and by the Sea of Cooperation in the east; both are part of the Southern Ocean. Nearly 1,500 km^2 of Enderby Land is ice-free. Two research stations—Molodezhnaya (Russia, 67º 40′ S, 45º 51′ E) and Syowa (Japan, 69° 00′ S, 39° 35′ E)—are established in Enderby Land (Fig. 4.1). The ice-free area includes several coastal oases (Table 4.1); however, the largest part is represented by high mountains and nunataks elevated above the ice shield in the central part of Enderby Land.

In this chapter, the results of soil studies in the Thala Hills oasis (or Molodezhny oasis) are mainly considered. It is one of the best studied oases of Enderby Land (MacNamara 1969a–c; MacNamara and Usselman 1972; Alexandrov 1985; Campbell and Claridge 1987; Negoita et al. 2001). A new series of geocryological studies was initiated by the Russian Antarctic Expedition (RAE) in 2007, and systematic soil research began in 2012–2013 and now it is still in progress.

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The soil cover was briefly characterized during landscape mapping of coastal oases in the western part of Enderby Land (Alexandrov 1985). Some soil properties were studied in the area of Syowa station (Yamanaka and Sato 1977; Ino et al. 1980; Ino and Nakatsubo 1986; Ayukawa et al. 1998) and in the Rundvägskollane oasis (69° 50′ S, 39° 09′ E) (Ohtani et al. 2000).

4.2 Study Area

4.2.1 Location and Topography

The Thala Hills oasis is located in the western part of Enderby Land (Fig. 4.1). It consists of two parts—Molodezhny and Vecherny sites—with a total area of 20 km^2. The Molodezhny site extends for 8.3 km along the coast, its maximum width is 2.7 km, and it is bordered by ice sheet from the south. The maximum elevation is 109 m a.s.l., and the total area is 13 km^2. The Vecherny site is 4 km to the east and extends for about 7 km; it has a maximum width of 1.9 km; the total area is 7 km^2. Mount Vechernyaya (272 m a.s.l.) is the major part of this oasis.

The Lutzow-Holm ice-free territory (it is a group of oases) has a maximum area of 481 km^2, and the Nikitin oasis has the minimum area of 1.2 km^2 among coastal oases (Sokratova 2010). To the west of Hays Glacier (45º 20′ E), ice-free territories are mainly mountains (Napier, Nye, Raggatt, Scott, Tula) and nunataks (Doggers, Gromov, Knuckey, Krasin, McLeod, Sandercock). Their summits (1600–2300 m a.s.l.) project above the ice sheet surface. Groups of nunataks and low mountains are known in the area as hills, e.g., Fyfe (650 m a.s.l.) (Alexandrov 1985).

4.2.2 Parent Materials and Age of Ice-Free Areas

The bedrock of Enderby Land is of Precambrian age. Two bedrock complexes are distinguished: the Proterozoic

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DOI 10.1007/978-3-319-05497-1_4

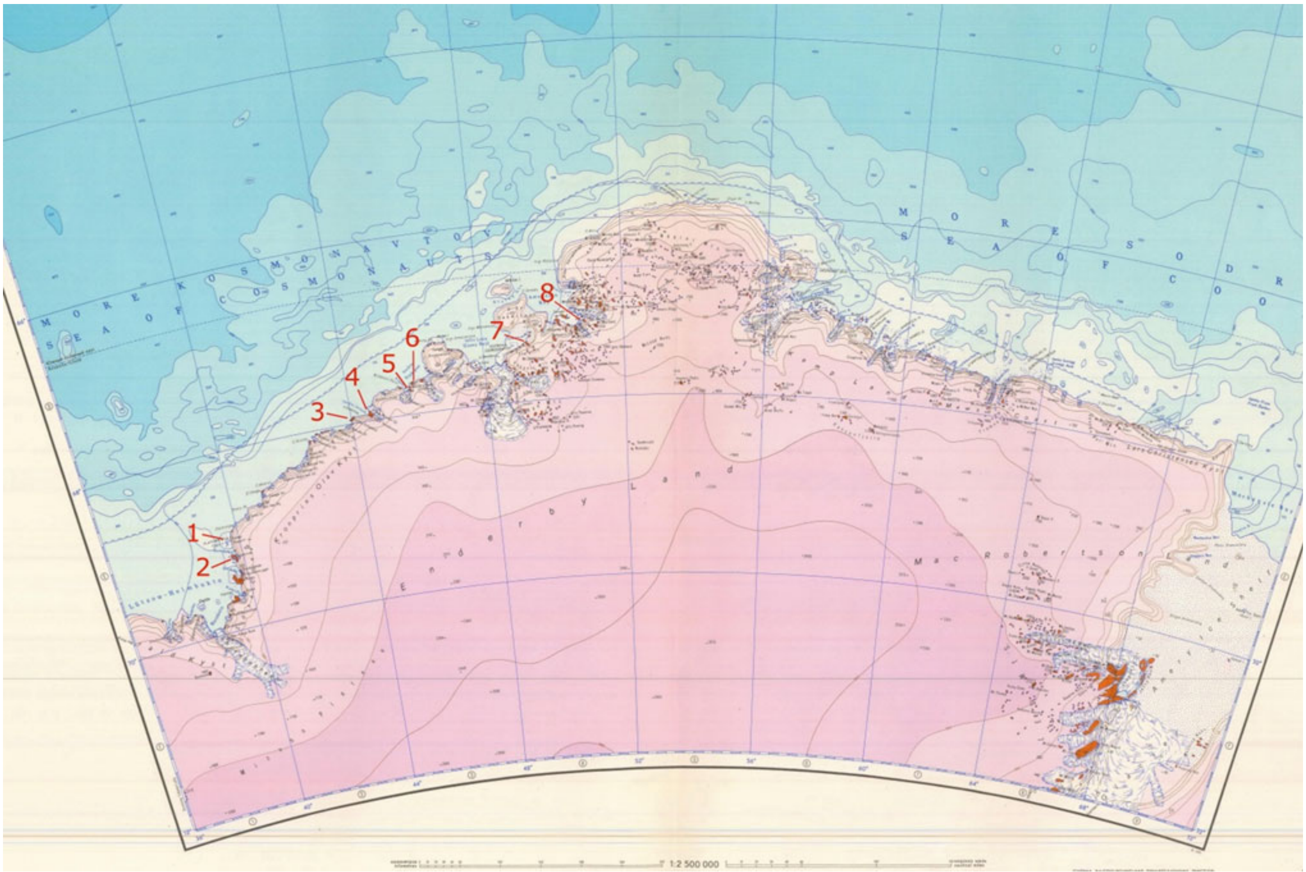

Fig. 4.1 Enderby Land, East Antarctica. *1* Syowa station (Japan), East-Ongul Islands; *2* Langhovde Oasis; *3* Polkanov Hills; *4* Tereshkova Oasis; *5* Konovalov Oasis; *6* Thala Hills oasis, Molodezhnaya station (Russia); *7* Nikitin oasis (Fyfe Hills); *8* Howard Hills

Table 4.1 Oases of Enderby land and its area (Sokratova 2010)

Name	Latitude, longitude	Area (km^2)
Lutzow-Holm	S69° 20′ E39° 30′	481
Polkanov Hills	S67° 58′ E44° 05′	13.3
Tereshkova Oasis	S67° 57′ E44° 33′	23
Konovalov Oasis	S67° 45′ E45° 45′	2
Thala Hills (Molodezhny site)	S67° 40′ E45° 51′	13.2
Thala Hills (Vecherny site)	S67° 39′ E46° 46′	6.7
Nikitin Oasis (Fyfe Hills)	S67° 23′ E49° 18′	1.2
Howard Hills	S67° 06′ E51° 03′	44

Rayner complex in the western part of Enderby Land, and the Archean Napier complex in the central part of the area. The Thala Hills are underlain by granulite-facies metamorphic and plutonic rocks of the Proterozoic Rayner complex (Black et al. 1987). The basement consists primarily of well-layered migmatitic, pyroxene, hornblende-biotite, garnet-biotite, and garnet-pyroxene gneisses, as well as charnockitic (enderbitic), and quartz monzodioritic to quartz dioritic gneisses of probable plutonic origin (Grew 1978).

The Molodezhny site of the Thala Hills oasis is a hilly area with ridges (Fig. 4.2). The ridges are 1 km long and up to 150 m wide. Depressions located between the ridges are mostly filled with snow patches, local glaciers, and lakes. The relative height of the ridges is about 10–40 m. The parent materials comprise drift and colluvium which provide a discontinuous and thin cover. Rock outcrops and patches of stony material dominate the area.

The Vecherny site in the Thala Hills comprise low-mountain relief with flattened tops that are 200–250 m a.s.l., steep slopes, and gently inclined terrace-like surfaces with smooth rocky faces (Fig. 4.3). Local depressions from 50 cm to several tens of meters in diameter are filled with detrital material of morainic or colluvial origins. There are inter-hill valleys of up to several hundred meters in length and several tens of meters in width that are also filled with gravelly silt sandy moraine or colluvial materials (Fig. 4.4). In the eastern part of the Vecherny site, the bedrock is often covered with relatively thick mantles of bouldery silty sand materials of moraine origin (Alexandrov 1985).

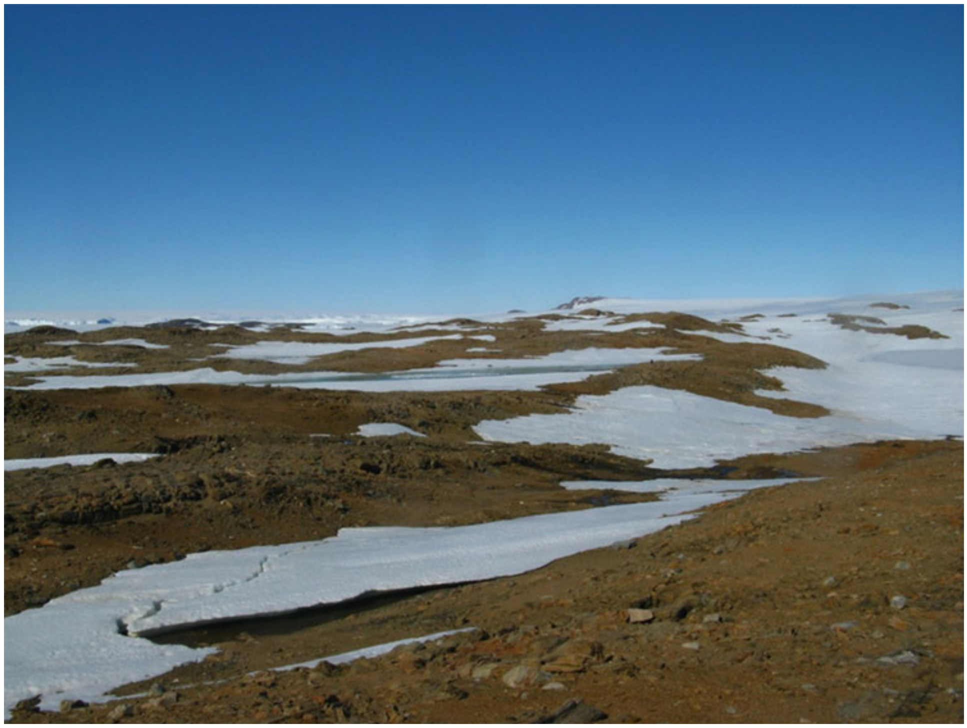

Fig. 4.2 Thala Hills oasis (early summer, December 2013)

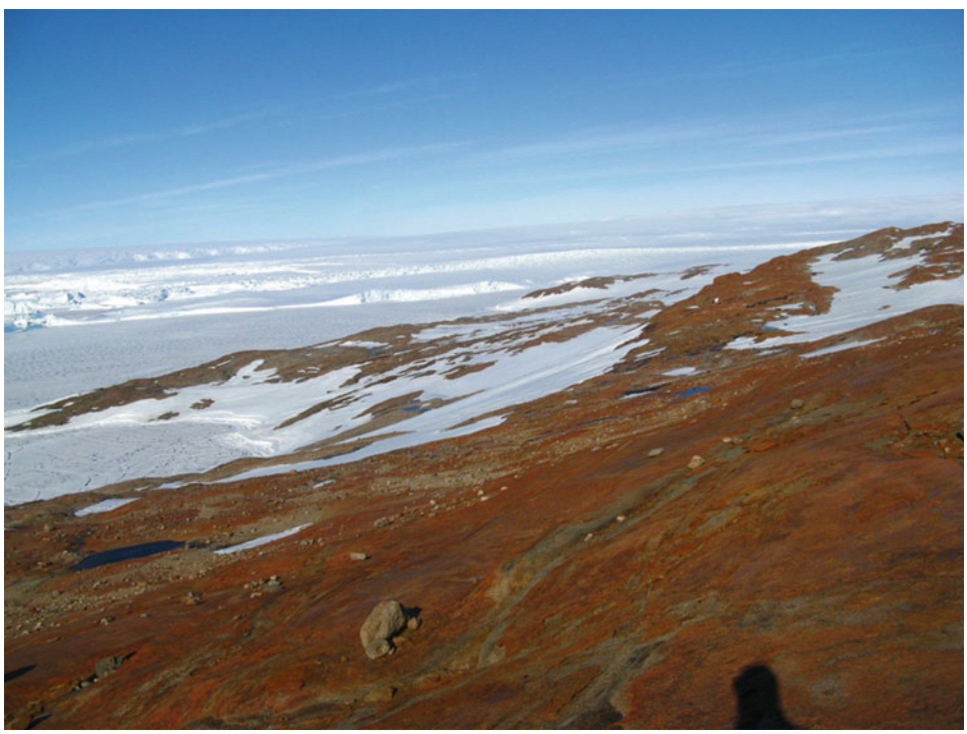

Fig. 4.3 Thala Hills oasis, northern slope of Mt. Vechernyaya

There are no detailed paleogeographic studies of the Tala Hills. However, there are data from other areas of Enderby Land that assist in reconstructing the late Pleistocene glacial history of the area. Radiocarbon dates were obtained from shells of shellfish in fluvial deposits along the Soya Coast. These dates suggest that there are two well-recognized stages of deglaciation in the coastal lowlands of Enderby Land, including the late Pleistocene (30–46 ky BP) and the Holocene (3–7 ky BP) (Takada et al. 1998; Zwartz et al. 1998). Raised beaches 20 m a.s.l. along the Lutzow-Holm

Fig. 4.4 Thala Hills, Vecherny valley site

coast are of early Holocene age (Miura et al. 1998). Radiocarbon dating of sediment from a freshwater lake shows that the basin became filled with lacustrine sediments about 10 ky BP (Zwartz et al. 1998). A varved organic clay (Richardson Clay) on Tula Till in the Mt Riiser-Larsen area of central Enderby Land yielded an AMS radiocarbon date of 40,250 ± 1,250 ky BP (Takada et al. 1998).

4.2.3 Climate

In spite of its somewhat northern location (67° 39′ S), the Thala Hills oasis has a more severe climate than coastal oases at similar latitudes in East Antarctica, such as the Vestfold Hills, the Larsemann Hills, and Grearson oasis (Chap. 5). This is due to the fact that the ice-free areas in Enderby Land are small, surrounded by ice, elongated sub-latitudinally, and in proximity to Dome F so that they bear the full brunt of the katabatic winds off the East Antarctic ice sheet The average air temperature at Molodezhnaya station is −11.0 °C (1963–1998). The average temperatures for the warmest (January) and coldest months (July) are −0.4 and −18.5 °C, respectively. Daytime temperatures in summer (December–February) reach +2 to +5 °C. The duration of the period with positive daytime temperatures is about two months.

The absolute minimum temperature is −42 °C (August), the absolute maximum is +8.5 °C (December). In summer the surface rocks warm up to +41 °C (MacNamara 1969b). The average wind speed is 10.3 m s^{-1}, the maximum wind speed is 40 m/s, and gusts up to 52 m s^{-1} have been recorded. The prevailing wind directions are southeast and east. The mean relative humidity is 68 %. Precipitation is mainly in the form of snow and is less than 250 mm (w.e) $year^{-1}$. Liquid precipitation occurs rarely and in small quantities. Snow cover is not continuous.

The climate of landscapes along the Lutziw-Holm coast (data are from the Syowa station; 69° 00′ S, 39° 35′ E) is similar to the climate of the Thala Hills oasis. The average air temperature at Syowa station is −10.4 °C (1981–2010). The average temperature in January is −0.7 °C, in July is −20.8 °C (http://www.data.jma.go.jp). For the coastal oasis Langhovde (69° 15′ S, 39° 46′ E) the mean annual air temperature (1988) in the coastal part of the valley was −8.6 °C, with a maximum of +6.3 °C and a minimum of −29.2 °C, The maximum rock (gneiss) temperature was +31.3 °C, with a mean January temperature of +6.8 °C) (Ohtani et al. 1990, 1992).

The climate of ice-free mountain areas likely is similar to those in other regions of East Antarctica (Queen Maud Land, the Prince Charles, and Grove Mountains of MacRobertson Land). There are data from automatic weather stations installed along a transect from Syowa station to Dome C. At an elevation of 1,076 m a.s.l, (site H21; 69° 05′ S, 40° 48′ E), the MAAT is −19.6 °C. The mean annual temperature at Mizuho Station (70° 42′ S, 44° 20′ E, 2,230 m a.s.l.) located on the glacial plateau is −33.2 °C (maximum −5.1 °C) (Takahashi et al. 2004). Presumably, positive air temperatures above 1,200 m do not occur.

4.2.4 Biota

The terrestrial flora has been categorized for the Thala Hills (Golubkova et al. 1968; Alexandrov 1985; Andreev 2013) and Lutzow-Holm (Horikawa and Ando 1961; Matsuda 1968; Kanda and Inoue 1994). Vegetation cover in the Thala Hills is sparse and consists of lichens, mosses, and algae. The predominant moss genera are *Bryum, Ceratodon,* and *Grimia*. Moss cushions cover 80 % of a 60 m^2 area at the Vecherny oasis in the Thala Hills. The site is located 400 m from an Adélie (*Pygoscelis adeliae*) penguin rookery and nesting site of South Polar skuas (*Catharacta maccormick*). The presence of ornithogenic materials appears to be conducive to the spread of moss vegetation. The largest areas of moss cover are confined to areas sheltered from the wind shelters and places actively visited by birds.

Lichens are widespread in Enderby Land and occur primarily in sheltered areas. In the Thala Hills, the maximum species diversity reported was 39 species of lichens in 21 genera and 11 families. Among the most common types growing on unconsolidated materials are *Rinodina olivaceobrunnea*, *Lepraria*, *Buellia, Amandinea punctata*, *Candelariella flava, Physciacaesia, Caloplaca tominii, Lecanora expectansi,* and *Caloplaca ammiospila*. Soils and rocky substrates are covered primarily with species in the genera *Lecideai, Lecidella, Umbilicariai Buellia*, and *Lecanora*. The Thala Hills oasis is dominated by crustose lichens (60–70 % of cover); foliose lichens cover 20 % of the oasis, and fruticose forms cover 13–15 %. Among fruticose lichens the genus *Usnea*, especially *U. sphacelata* is predominant (Andreev 2013).

In the Thala Hills oasis, the predominant soil algae are in the order *Nosctocales*; *Prasiola crispa* is common in ornithogenic soils. Habitats in the valleys of Lutzow-Holm oases are similar to other oases of Enderby Land and Queen Maud Land. There are widespread lichens and mosses, algae, microscopic fungi, and bacteria (Inoue 1995; Ohtani et al. 2000).

Coastal oases of Enderby Land contain rookeries of Adélie penguins *Pygoscelis adeliae*. Also, Antarctic skuas *Catharacta maccormicki* and different species of petrels *Fulmarus glacialoides*, *Dapltion capensis, Pagodroma nivea*, *Oceanites oceanicus* nest in coastal oases of Enderby Land. This is an important biogeochemical factor because birds contribute organic matter enriched with N and P from the ocean to the low-nutrient soils of Antarctica.

4.2.5 Methods

We collected field data from soils in the Thala Hills oasis (67° 40′ S 45° 50′). Field studies were conducted in accordance with the Antarctic Permafrost and Soils (ANTPAS) guidebook (Bockheim et al. 2006). Soils were classified according to *Soil Taxonomy* (Soil Survey Staff 2010). Soil moisture content was determined gravimetrically. Monitoring of soil temperature began in 2007 (Gilichinsky et al. 2010) and has continued to date. Soil temperature was measured with HOBO and iButton Thermochron loggers inserted at depths of 0, 20, 40, and 50 cm on unconsolidated and rocky substrates of contrasting "warm" and cold exposures. Thaw depth was measured weekly in the summer season of January 2012 to February 2013 at a site in Thala Hill oasis established according to the Circumpolar Active Layer Monitoring (CALM) protocol (http://www.gwu.edu/∼calm) at each of 121 sampling points.

pH, redox potential (Eh), and electrical conductivity (EC) were measured in the field on snow and soil leachates using HANNA Instruments Picollo HI-1280, ORPHI-98120, and DIST 5 HI-98311, respectively. The temperature correction function was used. Radiocarbon dating was conducted in laboratories of the Institute of Environmental Geochemistry in the National Academy of Sciences, Ukraine by Liquid Scintillation Counting method for total organic carbon. The radiocarbon content was measured by "Quantulus-1220T."

Analytical data were collected from one pedon, an ornithogenic soil, and included pH, organic C, loss-on-ignition, and extractable phosphate and K using standard techniques.

4.3 Soils of Enderby Land

4.3.1 Soils of Thala Hills Oasis

4.3.1.1 Soil Temperature Regime

As is typical in polar regions the mean annual soil temperature at a site in the Thala Hills oasis declined with depth; the oscillation and amplitude of soil temperature also decreased with depth. Temperature at a depth of 1 m in bedrock was less extreme than in the soil (c.f. Figs. 4.5 and 4.6). In summer, moss cushions have a major impact on soil temperature; below 20 cm only a gradual alteration of temperature is observed (Fig. 4.7). The transition to positive average daily temperatures at a depth of 50 cm occurred on December 1, 2012 and at a depth of 1 m on December 25, 2012 (Fig. 4.5). At the soil surface, a maximum temperature of +12.1 °C was recorded at the end of December 2012. By the second half of February 2013, a stable negative temperature had already become established.

Rock temperatures at 1 m were substantially warmer during the summer of 2012–2013 than the two previous summers (Fig. 4.6). The zero-degree isotherm is below 1 m (Figs. 4.5 and 4.6). This means that permafrost is deeper than 1 m, and if there is no cryoturbation (we did not observe cryoturbation in soils near the soil-temperature monitoring

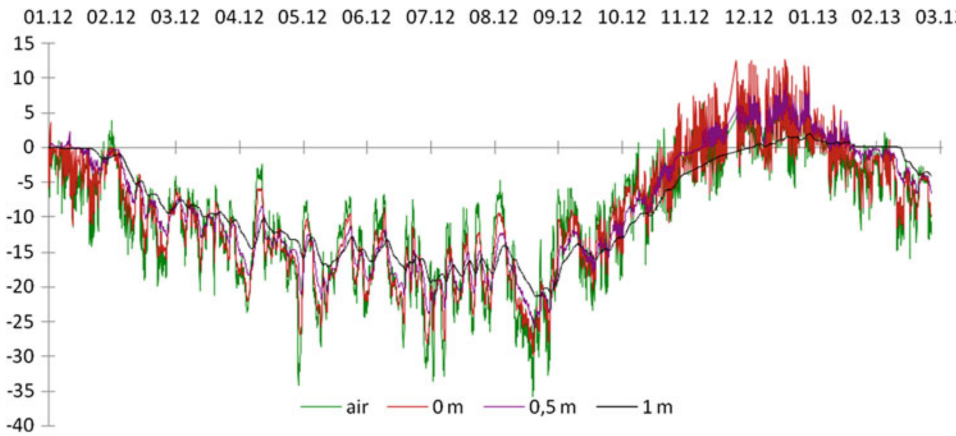

Fig. 4.5 Temperature dynamics (air and in borehole of the rock at different depths) at the Molodezhnaya station (29.01.2012–18.03.2013)

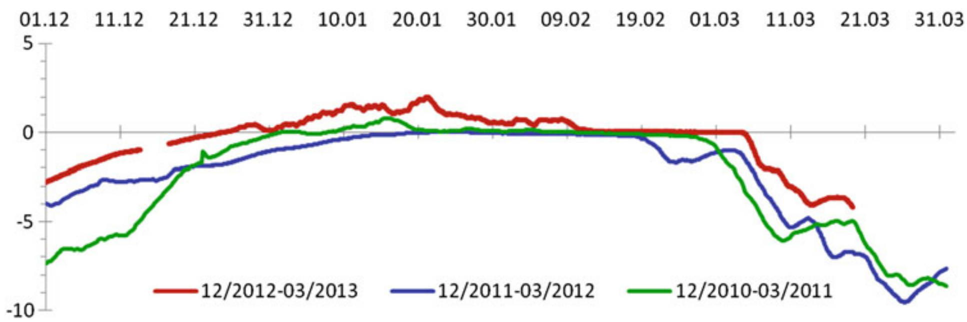

Fig. 4.6 Dynamic of the rock temperature at the depth of 1 m in 3 years (2010–2013), Molodezhnaya station

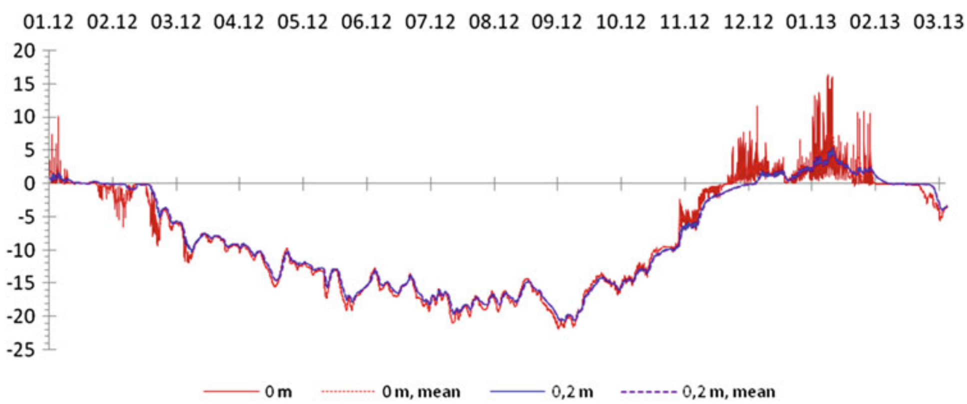

Fig. 4.7 Dynamics of soil temperatures in wind shelter with moss cover (MOLO 02; 17.01.2012–19.03.2013); *red* 0 cm, *blue* 20 cm

site), the temperature regime is subgelic rather than pergelic and the soil cannot be classified as a Gelisol. At a depth of 0.2 m, the average annual temperature in the soil with a moss layer was −9.2 °C (Fig. 4.6), which was comparable to the soil lacking a moss layer (Fig. 4.5).

The maximum thickness of the active layer was 92 cm in early February 2013). MacNamara (1969a) reported a thaw-layer depth of more than 1 m. At the CALM site, the average depth of thaw was 67 ± 6.5 cm on 09.01.2013, 72 ± 6.5 cm on 26.01.2013, and 78 ± 4.5 cm on 05.02.2013. The average maximum thaw depth in the previous year (2011–2012) season was 65 cm, which was 12 cm less than in 2012–2013.

4.3.1.2 Hydrological Conditions and Soil Moisture Characteristics

Most of the unconsolidated sediments in the Thala Hills oasis dry quickly in the summer, because there is practically no liquid precipitation. However, in the valleys with snow patches the summer moisture conditions are different. During most of the summer, water flows actively in valley bottoms from thawing of snow. The most important factor for soils in the valleys is the additional surface moistening due to the active melting snows in the warm season. As a result, the surface soil horizons, despite the strong wind-induced dehydration, continue to retain moisture.

In some years summer precipitation is minimal. During these comparatively warm snowless summers, as in 2012–2013, snow patches completely melt and water ceases to flow. In such cases there is a reduction of moisture content in the upper layers. However, these periods continue, presumably, for not more than 2 weeks because of the following long cold season when the temperature drops below 0 °C.

Data collected from natural waters show a sequence of fresh snow → melting snow → water after interaction with soil → subsurface water → water in rock closed hollows in terms of increasing alkalinity and conductivity (Table 4.1).

4.3.1.3 Soils of Rocky Hills Areas

Much of the Thala Hills oasis is occupied by rocky ridges and hills, including low mountains (up to 280 m). The depth to bedrock is rarely more than 50 cm. The surface is often covered with frutiose, foliose, and crustose lichens. Lithic Haplorthels are common here. However, soil temperature data imply that some soils with a lithic contact and without cryoturbations should be classified as Lithic Gelorthents, as they have no permafrost within 1 m.

Mantles of moraine deposits are located between the ridges and the individual hills. The thickness of unconsolidated material in these depressions is greater than 1 m. These areas contain soils with the finest soil-textural classes in the study area. Patterned ground is extensive in these areas and vegetation is limited to the edges of sorted polygons. Typic Haploturbels are common in these areas (Figs. 4.8 and 4.9).

Stratified weathering crusts and epi-endolithic soil-like bodies are characteristic of rocky outcrop areas (Fig. 4.10). Large areas of rocky outcrops of granite are covered with brown and reddish-brown plates, under which in exfoliation cracks primary minerals are destroyed and the formation of specific endolithic microhorizons takes place. An important product of biochemical weathering here are organomineral coatings inside the endolithic system (Mergelov et al. 2012). Physical and chemical weathering, together with biochemical weathering, result in a reddish-brown color of rocks at the slopes of mount Vechernyaya. However, the occurrence of endolithic communities within the site Molodezhny of Thala Hills is even greater than at Vecherny.

Locally, salt efflorescence and crusts are found on the surface. Soluble salts are mainly found near the coast. Carbonate encrustations are most commonly found and can apparently be formed in situ by the weathering. Calcite, gypsum, aragonite, and halite have been found previously in the Thala Hills oasis on soil ground, bedrocks and on the undersides of boulders. Soluble salts of marine origin are dominated. However, sometimes calcite cutans were found in the subsurface soil horizons (MacNamara and Usseleman 1972).

4.3.1.4 Soils of Wet Valleys

Inter-ridge valleys with melting snow patches in summer are important for biodiversity and organo-mineral interactions in oases of East Antarctica (Fig. 4.11). In contrast to the Dry

Fig. 4.8 Patterned ground (sorted circles) at the Vecherny site, Thala Hills

Fig. 4.9 Typic Haploturbels in polygon center (*left*) and border of stone circle (*right*)

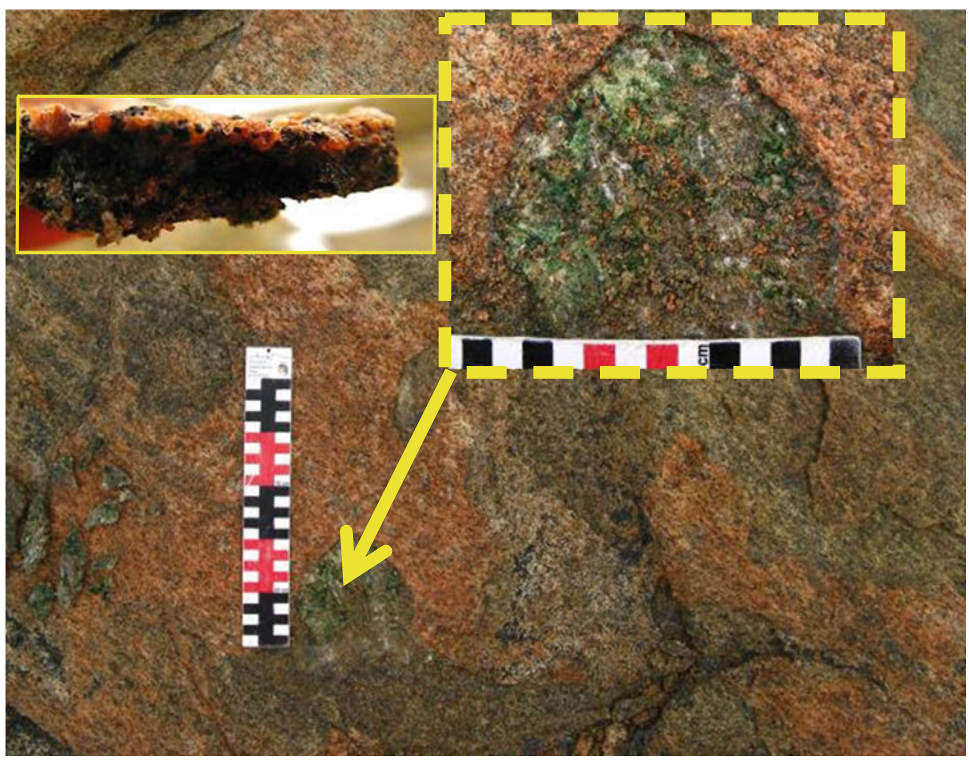

Fig. 4.10 Endolithic microsoils under exfoliation plates

Valleys, they have been named "wet valleys" (Mergelov 2011). The most important soil-forming factor in wet valleys is the additional surface moistening due to the active melting of snow patches in the warm season. As a result, the near-surface soil horizons continue to retain moisture, despite the strong wind desiccation. The bottom and the lower slopes of a valley are filled with gravel and coarse-textured materials. Here, the main component of the fine-earth fraction (<2 mm) is coarse sand of quartz-feldspar composition. Mosses, lichens, algae and fungi tend to occur under the desert

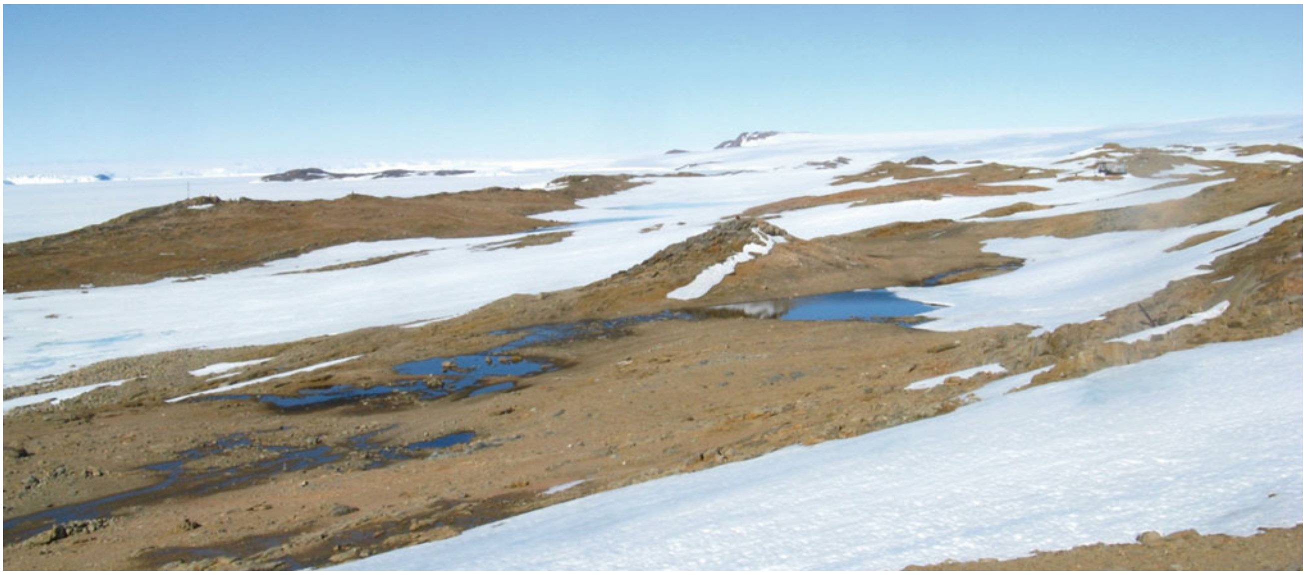

Fig. 4.11 Wet valley, Thala Hills

pavement rather than on the soil surface, which enables the biota to avoid desiccation, UV radiation, and wind abrasion.

In the valley bottoms water flows over fine-earth sediments of alluvial origin and algal covers are widespread (Figs. 4.12 and 4.13a, b). Algae can form a solid blackish film. While drying, these films turn into crusts with the thickness of 1 cm. Olive-colored algal horizons are formed here at a depth of 1–3 cm from the surface; below the algal layer are gray-brown organic-mineral horizons of 2–5 cm thick that contain partially decomposed organic matter. The deeper horizons may be buried because of the fluvial process. Some of these soils may have feature patterned ground. These soils may be classified as (Oxy)Aquic and Fluventic Haploturbels and Fluventic Haplorthels. "Oxyaquic" is not on the list of Haploturbels subgroups, but it should be included in the Keys, Aquic features doubtfully occur in Enderby Land because of the high Eh values.

At the margin of the zone of flowing water, the vegetation changes to mosses (*Bryum* and *Ceratodon*), which develop under the gravel pavement. These soils are depicted in Figs. 4.12 and 4.13c. The A horizon is located under mossy cushions. Below the A horizon is a mineral horizon with active development of micromycetes rich in fungal mycelia on the surfaces of sand grains. Cryoturbation occurs in these soils, but it is less pronounced than in the wet soil described previously. Typic Haplorthels and Typic Haploturbels are common soil taxa along the margins of wet valleys in the Thala Hills.

On higher slopes above the valley, the vegetation disappears (Figs. 4.12 and 4.14a). Soils lacking vegetation have an olive-colored desert pavement over a 1−2 cm thick organo-mineral horizon in which algae occur. The upper soil horizons in the summer are often dry. The average summer temperature here is +2.8 °C. Cryoturbation also is weakly expressed. In spite of some difference with previously described soils, these soils should also be classified as Typic Haplorthels and Typic Haploturbels.

Further upslope in the valley, the amount of moisture in the upper part of the profile decreases sharply. "Ahumic" soils dominate these areas (Figs. 4.12 and 4.14b). The moisture content in the summer in the upper horizons is 1–4 % during snowmelt and after short summer snowfalls it may rise to 10 %. As a result of this increase in moisture in places of snow accumulation, the algae appear under the desert pavement. The average summer temperature here rises to +3.9 °C at the surface. The active layer depth reaches a maximum of 85–92 cm. In some places there are cryoturbation features in soils, and patterned ground may appear on gentle slopes. These soils are closer to Anhyturbels but still we should classify them as Typic Haploturbels/Haplorthels because they are not dry enough. These soils are the most common not only in the valleys, but also in other areas with gravelly-sandy deposits. Patterned ground and cryoturbation are common on sites with sandy-silty loamy moraine deposits.

Rocky valley sidewalls contain endolithic microsoils. These soils are similar to the soils of rocky ridges (see above).

In wet valleys there is widespread accumulation of silt on the surfaces of rock fragments. The upper surface of the gravel acts as a trap. There appears to be an increase in the fine-silt fraction in subsurface horizons and the near-surface permafrost as well. This is the consequence of soil pervection. However, contrary to some evidence of MacNamara (1969b) the illuvial accumulation of clay that is enough for distinguishing of argillic horizon was never observed in our studies.

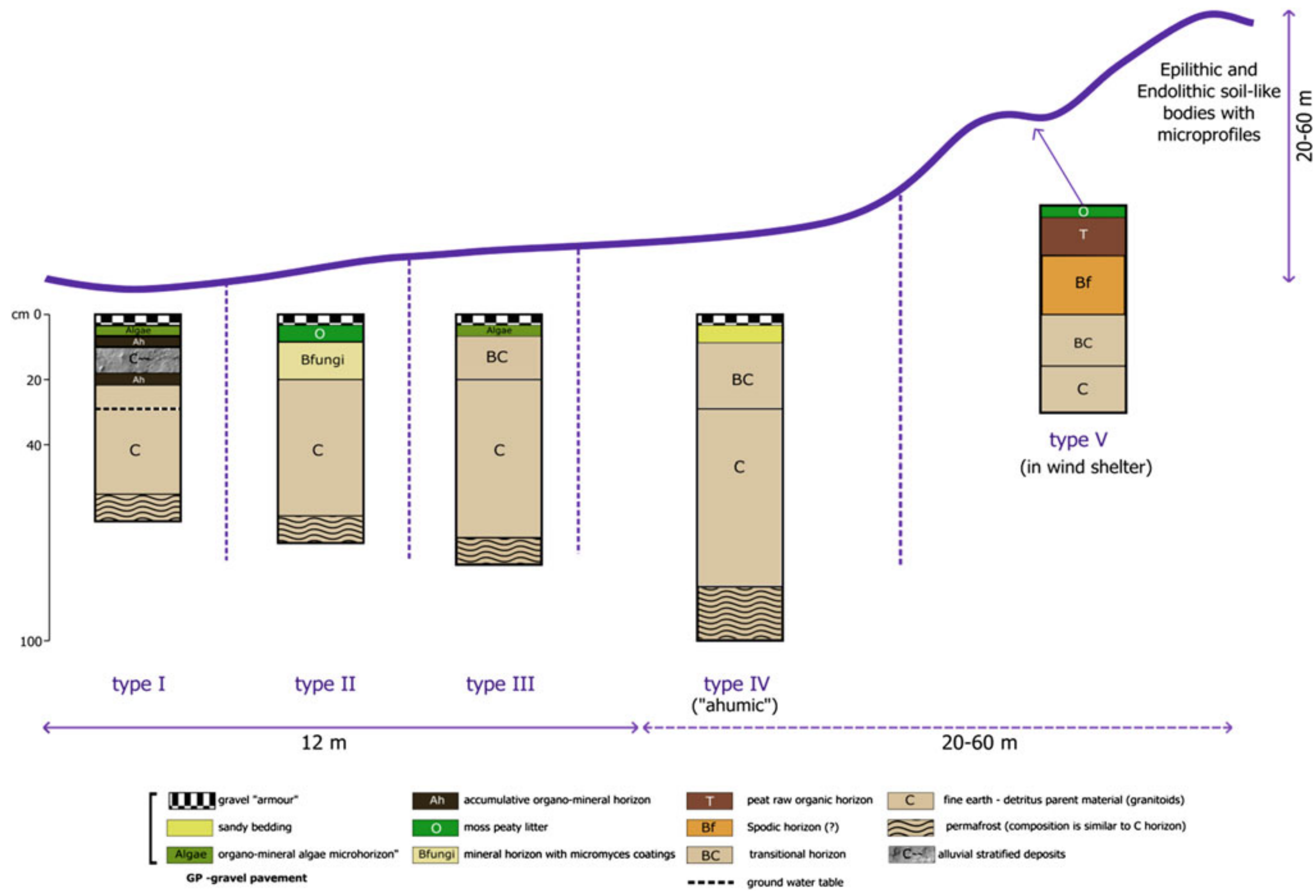

Fig. 4.12 Major types of soils and soil-like bodies in the wet valley

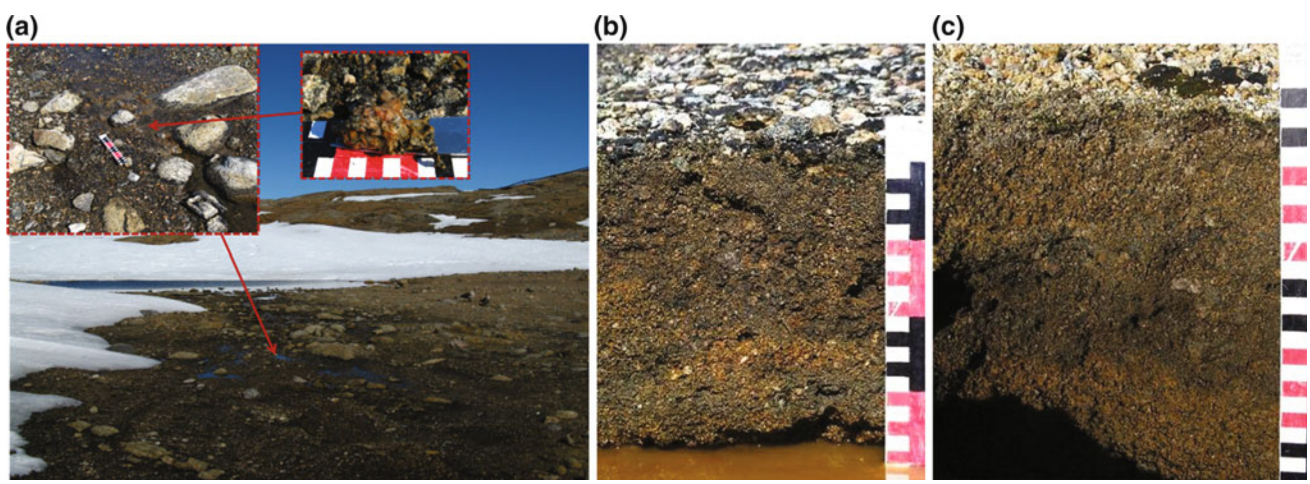

Fig. 4.13 **a** Valley bottom, a creek with algae cover, **b** Valley bottom, a soil under algae cover, **c** Valley bottom, organo-mineral soil under moss cover with the top horizon of micromycetes development

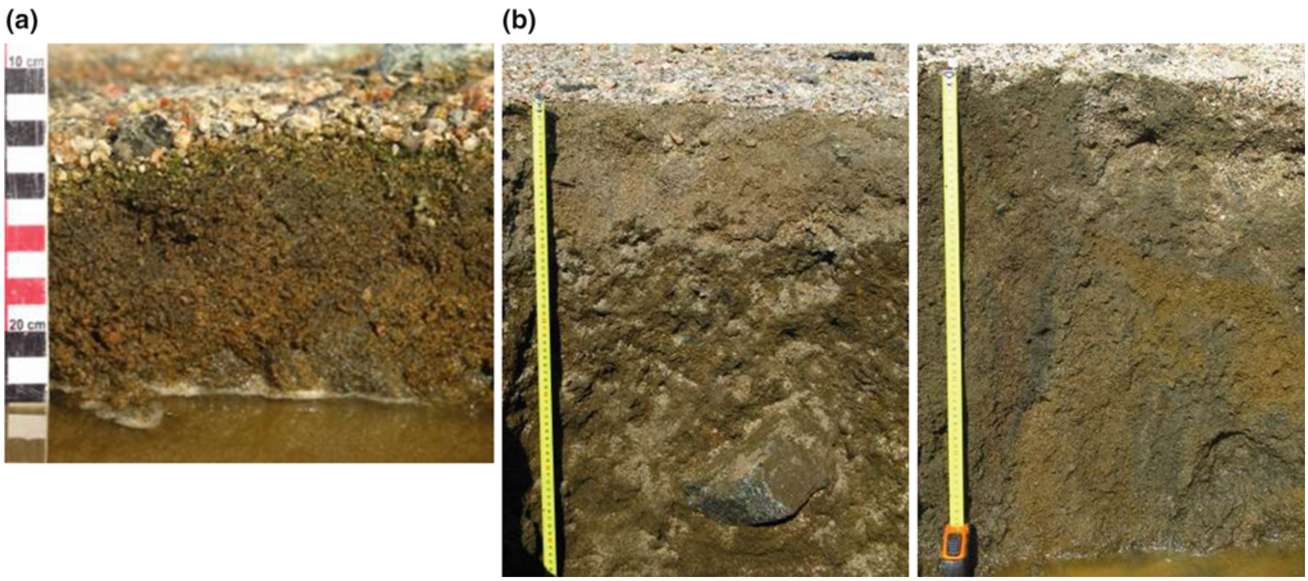

Fig. 4.14 **a** Soils with algae organic-mineral horizon, **b** Different "ahumic" soils

4.3.1.5 Soils of Wind Shelters

The most "succulent" vegetation of oases is related to wind shelters on colluvium in hollows formed in hard rock (Figs. 4.12 and 4.15). The orography of oases in Enderby Land contributes to the widespread occurrence of such shelters. Orientation of oasis ridges from the southeast to northwest coincides with the direction of the main katabatic winds. Summer cyclonic winds east and northeast, bring an abundance of snowfall which may persist until the following summer.

These events result in a thick moss cover with lichens that is underlain by organo-mineral soil with peat horizons up to 15 cm (Fig. 4.15). Radiocarbon age of the lowermost portion of the organic horizons is 360 ± 60 years BP (Ki-17840, TOC). This suggests that shelters with moss cover have operated for at least the past 500 years. Previous dating of organic matter at the base of an 18-cm thick peat horizon under *Ceratodon purpureus* moss yielded an age of 1,220 ± 80 BP.

Soils of wind shelters are characterized by the presence of an iron-accumulation horizon. Iron coatings can be seen both macro-and mesomorphologically. These soils are often found throughout the oases, but their total area is small. These soils are associated with inputs of organic material

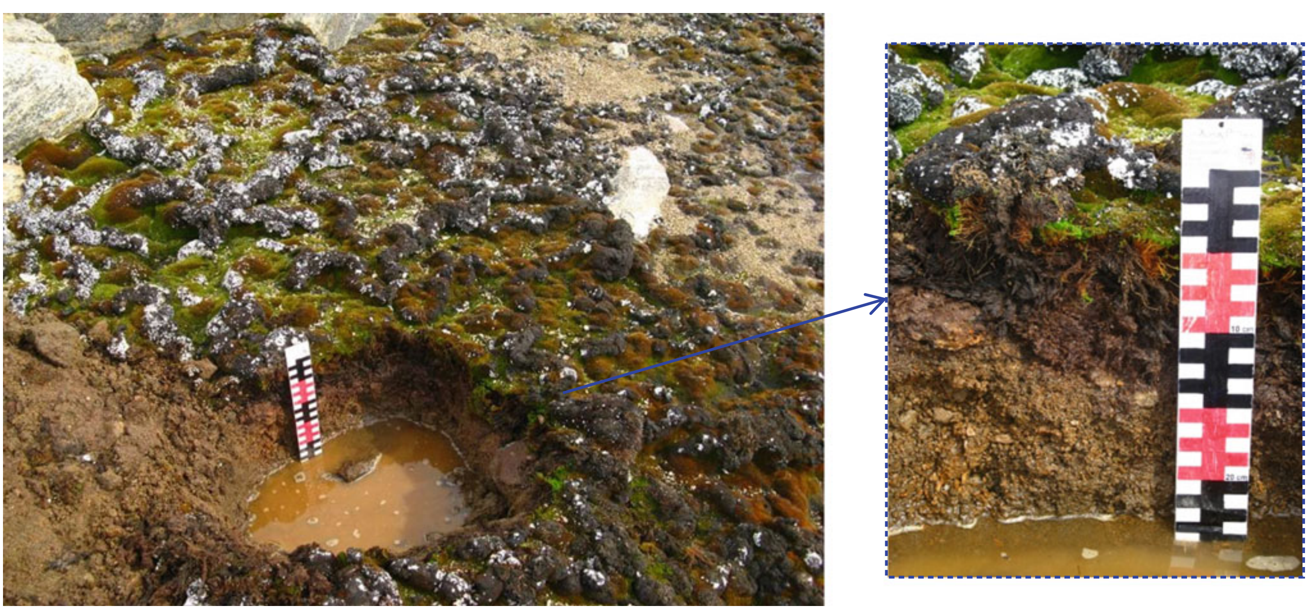

Fig. 4.15 Soils of wind shelters with peaty horizons

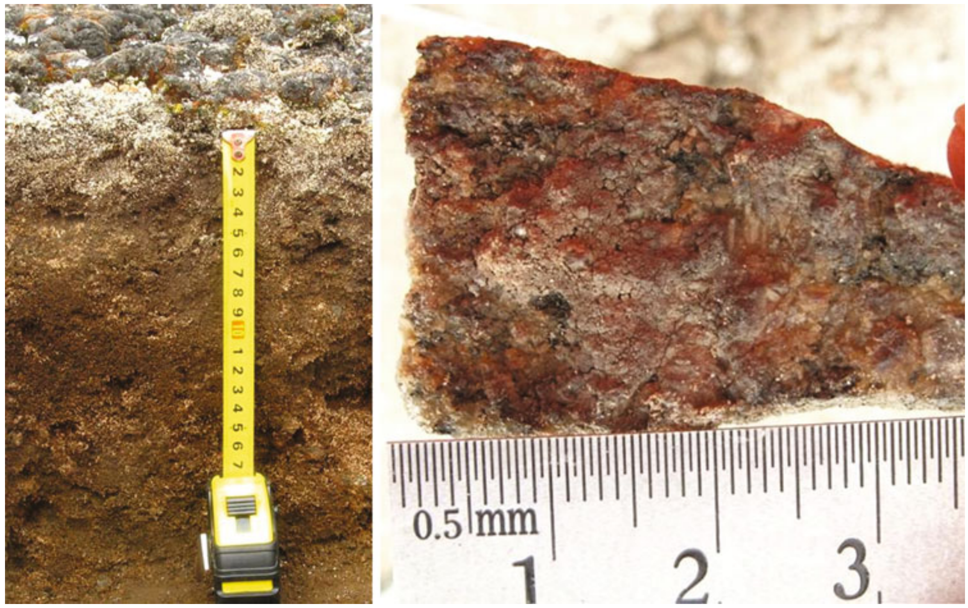

Fig. 4.16 Soils of wind shelters without peaty horizons (*left*), iron films on rock fragment in Bf (or Bs) horizon (*right*)

such as feathers and guano of *Catharacta maccormicki*. A similar soil a thinner organic horizon was described by MacNamara (1969b) as Protoranker soil. These soils have organo-mineral horizon 2–3 cm beneath lichens and up to 15 cm under moss cushions that is underlain by a horizon of iron and possibly aluminum accumulation (Bs horizon; Figs. 4.12, 4.15, and 4.16). These soils preliminary (we still do not have data on the content of oxalate soluble forms of Fe and Al,) can be classified as Spodic Psammorthels, Lithic Psammorthels, and Typic Haplorthels (if we have >35 % of rock fragments). Close analogues of such soils are Spodorthels in the Grearson Hills oasis, Wilkes Land (Chap. 6).

4.3.1.6 Miscellaneous Soils

Soils of the Lake Shores with Pulsating Water Regime
During summer, the coastline of small lakes retreats (Fig. 4.17). Underwater organisms (algal-bacterial mats, mosses) become exposed on the surface. Soils in this environment were named "soil-amphibians" (Abakumov and Krylenkov 2011). Surface soils in the Thala Hills oasis are covered by algo-bacterial mats with a thickness up to 5 cm. Under the mat there is an organo-mineral horizon up to 10 cm thick with organic matter of lacustrine origin. Redoximorphic features and shallow ground water table are characteristic of mineral horizons of these soils (Fig. 4.18). Texture of these soils is finer than other soils of the oasis. These soils should be classified as Typic Aquorthels as we have no Limnic Aquorthels in *Soil Taxonomy*.

Some of lakeshore soils have abundant sulfur mostly because of their former connection with the sea. Algal-bacterial mats almost completely cover the bottom of temporarily drained ponds. The deposits are of dark color because of high sulfide content. These soils have reductive Eh values and pH values less than 4.5. The profile depicted in Fig. 4.19 has a yellow oxidation zone on a dark gray background of the main material. This soil is Sulfuric Aquorthel. Similar soils were reported by Glazovskaya (1958) and are considered in detail in Chaps. 13 and 14.

Ornithogenic Soils
Ornithogenic soils are found at the Vecherny site of Thala Hills in an Adélie penguin rookery (Fig. 4.20). These soils commonly are located on rock outcrops. The thickness of guano layer in these soils does not exceed 35 cm. Bodies of dead birds, feathers, and eggshells are well preserved in these soils. These soils are underlain by bedrock at a depth of 30–50 cm. These soils can preliminarily be classified as Lithic Historthels. The areal distribution of these soils is closely connected with the boundaries of the rookery. In some places the surface is covered with the algae *Prasiola crispa*. *Prasiola crispa* also occurs in areas where penguins molt and skuas nest. Soils in these areas, classified as Typic Haplorthels, have abundant C, P, and N in the upper horizons (Table 4.2).

In wet valleys the moss cover may be more widely spread than in rookeries, due to the influx of extra organic material by birds (*Catharacta maccormicki* and *Pygoscelis adeliae*). Organic horizons up to 20 cm thick may be found in these locations (Fig. 4.21). The moss-covered area shown is over 60 m^2, and the organic matter is only partly decomposed. Ornithogenic material consists mainly of feathers and less of guano. Beneath the organic horizon are a B horizon with iron accumulation and a B horizon with redoximorphic features and cryoturbation. The thickness of the active layer

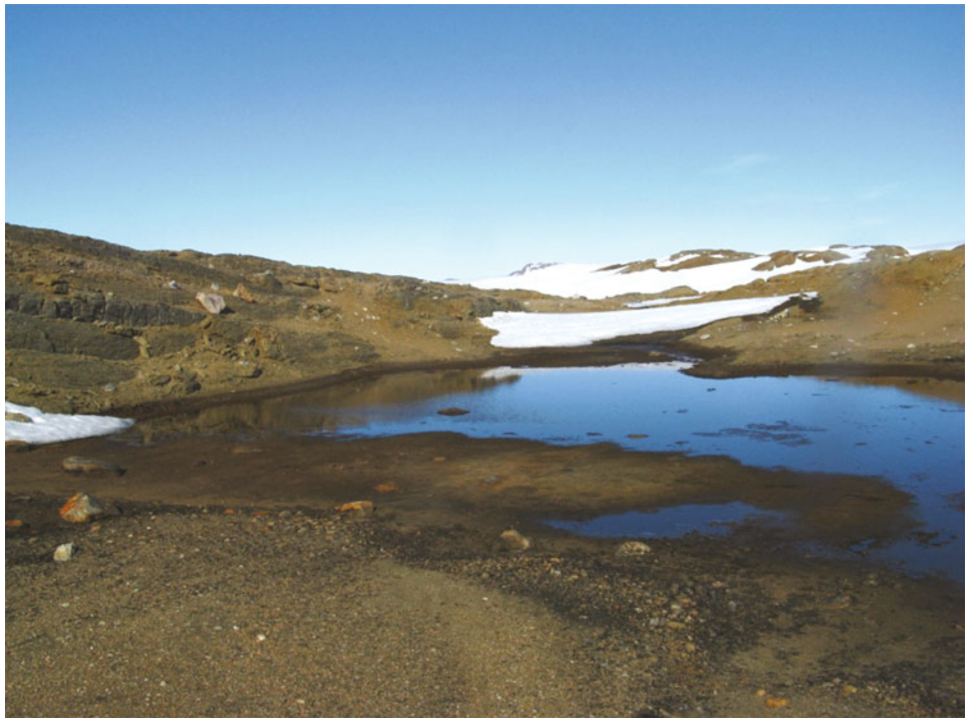

Fig. 4.17 A lake with the pulsating moisture regime along its coastline

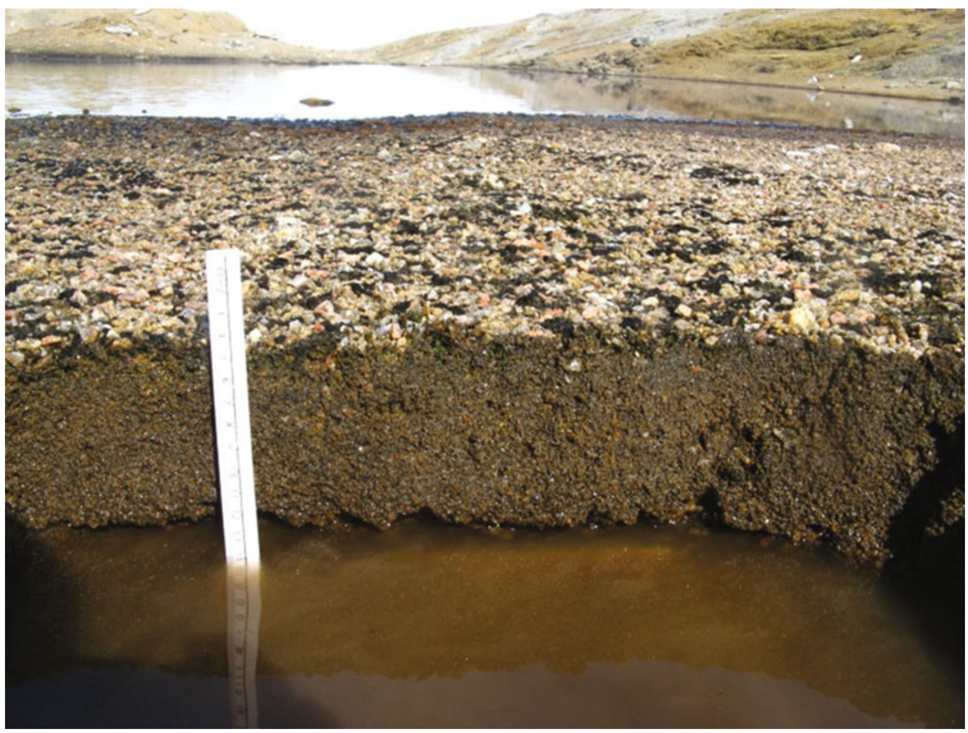

Fig. 4.18 Typic Aquorthel, bottom of lake

is 75 cm. This soil is similar to those of wind shelters. However, the formation of upper layers is definitely associated with the influx of ornithogenic organic material. These soils can be classified as Typic Histoturbels, Typic Aquiturbels, or even Spodic Psammoturbels. If they have no cryoturbation, they are classified as Typic Haplorthels (Table 4.3). These soils are similar to soils of abandoned penguin rookeries in Wilkes Land (Chap. 6).

Fig. 4.19 Sulfuric Aquorthel

4.3.1.7 Anthropogenically Influenced Soils

Human-induced disturbance of soils is widely found in the vicinity of the Russian Antarctic station "Molodezhnaya" (see also Chap. 16). Duration of economic development here is more than 50 years. Among anthropogenic features are garbage dumps, oil spills, and reworked unconsolidated materials. Soil disturbance is related to the use of caterpillar vehicles. In this case, enrichment of the upper layers by fine earth (<2 mm) is often marked at the expense of human physical disintegration of rocks. The material of soils subjected to human impact has relatively excess content of arsenic, lead, and cadmium (Lupachev et al. 2012). Also there is the trend to have higher content of various hydrocarbons associated with both global transfer from South America, Africa, Australia, and local anthropogenic pollution (Negoita et al. 2003).

4.3.2 Soils of Other Oases

4.3.2.1 Polkanov Oasis

Polkanov oasis (Fig. 4.1, site 3) is a low granite-cored hill with a sub-latitudinal orientation of parallel landforms and a maximum elevation of 400 m. More than 70 % of territory lies in a range between 50 and 150 m a.s.l. Moraine, eluvial, and colluvial materials form a discontinuous and thin mantle. Coarse sand and gravel deposits are found in shallow depressions, on slopes and terraces, and along the rocky fringe of the watershed. Patterned ground is common with polygons ranging between 0.5 and 2 m in diameter that contain gravelly or stony borders. Glaciers and snow patches cover nearly 33 % of oasis area, especially near the southern limit of the oasis where it is close to the main source of snow.

The oasis contains 107 lakes, all with freshwater, and a vast network of seasonal meltwater streams which can even form floodplains with gravely terraces 0.3–0.5 m high. Aquic and Fluventic Haploturbels, Fluventic Haplorthels form in the vicinity of seasonal streams. Mosses are restricted to shelters and wind "shades" of northern expositions, riparian rocky fragments, major boulders, and glacier bluffs. Widespread species are *Bryum algens* and *Ceratodon purpureus*. The most strongly developed peaty horizons found under *Ceratodon purpureus* litter were 4.5 cm thick and considered to be formed in approximately 300 years. In general, moss pads are less widespread and developed (four times thinner at maximum values) than in Thala Hills oasis. Moss habitats on sandy-gravel deposits of from periglacial processes are usually associated with Typic Haploturbels and Typic Haplorthels.

Fig. 4.20 Ornithogenic soil

Table 4.2 Chemical properties of natural waters from the Thala Hills

Sample	pH	Eh (mV)	EC (μS cm^{-1})
Fresh snow			
Melted snow	5.4–6.5	145–290	0–80
Snow patches	6.0–6.8	150–290	10–60
Surface water	6.2–7.1	180–290	30–100
Soil solution	6.4–7.0	190–295	40–115
Rock hollows	6.5–8.0	180–280	100–535

The major limiting factors for vegetation development are the same as for most Antarctica oases, which are the lack of moisture and wind abrasion. Elimination of both to a certain degree is necessary to create a favorable environment for vegetation to establish. For instance, bottom parts of cirques at Polkanov oasis with enough moisture sources do not have even discontinuous vegetation due to strong wind turbulence, wind-driven desiccation of top layers, and regular transfer of relatively light sandy particles. Surface soil horizons of coastal areas and in shelters on moraine slopes (Typic Haplorthels) with sufficient moisture content host various algae colonies.

Lichens are more widespread and colonize even windward rocky exposures, sometimes close to the ice sheet. In this case lichens are periodically sprinkled with snow and then are covered by thin ice crust protecting them from wind abrasion. The following species were identified: *Lepraria neglecta* on loose sediments and mosses, *Rinodina turfacea* on the same substrates, *Alectoria minuscule*, *Neuropogon acromelanus*, *Omphalodiscuc decussates*, *Protoblasterina citrina*, *Gasparrinia murorum* on rocky surfaces, and others. Dry colluvial sediments on lower part of valley slopes are quite widespread in oasis; they would usually provide an environment to Typic Haploturbels and Typic Haplorthels or even to Typic Anhyorthels and Typic Anhyturbels. Vast granite exposures containing Lithic Haplorthels are modified by exfoliation with two types of plates: 1–10 mm thick and 10–50 mm. The first are produced by physical and biochemical weathering, the latter only by physical disintegration. Epilithic (lichen driven) and endolithic (lichen, cyanobacteria, chlorophyta, fungi driven) soil-like microfeatures could be expected on these granite outcrops. Tafoni is common to boulders and rocky cliffs and considered to be most extensive among all other oasis studied at Enderby Land. Penguin rookeries were observed in the coastal part and occurrence of *Prasiola crispa* patterns with ornithogenic soils can be predicted to occur there.

4.3.2.2 Nikitin Oasis (Fyfe Hills)

The Nikitin oasis (Fig. 4.1, site 7) is a low granite hill with a predominantly northeast orientation and with a maximum elevation of 500 m. This is the only oasis among those considered in this chapter that is separated from open sea by the ice shelf. The major topographic elements of the oasis are rocky watersheds and cirques. Cirque bottoms are usually occupied by glaciers and lakes. Tafoni is very common on bedrock surfaces. Watershed slopes are mostly covered by stone streams with large fragments up to several meters in size. The rocky fragments have an eluvial, colluvial, or glacial origin. Lithic Haplorthels are expected to occupy significant area in oasis. Unconsolidated sediments are present to an even greater extent than in Thala Hills, Polkanov and Howard oases. Patterned ground occurs all around oasis with mudboils, polygons, and stripes 0.2–3 m wide and 20 m long. Mudboils are most common on colluvial sandy loams where they have circular shape 1.5–2 m in diameter (Typic Haploturbels expected). The mudboils often have a thin salty crust on its surface. Sandy loam material usually is concentrated as a central core surrounded by coarse sand and gravel.

Glaciers and snow patches cover almost 32 % of oasis area. The ice-free area is perpendicular to southeastern winds, which prevents further distribution of snow across oasis; thus moisture sources are distributed unevenly. Most

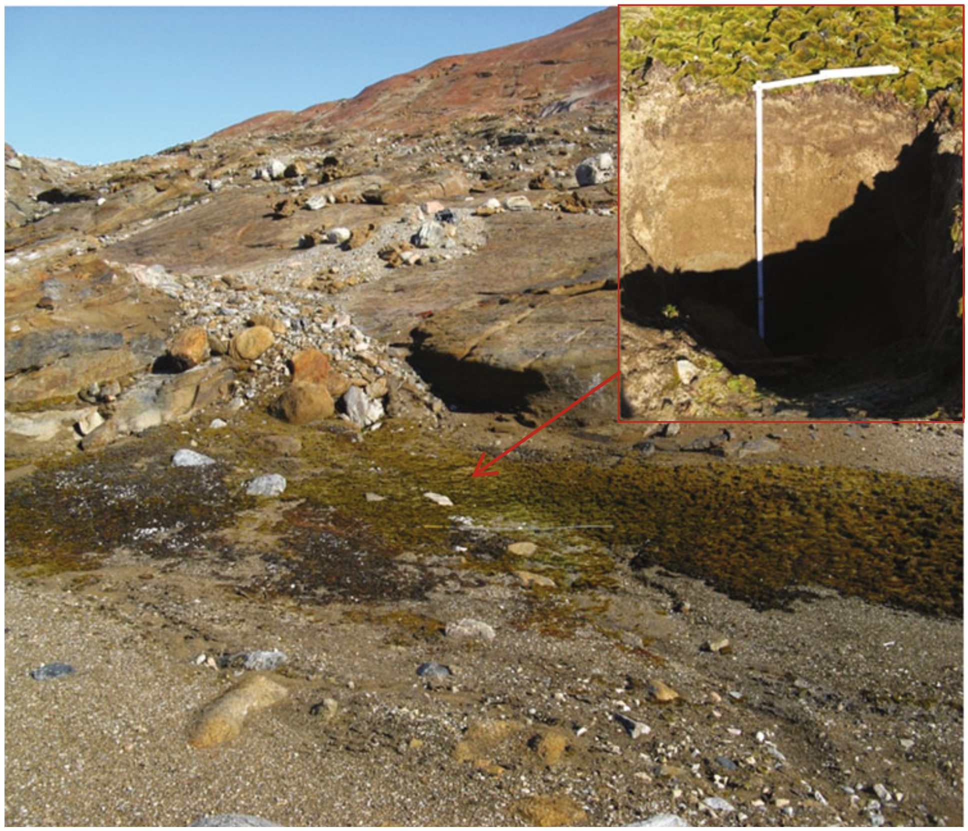

Fig. 4.21 Ornithogenic soil under moss cover in an abandoned penguin rookery

Table 4.3 Main chemical features (post-ornithogenic Typic Haplorthel)

Pit	Horizon	Depth (cm)	OC (%)	Loss-on-ignition (%)	pH (H_2O)	P_2O_5 (mg/100 g)	
LA56-Ml-03	O	0–2(4)	5.95	18.19	5.54	n.d.	n.d.
	AC	2–5(7)	4.63	7.73	5.43	16.83	2.48
	C	5–11	2.85	4.53	5.50	28.69	1.88

hill tops are dry while northern slopes of cirques are wet. Six freshwater lakes and a network of small streams are hosted by oasis. Vegetation colonizes almost all unconsolidated materials where there is sufficient moisture. Exceptions are recently exposed surfaces, areas periodically covered with firn, nd wind transferred substrates. The best locations for vegetation development are wet low parts of colluvial slopes with moss-lichen-algae associations. The most widespread moss species are *Bryum algens* and *Ceratodon purpureus*. Typic Haploturbels and Typic Haplorthels can be expected to be prevalent in this oasis.

4.3.2.3 Howard Oasis

The Howard oasis (Fig. 4.1, site 8) can be divided into two landform components: accumulative moraine landforms and denudational bedrock landforms. The depressions in the denudational part of the oasis are comprised of inter-hill valleys filled with unconsolidated material of eluvial, colluvial, glacial, and fluvial origin. Large boulders are common on slopes and bottom of valleys. Drift in the accumulative part of oasis reaches 50 m in thickness. Several extensive lake depressions (200 × 400 m) are found in the Howard oasis. Areas of thinner drift underlain by glacial ice contain thermokarst depressions that are 10–15 m wide and 100 m long. Thus, Glacic Haplorthels could be expected here. In general, thermokarst processes in Howard oasis are most intensive than in other oases described in this chapter. Patterned ground is very common on moraines. Periglacial features are common in the oasis, including mudboils and sorted polygons. Typic Haploturbels are predicted to develop here. Glaciers and snow patches cover only 7 % of oasis area. There are 30 lakes and a dozen major streams in the oasis. Some lakes are hypothesized to have a thermokarst genesis. Algae, mosses develop in more wind-sheltered locations. Typic Haploturbels and Typic Haplorthels are likely the most predominant soils. Lithic Haplorthels occupy rocky granite outcrops in denudational parts of the oasis.

4.3.2.4 Lutzow-Holm Coast (East-Ongul Islands, Langhovde Oasis)

Ohtani et al. (2000) studied algae communities, including Cyanophyceae, Chlorophyta, Xanthophyceae, and Bacillariophyceae in the vicinity of Syowa station at Lutzow-Holm Bay. The surface mineral soils have pH values ranging between 7.2 and 9.4. Electric conductivity of soil suspensions ranged from 119 to 730 μS cm^{-1}, which was probably due to chlorides contributed by marine aerosols. The total carbon content varied from 0.04 to 0.99 %, total N from 0.002 to 0.4 %, and extractable phosphorous from 0.16 to 0.81 %. The highest C, N and P values occurred in soils covered by *Prasiola crispa* near penguin rookeries. Soils influenced by penguins had the lowest C/N ratios of the soils examined. The highest C/N ratios (up to 19) were found in anthropogenically modified soils near the station. Except for these analytical data from the top few centimeters soil, we have no information on the soils of Syowa oasis. Based on soils in other coastal oases of Enderby Land, we expect the dominant soils to be Lithic Haplorthels, Typic Haploturbels, and Typic Haplorthels.

4.3.3 Soils of the Tula, Scott, Nye, Raggatt, and Napier Mountains

Napier, Nye, Raggatt, Tula, Scott Mountains have an elevation over 1,200 m a.s.l. It is unlikely that mean monthly temperature above 0 °C occur above 1,200 m are absent; however, rock surfaces should have positive temperatures during the daytime. The anticipated soils that can be found their besides rock outcrops are Lithic Haplorthels and to a lesser extent Lithic Haploturbels. Some Glacic Haplorthels can also be found at the sites with moraine on the glacier ice. Endolitic microsoils are also possible to exist in this harsh environment.

4.4 Discussion

4.4.1 Pedogenesis

The pedogenic processes in the soils of Enderby Land are rather diverse in spite of the fact that it is not the warmest and not the largest ice-free region of East Antarctica. Physical disintegration is the ubiquitous process in almost all soils of the region; however, the quartz-feldspar mineralogical composition of rocks limits this process mainly to formation of coarse sand material and tafoni forms. Biochemical weathering also takes place in soils of Enderby Land leading to dissolution of primary minerals. This process is evidenced by endolithic microsoils and rubification of rock surfaces.

The low biogenic activity and rather harsh climate and parent materials limit the accumulation and transformation organic matter. In Enderby Land, organic matter only accumulates in wind sheltered areas or on lake bottoms The ornithogenic input of organic matter from the sea to soils is much less widespread in Enderby Land than in other parts of Antarctica (e.g. Antarctic Peninsula and adjacent islands; Chaps. 12 and 13). Less common pedogenic processes are pervection (soil particle migration that does not result in argillic horizon formation), redoximorphism in former lakes bottoms, sulfide oxidation, weak salinization by sea aerosols, and weak calcification from biochemical weathering. Although our analytical data has not been processed yet, soil morphological data suggests that podzolization may occur in soils that are sheltered from the wind. The cryopedological processes of cryoturbation and frost sorting are not ubiquitous but do occur, along with thermokarst, in Howard oasis.

Generally, the pedogenic processes of Enderby Land are analogous to other ice-free areas in coastal East Antarctica.

4.4.2 Soil Geography and Classification

The Thala Hills and other coastal oases of Enderby Land are related to polar desert soil zone of Bockheim and Ugolini (1990) and Blume et al. (1997). In our opinion coastal oases of Enderby Land should be allocated to Mid-Antarctic snow-patch cryptogamic barrens (Goryahkin et al. 2011; Balks et al. 2013). Meltwater from snow patches enhances soil development, and pedogenesis of soils in wet valleys have features of more humid soils than are common to Antarctic, including pervection, cryoturbation, biochemical weathering, podzolization, and peat accumulation. At the same time soils of well-drained and wind-affected habitats may have some features of pedogenesis which are characteristic of a more arid climate, including desert pavement, desert varnish, salinization, and calcification). However, in the proposed Mid-Antarctic zone, these features are not strong enough to classify these soils as Anhyorthels and Anhyturbels. That is why the term "desert" in its narrow "arid" sense is not appropriate for soil landscapes of coastal oases of East Antarctic (Goryachkin et al. 2004). However, soils of mountains and nunataks of Enderby Land presumably should be allocated to Cold desert zone.

The most widespread soils of Enderby Land are Typic Haplorthels and Typic Haploturbel;. Lithic Haplorthels/Haploturbels are also characteristic for landscapes with shallow depth to bedrock. Other soils occupy much less areas, including Lithic Gelorthents (permafrost >1 m without cryoturbation), (Oxy)Aquic Haplorthels/Haploturbels, Aquiorthels/Aquiturbels, Spodic Psammorthels (?), Sulfuric Aquorthels. The patterns of the soil cover of Enderby Land coastal oases are similar to those of MacRobertson Land and a little bit less of Schirmacher oasis of Queen Maud Land (see Chaps. 3 and 11, respectively).

4.5 Summary

Enderby Land is the large portion of East Antarctica but it constitutes only about 3 % of the total ice-free area of Antarctica. This region has numerous coastal oases with small areas, including the Thala Hills, Polkanov, Howard, Nikitin, and Langhovde oases, as well as isolated mountain peaks and nunataks. Soils data for Enderby Land are sparse. Systematic pedological studies began recently and only for the Thala Hills oasis. There are some soils data for Langhovde oasis and the Thala Hills oasis, as well as data on landscape mapping from several other oases. We were unable to find any soils data for the mountainous areas.

Mosses, lichens, soil algae, and birds (penguins, skuas and petrels) play an important role in soil development in coastal areas of Enderby Land. Permafrost is continuous in Enderby Land, but a mantle of unconsolidated material in thin in many places so that permafrost extends into frozen. Active-layer depths may range from a few decimeters in the mountains to 100 cm or more on the coast. Patterned ground is not ubiquitous but cryogenic features are common throughout the region.

Soil-forming processes can be recognized as diverse even for one studied oases. Physical and biochemical weathering resulting in fine-earth formation, carbonation and rubification as well as pervection, soil organic matter accumulation, redoximorphism, sulphide oxidation, aerosol salinization are characteristic for coastal oases. Podzolization may occur in Enderby Land but will require analytical support and further investigation.

The dominant soil taxa along the coast are Haploturbels/Haplorthels, Aquiturbels/Aquorthels, and previously unclassified ornithogenic soils and endolithic microsoils. Lithic subgroups both for Haploturbels and Gelorthents (permafrost >1 m without cryoturbations) are predominant in the territories with shallow rock contact.

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5 Soils of MacRobertson Land

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5.1 Introduction

MacRobertson Land (region 3; Fig. 2.1) is that portion of Antarctica lying south of the Mawson Coast between 59° 34′ E and 72° 35′ E. At 5,400 km^2 MacRobertson Land constitutes the third largest ice-free area in Antarctica, accounting for 11 % of the total ice-free area. Less than 10 % of the ice area occurs along the coast. Region 3 has five major ice-free areas: (i) the Northern Prince Charles Mountains, including the Amery Oasis, (ii) the Southern Prince Charles Mountains, including the Mawson Escarpment, (iii) the Grove Mountains, (iv) a series of small coastal oases and inland Framnes Mountains along the Mawson Coast, and (v) the Vestfold Hills, Rauer-Bolingen Islands, and Larsemann Hills along the Ingrid Christensen Coast (Fig. 5.1). Research stations in the region include Mawson (AU), Progress II (Russia), Davis (AU), Zhongshan (China), and Law-Răcoviţ (Romania); Bharathi station (India) is soon to be officially opened.

At 3,100 km^2, the Prince Charles Mountains (PCM), which trend 450 km in a meridional direction, is the largest ice-free area of the region 3. They are comprised of several large mountain massifs and numerous nunataks to the west and south of the Amery Ice Shelf–Lambert Glacier. Accidental Valley, the only "dry valley" of the PCM is shown in Fig. 5.2. One of the "dry valleys" of the PCM—the Accidental Valley—is shown in Fig. 5.2. The southwestern portion of the PCM represents the furthest inland ice-free area (650 km from the Mawson Coast) in Antarctica. The highest elevation is Mount Menzies at 3,355 m a.s.l. The 700-km-long Lambert Glacier–Amery Ice Shelf system drains about 1.5 million km^2 of the East Antarctic Ice Sheet (Allison 1998). The subglacial Gamburtsev Mountains occur further to the south, are 1,200 km long, have a maximum elevation of 2,700 m, but are covered with as much as 600 m of ice that is part of the East Antarctic ice sheet. The Gamburtsev Mountains are believed to have been the first epicenter of Antarctic glaciations some 34 Ma ago (Rose et al. 2013).

The Lambert Glacier fills the Lambert graben, which is a prominent tectonic structure of East Antarctica that originated in the Late Paleozoic time and was activated in the Early Cretaceous during the breakup of Gondwana (120 Ma ago). This rift system extends across the continental shelf in Prydz Bay to its outer margin. The development of this system provided conditions for the accumulation of Permo-Triassic sediments, including coal measures, in the tectonically depressed paleo-Lambert basin (Harrowfield et al. 2005). The area around Lake Radok is the only area in East Antarctica, where these sediments, the Amery group, crop out on the surface. During the Cenozoic this area featured the earliest Antarctic glaciations, neotectonic uplift of the mountains, and development of the Lambert Glacier system.

The Mawson Escarpment, located to the southeast of the Amery Ice Shelf–Lambert Glacier, has an ice-free area of 1,400 km^2 (Fig. 5.1). Along with the PCM, this area is ideal for studying the linkage of onshore events with offshore sediment records from the Amery Ice Shelf–Prydz Bay region (Hambrey et al. 2007). The PCM and Mawson Escarpment are two of the most studied regions in East Antarctica in terms of its geology and landscape evolution during the Neogene and Quaternary periods. However, very little is known about the soils and biota of either area. No

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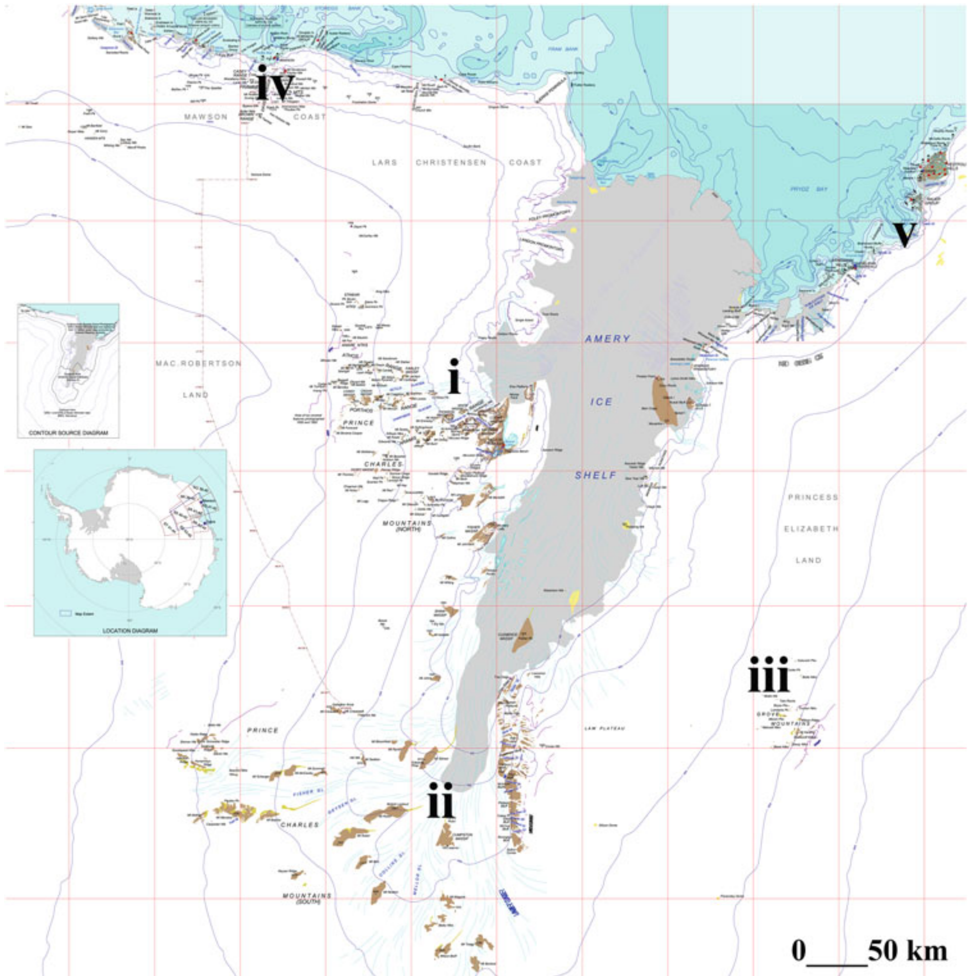

Fig. 5.1 Location of the Prince Charles Mountains and the Amery ice shelf northern in MacRobertson Land (Australian Antarctic Program)

detailed soil studies have been conducted, and no soil maps are available. The lack of soils information also applies to small coastal ice-free areas and inland Framnes Mountains along the Mawson Coast.

The third largest ice-free area in MacRobertson Land is the Grove Mountains (400 km^2), which contain 64 nunataks, the highest of which is Mt. Harding at 2,160 m (Fig. 5.3). Both the PCM and the Grove Mountains have acted as "dipsticks" for recording changes in ice sheet thickness during glacial-interglacial cycles (Mackintosh et al. 2007). The soils of Grove Mountains were studied by Li et al. (2003).

There are three smaller ice-free areas along the Ingrid Christensen Coast, including the Vestfold Hills (400 km^2), the Rauer-Bolingen Islands (50 km^2), and the Larsemann Hills (50 km^2) (Fig. 5.1). These coastal areas are deeply dissected by short (up to 1 km) valleys that formed along structural lineaments, particularly joints, in response to erosion by ice and water (Adamson and Pickard 1986; Kiernan et al. 2009). These "inter-hill valleys" are the major structural unit of the Vestfold and Larsemann Hills (Fig. 5.4). Both areas have hundreds of freshwater lakes. ^{10}Be exposure dating, radiocarbon determinations, salt and sediment geochemistry, and rock weathering observations

Fig. 5.2 “Accidental Valley”, one of the “dry valley” of the Prince Charles Mountains (photo by South Australia Museum)

indicate that parts of Larsemann Hills were subaerially exposed throughout much of the last glacial cycle, with the last glaciation occurring prior to 100 ka BP (Kiernan et al. 2009). Periglacial thermokarst landforms are common in both areas, including thaw pits, thaw lakes, ground ice slumps, linear depressions, and small-scale beaded drainage features (Kiernan et al. 1999).

The soils of these three coastal areas have been studied in terms of microbial ecology (Fletcher et al. 1985; Line 1988) and contamination by trace metals and petroleum products (Kerry 1993; Gasparon and Matchullat 2006). Leishman and Wild (2001) studied the relations between vegetation abundance and diversity to soil nutrients and soil water content in the Vestfold Hills. Negoita et al. (2001) examined chemical and biological properties of soils along the Antarctic east coast from Queen Maud Land to Mirnyy that included samples from Progress Station (69° 23′ S, 76° 24′ E) and the Stornes Peninsula (69° 24′ S, 76° 07′ E). Zhu et al. (2009) studied ornithogenic and seal affected soils near Prydz Bay.

The objectives of this chapter are to assemble soils data from MacRobertson Land and interpret these data regarding the likely soil taxa and the factors controlling their distribution. Results of a detailed soils study in the Larsemann Hills are presented here (Mergelov 2014).

5.2 Soil-Forming Factors in MacRobertson Land

5.2.1 Climate

Elevation differences of over 3,000 m and distances of ice-free areas from the coast up to 650 km inland create sharp contrasts in climatic conditions from a relatively “mild” climate along the Mawson and Ingrid Christensen Coasts to a cold desert climate on nunataks in the southern PCM and Grove Mountains. Climate data from the Larsemann and Vestfold Hills show a mean annual air temperature of

Fig. 5.3 Mason Peak, the summit of the Grove Mountains, MacRobertson Land (photo by Sinhua News, China)

−9.2° (Zhongsan Station) to −11.2 °C (Mawson Station) (Table 2.2). The warmest monthly temperature (January) varies from 0.8° (Zhongsan Station) to 0.3 °C (Davis Station). The mean annual precipitation is around 200–250 mm. Katabatic winds are strong from interior areas of MacRobertson to the coast.

In the Grove Mountains (73.25°, 74.55° E), Li et al. (2003) reported a monthly temperature for January of −18.5 °C at an elevation of 2,160 m. From Figs. 2.4 and 2.5, the mean annual precipitation and temperature in the southern PCM and Grove Mountains should be 75 mm and −30 °C, respectively. These data are consistent with Australian Automatic Weather Stations (AWS) data. Six of the stations were installed in 1994 at different locations on the ice sheet around the Lambert Glacier at surface elevations ranging from 1,830 to 2,741 m a.s.l. All of these stations had permanently cold air temperatures with mean summer air temperatures of about −20 to −28 °C and mean winter air temperatures of −35 to −45 °C (Allison 1998).

Climatic data from the Zhongshan Station and three AWS on the ice sheet surface on the traverse to Dome A (80º 22′ S, 77º22’ E; 4,093 m a.s.l.; 1,228 km from the coast) collected by Ma et al. (2010) show that firn temperatures at a depth of 10 m are significantly (1.1–6.6 °C) lower than the mean annual air temperatures, which was explained by surface inversions. Snow accumulation decreased from the coastal region inland from 199 to 31 mm w.e. year^{-1} at Dome A.

Areas along the Mawson and Ingrid Christensen Coasts may support “snow-patch barrens”, which were observed in other coastal areas of East Antarctica (Goryachkin et al. 2011). Snow-patch barrens are characterized by significant accumulations of snow (200–250 mm w.e. year^{-1}), with pronounced redistribution by wind in the winter, active snow melting in the summer, and the formation of subsurface water in coarse-textured sediments and intermittent surface water in the bottoms of local depressions. These comparatively mild temperature conditions in the Amery Oasis may exist at altitudes from 0 to about 300–400 m a.s.l. It is probable that at higher elevations (400–1000 m a.s.l.), a transitional zone between the climate of snow-patch barrens and permanently cold climate of glacial deserts can be distinguished. The differences in the climatic (primarily, temperature, and precipitation) conditions should be reflected in the character of pedogenesis.

Fig. 5.4 Vestfold Hills, near Davis Station in East Antarctica (photo by J. Alean, M. Hambrey)

5.2.2 Biota

MacRobertson Land contains at least seven moss species, 25 lichen species, approximately 200 non-marine algal taxa, and 100–120 fungal taxa (Seppelt et al. 1988; WP8 2006). Abundant microbiological populations were observed in soils beneath a moss bed or beneath translucent quartz pebbles containing green algae in the vicinity of Mawson Base and the Vestfold Hills (Line 1988). Four major environmental factors have been identified as important influences on Antarctic terrestrial vegetation in East Antarctica: moisture availability, nutrients, salinity, and microtopography (Leishman and Wild 2001). As in other areas of Antarctica, penguins and other birds play an important role in supplying nutrients to nesting sites.

5.2.3 Geology

The bedrock geology of MacRobertson Land is complex but is comprised dominantly of Precambrian gneisses, schists, and quartzites (Fig. 2.10). Unconsolidated Quaternary age sediments include moraines, mostly ice cored, on top or flanks of glaciers and till deposited on mountains and nunataks when glacier levels were higher than at present (Hirvas et al. 1993; Hambrey et al. 2007; Liu et al. 2010). From surface exposure dating, Hambrey et al. (2007) recorded at least 10 million years of landscape evolution at Radok Lake in the northern PCM. Landscapes of the Amery Oasis evolved primarily under the influence of wet-based (probably polythermal) glaciers during the Miocene and Pliocene; in contrast, the Quaternary Period was characterized by cold-based glaciers that had relatively little impact on the landscape. The late Pleistocene and Holocene history of Amery oasis was reconstructed from analysis of lacustrine sediments in Lakes Terrasovoe and Radok (Wagner and Cremer 2006). Basal glacial and glaciofluvial sediments are overlain by 2.70 m of laminated algal and microbial mats and a few interspersed moss layers. Radiocarbon dating yielded an age of the onset of biogenic accumulation of 12,400 cal. years BP. Several warmer and colder stages were recorded in the Holocene.

Permafrost is continuous in MacRobertson Land. Active-layer depths range between 25 cm in the Grove Mountains (Li et al. 2003) and 110 cm on the coast

Fig. 5.5 Patterned ground features to the west-southwest of Lake Radok as seen on Google Earth

Fig. 5.6 Small-size sorted polygons in the Amery oasis (Souz base) composed of Permo-Triassic siltstone

Fig. 5.7 Solifluction stripes on slope in the area composed of Permo-Triassic sediments

(Kaup and Burgess 2002). Patterned ground is common in the areas with frost-susceptible parent materials throughout the region (Figs. 5.5, 5.6 and 5.7).

5.3 Soils of MacRobertson Land

As indicated previously, soils data for the MacRobertson Land are sparse. We were unable to find any soils data for the Prince Charles Mountains.

5.3.1 Grove Mountains

In the Grove Mountains, Li et al. (2003) emphasized the following soil features: a surface desert pavement, abundant soluble salts in the profile, strongly stained horizons in the upper soil profile, slightly acid to neutral reaction (pH 6.0–6.7), and negligible organic matter content (Table 5.1). Analysis of 1:5 soil–water extracts indicated that the dominant cations were Mg^{2+} and Na^{+}, followed by Ca^{2+} and K^{+}; the main anion was SO_4^{2-}, followed by Cl^{-} and NO_3^{-}

Table 5.1 Analytical properties of soils from the Grove Mountains, MacRobertson Land (Li et al. 2003)

Depth (cm)	>2 mm (%)	Sand (%)	Silt (%)	Clay (%)	Fed (%)
B9221; Lithic Anhyorthels					
0–4	2.7	92.4	5.6	2	0.76
4–7	4.9	92.4	3.6	4	0.57
7–12	6.2	85.8	4.8	9.4	0.49
B9231; Lithic Anhyorthels					
0–4	6.2	91.4	3.1	5.5	0.64
4–9	5.3	93.8	2.8	3.4	0.55
9–14	9.3	88.7	3.7	7.6	0.53
14–17	19.6	93.3	3.9	2.8	0.53
B9261; Lithic Anhyorthels					
0–5	0.2	95.5	0.1	4.4	0.6
5–10	5.2	84	4.3	11.7	0.41
B9271; Lithic Anhyorthels					
0–7	40	88.9	4.9	6.2	0.55
T92111; Lithic Anhyorthels					
0–6	13	86.5	3.9	9.6	0.62
6–10	19.5	90.8	4.1	5.1	0.76
T902121; Lithic Anhyorthels					
0–5	22.9	93.6	3.9	2.5	1.08
T92310; Lithic Anhyorthels					
0–15	28.3	91.6	6.8	1.6	0.88
T92311; Lithic Anhyorthels					
0–12	4.8	95.7	1.8	2.5	1.05
12–26	16.4	94.8	2.6	2.6	1.03
26–32	18.9	92.6	1.4	6	0.88
32–40	6.3	84.8	6.2	9	0.95
T92301; Lithic Anhyorthels					
0–20	24.5	91.9	1.9	6.2	0.71
20–40	19.4	91.9	2.9	5.2	0.76

(Table 5.2). Gypsum and other sulfate minerals were the most common salts in the soils. The salt stages ranged from 0 (none) to 5 (strong salt cementation), but most of the salts were stage 2 (few flecks) (Table 2.7).

The upper horizons of some soil profiles were stained, reflecting rubification, or weathering of iron-bearing minerals. The reddish hues of cold desert soils were attributed to relatively high concentrations of dithionite-extractable Fe (Fed), which varied from 0.41 to 1.1 % (Table 5.1). The soils are derived from Fe-rich granitic materials.

Soils in Grove Mountains are coarse sand (57–84 %), and the clay content varies from 1.6 to 12 % (Table 5.1). The major clay minerals were illite, smectite, and illite-smectite (Li et al. 2003). The soils were weathering stage 3 or 4 (Table 2.6); from this their ages were estimated at 0.5–3.5 Ma. ^{10}Be exposure ages of samples taken from different elevations on Mount Harding and adjacent Zakharoff Ridge (Liu et al. 2010) were consistent with these estimates.

Although the lower soil horizons were ice cemented, no indication was given of the presence of visible ice crystals (schlieren, lenses, etc.). Judging from the absence of cryoturbation and organic matter accumulation, the shallow depth to bedrock (7–40 cm), and the coarse soil textures, the soils can be classified as Lithic Anhyorthels, since lithic subgroups key out before gypsic or petrogypsic subgroups.

5.3.2 Vestfold Hills

Previous soil studies in the Vestfold Hills have focused on ornithogenic soils (Line 1988; Leishman and Wild 2001; Zhu et al. 2011). Ornithogenic soils are moist (0.1–63 %),

Table 5.2 Chemistry of soil:water extracts from the Grove Mountains, MacRobertson Land, Antarctica (Li et al. 2003)

Depth (cm)	Ca^{2+} ($\times10^{-2}$ mg g^{-1})	Mg^{2+} ($\times10^{-2}$ mg g^{-1})	Na^{+} ($\times10^{-2}$ mg g^{-1})	K^{+} ($\times10^{-2}$ mg g^{-1})	SO_4^{2-} ($\times10^{-2}$ mg g^{-1})	NO_3^{-} ($\times10^{-2}$ mg g^{-1})	Cl^{-} ($\times10^{-2}$ mg g^{-1})	HCO_3^{-} ($\times10^{-2}$ mg g^{-1})	pH	Gypsum (%)	$CaCo_3$ (%)	TOC (%)
Profile B9231; Lithic Anhyorthels												
0–4	4.42	0.69	0.51	0.12	4.6	0.08	1.2	0.16	6.4	0.40	1.81	–
4–9	2.39	4.35	53	0.13	57.8	0.54	0.49	0.24	6.7	–	1.64	0.70
9–14	1.88	84.6	15.2	0.47	104	0.65	1.04	0.18	6.0	–	1.51	–
14–17	1.18	31	7.74	0.37	38.6	0.47	1.08	0.18	6.4	–	1.43	1.46
Profile B9261; Lithic Anhyorthels												
0–5	3.71	0.5	0.48	0.06	4.58	0.02	0.1	0.15	6.0	0.39	1.95	–
5–10	2.34	128	18.3	0.11	148	0.73	0.55	0.19	6.7	–	1.52	1.22
Profile T92311; Lithic Anhyorthels												
0–12	6.48	1.55	0.56	0.42	7.67	0.54	0.33	0.19	6.7	0.66	2.14	0.26
12–26	0.41	1.05	6.94	0.35	7.94	0.74	0.37	0.22	6.4	–	2.27	0.62
26–32	7.07	1.44	36.9	0.42	46.9	0.74	0.43	0.12	6.4	–	1.66	0.71
Profile T92301; Lithic Anhyorthels												
0–40	0.23	1.22	34.7	0.51	42.2	0.75	0.39	0.12	6.7	–	0.45	0.64
Profile T92111; Lithic Anhyorthels												
0–10	3.88	64	40	0.51	104	0.25	0.67	0.17	6.4	–	0.22	1.33

Table 5.3 Properties of ornithogenic and non-ornithogenic topsoils from MacRobertson Land, Antarctica

Location	Soil group	Sampling depth (cm)	No. of samples	Field moisture (%)	EC (mS/cm)	TOC (%)	Total N (%)	Total P (mg/kg)	pH	References
Vestfold Hills	Ornithogenic	0–62	5	13–63	–	–	0.27–2.06	–	6.49–8.05	Zhu et al. (2011)
Vestfold Hills	Ornithogenic	0–10	18	0.6–16.2	–	–	0.00–0.27	616–1,76	–	Leishman and Wild (2001)
Vestfold Hills	Non-ornithogenic	0–10	18	0.3–8.1	–	–	0.00–0.03	538–1,306	–	Leishman and Wild (2001)
Mawson	No data	0–5	6	2.6–19.9	0.1–11.8	–	–	–	5.9–7.7	Line (1988)
Davis	No data	0–5	34	0.6–56.6	0.02–40.2	–	–	–	4.7–9.3	Line (1988)

Fig. 5.8 The inter-hill valley in the Larsemann Hills showing patterned ground and saturated soils

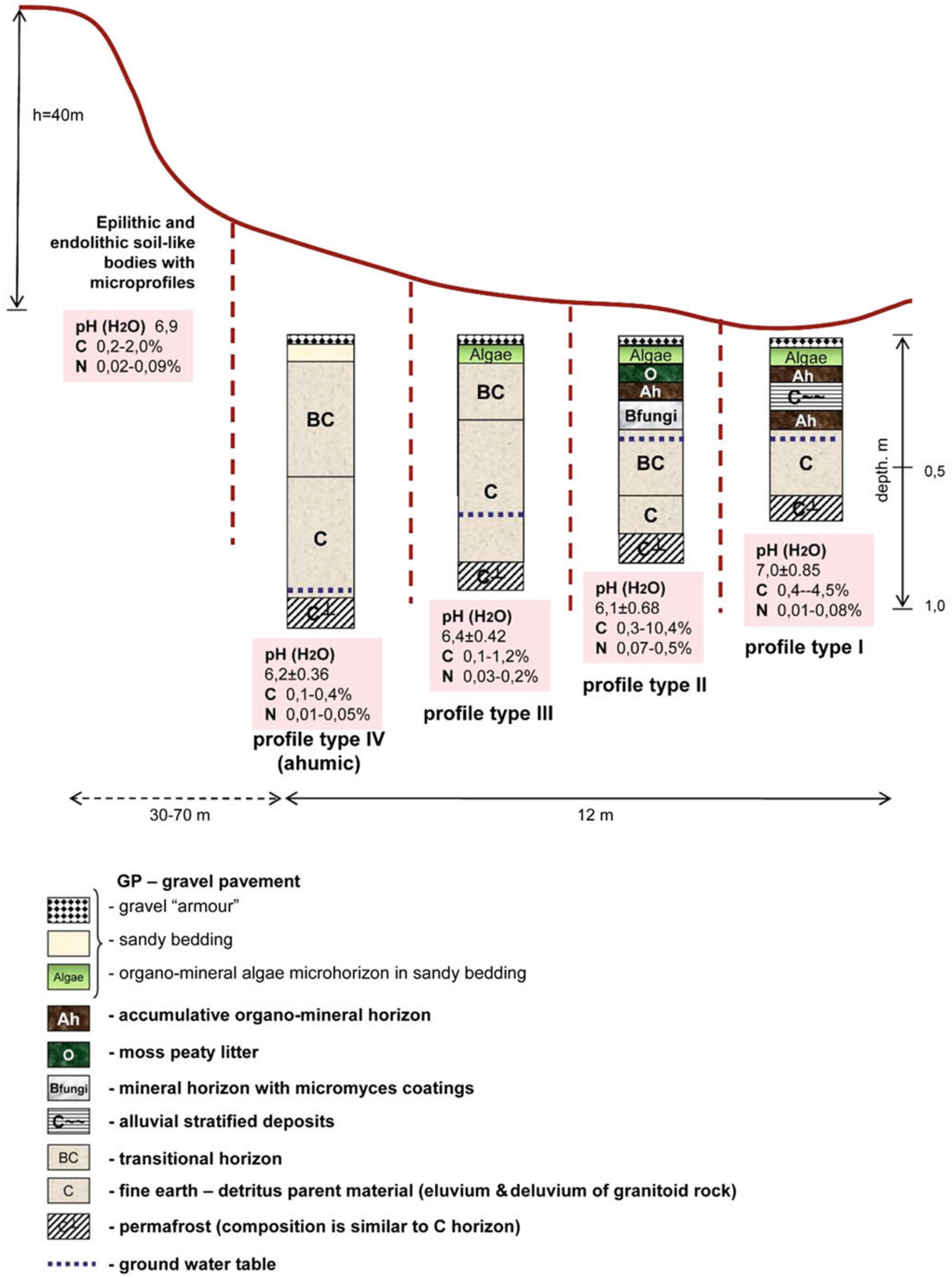

Fig. 5.9 Major types of soils and soil-like bodies in a wet inter-hill valley of the Larsemann Hills (S69° 23′, E76° 24′)

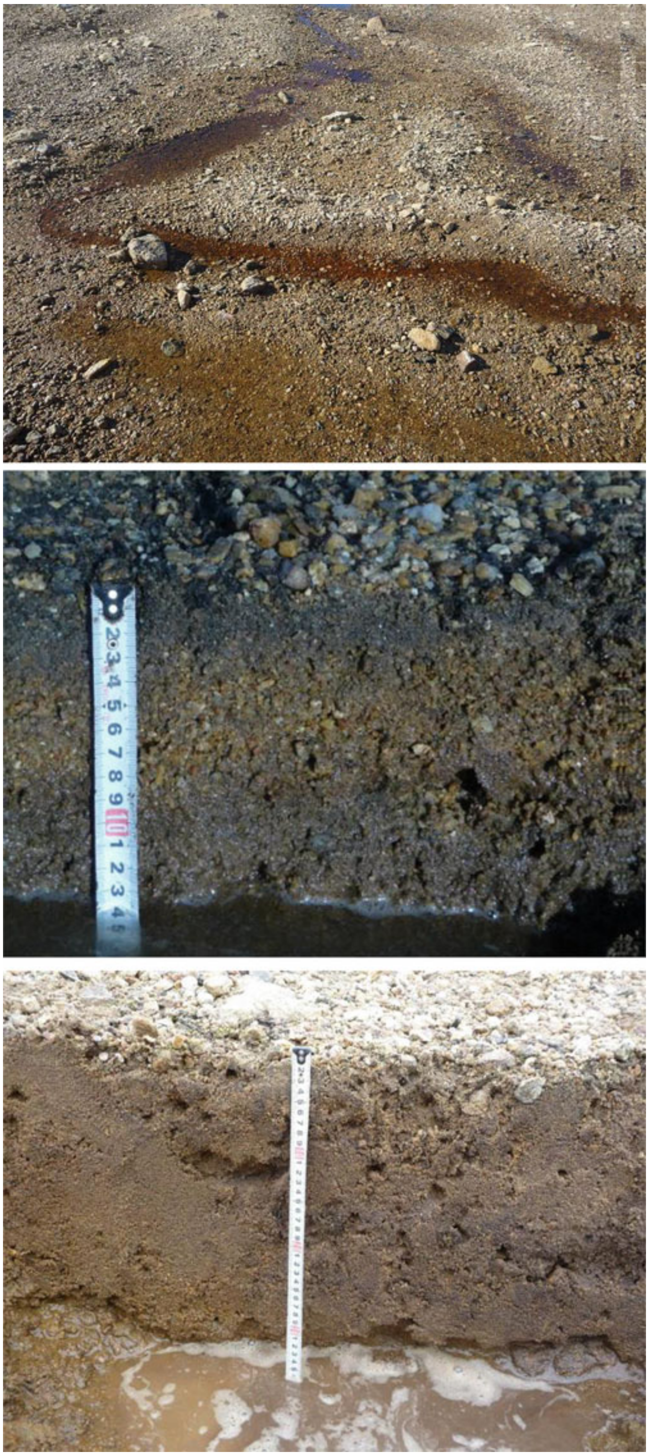

Fig. 5.10 Soils (Typic Aquiturbels) of the wet valley within the meltwater flow area

low in soluble salts (90–4.0 dS m^{-1}), have a range in pH (4.7–9.3), and contain moderately high amounts of total N (0.27–2.1 %) and total P (538–1,765 mg kg^{-1}) (Table 5.3). It is difficult to classify the soils of this region, because previous studies examined the upper 5–10 cm and did not report the presence or absence of cryoturbation or active-layer depths.

5.3.3 Larsemann Hills

Mergelov (2014) conducted a study in December 2009–March 2010 that is monitoring temperature regimes, thaw depth, and soil moisture content at a wet valley bottom site in the Larsemann Hills (Fig. 5.8). In addition, samples from eight representative pedons were collected and analyzed for pH, SOC, total N, oxalate-extractable Fe and Al, dithionite-extractable Fe, exchangeable cations (Ca, Mg, Na), salinity, electrical conductivity, total elemental analysis, and particle size distribution. Key findings of this study follow.

5.3.3.1 Geocryology

Cryoturbation and patterned ground formation are active processes in wet valley bottoms of the Larsemann Hills, especially in the vicinity of late-lying snow patches (Fig. 5.8). The average active-layer depth during 2010 was 83 ± 14 cm. The deepest active layer (110 cm) was on north-facing slopes devoid of any vegetation. The shallowest active layer occurred beneath snow patches.

5.3.3.2 Soil Morphology

A transect across an inter-hill wet valley with sidewalls is depicted in Fig. 5.9. Four general soil groups were identified in the inter-hill valley of the Larsemann Hills: (i) soils within the meltwater channel area; (ii) soils influenced by moisture but outside the meltwater area; (iii) soils on lower sideslopes above the valley wall, and (iv) soils on the upper valley walls. The fifth group of soils was identified in penguin rookeries along the coast; and the sixth group, on lacustrine sediments along lake shores. Signs of endolithic and epilithic life and associated soil-like microfeatures could be found on nearly half of all granitoid surfaces in Larsemann Hills (discussed in detail in Mergelov et al. 2012).

Soils within the anastomosing meltwater channels zone do support algae and have a water table within 30 cm of the surface during maximum thaw period (Fig. 5.10). These

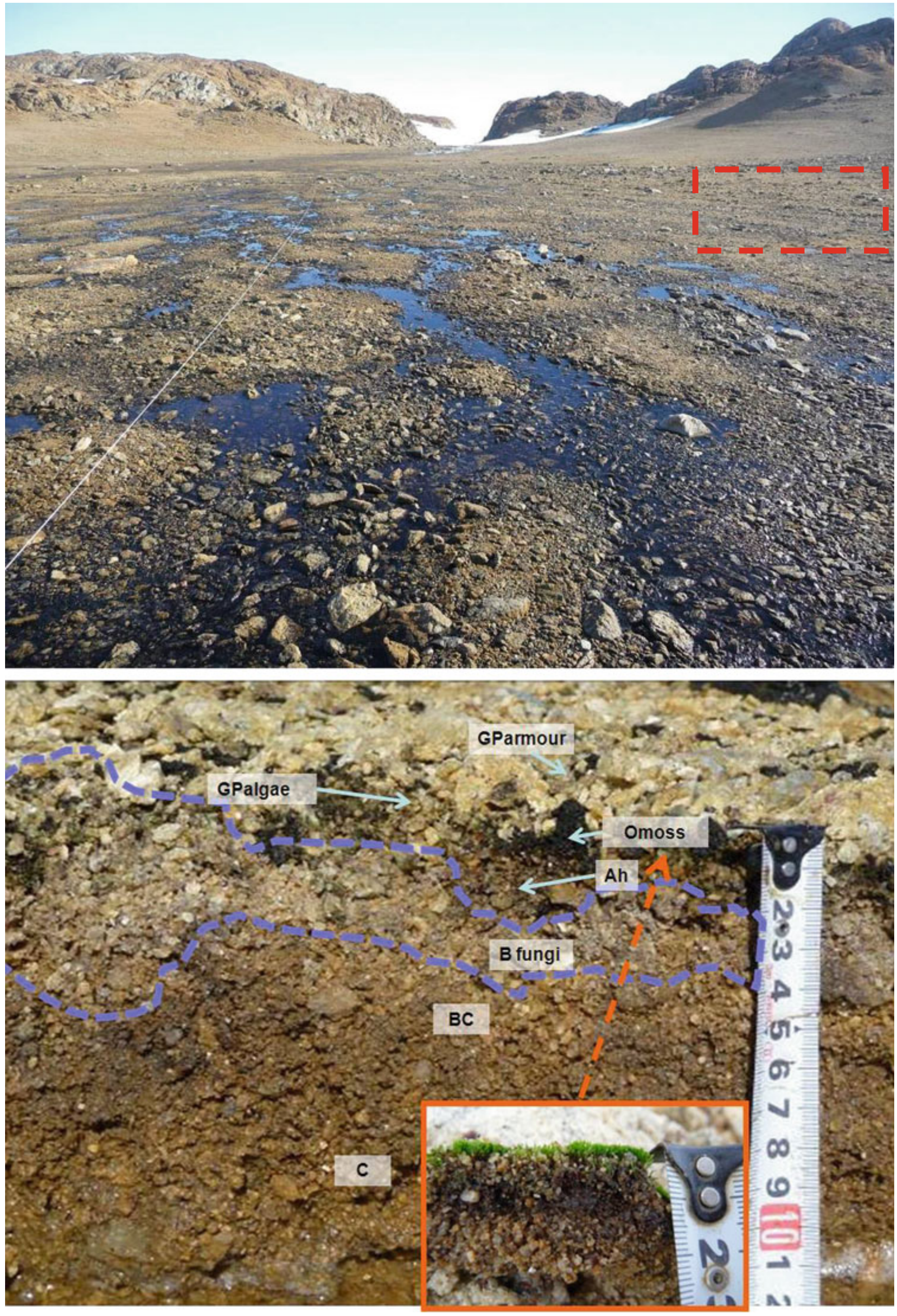

Fig. 5.11 A soil (Aquic Haploturbels) of the wet valley outside the meltwater flow zone (moss zone)

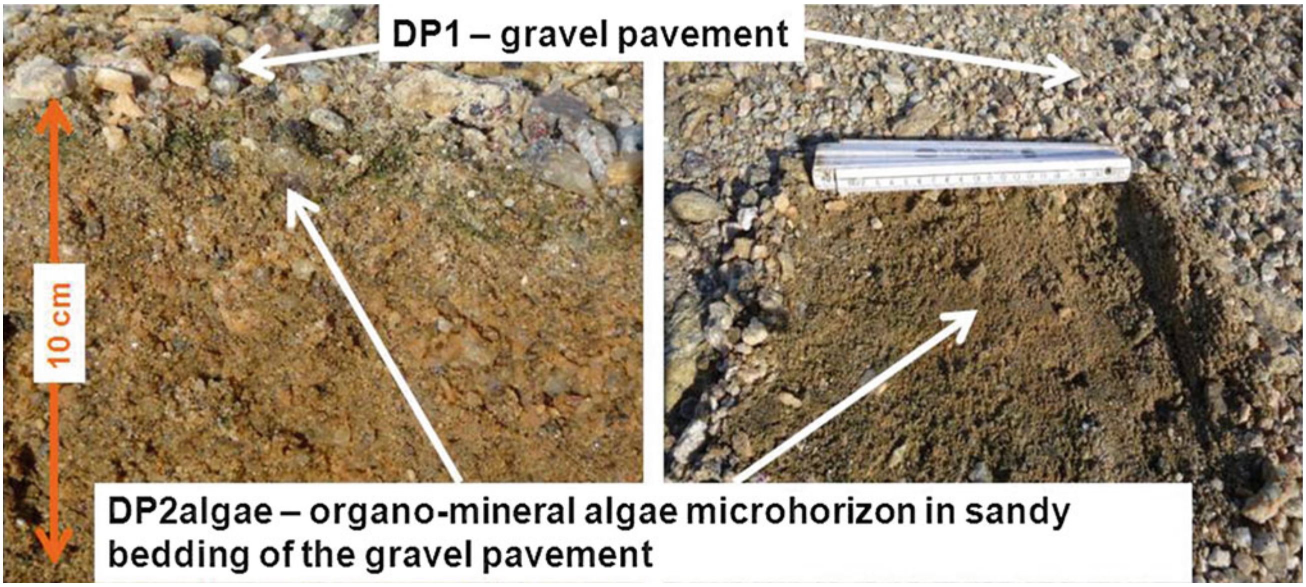

Fig. 5.12 Soils on the lower valley walls in the Larsemann Hills

soils are saturated and can have some redoximorphic features but do not show any gleying. They also show strong cryoturbation. Soils slightly above the meltwater channels are colonized by mosses and algae and may have water for short periods of time in the upper 30 cm; they do not show redoximorphic features (Fig. 5.11). These soils also have strong cryoturbation. Soils on the lower sideslopes above the meltwater channel zone have algae and are well oxidized (Fig. 5.12). Soils on the upper side valley walls lack vegetation, have well-developed desert pavements, and show well-oxidized colors (Fig. 5.13). The ornithogenic soil examined in the Larsemann Hills is poorly developed relative to ornithogenic soils elsewhere in coastal East Antarctica. The soil has a 1-cm thick organic horizon over a dark-colored, 3-cm thick A (Ah) horizon (Fig. 5.14). The soils with well-developed profiles are formed on lacustrine sediments under algae-bacterial mats. Organomineral horizons are up to 20 cm thick. The underlying mineral material has strong gleying features (Fig. 5.15).

5.3.3.3 Analytical Soil Properties

Soils within the meltwater flow zone are neutral to slightly alkaline (pH range = 6.3–8.4; mean = 7.3) (Table 5.4). In the area just above the meltwater zone, the soils are slightly acid (pH range = 5.3–7.1; mean = 6.1), because of the moss acidifying influence. Soils on the lower and upper slopes are slightly acidic and have mean pH values of 6.5 and 6.2, respectively. The soil in the penguin rookery is also slightly acidic (mean pH = 6.3) (Table 5.5). The soils of lake shores have pH in a range from 6.6 to 7.2 (Table 5.6). The soils are nonsaline, with electrical conductivities of less than 0.43 dS m^{-1}.

Soil organic C values generally were greatest at the surface and declined with depth. The greatest SOC values (8.4–15.5 %) were in the A (Ah) horizon of the ornithogenic soils (Table 5.5), followed by the moss sites (1.0–8.2 % at the surface) (Table 5.4), limnogenic soils (0.9–2.1 % in top 10 cm) (Table 5.6), and remaining three groups of inter-hill valley soils having values of less than 0.74 % for the topsoil. Total N values followed the same trends as SOC. Ornithogenic soils had values as large as 0.9 %; the moss affected soils had values as high as 0.5 %, and the remaining soils generally had concentrations of less than 0.05 %.

Most of the extractable Fe was crystalline, and only small proportions were organic- or amorphous bound (Table 5.4). Extractable Fe was maximized in the subsurface, but extractable Al showed no depth differentiation. In oxalate extracts, Fe was greater than Al.

The clay concentrations were very low for all soils, ranging from 2 to 8 %; similarly, silt contents were low, commonly ranging between 2 to 16 % (Table 5.7). Therefore, the soils are mainly sands and loamy sands.

5.3.3.4 Pedogenesis

The dominant soil-forming processes along the Ingrid Christensen Coast are physical disintegration and biochemical weathering resulting in fine earth production, rubification, pervection, and desert pavement formation. The last one, once established, becomes an important soil-forming

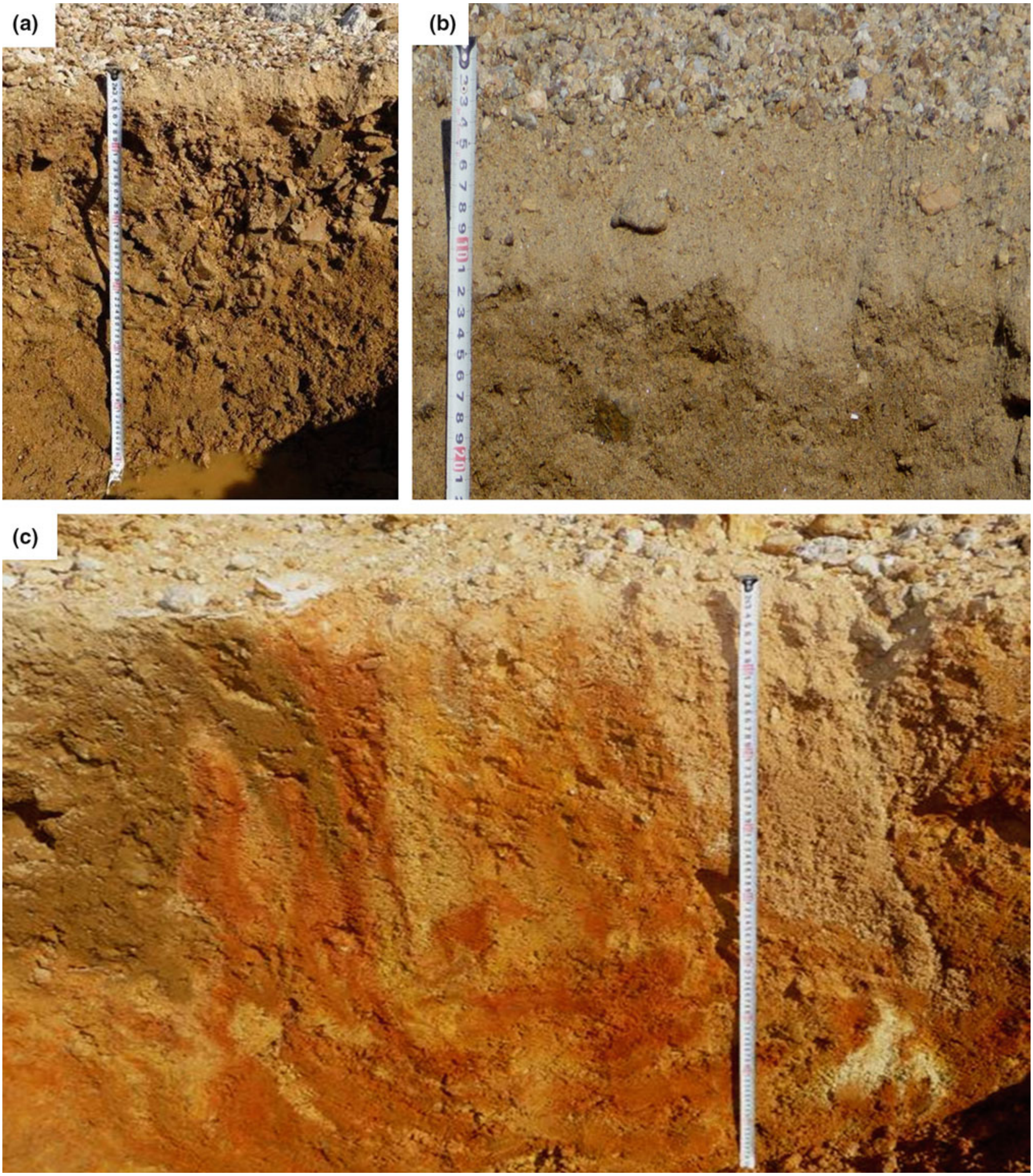

Fig. 5.13 Soils on the upper valley walls with no macro-vegetation: **a**, **b**—widespread Typic Haplorthels; **c**—Typic Haploturbels on sparse *red-colored* sandy loam depositions

Fig. 5.14 Ornithogenic (Typic Haplorthels) soil in the Larsemann Hills

factor—a shield for biota to escape harsh superficial environment and thus to promote further soil development. Carbonation, salinization, and organic matter accumulation operate at low rates; and there was no evidence for podzolization (Fig. 2.12). Soils of wet locations do not have strong redoximorphic features except for lake shore habitats. Well-drained soils have strong colors, reflecting release of Fe from chemical weathering. Pervection results in cryoturbation, solifluction, and formation of patterned ground. The soils have moderately well-developed desert pavements, possibly reflecting the age of the surfaces (ca. >100 ky).

Carbonation is evidenced by the presence of calcite crusts on some coarse fragments; it is more pronounced in the inland oases, particularly in the areas with the presence of carbonate minerals in the bedrock, such as in the Amery Oasis (Fig. 5.16). The soluble salt content of the soils along the coast is low. Although organic matter accumulates in some soils, notably those with mosses or those having been influenced by birds and lakes, the levels are small compared to soils in the South Orkney and South Shetland Islands.

5.3.3.5 Soil Classification

A portion of a large-scale soil map of the Broknes Peninsula in the Larsemann Hills is shown in Fig. 5.17. From the primary research site, including the base and walls, of the wet valley, Lithic Haplorthels are the dominant soil, followed by Typic Haplorthels and Typic Haploturbels, then by Aquic Haploturbels and Typic Aquiturbels. Similar sequences were observed throughout most wet valleys in Larsemann Hills. It is disputable whether the soils in Anhy-great groups could be expected in dry habitats at the upper valley walls. We believe that these soils should be

Fig. 5.15 Limnogenic soil (Typic Haploturbels) of the lake shore with pulsating regime in the Larsemann Hills

Table 5.4 Chemical soil properties of selected soils along the wet valley floor in the Larsemann Hills

Profile no.	Horizon	Depth (cm)	pH		Total acidity (cmol/kg)	EC (dS m^{-1})	C (%)	N (%)	Fe_2O_3 Tamm (%)	Al_2O_3 Tamm (%)	Fe_2O_3 Jackson (%)
			H_2O	KCl							
Meltwater, 14P1	GP/Balgae	0–1	8.4	6.0	0.48	0.119	0.37	0.041	0.019	0.040	0.157
	B1fungi	1–3	7.2	4.8	0.40	0.074	0.28	0.035	0.021	0.047	0.164
	B2	3–15	7.5	5.1	0.39	0.040	0.12	0.019	0.023	0.046	0.172
Moss, 10-06	GP	0–1	–	–	–	–	–	–	–	–	–
	GP/Bmoss	1–2	7.0	5.9	0.65	0.090	1.02	0.049	0.038	0.058	0.158
	Ah	2–4	5.3	4.2	2.41	0.099	10.42	0.488	0.037	0.059	0.117
	B	4–25	5.6	4.5	0.8	0.068	–	–	0.045	0.078	0.153
Moss, 10-08	GP	0–1	7.1	5.6	–	0.071	0.68	0.034	0.023	0.052	0.087
	O moss	1–2			–	0.412	1.92	0.217	0.034	0.066	0.124
	O mineral	1–2	6.8	5.7	1.23	0.214	1.76	0.189	0.023	0.041	0.150
	O moss	2–3	6.2	4.7	0.93	0.051	–	–	0.026	0.055	0.085
	B1 fungi	2–4	5.2	4.4	1.16	0.052	0.26	0.041	0.028	0.057	0.078
	B2	4–20	6.4	4.6	0.86	0.037	0.19	0.021	0.030	0.059	0.096
	B2/BC	20–35	5.9	4.9	–	0.047	–	0.017	0.053	0.154	0.127
Algae, 10-04	GP/Balgae	1–2	7.3	5.4	0.62	0.081	0.48	0.041	0.040	0.018	0.160
	B1fungi	2–10	7.6	5.5	0.39	0.046	0.30	0.029	0.050	0.017	0.130
	B2	10–14	7.4	–	0.46	0.060	–	0.016	0.110	0.015	0.140
	B3	14–40	6.0	4.2	–	0.100	0.22	0.024	0.380	0.065	0.460
	B3/BC	40–60	6.3	4.5	–	0.059	–	–	0.350	0.048	0.410
No macro-vegetation, 10-19	GP sandy bedding	1–7	6.5	4.5	0.93	0.029	0.36	0.040	0.048	0.058	0.152
	BC	7–20	6.4	4.6	0.93	0.029	0.13	0.032	0.020	0.076	0.139
	BC	20–40	6.6	4.8	0.25	0.036			0.032	0.085	0.149
	BC	40–60	5.8	4.8	0.18	0.039	0.17	0.027	0.051	0.140	0.108
	BC	60–90	5.7	4.9	–	0.042	–	–	0.075	0.017	0.223
	BCfrozen	90–95	6.3	4.9	–	0.037	–	0.020	0.112	0.261	0.273

Table 5.5 Properties of ornithogenic soil in Larsemann Hills

Horizon	Depth (cm)	pH	pH	Total acidity (cmol/kg)	EC (dS m^{-1})	C (%)	N (%)	Fe_2O_3 Tamm (%)	Al_2O_3 Tamm (%)	Fe_2O_3 Jackson (%)
		H_2O	KCl							
O/Ah	0–1	6.1	5.3	3.5	0.27	8.4	0.5	0.09	0.06	0.16
Ah	1–4	6.0	4.5	3.9	0.43	15.5	0.9	0.11	0.06	0.21
BC	4–15	6.9	5.2	1.3	0.05	0.7	0.1	0.08	0.09	0.19

Table 5.6 Properties of limnogenic soil in Larsemann Hills

Depth (cm)	C (%)	Hygroscopic moisture (%)	pH H_2O	Exchange cations (cmol/kg)			
				Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}
0–2	0.90	0.76	6.55	1.00	0.90	0.39	0.15
2–8	0.21	0.40	6.64	1.00	0.90	0.45	0.12
0–2	2.05	0.59	6.83	1.50	1.50	1.58	0.19
2–4	0.72	0.49	7.19	0.90	0.80	0.51	0.17
4–12	1.03	0.43	7.12	1.00	0.90	0.45	0.14

Table 5.7 Particle-size distribution in soils of the wet valleys in Larsemann Hills

Depth (cm)	Hygroscopic water (%)	Content of fractions (%) (particle size, mm)							
		2–1	1–0.25	0.25–0.05	0.05–0.01	0.01–0.005	0.005–0.001	<0.001	<0.01
10-14P1 (meltwater area)									
0–1	0.38	28	46	20	2	1	1	2	4
1–3	0.32	21	54	19	2	1	0	3	4
3–15	0.25	25	52	17	2	1	1	3	4
NSM-10-14T2 (meltwater area)									
0–1	0.43	30	41	23	2	1	1	3	4
1–5	0.41	13	50	31	2	1	1	3	5
5–15	0.39	23	40	28	4	1	1	4	5
NSM-10-08 (moss area)									
0–1	0.22	28	60	8	1	0	1	2	3
1–2	0.34	20	61	14	1	0	1	2	3
2–3	0.23	28	57	11	1	0	0	2	3
3–4	0.22	26	57	13	1	1	0	2	3
4–20	0.20	20	58	17	1	1	0	2	3
20–35	0.31	16	66	14	1	0	1	3	4
NSM-10-19 (no macro-vegetation)									
1–7	0.16	13	61	22	1	0	0	2	3
7–20	0.17	15	65	16	1	0	1	2	3
20–40	0.20	27	60	10	1	1	1	2	3
40–60	0.22	32	51	13	1	1	1	2	4
60–90	0.29	36	42	14	3	1	1	3	5
90–95	0.37	25	52	14	3	1	1	3	6
NSM-10-04P (algae area)									
1–2	0.27	21	49	24	2	1	1	2	4
2–10	0.21	21	55	20	1	1	1	2	4
10–14	0.24	18	43	24	9	1	3	2	7
14–40	0.82	12	42	23	8	2	5	8	15
40–60	0.65	14	42	25	7	1	5	6	13
NSM-10-03 (algae area)									
2–3	0.25	25	50	19	2	1	1	3	4
3–10	0.27	17	48	30	2	0	1	3	4
10–30	0.27	21	57	15	2	1	1	4	5
30–50	0.28	24	55	13	2	1	1	4	6
50–65	0.27	25	51	16	3	1	1	3	5
NSM-10-30 (lake shore)									
3–17	0.20	14	45	31	5	1	1	3	5
3–17	1.64	12	42	24	11	2	3	7	12
17–27	0.50	12	44	26	6	1	4	5	11
27–45	0.63	7	31	26	16	4	8	8	20

Fig. 5.16 Calcitic crust on elevated parts of the ridged microtopography of the Amery oasis

in Hapl- great groups, because they meet one or several of the following conditions (i) the mean annual precipitation is far in excess (200–250 mm year^{-1}) of the 50 mm year^{-1} requirement for anhydrous conditions, (ii) the wet valleys have a seasonal water table, (iii) dry permafrost is lacking in the coastal hills, and (iv) the layer from 10 to 70 cm does not have a temperature of 5 °C or less throughout the year.

5.4 Summary

MacRobertson Land constitutes the third largest ice-free area in Antarctica, accounting for 11 % of the total ice-free area. Region 3 has five major ice-free areas: (i) the Northern Prince Charles Mountains, including the Amery Oasis, (ii) the Southern Prince Charles Mountains, including the Mawson Escarpment, (iii) the Grove Mountains, (iv) a series of small coastal oases and inland Framnes Mountains along the Mawson Coast, and (v) the Vestfold Hills, Rauer-Bolingen Islands, and Larsemann Hills along the Ingrid Christensen Coast. Soils data for the MacRobertson Land are sparse. We were unable to find any soils data for the Prince Charles Mountains and the Amery Oasis. There is one study for the Grove Mountains, and previous work in the Vestfold and Larsemann Hills has emphasized biological properties of topsoils.

Elevation differences of over 3,000 m and distances of ice-free areas from the coast up to 650 km inland create sharp contrasts in climatic conditions and have a marked impact on pedogenesis. Mosses, lichens, non-marine algae, and birds play an important role in soil development in coastal areas. Permafrost is continuous in MacRobertson

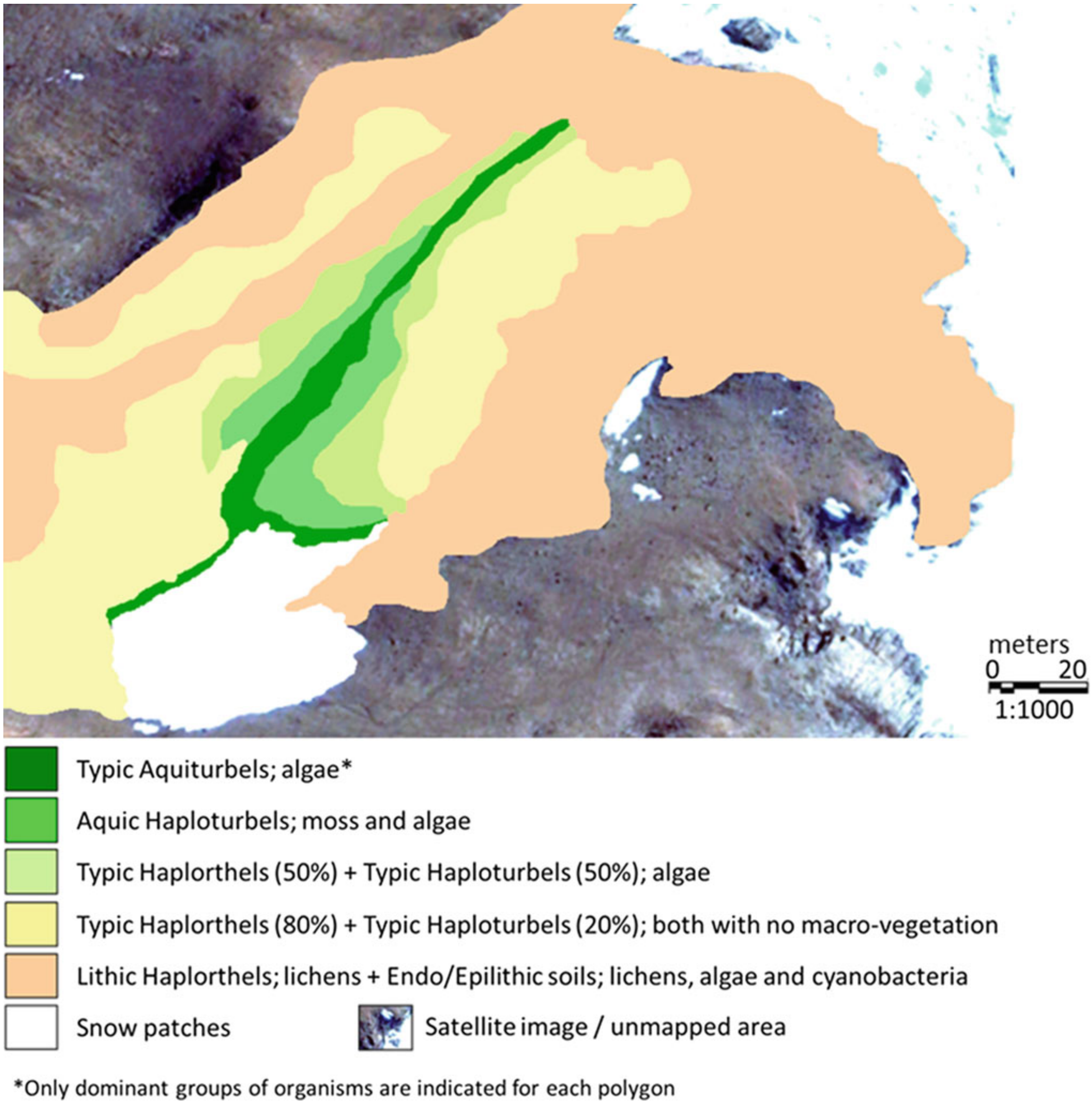

Fig. 5.17 A portion of the large-scale soil map of Broknes Peninsula (Larsemann Hills) showing distribution of soils at bottom and walls of one particular wet valley

Land. Active-layer depths range from 25 cm in the Grove Mountains to 110 cm or more on the coast. Patterned ground is ubiquitous in the areas with frost-susceptible parent materials throughout the region. Soil-forming processes can be examined along an elevational–longitudinal gradient from the Vestfold–Larsemann Hills to the southern Prince Charles and Grove Mountains. Salinization, manifested in salt efflorescence, carbonation, and permafrost development are expected to increase from the coast inland; pervection, and soil organic matter accumulation are greatest along the coast. Desert pavement formation and rubification are important processes along the entire gradient. Unlike regions 4 (Wilkes Land) and 8 (South Shetland Islands), podzolization has not been reported in MacRobertson Land.

The dominant soil taxa along the coast are Aquiturbels, Haploturbels, previously unclassified ornithogenic and limnogenic soils, and endo- and epilithic soil-like bodies. Lithic Anhyorthels are predominant in the inland mountains.

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6 Soils of Wilkes Land (The Windmill Islands)

Hans-Peter Blume and Manfred Bölter

6.1 Introduction

The Windmill Islands and surrounding area (Fig. 6.1) constitute the largest ice-free area in Wilkes Land at 500 km^2 (Table 2.1). There are three scientific bases in Wilkes Land, including Mirnyy (Russia), Casey (Australia), and Dumont D'Urville (France). The first visit to Wilkes Land was by the Australian Antarctic Division in 1956. What was eventually to become Casey Station began in 1959 as Wilkes Station on Clark Peninsula, became "The Tunnel" on the Bailey Peninsula in 1969, and Casey Station (66° 17′ S, 110° 31′ E) was built on the Bailey Peninsula in 1988.

Blume and Bölter (1993, 1996) began studies at Casey Station in the early 1990s with the objectives of understanding soil development in the region and comparing the soils at Casey with soils elsewhere in Antarctica (Blume et al. 1997). They became interested in the interactions between vegetation and soils, i.e., the processes of weathering of plant debris, and its influence on soil formation and new habitats for plants and soil organisms. Reviews of the effects of vegetation on soil biology by Seppelt (2002) and Kappen and Schroeter (2002), though valuable, did not contribute substantively to our understanding of soil-forming processes, soil classification, soil–plant relations, which became the focus of our studies (Beyer and Bölter 1999; Beyer et al. 2000a, b, 2001). The results presented herein give an overview of the soils of this area and provide the background for comparisons with other regions of the Antarctic.

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6.2 Study Area

The Windmill Islands are located in Vincennes Bay along the Budd Coast, which extends between 66° 30′ E and 112° 0′ E. Four peninsulas project out into the bay, the largest of which are the Mitchell and Browning Peninsulas in the south and the Bailey (Fig. 6.2) and Clark Peninsulas in the north (Fig. 6.1). Together with the Bunger Oasis, about 400 km to the northwest, the Windmill Islands have been linked to the Australian continent 120 Ma before the breakup of Gondwana Land (Oliver et al. 1983).

The early geology of the Windmill Islands was summarized by Blight and Oliver (1977, 1982) and Seppelt (2002). Rock outcrops are comprised of layered sequences of schists, gneisses, and migmatites that are part of the Windmill Metamorphics, the Ardery Charnockite, and the Ford Granite formations (Blight and Oliver 1982). The rocks were covered with marine sediments during the Last Glacial Maximum. The landscapes in the Windmill Island region developed from glacioeustatic rebound after glacier retreat during the Holocene around 8 ka BP (Goodwin 1993). Deglaciation occurred in two stages. The southern islands and the Browning Peninsula were first to become ice-free (8 ka BP); the northern islands and peninsulas became ice-free about 5.5 ka. The uplift was about 0.5–0.6 m/100 years to a total height of about 53 m a.s.l. (Hollin and Cameron 1961; Goodwin 1993). Organic matter from abandoned penguin rookeries has been dated at about 4.5 ka BP and some brown earth material to about 5.0 ka BP (Goodwin 1993). The inland areas of the Bailey and Clark Peninsulas to the Antarctic ice cap feature the Løkken Moraine (Fig. 6.1). Neoglacial solifluction deposits cover much of the area today.

The only significant, active penguin rookeries on the mainland are on the Clark and Browning Peninsulas. Shirley Island (66° 17′ S, 110° 30′ E), a rocky island about 1.6 km long, is a main breeding ground for Adélie penguins and petrels in the region. The Windmill Islands are inhabited only by cryptogams, primarily crustose and foliose lichens

J.G. Bockheim (ed.), *The Soils of Antarctica*, World Soils Book Series,
DOI 10.1007/978-3-319-05497-1_6

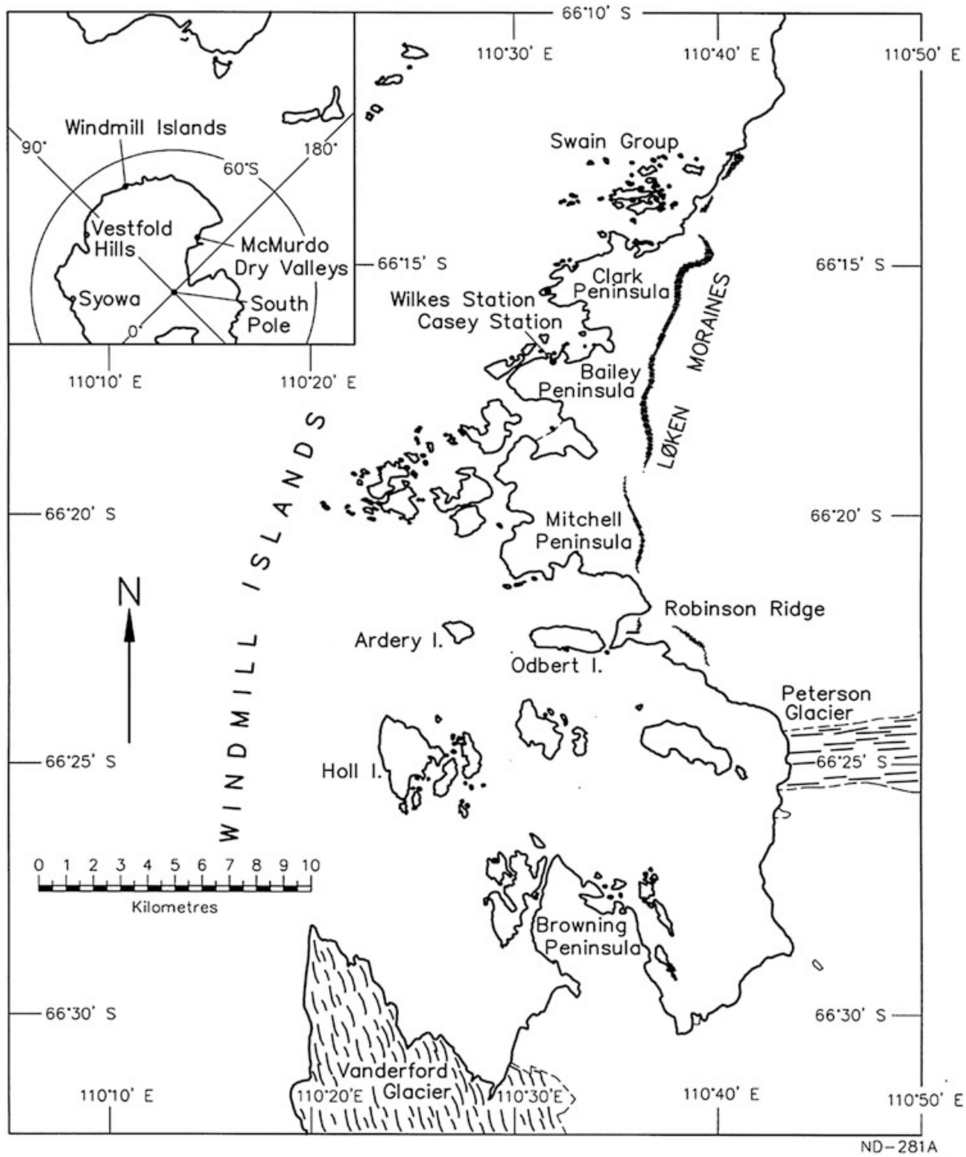


Fig. 6.1 Map of the Windmill Island Region and locations (adapted from Beyer et al. 2002, *Source* ANARE)

and mosses (Williams et al. 1994; Seppelt 2002), nonmarine algae, and microorganisms (fungi and bacteria).

The Windmill Islands are underlaid by continuous permafrost. Active-layer thicknesses range between 30 and 80 cm (Blume et al. 2002a). Patterned ground is common in exposed areas (Fig. 6.3). Gelifluction is an active process in the islands as evidenced by lobes and rock garlands. Cryoturbation is a predominant process in the Windmill Islands, especially in areas devoid of vegetation cover (except some soil algae).

Meteorological data from Casey Station (Bailey Peninsula) show mean temperatures of 0.3° and −14.9 °C, for the warmest and coldest months, respectively, a mean annual precipitation of 230 mm, and 96 days of strong winds (>17.5 m s^{-1}). These factors contribute to the dry conditions of the area (Seppelt 2002). The mean annual temperature between 1957 and 1983 was −9.3 °C (Jacka et al. 1984) and between 1989 and 2010 was −5.8 °C (Australian Government, Bureau of Meteorology), reflecting a warming of about 0.7° per decade.

6.3 Materials and Methods

6.3.1 Field

A total of 23 soil profiles were described and sampled in the Windmill Islands using standard techniques (FAO 2006). Detailed soil maps were prepared for selected areas, beginning in 1992–1993 (Blume et al. 2002a). The soils were classified according to the WRB (IUSS, WRB 2006) and *Soil Taxonomy* (ST; Soil Survey Staff 2010). ST is reported here.

Fig. 6.2 Landscape of the Bailey Peninsula (*Photo* by M. Bölter)

Additional small-scale investigations were performed in 1995–1996 in other areas to determine soil variability in the Windmill Islands (Beyer et al. 2002). Field analyses included coarse fragment contents (>2 mm), soil moisture content, pH ($CaCl_2$ or KCl), and electrical conductivity (EC).

6.3.2 Laboratory Analyses

Oxyhydroxide metals were extracted with acid ammonium oxalate (Fe_o, Al_o, Mn_o, and Si_o), sodium pyrophosphate (Al_p, Fe_p), dithionite-citrate (Al_d and Fe_d), and hot HCl (Fe_v and Mn_v). Optical densities of the oxalate extract (ODOE) and the pyrophosphate extract (ODPE) were determined. For interpretative purposes, Fe_v–Fe_d ($Fe_{v\text{-}d}$) reflects Fe associated with clay minerals; Fe_d–Fe_o ($Fe_{d\text{-}o}$) represents well-crystallized iron oxides such as goethite and lepidocrocite; Fe_o–Fe_p ($Fe_{o\text{-}p}$) is poorly crystallized iron oxides such as ferrihydrite, but it also includes iron carbonates; and Fe_p reflects organically bound (and exchangeable) Fe as well as Fe-phosphates. The same pattern is valid for Al and Mn compounds, but it is not as precise as for Fe. Occasionally, with high contents of Fe-phosphates, data for Fe_p may be higher than for Fe_o. The reason for this is that Fe-(and Al-) phosphates are not soluble at pH 3.25. Weathering and clay formation are normally associated with an enrichment of Fe-, Al-, and Mn-oxides. However, their contents are normally highly correlated with clay content. Podzolization or gleying on soils is reflected by clay-related (oxides/clay ratio) depth functions. This method is better than by pure oxide-related depth functions. Si_o, in combination with Al_o, represent allophanes, a weathering product of silicate minerals (Schlichting et al. 1995).

Following pretreatment, the mineralogy of some soils was studied using X-ray diffraction for the clay (<2 µm) and fine silt (2–20 µm) fractions (Schlichting et al. 1995) and microscopy for the coarse silt (20–63 µm), fine sand (63–200 µm), and medium sand (200–630 µm fractions (FitzPatrick 1993). Core samples were taken to measure the bulk density, pore volume, and pore-size distribution (Schlichting et al. 1995).Thin sections were prepared for some horizons for micromorphologic examination (FitzPatrick 1993). General physical and chemical characterisations are given in Blume et al. (2002a).

Fig. 6.3 A stone circle near Casey Station. The lichens growing on the sand indicate a stable environment (*Photo* M. Bölter)

6.4 Results

6.4.1 Soil Mapping and Classification

Figure 6.4 is an example of a soil map of a 6.4-ha hill near Casey Station. The map shows 10 soil associations that illustrate the strong soil heterogeneity of the area. Table 6.1 compares the WRB and ST taxa, and Table 6.2 gives landscape and vegetation conditions for major soil subgroups shown on the map and elsewhere in the Windmill Islands.

All of the soils are classified as Gelisols, including mineral soils that are cryoturbated (Turbels), mineral soils with no cryoturbation (Orthels), and organic soils underlain by permafrost in the upper 1 m (Histels). Turbels include Haploturbels in areas of patterned ground, Aquiturbels in depressions where there is water saturation above the permafrost, and Psammoturbels in sandy areas. Orthels include Haplorthels on dry ridges and Spodorthels in abandoned penguin rookeries. Histels (Fibristels and Hemistels) occur in peaty depressions, and Folistels occur in shallow bedrock depressions. Many of the soils have bedrock within the upper 50 cm and are classified into Lithic subgroups.

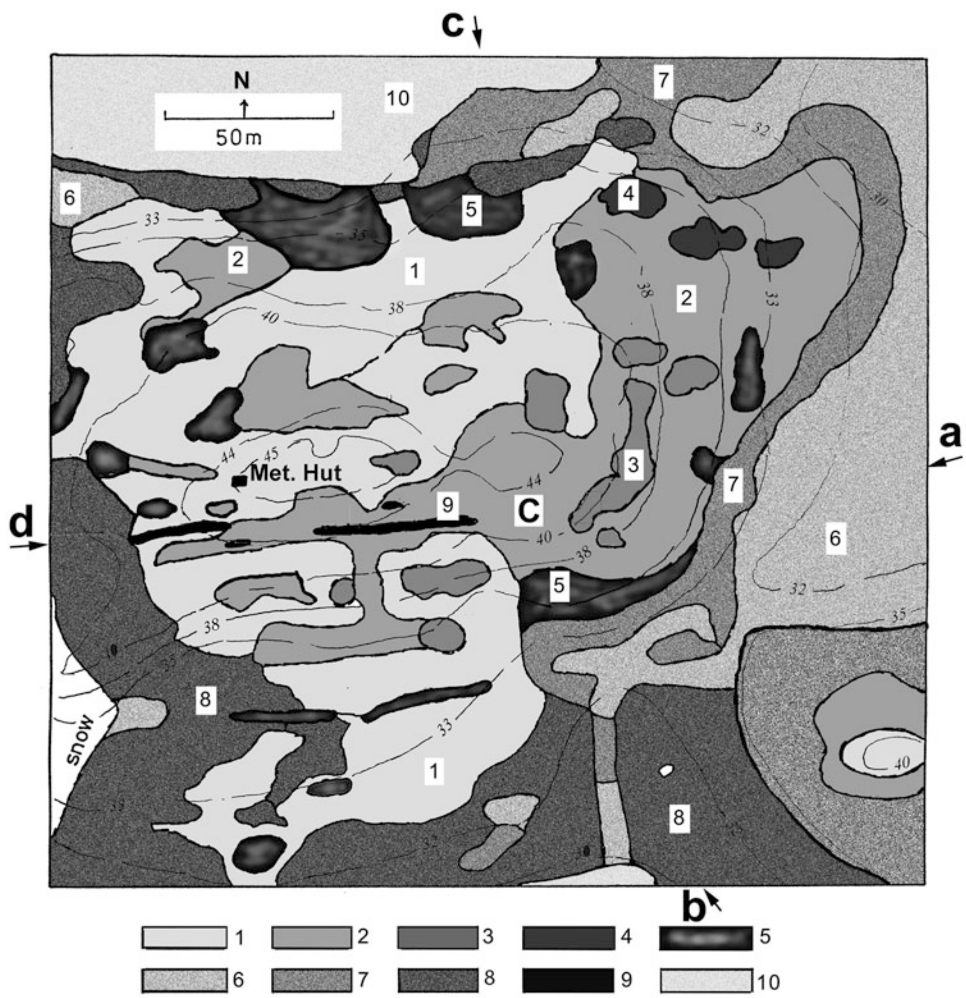
6.4.2 Soil Properties

Soil properties, including morphological, chemical, physical, and mineralogical are provided for three areas in the Windmill Islands, including the Bailey Peninsula (Casey Station), the Clark Peninsula (Whitney Point and Lokken Moraine), and the outer islands (Hollin Island).

6.4.2.1 Soil Morphology

All the soils of the ice-free areas of the Windmill Islands have permafrost at depths between 30 and 80 cm. Most of the soils have a desert pavement, and a large portion of the soils are subject to cryoturbation. Vesicular structure is commonly observed within the first 1–10 cm as has been reported in the Transantarctic Mountains (Bockheim 2010) and in hot deserts (Blume et al. 1984). On the Bailey Peninsula (Casey Station), there is no active cryoturbation in sandy soils vegetated with lichens (Table 6.3, sites 3–5, 9); in contrast, loamy soils beside them (sites 2, 8) with algae but no lichens are strongly cryoturbated. Soils blown free of snow (site 1) and soils on young moraines (site 7) also lack a plant cover. Various crustose, but also some foliose lichens, cover large boulders and rock outcrops. Cryptoendolithic

Fig. 6.4 Soil associations on Mable Hill near Casey Station, Windmill Islands (revised from WRB to *Soil Taxonomy* from Blume et al. 2002a, b). *Numbers 1–6* and *8* indicate sampling sites; *C* indicates the center of the lines in four directions of the transects: *a*, *b*, *c*, and *d*. The soil associations are indicated by individual tones: *1* Lithic Haplorthels and Typic Spodorthels on gneiss; *2* Haplorturbels, Aquiturbels, Spodorthels, and Histels on patchy drift; *3* Spodorthels and Haploturbels on moraines; *4* ornithogenic soils and Haploturbels of former penguin rookeries; *5* Haploturbels on patchy drift over schist; *6*, *7* Haploturbels on blocky moraines; *8* Lithic Haplorthels and Lithic Haploturbels of rock outcrops in valleys; *9* Haploturbels on basic gneiss and schist; *10* Fibristels and Haploturbels of lake margins



organisms, which penetrate rock fissures, play an important role in chemical weathering.

The very young soils on the Løkken Moraines show a gray (2.5Y5/1, 5Y5/1) to olive gray (5Y4/2, 5Y4.5/2) color. Elsewhere, however, the soils bear strong colors because of abundant organic matter and extractable Fe. On the Bailey Peninsula, sandy and gravelly soils with a vegetation cover are podzolised. Antarctic Spodosols are characterized by a very thin bleached E horizon, which is not more than 1–3 cm over thicker spodic horizons (Table 6.3, sites 3, 9). Only Spodosols with gravel contents of 90 % or more have thicker E horizons (site 4).

6.4.2.2 Soil Chemical and Physical Properties

Chemical and physical data for Bailey and Clark Peninsulas are given in Tables 6.3, 6.4, 6.5 and for the outer islands in Tables 6.6 and 6.7. On the Bailey Peninsula, most of the soils are very strongly acidic with pH values around 4. Only soils on recent moraines (<100 years; Table 6.3, site 7) and those in active penguin rookeries (site 10) have a near-neutral reaction. Soils of young moraines and of active bird rookeries are eutrophic with a base saturation excess of 60 %, and some of the Spodorthels (site 9) are dystrophic with a base saturation less than 30 %.

Organic matter has accumulated in all of the soils on the Bailey Peninsula. Those of very young moraines contain only 0.2–0.4 g kg^{-1} total organic carbon (TOC, Table 6.3, site 7). Soils which are covered with snow for more than 11 months per year have 1–4 g kg^{-1} TOC (site 1), and loamy soils subject to cryoturbation and lacking vegetation cover have 2–9 g kg^{-1} TOC (sites 2, 8). Podzolised soils with vegetation cover have 5–40 g kg^{-1} TOC (sites 3, 4, 9), and peaty soils and soils of recent rookeries have 160–300 g kg^{-1} TOC (sites 5, 6, 10). The dominant carbon sources are from mosses. Humification of SOC is controlled primarily by temperature, moisture, and microbial populations, especially cyanobacteria (Beyer 2000).

Birds, mainly penguins, influence many soils in the past before the landscape was lifted and closer to the sea. These soils have abundant available P (>0.12 g kg^{-1}, Table 6.3), which corresponds to 1.5 g kg^{-1} citrate extract P_2O_5. Of the soils examined on Bailey Peninsula, only sites 7 and 9 seem

Table 6.1 Classification of the soils on the Bailey Peninsula, Windmill Islands

WRB system IUSS, WRB (2006)	US Soil taxonomy Soil Survey Staff (2010)
Leptic Cryosol	Lithic Haploturbel
Leptic Cryosol (reductaquic)	Lithic Aquiturbel
Turbic Cryosol (arenic)	Psammoturbel
Turbic Cryosol	Typic Haploturbel
Turbic Cryosol (skeletic)	Typic Haploturbel
Turbic Cryosol (reductaquic)	Lithic Aquiturbel
Lepti-fibric Histosol (gelic)	Lithic Fibristel
Lepti-folic Histosol (gelic)	Lithic Folistel
Lepti-hemic Histosol (gelic)	Lithic Hemistel
Hemic Histosol (gelic)	Typic Hemistel
Lithic Leptosol (gelic)	Lithic Haplorthel
Haplic Leptosol (ornithic, gelic)	Lithic Haplorthel of abandoned birds rookery
Nudlithic Leptosol (gelic)	
Nudlithic Leptosol (gelic, protic)	
Leptic Podzol (gelic)	
Entic Podzol (gelic, skeletic)	Typic Spodorthel
Albic Podzol (ornithic, skeletic)[a]	Ornithogenic soil
Leptic Regosol (ornithic, eutric, skeletic)	Ornithogenic soil

[a]rich in stones

Table 6.2 Classification of soils at Whitney Point on the Clark Peninsula (WP 1–WP 6 are close to the penguin colony, ASPA 136, 66° 15′ S, 110° 32′ E) and L1–L2 are on the Løkken Moraine (66° 15′ S, 110° 38′ E) (Beyer and Bölter 2000)

Code	Soil type	Location/Landscape position	Vegetation
WP 1	Lithic Haplorthel[a]	Abandoned penguin rookery	Scattered algal growth
WP 2	Lithic Haplorthel	Abandoned penguin rookery[b]	Scattered algal growth
WP 3	Ornithogenic soil	Current penguin rookery	Nil vegetation
WP 6	Lithic Hemistel	Middle slope between bare rock	Dense moss carpet
WP 5	Typic Haplorthel[c]	Outwash at meltwater lake beach	100 % mosses
WP 4	Typic Hemistel	Middle slope between bare rock	Dense moss carpet
L 1	Typic Haploturbel	Inner edge of a stone circle	Scattered mosses
L 2	Lithic Haploturbel	Center of a stone circle	Scattered mosses

[a]rich in stones
[b]occasionally recolonized by penguins
[c]high degree of podzolization

to be free of avian influence, as they do not show elevated phosphate levels. Birds also contribute to the high levels of Mg (Tables 6.4 and 6.5).

Based on electrical conductivity (EC) values, most of the soils are enriched with airborne salts from the sea in the first 1–3 cm (Table 6.3). The salts accumulate at the surface soil from capillary rise prior to sampling.

Soil properties and soil formation are more weakly expressed on the islands than on the Clark and Bailey Peninsulas (Tables 6.6 and 6.7). The unconsolidated sediments are very thin, and almost all of the soils have a lithic contact within the first 40 cm. The entire profile is contained within the active layer. Soils are mainly covered by mosses and lichens, or show a scattered algal growth. Soil weathering, acidification, and braunification are less pronounced, the soils are less acidified, pH values are nearly one unit higher as described for the soils at Bailey Peninsula.

Seawater and airborne salts input have a much higher impact on soil formation in the islands than on the peninsulas. The organic matter in these soils is poorly humified. Spodosols with a bleached AE horizon and an illuvial Bh horizon do not contain Fe-organic complexes. In contrast, the Spodosols near Casey are enriched with translocated metal–organic complexes in their Bhs and Bsh horizons (see in Table 6.3, profiles 3 and 4, the relatively high Fe_p contents). These horizons are enriched with phosphates (Pa): this is typical for soils, which are influenced by penguin excrements.

6.4.2.3 Soil Mineralogy

We examined the mineralogy of three pedons, including a typic Haploturbel near Casey Station (Table 6.8), a Lithic Aquiturbel derived from basic gneiss and schist (Table 6.9), and a Typic Spodorthel in an abandoned penguin rookery on gneiss (Table 6.10). The Haploturbel contains primarily quartz, feldspars, and mica that are derived from leuco gneiss (Table 6.8). These primary minerals also dominate the clay fraction, suggesting strong cryoclastic weathering. However, the low pH level (Table 6.3), occurrence of some mineral grains with weathered surfaces, pedogenic iron, and very little smectites reflect early stages of chemical weathering.

The parent material of an Aquiturbel consists of schist and basic gneiss and, therefore, contains clay (Table 6.3, site 2). The quartz contents are low, especially in the subsoil (Table 6.9). However, the topsoil is somewhat influenced by weathering of leuco gneiss. Stones and sands abound in the topsoil and the depth function of organic carbon is discontinuous due to cryoturbation. Strong cryoclastic weathering forms clay.

The Aquiturbel contains pedogenic iron (Fe_p, $Fe_{d\text{-}p}$) (Table 6.4) as well as large amounts of partly weathered minerals, e.g., feldspars; smectite has also formed (Table 6.9). The acidic conditions in combination with

Table 6.3 Soil properties near Casey Station, Bailey Peninsula

Horizon	Depth (cm)	>2 mm (%)	Color moist	pH $CaCl_2$	Bulk den. (g cm^{-3})	Sand (%)	Silt (%)	Clay (%)	TOC (g kg^{-1})	C/N	Fe_p (g/kg)	EC (ms/cm)	Base sat. (%)	Fe_{d-p} (g kg^{-1})	P_a (g kg^{-1})
1 (202) Typic Haploturbel on stony moraine with soil algae															
Az	0–1	54	2.5Y4/2	4.6	1.6	66	33	1.4	1.8	7.8	0.54	14	72	2.4	0.13
AC1	−5	17	2.5Y4/2	4.5	1.4	54	42	4.0	1.4	9.8	0.58	2.3	55	3.0	0.14
AC2	−20	41	2.5Y4/2	4.4	1.7	67	28	4.7	1.8	5.5	0.76	0.4	48	2.5	0.21
Cw1	−50	66	2.5Y5/2	4.4	–	70	25	5.4	3.9	7.9	0.82	–	59	1.5	0.15
Cw2	−70	62	2.5Y5/2	4.0	–	83	11	6.3	3.0	5.8	0.92	–	63	1.9	0.17
2 (2) Lithic Aquiturbel on basic gneiss and schist with algal layer; 4 m a.s.l.															
Ah	0–1	33	2.5Y5/2	4.4	1.3	63	22	15	7.2	12	1.4	2.1	55	2.1	0.06
AB	−5	20	2.5Y6/4	4.4	1.3	36	31	34	4.9	10	6.2	1.0	55	2.1	0.10
Bg1	−20	13	8YR5/8	4.3	1.3	33	29	38	6.6	9.7	5.5	0.3	53	1.3	0.26
Bg2	−30	10	a GY6/1	4.4	–	31	24	45	2.6	9.0	7.0	–	55	7.0	0.17
3 (25) Spodorthel on gneiss with lichens; 44 m a.s.l.															
AE	0–1	44	10YR5/2	5.0	1.6	95	3	2	29	7.6	0.5	2.1	62	0.7	0.02
Bh	−5	38	5YR3/2	4.2	1.6	90	7	3	21	5.0	1.5	1.0	35	1.4	0.13
Bhs	−26	28	9YR3/3	4.4	1.4	66	29	5	29	5.6	2.2	–	43	1.9	0.35
4 (210) Spodorthel in former penguin rookery on gneiss with lichens; 38 m a.s.l.															
AE	6–8	99	10YR6/2	4.2	1.8	88	7	5	39	24	1.5	3.8	65	0.9	0.33
Bh	−11	85	10YR3/2	4.3	1.8	83	12	5	41	11	5.9	1.5	60	1.0	0.47
Bsh1	−18	85	10YR3/4	4.4	1.6	67	19	13	24	5.0	9.6	1.1	67	1.4	0.86
Bsh2	−30	88	8YR4/5	4.6	–	„	„	„	29	8.0	6.5	1.1	67	0.3	–
Bsh3	−40	85	10YR4/5	4.8	–	78	17	5	30	7.3	4.5	2.0	76	1.9	1.36
Cgw	−50	70	2.5Y5/4	5.3	–	san	dy	loam	3	10	3.1	1.4	93	1.6	n.d.
5 (137) Lithic Folistel on gneiss with lichens and dry moss cushions, 38 m a.s.l.															
LH	0–3	0	–	4.7	0.3	–	–	–	290	19	–	3.5	88	1	0.18
H1	−8	6	5YR3/2	3.9	0.4	–	–	–	200	9.1	–	2.8	73	3-5	0.17
H2	−16	9	5YR2/2	3.8	0.6	–	–	–	190	9.1	–	0.8	60	8-9	0.25
HC	−28	21	5YR2/2	3.8	–	–	–	–	160	12	–	0.4	46	9	0.23
6 (148) Lithic Fibristel on gneiss in former meltwater lake; water depth 20 cm, 33 m a.s.l.															
H1	0–1	0	5Y6/1	6.0	0.1	–	–	–	270	20	–	1.8	85	1-2	2.1
H2	−8	0	5GY5/1	5.3	0.1	–	–	–	260	21	–	4.9	68	1-2	0.63
H3	−18	0	5GY5/1	4.9	0.2	–	–	–	160	18	–	0.6	83	2-3	0.01

(continued)

Table 6.3 (continued)

Horizon	Depth (cm)	>2 mm (%)	Color moist	pH $CaCl_2$	Bulk den. ($g\ cm^{-3}$)	Sand (%)	Silt (%)	Clay (%)	TOC ($g\ kg^{-1}$)	C/N	Fe_p (g/kg)	EC (ms/cm)	Base sat. (%)	$Fe_{d\text{-}p}$ ($g\ kg^{-1}$)	P_a ($g\ kg^{-1}$)
7 (216) Typic Haploturbel on blocky moraine with glacial ice and algal layer															
Au	0–3	46	2.5Y5/1	5.9	1.8	81	27	1.7	0.2	15	–	1.0	78	1.4	0.01
Cw1	−15	42	2.5Y5/2	6.2	1.8	65	21	13	0.4	13	–	0.6	85	1.5	0.01
Cw2	−25	64	2.5Y5/2	6.3	1.8	81	26	2.4	0.2	7.5	–	0.6	85	1.4	0.01
8 (155) Typic Aquiturbel on basic gneiss with algal layer															
Ah	0–1	32	2.5Y4/2	4.2	1.4	76	15	6.6	8.0	6.3	1.5	2.9	63	1.7	0.20
Bw	−20	36	2.5Y3/4	4.1	1.7	68	25	7.2	9.4	7.4	1.7	0.3	52	2.9	0.27
Bg	−40	38	1.5Y4/4 +	4.2	1.8	86	9.2	5.2	5.3	6.2	0.9	0.4	58	1.3	0.15
R/Bg	−60	40	+7YR5/6	4.0	1.8	76	18	6.2	3.7	8.6	3.6	0.5	51	4.5	0.28
9 (217) Typic Spodorthel on glaciofluvial gravels with lichens															
AE	0–3	55	10YR7/3	4.1	1.9	99	0.5	0.9	13	24	0.3	2.7	24	0.5	0.01
Bh	−8	48	8YR5/4	4.3	1.8	97	2.0	1.2	9.1	10	1.1	0.9	10	0.1	0.04
Bhs	−15	53	8YR6/5	4.4	1.9	98	1.5	0.4	5.3	11	1.0	0.4	11	0.2	0.04
Bsw	−25	37	10YR4/3	4.5	1.8	72	26	2.4	2.4	9.2	0.4	0.5	9.2	0.4	0.06
10 (211) Typic Haplorthel (ornithogenic) in abandoned penguin rookery, no vegetation															
Ah1	0–1	>70	9YR6/4	–	–	–	–	–	–	–	–	–	–	–	–
Ah2	−20	>70	5YR3/2	6.5	–	–	–	–	158	1.4	–	–	96	0.32	4.3

Numbers in brackets indicate sampling points

Table 6.4 Chemical properties of soils on the Clark Peninsula, including Whitney Point (WP) and Løkken Moraine (L), for location details see Table 6.1, data from Beyer et al. (1998) and Beyer et al. (2000b)

Code horizon	Depth (cm)	Color Munsell	pH $CaCl_2$	pH H_20	EC (dS m^{-1})	TOC (g kg^{-1})	LOI (g kg^{-1})	TOC LOI	N_t (g kg^{-1})	TOC N_t	ODOE
WP 1: Lithic Haplorthel in an abandoned penguin rookery											
D[a]	0–5	Gravel pavement									
Ah1	−10	10YR3/3	5.28	5.62	3.8	64.2	144.4	0.44	11.55	5.6	119
Ah2	−14	10YR4/3	4.86	5.40	3.0	48.4	110.2	0.44	3.59	13.5	105
IIAC	19	2.5Y4/4	4.68	5.52	2.6	11.0	27.5	0.40	1.24	8.9	47
R	>19	Rock									
WP 2: Lithic Haplorthel in an abandoned penguin rookery[b]											
Ah	0–14	5YR3/3	5.30	5.55	15.3	116.2	255.1	0.46	21.69	5.4	100
IIC	−19	5YR4/3	5.61	5.60	13.0	111.2	237.1	0.47	18.60	6.0	108
C	>19	Moraine rubble from gneiss									
WP 3: Typic Haplorthel (Ornithogenic) in an active penguin rookery											
AC	0–15	10YR6/4	6.35	6.59	46.9	25.2	64.9	0.39	1.16	5.5	71
C	>15	Moraine rubble									
WP 4: Typic Hemistel beneath mosses											
Hi	0–5	7.5YR2/2	4.24	4.50	3.9	361.7	841.5	0.43	13.75	26.3	211
He	−10	7.5YR3/2	3.80	4.05	2.1	237.1	512.2	0.46	14.50	16.4	387
Ha1	−15	2.5YR2/1	3.35	4.34	0.7	220.9	441.3	0.50	15.13	14.6	451
Ha2	−20	2.5YR2/2	3.55	4.18	1.4	193.3	371.3	0.52	10.80	17.9	399
Hfa	>20	Permafrost									
WP 5: Typic Spodorthel under mosses											
AE	0–4	10YR4/1	3.83	4.81	2.3	39.5	92.5	0.43	2.96	13.4	146
Bh	−7	10YR2/1	3.83	4.40	2.1	64.7	133.9	0.44	4.99	13.0	414
BC	−20	10YR4/3	4.09	4.80	1.0	19.0	36.5	0.52	1.75	10.9	165
Cfm	>20	Permafrost									
WP 6: Lithic Hemistel under mosses											
Hi	0–5	7.5YR3/3	4.06	4.38	3.3	429.8	906.4	0.47	9.26	46.4	242
He1	−13	5YR3/3	3.78	3.96	ND	351.2	705.4	0.50	14.23	24.7	802
He2	−21	5YR3/3	3.68	3.86	1.5	298.0	636.0	0.47	15.80	18.9	836
Ha	−30	5YR3/3	3.71	3.83	2.5	288.5	613.8	0.47	22.49	12.8	709
R	>30	Rock									
L 1: Typic Haploturbel on basic gneiss, no vegetation											
A@	0–4	2.5Y5/1	4.79	6.15	0.3	2.2	3.0	0.51	0.25	8.3	32
C@	−10	5Y5/1	6.05	7.09	0.1	0.6	1.7	0.36	0.09	7.1	11
Cfm	>10	Permafrost									
L 2: Lithic Haploturbel on basic gneiss, no vegetation, no vegetation											
Ah@	0–1	5Y4/2	4.85	5.92	0.9	3.6	6.9	0.52	0.27	13.2	21
AC@	−4	5Y5/1	5.90	6.50	0.5	1.2	3.3	0.36	0.13	9.2	20
C@	−15	5Y4.5/2	6.14	7.35	0.6	0.9	3.8	0.23	0.11	8.5	14
R	>15	Rock									

[a]term D (for gravel pavement), adopted from Bockheim (1997)
[b]abandoned penguin rookery occasionally recolonised
EC Electrical conductivity, *TOC* total organic carbon, *LOI* loss on ignition
N_t total nitrogen, *ODOE* optical density of oxalate extract
@ evidence of cryoturbation

Table 6.5 Chemical properties of soils on the Clark Peninsula, Windmill Islands

Code horizon	Ca	Mg	K	Na	H	Al_e	CEC_e	CEC_p	BS (%)	K_{lac}	Mg_{lac}	P_{lac}
	(mmol$_c$ kg^{-1})									(mg kg^{-1})		
WP 1: Lithic Haploturbel in an abandoned penguin rookery												
Ah1	279	191	5	20	14	0.8	511	723	68	173	2491	3591
Ah2	149	100	5	14	10	2	280	467	58	149	1497	2980
IIAC	54	26	5	8	5	1	99	167	56	172	457	956
WP 2: Lithic Haploturbel in an abandoned penguin rookery[b]												
Ah	86	1054	7	19	76	2	1245	1333	93	271	14623	4301
IIC	62	637	12	20	67	2	801	ND	ND	279	12786	3861
WP 3: Typic Haplorthel in a recent penguin rookery												
AC	33	117	33	40	15	0.6	238	370	60	744	1397	2581
WP 4: Typic Hemistel beneath mosses												
Hi	273	112	50	23	35	20	513	ND	ND	ND	ND	ND
He	142	36	8	11	15	60	271	ND	ND	259	543	271
Ha1	126	25	7	10	14	64	245	1170	14	225	376	314
Ha2	126	22	4	11	11	54	229	632	35	132	220	234
WP 5: Typic Spodorthel beneath mosses												
AE	13	11	2	5	2	7	41	163	19	83	150	49
Bh	12	8	1	4	2	16	44	222	12	48	114	133
BC	4	2	0.3	2	0.6	5	14	84	10	17	27	102
WP 6: Lithic Hemistel under mosses												
Hi	205	107	4	17	20	59	413	1298	26	1746	1373	423
He1	114	34	7	21	17	118	313	1440	12	279	340	985
He2	109	25	5	13	14	112	280	1192	16	190	224	955
Ha	67	21	5	13	11	88	205	653	16	171	228	1055
L 1: Typic Haploturbel												
A@	5	2	0.7	1	0.3	0.7	10	16	56	31	60	135
C@	6	2	0.8	1	0.1	0.1	10	13	73	34	57	18
L 2: Lithic Haploturbel												
Ah@	10	4	0.8	2	0.4	0.3	17	24	66	36	59	6
AC@	15	2	1	1	0.1	0.1	20	22	90	45	48	7
C@	19	3	2	2	0.5	0.3	26	27	92	61	50	10

[b]abandoned penguin rookery, occasionally recolonized
CEC_e effective cation exchange capacity; *CEC_p* potential cation exchange capacity
Al_e effective Al; *BS* base saturation
K_{lac} lactate-soluble potassium; *Mg_{lac}* lactate-soluble magnesium
P_{lac} lactate-soluble phosphorus
ND not determined; *NE* not found, below detection limit
@ evidence of cryoturbation
WP Whitney Point, *L* Løkken Moraine

variable redox conditions (strong mottling of subsoil: see Munsell color bright brown to orange beside light greenish gray in the Bg2) may have influenced this process. The strong orange colored mottles suggest that crystallized lepidocrocite is formed under stagnic (not gleying!) moisture regime conditions.

The third profile, a Typic Spodorthel, formed in an abandoned penguin rookery (Fig. 6.5). The birds collect coarse gravels and stones for their nests and leave bones and feathers (Table 6.3, site 4). This soil has a low pH and stagnic conditions in the subsoil, resulting in extremely high amounts of different phosphate minerals, mainly apatite (due to low pH in the Bsh) but also strengite and vivianite (due to stagnic conditions in the Bg) (Table 6.3). We think that active cryoturbation was absent in the soil for long time, because otherwise the clear horizontation and an enrichment

Table 6.6 Chemical properties of soils of some islands in the coastal region of the Windmill Islands

Code horizon	Depth (cm)	Color Munsell	pH $CaCl_2$	pH H_20	EC (dS m^{-1})	TOC (g kg^{-1})	LOI (g kg^{-1})	TOC LOI	N_t (g kg^{-1})	TOC N_t	ODOE
H 1: Lithic Haploturbel from moraine deposits											
Ah@	0–1	Green[a]	5.10	5.47	17.3	54.6	167.4	0.33	5.83	9.4	41
BwAh@1	−5	2.5Y3/1	4.80	5.65	3.1	35.1	85.1	0.41	4.74	7.4	26
BwAh@2	−10	5Y2.5/2	5.00	6.26	1.6	76.0	176.8	0.43	19.94	3.8	23
C	>10	Moraine rubble									
H 2: Lithic Haplorthel from gravel[b]											
D[c]	0–5										
AE	−12	5Y5/3	5.70	6.44	7.6	12.6	49.4	0.25	1.82	6.9	29
Bh	−20	7.5YR4/3	5.73	6.69	3.6	23.2	53.1	0.44	5.97	3.9	52
C	>25	Rock fragments									
H 3: Typic Haploturbel from gneiss rock rubble											
A	0–1	5Y6/2	5.83	6.26	14.2	65.9	144.4	0.46	7.84	8.4	31
AhBw@1	−3	5Y6/2	5.84	6.72	5.0	53.2	107.7	0.49	4.70	11.3	32
AhBw@2	−9	10YR6/6	5.52	6.49	3.1	56.7	136.0	0.42	11.01	5.2	37
AhBw@3	−19	10YR6/6	5.26	6.51	2.0	16.2	41.1	0.39	0.82	19.8	25
Cfm	>19	Permafrost									
MG 1: Lithic Haplorthel from gneiss rock rubble											
D[C]	0–2										
Ah	−3	2.5Y6/2	5.68	6.32	5.9	16.5	42.0	0.39	0.18	92.1	46
E	−5	10YR7/2	5.90	6.88	1.5	3.9	11.9	0.33	0.43	9.1	18
Bwh	−10	10YR6/4	6.58	7.59	2.0	23.9	54.4	0.44	0.71	33.9	44
R	>10	Rock									
P 1: Lithic Haplorthel from gneiss rock rubble											
D[C]	0–1										
Ah1f	−2	10YR5/2	5.36	6.16	5.3	23.2	90.0	0.26	1.47	15.8	62
Ah2f	−4	10YR5/2	5.26	6.38	2.8	11.7	36.3	0.32	1.97	5.9	43
Bwf	−11	10YR6/4	5.46	6.49	2.4	9.4	25.1	0.37	1.31	7.2	70
C	−21	10YR6/2	5.40	6.50	1.0	4.4	14.1	0.30	0.98	4.4	63
R	>21	Bare rock									

H: Hollin Island, MG: Midgley Island, P: Pidgeon Island (data by L. Beyer, Inst. for Soil Science and Plant Nutrition, Univ. Kiel, unpubl.)
[a]green algae layer at surface
[b]suggested abandoned and lifted penguin rookery (Beyer et al. 2000a)
[c]Term adapted from Bockheim (1997)
EC Electrical conductivity
TOC total organic carbon, *LOI* loss on ignition
N_t total nitrogen
ODOE optical density of the oxalate extract
@ evidence of cryoturbation

of seaborne sponge spicules only in the topsoil would not exist. A strong chemical weathering of special mineral species (e.g., chlorites, feldspars, micas) has occurred (Table 6.10), probably due to the formation of nitric and sulfuric acids from urea and proteinaceous bird excrements.

Blume and Bölter (1996) studied total porosity and pore-size distribution (using 100 cm^3 steel cylinders for volume samples) of four soils with different textures and levels of cryoturbation. In the topsoil of an Aquiturbels in the center of a 5 m diameter sorted circle, they measured high concentrations of silt that they were able to correlate with an abundance of medium pores. This enabled them to determine that cryoturbation takes place primarily in the upper 20 cm during the single summer month when the soil is snow-free. They observed large pores in a Typic Spodorthel with a gravelly sand texture in a former penguin rookery that enable

Table 6.7 Chemical properties of soils on some islands in the coastal region of the Windmill Islands

Horizon	Ca	Mg	K	Na	H	Al	CEC_e	CEC_p	BS (%)	K_{lac}	Mg_{lac}	P_{lac}	K_{lac}	Mg_{lac}
	$mmol_c$ kg									mg kg^{-1}			K_{CEC}	Mg_{CEC}
H 1: Typic Umbriturbel from moraine deposits														
Ah@	24	43	22	20	12.2	2.3	124	209	53	637	340	172	0.74	0.66
BwAh@1	19	29	2	16	1.6	0.5	68	127	52	74	341	49	0.95	0.98
BwAh@2	29	43	2	24	3.1	2.5	104	ND	ND	93	677	85	1.19	1.31
H 2: Typic Spodorthel from gravel														
AE	42	34	4	31	0.9	NE	112	132	84	115	281	901	0.74	0.69
Bh	123	42	2	29	0.5	0.2	195	270	72	70	632	2375	0.90	1.25
H 3: Typic Umbriturbel from gneiss rock rubble														
A	73	104	16	42	5.0	1.7	242	273	86	527	949	224	0.84	0.76
AhBw@1	56	73	4	37	1.8	0.5	172	209	81	178	920	94	1.14	1.05
AhBw@2	46	58	2	37	1.1	0.3	145	202	71	93	708	51	1.19	1.02
AhBw@3	12	23	2	19	0.8	1.7	61	93	63	42	139	43	0.54	0.50
MG 1: Typic Spodorthel from gneiss rock rubble														
Ah	25	36	5	17	2.0	0.8	86	97	86	204	442	72	0.96	1.02
E	12	11	2	9	0.3	NE	34	36	93	57	143	12	0.73	1.08
Bwh	37	40	5	40	0.3	NE	122	131	93	139	413	12	0.71	0.86
P 1: Lithic Haplorthel from gneiss rock rubble														
Ah1f	20	18	6	14	4.0	2.0	63	90	64	74	98	179	0.32	0.45
Ah2f	23	12	2	15	0.6	0.2	55	85	60	53	132	444	0.68	0.92
Bwf	50	16	2	16	0.5	NE	85	142	59	64	134	1284	0.82	0.70
C	16	5	2	8	0.5	NE	31	62	50	83	94	913	1.06	1.57

CEC_e effective cation exchange capacity
CEC_p potential cation exchange capacity
BS base saturation
K_{lac} lactate-soluble potassium
Mg_{lac} lactate-soluble magnesium
P_{lac} lactate-soluble phosphorus
K_{CEC} K of CEC in mg kg^{-1}
Mg_{CEC} Mg of CEC in mg kg^{-1}
ND not determined, *NE* not found or below detection limit

rapid transfer of water from snowmelt that temporarily created anoxic conditions. A third soil (Typic Aquiturbel) was strongly cryoturbated and contained sand and gravel in the topsoil and clay at depth. The clay-enriched subsoil contained abundant fine and medium pores that caused reducing conditions during snowmelt. Finally, medium pores were predominant in a peat-covered Folistel.

6.5 Discussion

The predominant soil-forming processes in the Windmill Islands include cryoturbation, physical and chemical weathering, organic matter accumulation, podzolization, redoximorphism (Blume and Bölter 1993; Blume et al. 1997; Beyer et al. 1998, 2002).

6.5.1 Cryoturbation

Practically, all of the soils around Casey have permafrost and are classified as Gelisols. Most of the soils in ice-free areas of Wilkes Land are cryoturbated and are classified as Turbels. Cryoturbation is manifested on the land surface by patterned ground. Particle sorting occurs within the profile, with sand and gravel accumulating on the surface and clay becoming concentrated at depth. Cryoturbation is triggered by frequent freeze–thaw events and their effects on soil water, occurring primarily during the 0.5- to 2-month summer. Only soils with extremely low contents of clay and silt as in Spodorthels show no current cryoturbation due to the low moisture contents in the active layer. Vesicular structure is common in the upper 10 cm of cryoturbated soils. The very young soils on the Løkken Moraine have a vesicular

Table 6.8 Mineralogy of a Typic Haploturbel; Casey (site 1 of Table 2 in: Blume et al. 2002b; Table 8.1)

(a) Mean of 20–630 µm ∅ in % (unw. = unweathered, w. = medium weathered)

Horizon	Depth (cm)	Chlorite		Pyroxenes	Amphiboles	Mica		Weath. min.	Opaque min.[a]
		unw.	w.			unw.	w.		
Az	0–1	4.2	0	0.9	0.9	16.6	0	0	2.0
AC	5–20	4.2	0	0	3.3	14.9	0	0.2	1.7
Cw2	50–70	5.3	0	0.7	2.0	13.8	0	0.2	1.6

Horizon	Depth (cm)	Plagiocl.	Alkali feldsp.	Weath. feldsp.	Epidote	Quartz	Garnet	Rock fragm.	Others
Az	0–1	22.6	16.9	0.9	0.7	28.6	0.2	3.8	1.6
AC2	5–20	22.0	16.3	1.3	0.4	29.5	0.7	4.4	1.1
Cw2	50–70	21.1	16.9	1.8	1.8	30.0	1.3	2.4	1.1

(b) Clay and fine silt fraction

Horizon	Depth (cm)	Quartz	Feldspars	Pyroxene	Olivine serpent.	Chlorite	Illite/mica	Smectite
Clay fraction (<2 µm ∅) in %, semiquantitative								
Az	0–1	20`	43	0	7	<1	30	<1
Cw2	50–70	14	56	0	0	<1	30	<1
Silt fraction (2–20 µm ∅) in %, semiquantitative								
Az	0–1	27	43	11	0	9	10	<1
Cw2	50–70	29	20	0	10	3	36	<1

[a]Anatase and rutile also present

Table 6.9 Mineralogy of Lithic Aquiturbel on basic gneiss and schist (site 2 in: Blume et al. 2002b; Table 8.2)

(a) mean of 20–630 µm ∅ in % (unw. = unweathered, w. = medium weathered)

Horizon	Depth (cm)	Chlorite		Pyroxenes	Amphiboles	Mica		Weath. min.	Opaque min.[a]	Garnet
		unw.	w.			unw.	w.			
Ah	0–1	3.1	0	0.2	2.5	15.8	7.1	0	1.3[b]	1.3
AC	1–5	6.2	0	1.5	2.8	25.6	6.6	0	1.1	1.5
Bg2	20–30	5.6	0	1.8	2.0	20.2	1.1	0	1.1	1.6

Horizon	Depth (cm)	Plagiocl.	Alkali feldsp.	Weath. feldsp.	Epidote	Quartz	Rock fragm.	Others
Ah	0–1	17.2	8.9	4.7	0.7	29.5	4.4	3.3
AC	1–5	16.2	11.0	0.9	0.4	21.6	2.8	1.8
Bg2	20–30	18.6	14.0	3.3	0.5	26.6	2.2	0.9

(b) Clay and fine silt fraction

Horizon	Depth (cm)	Magnetite	Quartz	Feldspars	Chlorite	Illite/mica	Smectite	Mixed layers	Kaolinites
Clay fraction (<2 µm ∅) in %, semiquantitative									
Ah	0–1	<1	20	58	<1	22	<1	0	0
AB	1–5	<1	17	16	4	43	20	<1	0
Bg2	20–30	<1	11	58	0	31	0	0	<1
Silt fraction (2–20 µm ∅) in %, semiquantitative									
Ah	0–1	6	22	34	5	33	0	0	0
AB	1–5	14	20	30	6	30	<1	0	0
Bg2	20–30	24	17	13	11	35	<1	0	0

[a]Anatase and rutile also present

Table 6.10 Mineralogy of a typic Spodorthel from a former penguin rookery, on gneiss (site 4 in: Blume et al. 2002b; Table 8.4)

(a) Mean of 20–630 μm ∅ in % (unw. = unweathered, w. = medium weathered)

Horizon	Depth (cm)	Vulc. glas	Apatite	Chlorite		Pyr. + amp.		Micas		Strongly w. minerals
				unw.	w.	unw.	w.	unw.	w.	
AE	6–8	1.1	0.7	9.8	0	1.5	0.4	12.6	0	1.3
Bh	8–11	0	0	9.4	4.2	3.3	0	12.5	0.4	1.1
Bsh	11–30	0	0	16.7	29.8	0.4	0	17.5	0.4	3.8
Cgw	40–50	0	0	6.9	0	3.1	0	16.9	0.9	1.6

Horizon	Depth (cm)	Plagioc.	Alkali feldsp.	Weath. feldsp.	Quartz	Chalcedone	Opaque min[a]	Rock fragm.	Other[b]	Biota[c]
AE	6–8	18.6	14.2	1.8	30.8	0.9	2.1	1.6	1.9	Many
Bh	8–11	19.3	17.7	2.2	25.1	0	0.6	1.8	1.9	0
Bsh	11–30	8.2	6.0	3.8	7.5	0.2	2.7	1.1	1.9	0
Cgw	40–50	21.5	13.3	2.7	18.9	1.3	1.3	7.3	4.3	0

(b) Clay and fine silt fraction

Horizon	Depth (cm)	Quartz	Feldspars	Pyroxene	Mica illite	Mixed layers	Apatite	Strengite	Vivianite	Kaolinite	Chlorite
Clay fraction (<2 μm ∅) in %, semiquantitative											
AE	0–8	41	33	8	9	0	4	5	0	<1	0
Bh	8–11	26	36	17	6	0	15	0	0	0	0
Bsh	11–30	0	16	0	<1	0	80	4	0	0	0
Cgw	40–50	24	32	0	31	<1	6	0	7	0	0
Silt fraction (2–20 μm ∅) in %, semiquantitative											
Bh	8–11	40	13	5	15	0	27	0	0	<1	0
Bsh	11–30	10	10	0	23	0	45	10	0	0	2

[a]and anatase, ilmenite, rutile, zircon; [b]garnet, epidote, silimanite; [c]sponge spicules

Fig. 6.5 Spodorthel near Casey Station in an abandoned penguin rookery

structure from air entrapped in pores during wetting–drying cycles after periodic snow falls.

6.5.2 Physical (Cryoclastic) Weathering

Physical weathering is an important process in soils of Wilkes Land, especially in the topsoil. The predominant soil minerals are. Primary minerals, such as quartz, feldspars, and mica that are derived from leuco gneiss, are subject to frost disintegration (cryoclastic weathering). The high content of primary minerals in the clay fraction demonstrates that this process not only occurs in the sand and silt fractions, but also occurs in the clay fraction. This is especially true for easily fissile minerals such as feldspar and mica, but also occurs with quartz gains. During the summer months, the physical weathered soil material is cycled deeper in the soil from cryoturbation. Sandy and gravelly soils of hills often have a well-developed lichen cover that insulates the mineral soil against the cryoclastic process (Melick et al. 1994a).

6.5.3 Acidification, Chemical Weathering, and Mineral Formation

Most of the soils of Wilkes Land are very strongly acidic, many with pH values lower than 4.5. Our pH values are significantly lower than those measured on Ongul Island in Queen Maud Land (region 1, Fig. 2.1) by Ohtani and Kanda (2002). Only soils of young moraines (e.g., site 7 of Table 6.3) and of recent penguin rookeries (e.g., Table 6.4, site WP3) show pH ($CaCl_2$) values higher than 6.0. The low pH values in the Windmill Islands may be attributed not only to the lack of carbonate rocks, but also to mineralization of soil organic matter (Blume and Bölter 1996). Cyanobacteria can promote these processes by nitrogen fixation and ammonia excretion; acidification is also promoted by exudates from lichens and mosses. Spodosols in former penguin rookeries are very acid due to excrement with high contents of proteins, which were mineralized and transformed to nitric and sulfuric acids.

Chemical weathering of the Typic Haploturbel on a stony moraine was low (Table 6.8), but feldspars and mica Typic

Table 6.11 Frequency distribution of organic carbon (TOC in kg/m^2) in soils of Wilkes Land (after Blume et al. 1997; Fig. 6.3)

Soils	Lithic Haploturbels	Typic Haploturbels	Typic Aquiturbels	Histels	Spodorthels	Spodorthels (ornithogenic)	Typic Haploturbels
Number	1	6	2	2	4	1	2
TOC	1.5	0.2–2	3–4	5.5–22	1–7.5	3.5	0.01–0.03

Aquiturbel derived from schist were weathered more intensively, and smectites formed under the combined influence of low pH and strong cryoturbation (Table 6.9). In a Typic Spodorthel in a former penguin rookery, strong chemical weathering was evidenced by breakdown of chlorites, feldspars, and micas (Table 6.10). Organic, nitric, and sulfuric acids from penguin guano promote the proton production (Beyer et al. 1997a). These weathering reactions enable formation of phosphate minerals such as apatite, vivianite, and strengite.

6.5.4 Organic Matter Accumulation

The humus content of soils without vegetation, covered by snow for more than 11 months and sometimes all year-around, is low in Wilkes Land. Total organic C contents range from 0.2 to 0.4 %, and the SOC is derived from snow algae and soil algae. The SOC is probably translocated and preserved by cryoturbation into the subsoil. In loamy soils of the hills with a more extensive vegetation cover, and with many soil algae but no lichens, approximately 0.7 % TOC occurs. Fungi and bacteria decompose the organic matter, while higher organisms are widely absent (Azmi and Seppelt 1997, 1998). The observed amounts of 0.2–0.4 % TOC are high compared with most hot desert soils (Blume et al. 1984). Sandy soils contain 2–3 % TOC in the entire profile, due to the lack of snow cover for at least 2 or 3 months per year and the extensive lichen cover (Blume et al. 2002a).

Loamy soils with many soil algae but no lichens contain approximately 1 % TOC. Our data on TOC are comparable to those from Ongul Island (Ohtani and Kanda 2002). The extensive vegetation cover influences both total organic carbon and cation exchange capacity of the soils. The surface vegetation may create a favorable soil environment for itself, as has been observed in geo-ecological investigations of hot desert systems (Beyer et al. 1998).

On slope terraces, where are steps with small depressions of bedrock with meltwater stagnation, peat is formed from mosses (Table 6.3, site 5) (Beyer et al. 1997a). The peat is strongly humified (h8 to h9 after v. Post 1924) in the subsoil, and it contains substantial amounts of aromatic, phenolic, and carboxylic compounds (Beyer et al. 1995). The mean radiocarbon-dated age of the surface layer is 850 (±40) years, and the age of the subsurface layer is 1,420 (±50) years (Blume et al. 1997). At the bottom of a shallow meltwater lake, dead algae sometimes accumulate (Table 6.2, site 6), which shows no visible humification (h1-h2). The mean ^{14}C-dated age of the top cm is about 290 (±35), of deeper layers 850 (±40) years and 2,110 (±50) years (Blume et al. 1997).

Profile quantities of TOC were calculated for soils and arrayed by soil taxa (Table 6.11). The greatest quantities occur in Histels, followed by Spodorthels, Aquiturbels, Lithic Haploturbels, and Typic Haploturbels. The German microbiologist, Christian Gottfried Ehrenberg (1795–1876) seems to be the first, who described the properties and organisms of a soil of a former penguin rookery on Cockburn Island, Weddell Sea (position given by Ehrenberg: 62° 12′ S, 59° 51′ E; corrected: 64° 12′ S, 56° 51′ W) (Ehrenberg 1854, pp 1–2).

Plant growth is extremely low in Wilkes Land due to low temperatures. But the annual litter production should be higher than the intensity of litter mineralization by soil organisms: The mean annual temperature of Casey Station is −9.3 °C. The daily highest temperatures of noontime during snow-free months reach +8–9 °C above soil surface. But in the topsoil the daily fluctuation should be between the monthly maximum and minimum values of +4 and −3 °C, whereas in the subsoil near the permafrost layer we should have the monthly mean values between +0.1 and −0.2 °C (Blume and Bölter 1996). Therefore, in soils with an oxygen deficiency as in Histels and Aquiturbels during hundreds to thousands of years relatively high amounts could be accumulated. Similar conditions were found in the subsoil (Bh horizon) of Spodosols in abandoned penguin rookeries.

Polysaccharides are the dominant primary organic compounds, the composition of which was found to be similar to peat litter from temperate soils (Beyer et al. 1997b). Patterns of SOM show great varieties in long-chain alcohols, acids, and ketones, which are generally not typical moieties for soils (Beyer et al. 2001). Many of these long-chained compounds had functional groups, heterocyclic structures, and alkylations, and were cyclic ionized. Thus, the Spodorthels can be regarded as soils that store C and N in East Antarctica (Beyer et al. 2000a).

6.5.5 Podzolisation

One of the most striking features of the Windmill Islands is the occurrence of soils influenced by podzolization (Blume and Bölter 1993; Blume et al. 1997; Beyer and Bölter 2000a, b; Blume et al. 2002a). Spodorthels were observed not only in abandoned penguin rookeries (Table 6.3, site 4; Table 6.4) but also on gravelly glaciofluvial deposits derived from leuco gneiss (Table 6.3, sites 3 and 9; Table 6.4, WP5). The soils are slightly bleached (AE horizon) or even at more developed stages (E horizon) with a spodic Bh horizon. Excrements, bones, and feathers form the rookery are common. Organic moieties from lichens and mosses are probably involved in the formation of Spodosols. Spodic horizons (Fig. 6.5) can only be formed under the absence of cryoturbation.

6.5.6 Redoximorphism

Loamy subsurface horizons in different soils frequently have Fe and Mn mottles (Table 6.3, sites 2, 4, 8). Obviously, aerobic and anaerobic soil conditions alternate with each other and occasionally water saturation occurs. Vivianite is only persistent under anaerobic conditions, but was found in the subsoil of a Spodorthel in a former penguin rookery. In Aquiturbels (Table 6.3, sites 2 and 8), the strong orange colored mottles suggest that crystallized lepidocrocite has formed under stagnic (not gleyed!) moisture regime conditions.

6.5.7 Soil Formation on Boulders and Rocky Outcrops

We found boulders and rock outcrops, which are covered by an epilithic as well as an endolithic flora of lichens, algae, and bacteria. These environments show physical and chemical changes within the upper few millimeters to centimeters of the rock surface (Friedmann 1982; Chen et al. 2000) due to the different weathering processes. These soils are classified in lithic subgroups in *Soil Taxonomy*.

Biota and humus accumulate at low levels in sandy and gravelly soils with a well-developed lichen cover, which insulate the mineral soil against freeze–thaw cycle impact (Melick et al. 1994b). Due to the lack of sufficient N-sources, low temperature and moisture in sandy soils, the organic matter degradation is hampered, which leads to a weak detritus and humus accumulation. Significant N-inputs can only be related to cyanobacteria, which are often associated with mosses and some lichens, the dominant sources for dissolved organic carbon and plant debris (Beyer 2000). This development of localized "fertile islands" (Evenari 1985) may be an important survival strategy also in cold desert ecosystems and should be an aspect of future soil ecological research in the terrestrial ecosystems of East Antarctica.

Observations from single soil profiles do not permit the development of general hypothesis on ecosystem processes with regard to plant adaptations and soil formation. Such profiles do, however, provide insights on the correlation between soil, vegetation cover, and the biology of the soil/plant ecosystem. Small-scale variability in Antarctic soil ecosystems (Beyer et al. 1998, 1999, 2000b, 2004), microclimate (Smith 1990), and soil microbiology (Bölter 1990) makes it difficult to transfer data from a profile level to a landscape level.

6.6 Summary

Wilkes Land contains an ice-free area of 1,500 km^2, the largest of which is the Windmill Islands and surrounding area at 500 km^2. The Windmill Islands are underlaid by continuous permafrost. Active-layer thicknesses range between 30 and 80 cm. Soils in Wilkes Land are of Late Glacial Maximum age and younger. Vegetation is limited to lichens, mosses, and soil algae. Penguin rookeries are restricted to small areas on the Clark and Browning Peninsulas. Overall, the soils of Wilkes Land are poorly developed. The dominant soil-forming processes include acidification, organic matter accumulation (humification), and redoximorphism. Podzolization occurs in abandoned penguin rookeries. Chemical weathering occurs to a limited extent.

All of the soils are classified as Gelisols. Haploturbels occur in areas of patterned ground, Aquiturbels in depressions where there is water saturation above the permafrost, and Psammoturbels in sandy areas. Haplorthels are present on dry ridges and Spodorthels in abandoned penguin rookeries. Fibristels and Hemistels occur in peaty depressions, and Folistels exist in shallow bedrock depressions. Many of the soils have bedrock within the upper 50 cm and are classified into Lithic subgroups.

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7 Soils of North Victoria Land

James G. Bockheim

7.1 Introduction

North Victoria Land (NVL) is that portion of the 3,500 km long TAM that extends from the Wilson Hills along the Pennell Coast at approximately 69° 30′ S to the Mawson Glacier at about 76° S (Fig. 7.1). The total ice-free area of NVL is about 1,900 km^2; and the key ice-free areas include the Adare Peninsula, the Morozumi Range, Mt. Gerlache, the Helliwell Hills, the Hallett Peninsula, Coulman Island, and the Sequence Hills. Major scientific bases include Leningradskaya (Russia) at the northernmost portion of NVL (69° 30′ S, 159° 23′ E) and Mario Zucchelli (74° 42′ S, 164° 07′ E; Italy).

NVL is very mountainous, with elevations ranging from sea level to about 3,720 m (Mt. Hewson). The climate reflects these differences in elevation, with mean annual air temperatures ranging from –25 to –35 °C (Fig. 2.4) and mean annual precipitation ranging from 100 to 300 mm year^{-1} (Fig. 2.5). Vegetation is limited to isolated cryptogams.

Upper Precambrian metasedimentary rocks are dominant in NVL, with smaller areas of Cenozoic volcanic rocks, Beacon sandstone, Ferrar dolerite, and granite intrusives of varying ages (Fig. 2.6). The entire area was glaciated by ice flowing from the Talos Dome of the East Antarctic ice sheet (Denton et al. 1986). At least two episodes of alpine glaciations have been mapped in NVL. The Evans drift is comprised of drift patches and erratics below the glacial trimline of probable late Wisconsin/Holocene age, and the Rennick drift features ice-cored moraines of likely late Holocene age. The entire area is underlain by ice-cemented permafrost, and the active-layer depths range from 8 to 70 cm in depth. Dry-frozen permafrost is present below 70 cm in the Morozumi Range and possibly other areas as well.

In addition to the study described herein by Denton et al. (1986), soils have been examined in penguin rookeries along the Ross Sea coast at Cape Hallett (Hofstee et al. 2006), Inexpressible Island (Campbell and Claridge 1966), and Terra Nova Bay (Maladrino et al. 2009). Barrett et al. (2006) studied covariation between soil microbial communities (microbial and invertebrate) with biogeochemical properties at Cape Hallett, Luther Vale, and Terra Nova Bay.

7.2 Methods

7.2.1 Field

Fourteen pedons were described and sampled in NVL from five sites on a latitudinal gradient, including the Helliwell Hills and Morozumi Range (71° 30′–72° 00′ S), Gallipoli Heights (72° 25′ S), the Mesa Range (72° 50′ S), and the Lichen Hills (73° 15′ S). Soil pits were excavated to at least 100 cm, unless ice-cement or large boulders prevented digging to that depth. The following soil properties were measured in the field. The depth of staining refers to the thickness of the layers showing the strongest hues and chromas from oxidation of iron-bearing minerals and corresponds to the bottom of the Bw horizon. The depth of coherence refers to the thickness of consolidated soil from accumulation of weathering products such as salts and iron oxides; below the depth of coherence, soil readily caves into the pit. The depth of visible salts refers to the maximum depth for which salt encrustations beneath clasts, salt flecks, and salt cementation are readily visible to the naked eye.

The six-stage sequence described in Chap. 8, in which the form of soluble salts was related to total dissolved salts from electrical conductivity measurements and soil age, was employed in this study. The depth to ice or ice-cemented permafrost also was determined. The active layer in the study areas varies between 15 and 50 cm; material below this depth that is not cemented by ice contains dry-frozen permafrost, i.e., perennially frozen materials lacking sufficient interstitial water to cause cementation. The weathering stage is an overall representation of the landscape/material

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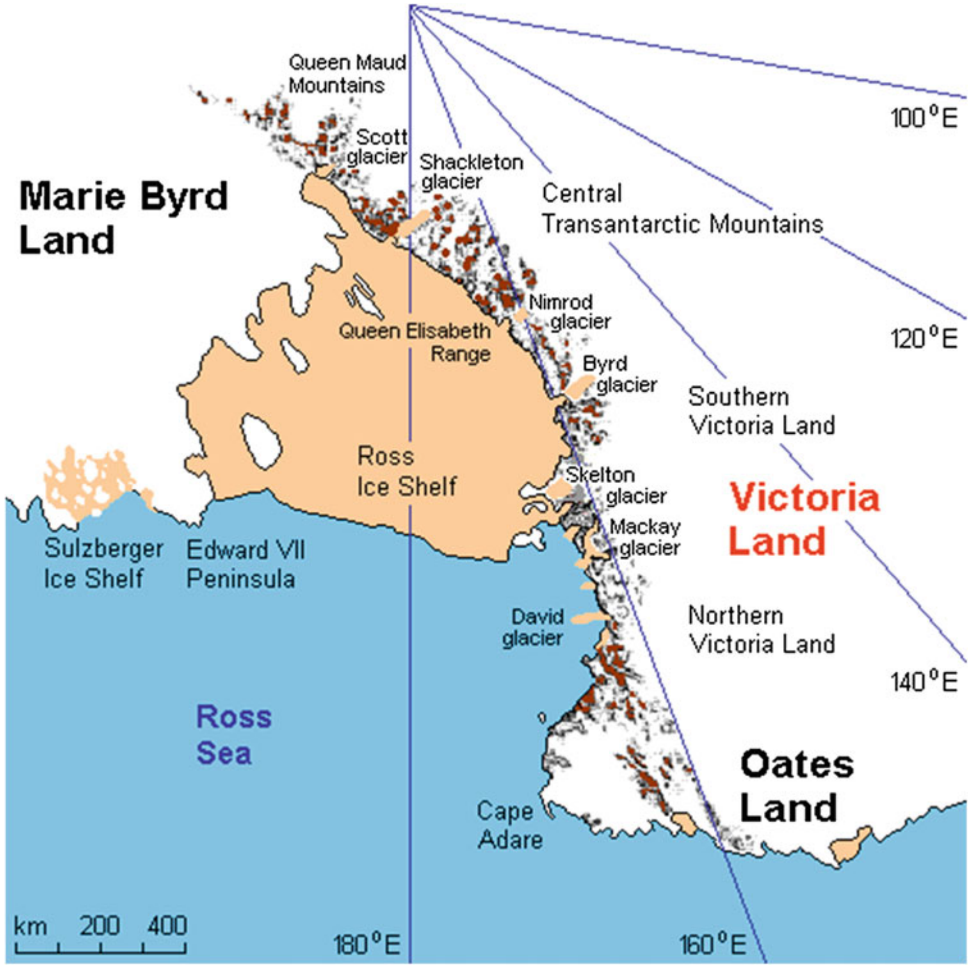


Fig. 7.1 Map of Northern Victoria Land. Ice-free areas are shown in *red*. NVL is considered here to include the area from Cape Adare-Oates Land to just south of the David Glacier at 76° S latitude (*Source* Wikipedia)

based on the degree of surface boulder weathering, soil morphology, and patterned ground and permafrost forms (see Chap. 8).

Soils were classified into the Gelisol order to the family level (Soil Survey Staff 2010); mineral soils showing cryoturbation are classified as Turbels; mineral soils without obvious cryoturbation are Orthels. Soils with ice-cemented permafrost within 70 cm of the surface are classified as Haplorthels or Haploturbels. Soils with dry-frozen permafrost below 70 cm are classified as Anhyorthels or Anhyturbels. Soils in lithic subgroups have bedrock within 100 cm of the surface.

7.2.2 Laboratory

Several measurements were performed in the laboratory, including electrical conductivity (EC), pH, and major cations and anions in 1:5 soil:distilled water extracts (U.S. Salinity Laboratory Staff 1954; APHA et al. 1975). Profile quantities of salts (mg cm^{-2}) to a depth of 70 cm were calculated (see Chap. 8).

7.3 Results

7.3.1 Areas of Ice-Free Regions

The ice-free area of NVL within the 69° 30′–76° 00′ S is approximately 1,900 km^2. The largest ice-free areas include the Adare and Hallett Peninsulas and Coulman Island and inland mountain areas such as the Morozumi Range, Mt. Gerlache, the Helliwell Hills, and the Sequence Hills.

7.3.2 Description of Soil Taxa

From 14 soil descriptions and a provisional reconnaissance-scale soil map, the dominant soil taxa are from most to least abundant: Lithic Anhyorthels (LAo), Typic Anhyturbels (TAt), Glacic Anhyturbels (GAt), and Typic Anhyorthels (TAo). Pedon 81-28 (Fig. 7.2) is a Lithic Anhyorthel on Evans drift at Mt. Alford in the Helliwell Hills. The pedon contains a well-developed desert pavement over an 8 cm thick salt-rich horizon (Bwz), a BC horizon, and diorite bedrock at 35 cm. The Typic Anhyturbel depicted in Fig. 7.3 (pedon 81-19)

Fig. 7.2 Cape Adare (photo by G. Law; http://www.100megsree3.com/glaw/scott/60s.htm)

Fig. 7.3 Cape Hallett station and adelie penguins (photo by Megan Balks)

is derived from argillite-rich Evans drift in the Morozumi Range. The pedon is located in a area of high-centered non-sorted polygons and features 10 cm of unoxidized material (weathering stage 2) over ice-cemented permafrost.

Pedon 81-26 (Fig. 7.4) is derived from Rennick drift that is comprised on argillite and dolerite. The pedon contains a weakly developed desert pavement over 35 cm of unoxidized material (weathering stage 1) over buried ice. Pedon 81-30 (Fig. 7.5) is derived from diorite till and residuum. The soil contains a strongly oxidized Bw horizon to a depth of 19 cm with stage 4 salts in places. Ice-cemented permafrost occurs at a depth of 35 cm. Pedon 81-30 is the most strongly developed soil (weathering stage 4) observed in NVL.

Hofstee et al. (2006) examined ornithogenic soils at Seabee Hook, Cape Hallett, NVL. Soils on relict beach ridges favored by penguins for nest were classified as Typic

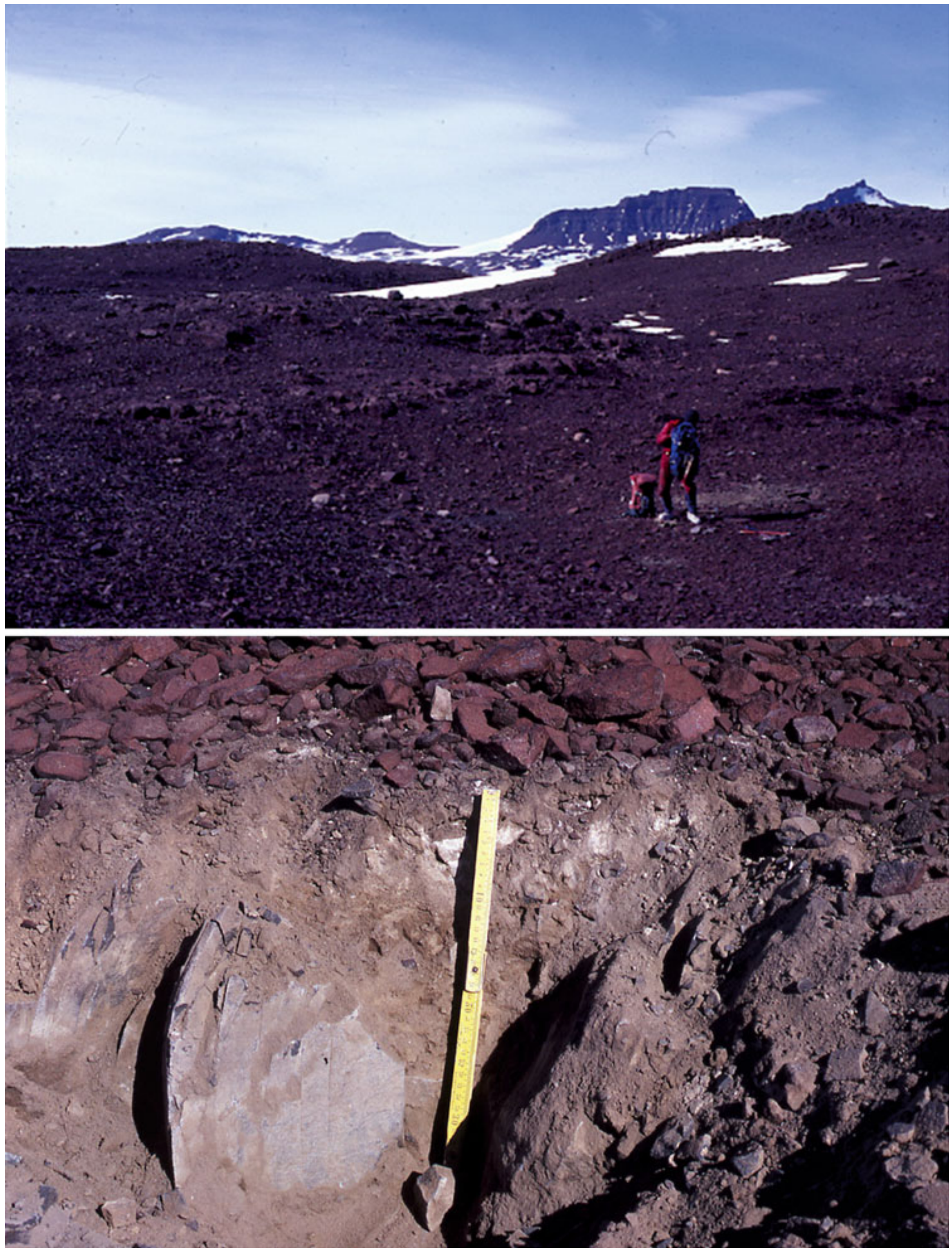


Fig. 7.4 Lithic Anhyorthel landscape (*top*) and soil (*bottom*) at Mt. Alford, Helliwell Hills, NVL (site 81-28) (photos by S.C. Wilson)

Haplorthels. In depressions, Typic Haplorthels were associated with Typic Aquorthels (Table 7.1, Figs. 7.6 and 7.7).

7.3.3 Chemical and Physical Soil Properties

Soils in inland areas had a low EC, a slightly to moderately alkaline pH (mean = 7.9), and Na and HCO_3 were the dominant cation and anion, respectively (Table 7.2). From field estimates, the soils had abundant coarse fragments (67 +/1 21 %), and common texture classes of the fine-earth fraction were loamy sand and sandy loam. Soils on penguin mounds at Cape Hallett had a neutral pH (mean = 7.2), abundant SOC (mean = 12.9 % in upper 2–4 cm), extremely high levels of total N (mean = 11.8 in upper 2–4 cm), a C:N of 1.2, and abundant soluble salts (3.1 dS cm^{-1} (Hofstee et al. 2006).

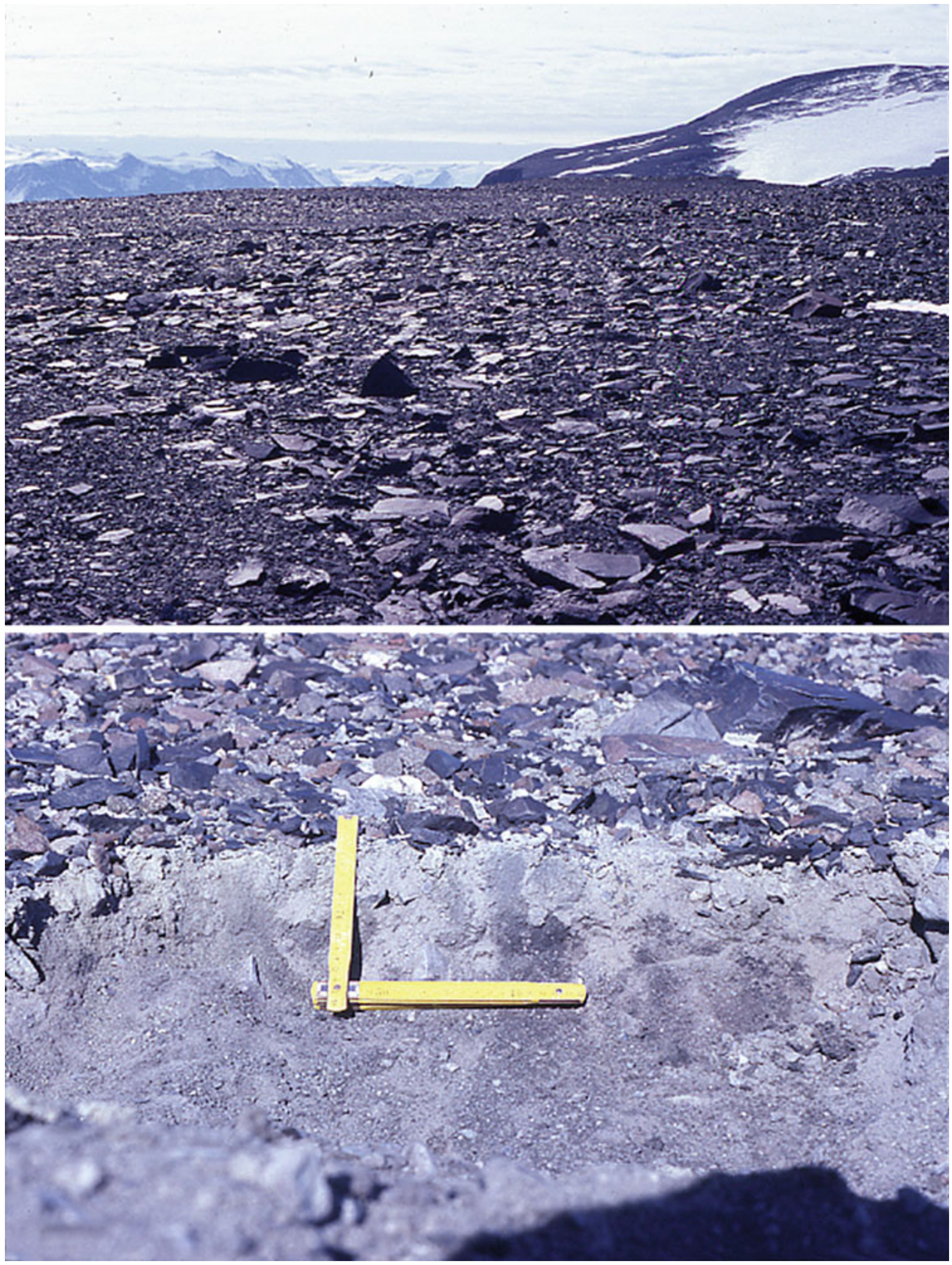


Fig. 7.5 Typic Anhyturbel landscape (*top*) and soil (*bottom*) in the Morozumi Range, NVL (site 81-19) (photos by S.C. Wilson)

7.4 Discussion

7.4.1 Soils and Landscape Evolution

Soils of inland areas of NVL are poorly developed because most of them are of late Wisconsin age. In contrast, soils in penguin rookeries along the coast are strongly developed and are comparable to those reported in the South Shetland Islands (Chap. 13).

7.4.2 Pedogenic Processes

Carbonation appeared to be the dominant soil-forming processes in NVL, as many of the soils were strongly or violently effervescent to 10 % HCl and HCO_3 was the dominant anion (Table 7.2). Salinization, rubification, desert pavement formation, and sublimation of interstitial ice were all weak processes in inland areas. Phosphatization was a dominant process in penguin rookeries along the coast.

Table 7.1 Soil weathering features in North Victoria Land (from Denton et al. 1986)

Pedon	Location	Elev. (m)	Thick. of solum (cm)	Depth coherence (cm)	Depth ghosts (cm)	Depth to ice cement (cm)	Salt stage[a]
Weathering stage 1							
81-23	Morozumi range	670	0	22	0	70	0
81-26	Helliwell hills	1170	0	0	0	35	0
81-27	Lichen hills	2396	0	0	0	8	0
81-29	Helliwell hills	844	0	0	0	30	0
81-31	Gallipoli hts.	1888	0	0	0	8	0
Average			0	4	0	30	0
Weathering stage 2							
81-19	Morozumi range	1100	0	10	0	10	1
81-20	Morozumi range	1080	0	8	0	8	0
81-21	Morozumi range	717	6	22	0	>100	1
81-22	Morozumi range	1060	0	49	0	22	0
81-24	Morozumi range	1000	11	50	0	>100	1
81-25	Helliwell hills	1186	0	24	0	50	1
Average			3		0	> 48	1
Weathering stage 3							
81-18	Mesa range	3034	23	23	6	23	2
Weathering stage 4							
81-28	Helliwell hills	1298	35	35	0	R	4
81-30	Mt. Vander hoeven	1652	35	35	0	35	4
Average			35	35	0	35	4

[a]Salt stage: 0, none visible; 1, salt encrustations beneath clasts; 2, few salt flecks (0.5–2 mm diameter); 3, abundant salts flecks; 4, weakly cemented salt pan

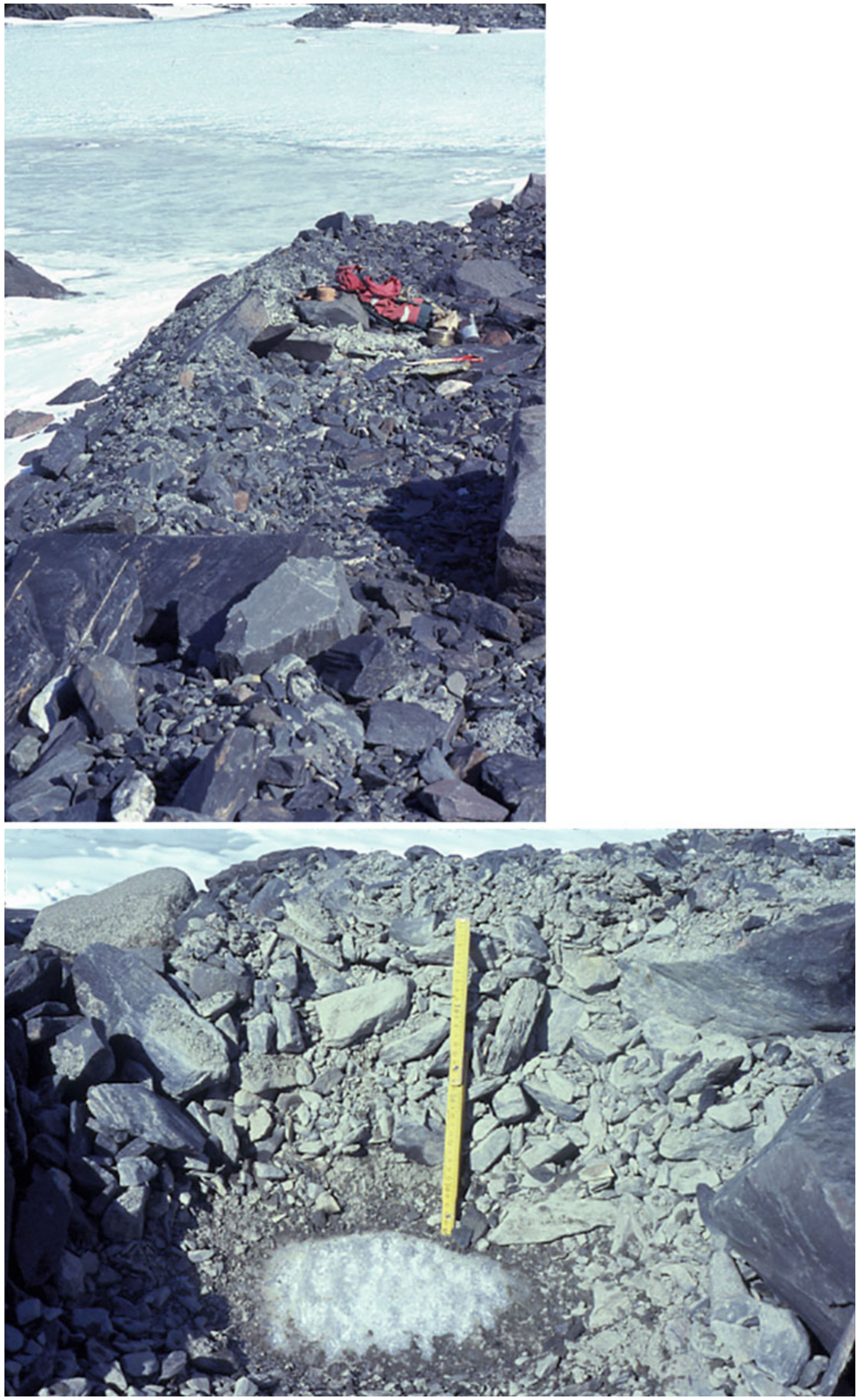
7.4.3 Pedodiversity

Soils in inland areas exhibited low pedodiversity compared to other regions of Antarctica, possibly of recent glaciation. Pedodiversity was greater along the coast. Hofstee et al. (2006) recorded three soil taxa and 11 soil-map units at Seabee Hook (∼9 ha).

7.4.4 Soil Taxa and the Occurrence of Organisms

Based on ecological factors listed in Table 7.3, the soils of inland NVL would be of moderate quality for biota such as microorganism, microarthropods, macroarthropods, and algae and cryptogams.

Fig. 7.6 Glacic Anhyorthel landscape (*top*) and soil (*below*) in Boggs Valley, Helliwell Hills (site 81-26) (photos by S.C. Wilson)



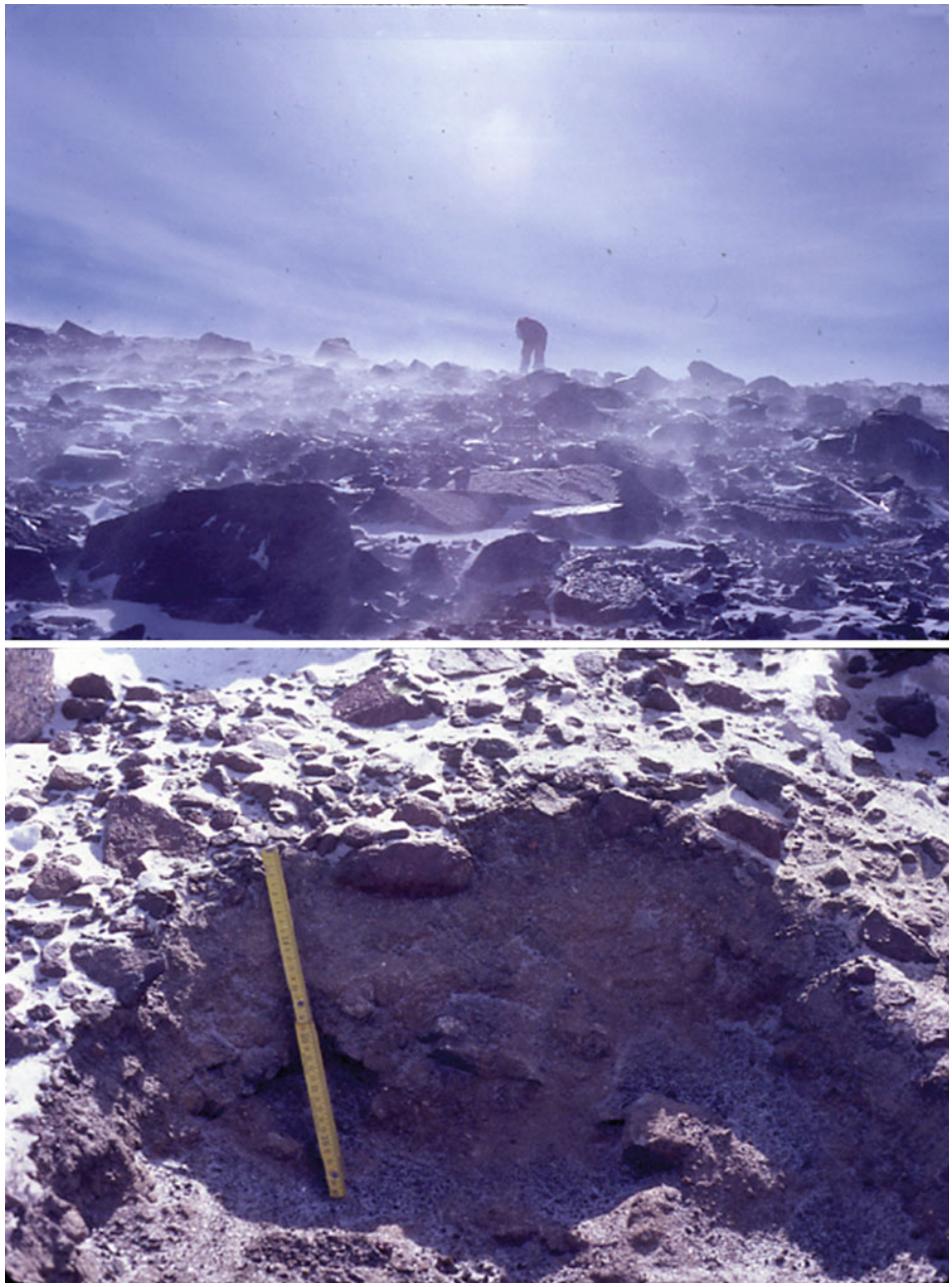


Fig. 7.7 Typic Anhyorthel landscape (*top*) and soil (*bottom*) on Mt. Vander Hoeven (site 81-30) (photos by S.C. Wilson)

Table 7.2 Chemistry of 1:5 soil:water extracts from soils in North Victoria Land (Denton et al. 1986)

Pedon no.	Drift	Weath. stage	Horizon	Depth (cm)	EC (dS/m)	mmol$_c$/L								
						pH	Na^+	Ca^{2+}	Mg^{2+}	K^+	Cl^-	$S0_4^{2-}$	$N0_3^-$	HCO_3^-
81-23	Rennick	1	C1n	0–22	0.1	7.7	0.1	0.3	0.0	0.1	0.07	0.08	0.01	0.3
81-26	Rennick	1	C1n	0–35	0.1	7.7	0.2	0.6	0.1	0.1	0.06	0.3	0.01	0.6
81-27	Rennick	1	C1n	0–8	0.1	6.7	0.2	0.1	0.1	0.0	0.02	0.32	0.01	0.1
81-29	Rennick	1	C1n	0–20	0.1	8.1	0.4	0.3	0.0	0.0	0.01	0.24	0.01	0.5
81-19	Evans	2	C1n	0–10	0.4	8.2	3.0	0.0	0.4	0.3	0.67	1.01	0.01	2.0
81-20	Evans	2	C1n	0–8	0.8	8.9	6.9	0.0	0.0	0.2	2.3	0.97	0.01	3.8
81-21	Evans	2	C1ox	0–6	0.2	7.8	0.4	1.0	0.3	0.2	0.06	1.21	0.01	0.6
81-22	Evans	2	C1n	0–22	0.5	8.3	3.2	0.3	0.3	0.2	1.9	0.82	0.66	0.6

Table 7.3 Ecologic factors favoring biota in Antarctica

Ecologic factor	Micro-organisms	Micro-arthropods[a]	Macro-arthropods[b]	Algae, Cryptogams	Vascular plants
Site factor					
N-S orientation	x			x	
High solar radiation	x			x	
Protected habitat	x				
Absence of wind	x				
Low elevation		x		x	
Proximity to lakes, streams		x			
High humidities	x				
Slow or impeded drainage	x			x	
Translucent coarse fragments	x				
Soil factor					
Lengthy duration of available water content	x	x		x	x
Lengthy duration of soil temperature > 0 °C	x			x	x
Non-saline soils (low EC)	x	x	x		x
Near-neutral pH	x	x	x		
Low inorganic N	x	x			
Abundant organic N	x		x		
Narrow C:N	x				
Abundant organic matter	x	x			

[a]Nematodes
[b]Tartigrades, rotifers, springtails (Collembola), mites (Acari)
Sources Cameron (1971), Powers et al. (1998), Courtright et al. (2001), Zeglin et al. (2009), Simmons et al. (2009), Ganzert et al. (2011), Lee et al. (2012)

7.5 Summary

NVL is that portion of the 3,500 km long TAM that extends from the Wilson Hills along the Pennell Coast at approximately 69° 30′ S to the Mawson Glacier at about 76° S. The total ice-free area of NVL is about 1,900 km^2. NVL is very mountainous, with elevations ranging from sea level to about 3,720 m. Vegetation is limited to isolated cryptogams. Most of the soils are of Late Glacial Maximum or younger age. Penguin rookeries occur along the Ross Sea coast at Cape Hallett and comprise a very small proportion of the ice-free area. Carbonation appeared to be the dominant soil-forming processes in NVL; salinization, rubification, desert pavement formation, and sublimation of interstitial ice were all weak processes in inland areas. The dominant soil taxa are from most to least abundant: LAo, TAt, GAt, and TAo.

Acknowledgments The Division of Polar Programs, National Science Foundation, supported this research. The officers and enlisted personnel of VXE-6 are thanked for helicopter and LC-130 support in northern Victoria Land. E. Stump and J.F. Splettstoesser, chief scientist and scientific coordinator, respectively, ensured the success of this study. S. W. Wilson and H.B. Conway conducted the field work.

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8 Soils of Central Victoria Land, the McMurdo Dry Valleys

James G. Bockheim and Malcolm McLeod

8.1 Introduction

Central Victoria Land is considered here to extend from the Mawson Glacier (76° S) to the Mulock Glacier (79° S), which constitutes the largest ice-free area (6,692 km^2) in Antarctica: the McMurdo Dry Valleys (MDV) (Fig. 8.1). The vegetation, surficial geology, climate, soils, and other resources of the McMurdo Dry Valleys have been studied intensively and summarized by Tedrow and Ugolini (1966) and Campbell and Claridge (1987). This chapter emphasizes soils and soil formation in the MDV since Campbell and Claridge's book, *Antarctic Soils, Weathering, and Environment* (1987).

Soils have played an integral role in elucidating the glacial history and paleoclimate of the MDV, particularly in identifying the spatial extent of drift sheets (Prentice et al. 1993; Hall et al. 1993; Bockheim and McLeod 2006). Studies of soil development rates have assisted in the establishment of glacial chronologies and prediction of ages on surfaces for which numerical ages are nonexistent (Bockheim 1990, 1979a). Soils have been useful in regional and long-distance correlation of drift sheets in areas where soil-forming factors are similar (Bockheim et al. 1989). Buried, relict, and exhumed soils have validated moraine-crosscutting relationships, overriding of cold-based glaciers, and the identification of "windows" of older drift in more recent drift units (Bockheim 1982). The progressive increase in salts in Antarctic soil chronosequences and persistence of salts in Pliocene-aged soils attest to the existence of cold desert conditions for the past ca. 3.9 Ma (Marchant et al. 1994; Bockheim 2013).

Over the past 44 years, the senior author has collected data from more than 900 soils in the MDVs, some of which are on the website: http://nsidc.org/data/ggd221.html. The objective of this chapter is to use these data to construct a provisional soil map of the MDV, to describe the soil map units in the context of the soil-forming factors and processes, and to illustrate the utility of soils in studying glacial-geomorphological processes.

8.2 Study Area

The MDV region, as considered here, ranges from 76°–79° S and 158°–170° E. The key place names mentioned here are shown on Fig. 8.1, and coordinates are given for sites not shown on the map. The largest ice-free areas are the Mount Discovery area (996 km^2), which includes Minna Bluff and the Brown Peninsula; the Denton Hills (753 km^2), which comprise the eastern foothills of the Royal Society Range; and the Convoy Range (661 km^2), which includes the Convoy Range, the Coombs Hills, the Allan Hills, and the St. Johns, Clare, and Willett Ranges. Additional key ice-free areas include the Victoria Valley system (653 km^2), which includes Barwick, Balham, McKelvey, and Victoria Valleys, and Bull Pass; Taylor Valley (630 km^2), which includes Marble Point and Gneiss Point; and Wright Valley (485 km^2), which includes the Asgard Range. Smaller ice-free areas include the Quartermain Mountains (397 km^2), the Ferrar Valley (348 km^2), and Ross Island (209 km^2).

The MDV can be subdivided into three climatic zones: a coastal thaw zone (subxerous), an inland mixed zone (xerous), and a stable upland zone (ultraxerous) (Campbell and Claridge 1987; Marchant and Head 2007). The coastal zone shows active solifluction terraces, gelifluction lobes, levees, streams, debris flows, and subxerous soils. The inland zone contains little evidence for modern downslope movement, and mass-wasting features are restricted to north-facing slope with high moisture content; the soils are xerous. The upland zone shows Miocene- and Pliocene-age sand wedges,

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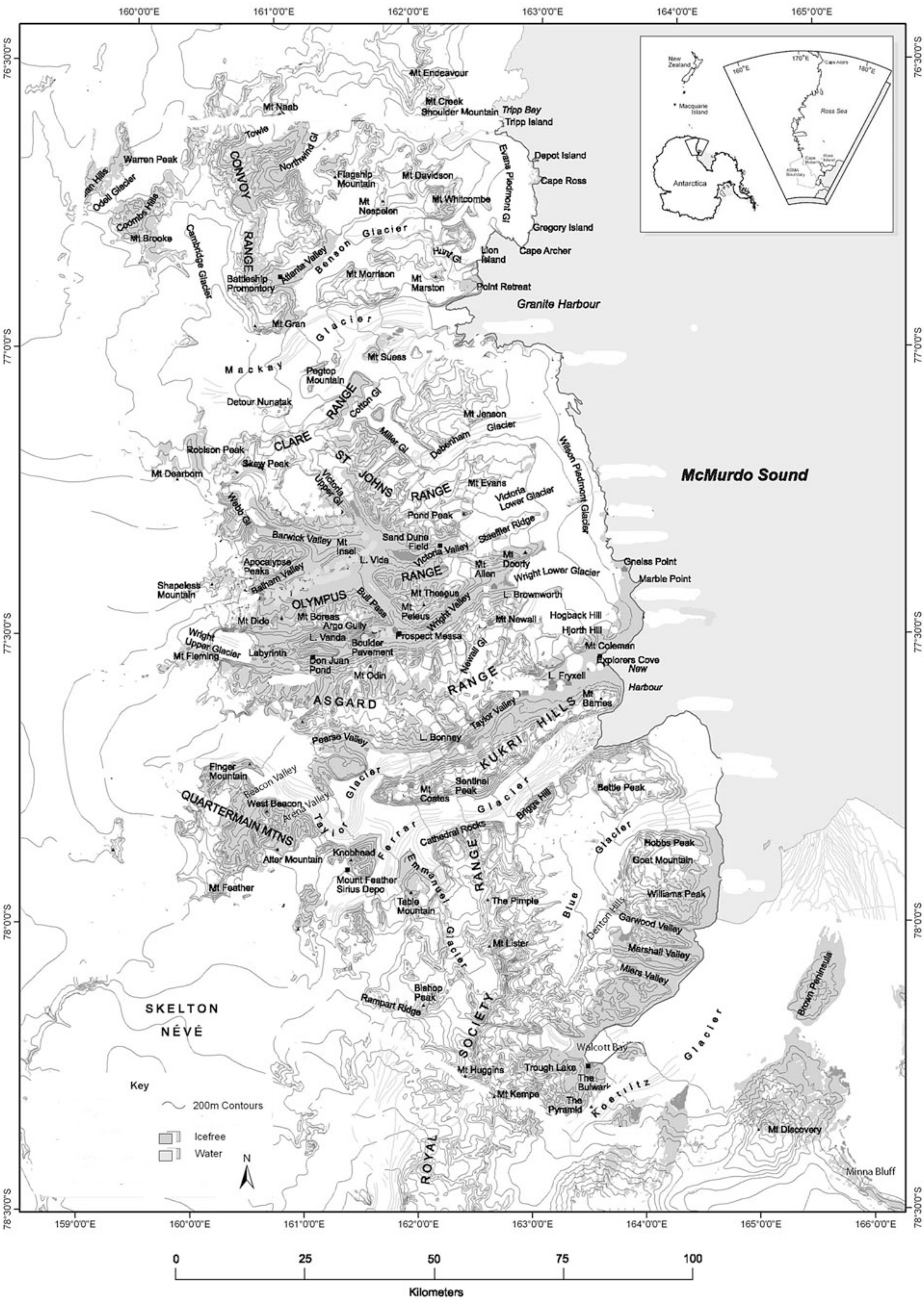


Fig. 8.1 The McMurdo Dry Valley region with place names (base map United States Geological Survey, 1:1 million topographic map of McMurdo Sound area)

avalanche cones, and strongly developed desert pavements; the soils are ultraxerous.

Mean annual air temperature in the MDVs ranges from −20 to −35 °C, and mean annual water-equivalent precipitation ranges from less than 10–100 mm $year^{-1}$ (Doran et al. 2002). Strong winds redistribute snow and exacerbate evaporation and sublimation losses of soil moisture.

Surficial sediments are primarily glacial till derived from granitic rocks in the eastern portion of the study area and dolerite and sandstone in the west. Volcanic rocks are dominant on Ross Island and in the Mt. Discovery area. There are three interacting glacial systems in the McMurdo Dry Valleys: (i) outlet glaciers such as the Fry, Mackay, Wright Upper, Taylor, and Ferrar glacier that extend eastward from the Taylor Dome on the Polar Plateau into the Ross Sea; (ii) piedmont glaciers along the Ross Sea that advance into the MDV when ice in the Ross Embayment became grounded during Northern Hemisphere glaciations; and (iii) Alpine glaciers that retreated during Ross Sea glaciations and advanced concurrently with outlet glaciers during Northern Hemisphere interglacial (Denton et al. 1991).

Patterned ground is common in the MDV, including ice-wedge polygons in the subxerous and xerous zones and sand-wedge polygons in the xerous and ultraxerous zones. Active-layer depths range from 5 cm at Mt. Fleming (77° 33′ S, 160° 06′ E) along the Polar Plateau to 80 cm at Granite Harbour along McMurdo Sound (75° 06′ S, 163° 41′ E) (Campbell and Claridge 2006; Bockheim et al. 2007; Adlam et al. 2010).

Soils of the region occur nearly entirely in the Gelisol order (Bockheim 2002; Bockheim and McLeod 2006). Soils with ice-cemented permafrost within 70 cm of the surface generally are cryoturbated and classified in the Turbel

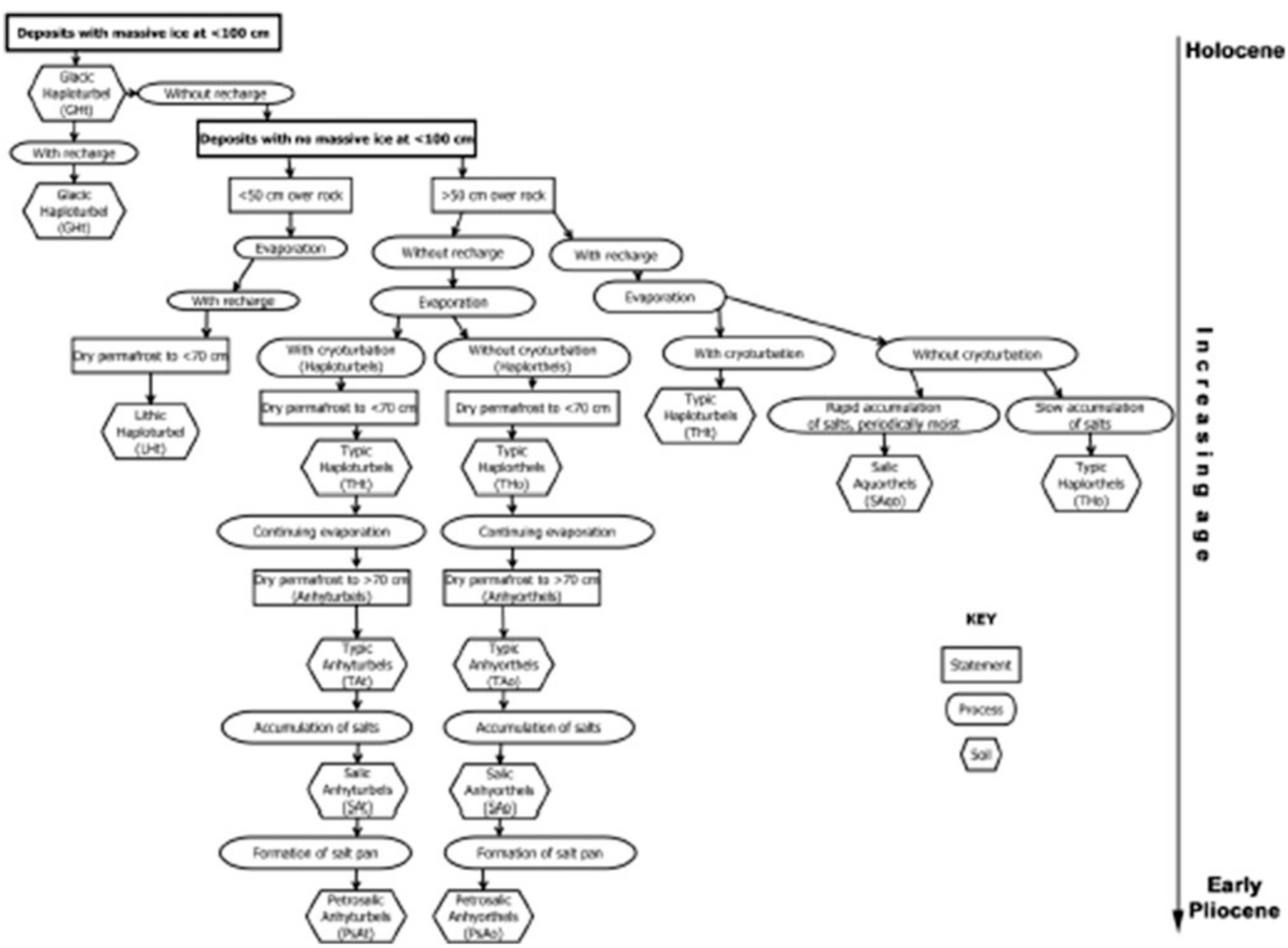


Fig. 8.2 Gelisol flowchart as applied to soils of central Victoria Land (Bockheim and McLeod 2008; modified by McLeod 2012)

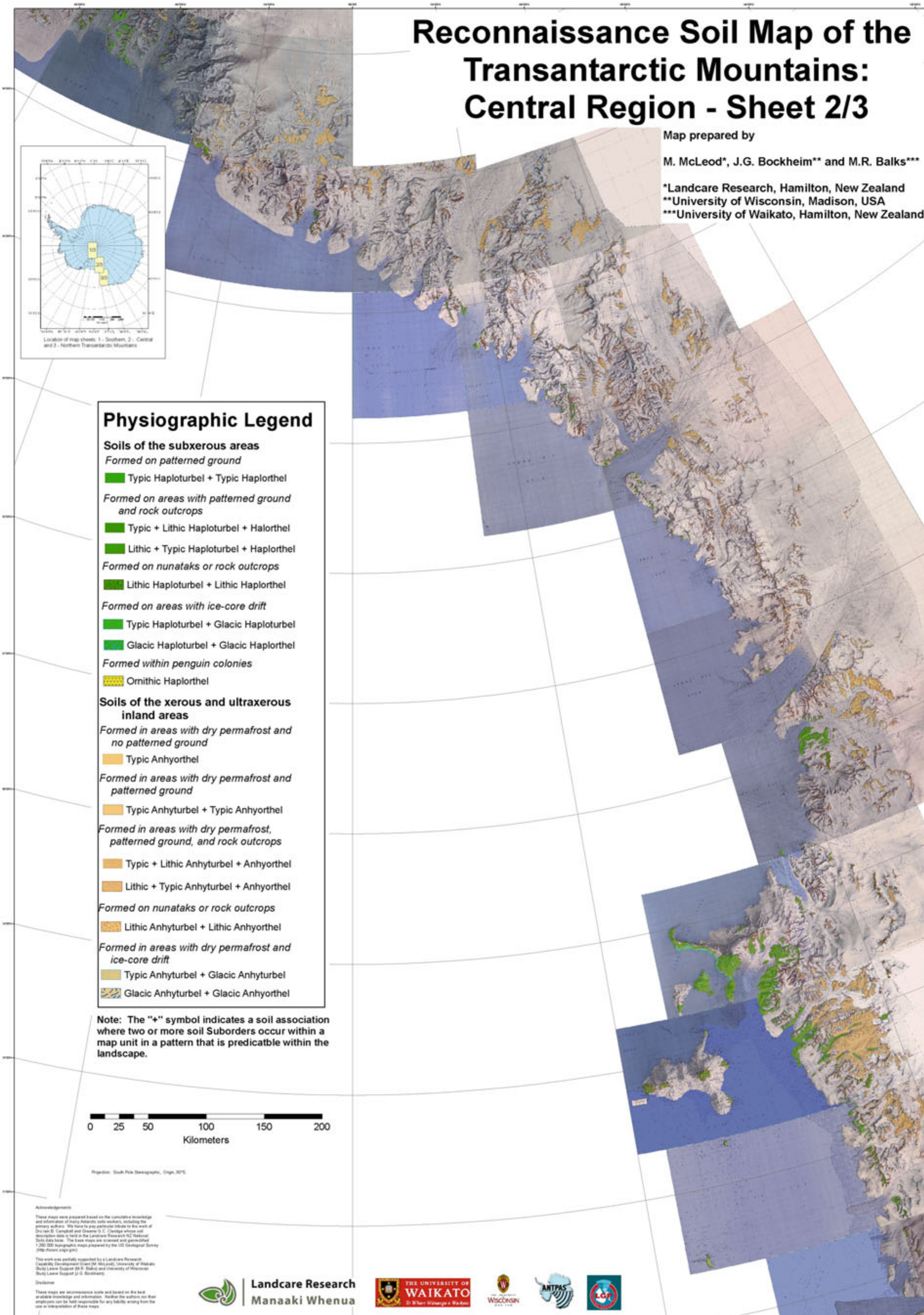


Fig. 8.3 Reconnaissance (1:10 million) soil map of the Transantarctic Mountains, Central Region (McLeod et al. 2008a)

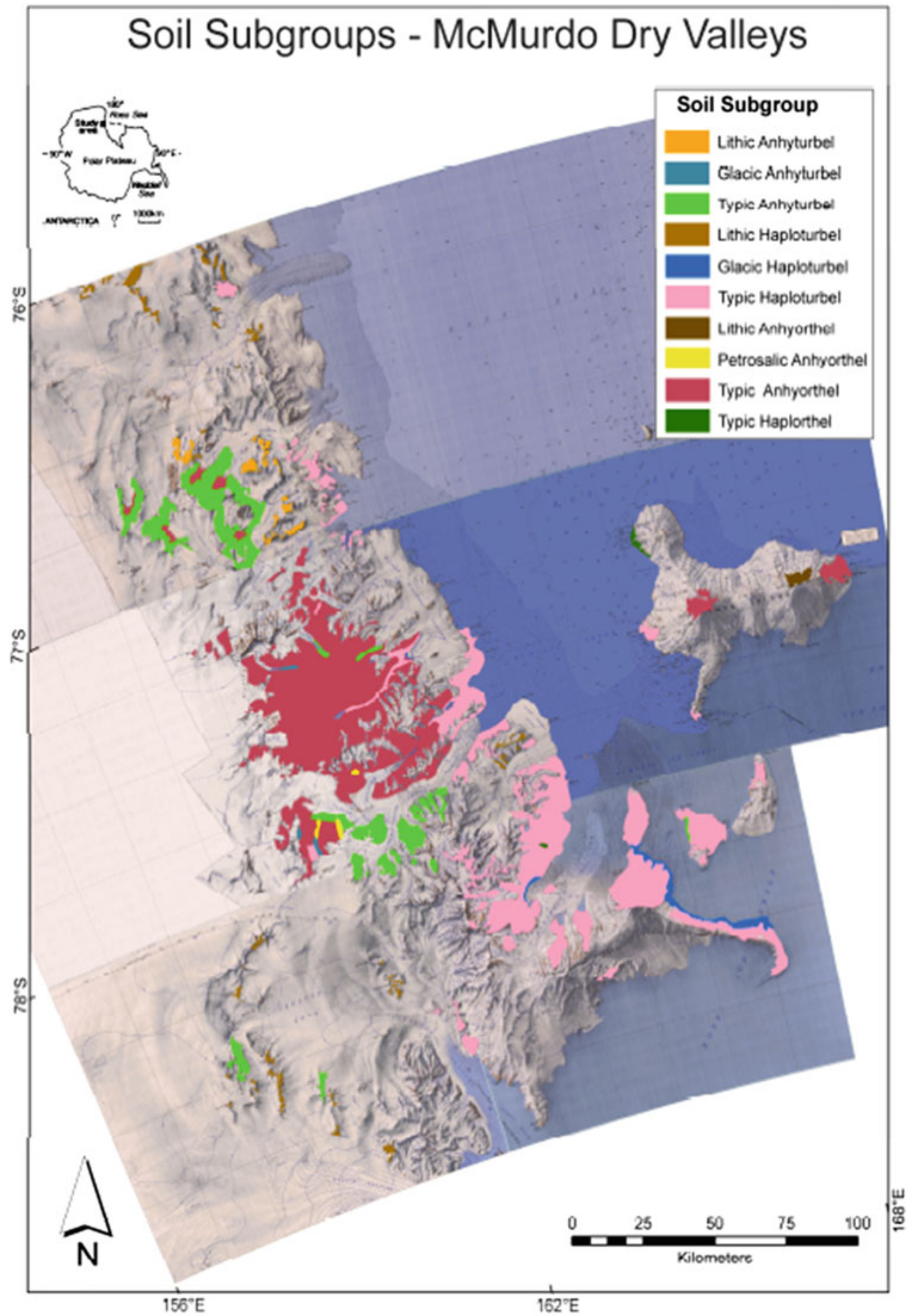


Fig. 8.4 Soil map of the McMurdo Dry Valleys (Bockheim and McLeod 2008)

suborder; soils with dry-frozen permafrost and minimal cryoturbation are classified as Orthels (Fig. 8.2). Soils in the subxerous region are in Haplo-great groups, and soils in the xerous and ultraxerous regions are in Anhy-great groups because of the anhydrous soil moisture regime. Soils of the MDV are further differentiated at the subgroup level based on the amount and type of salts and other diagnostic features.

8.3 Methods

Approximately 900 soil pits were excavated on key geomorphic surfaces to a depth of at least 100 cm, unless bedrock, ice-cement, or large boulders prevented digging to that depth. Soil horizons were distinguished using standard soil horizon nomenclature (Soil Survey Staff 2010). The identification of cryoturbation (Bockheim and Tarnocai 1998)

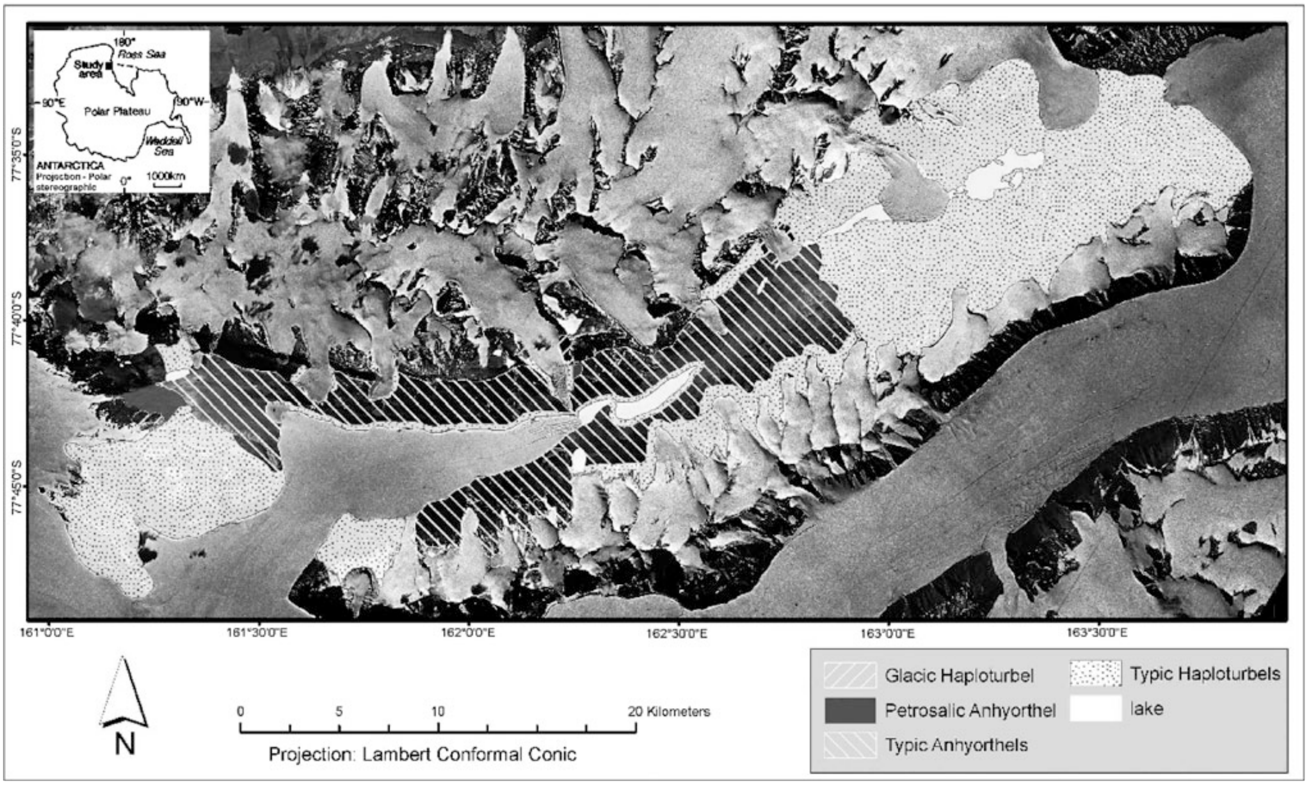


Fig. 8.5 Soil map of Taylor Valley, Antarctica (Bockheim et al. 2008a)

and salt stage (Bockheim 1990) were critical for taxonomic purposes.

Samples were collected from each horizon and taken to the USA or after 2004 to New Zealand for characterization. Morphological and analytical data were put into spreadsheets and forwarded to the USA National Snow and Ice Data Center (NSIDC) for archiving (http://nsidc.org/data/ggd221.html). The analytical data file contains chemical and physical properties for 46 % of the soils. Soils were classified according to *Soil Taxonomy* (Soil Survey Staff 2010).

Soil maps were prepared at three scales: (i) 1:10 million of the central TAM; (ii) 1:2 million of the MDV; and (iii) 1:50,000–1:250,000 of specific areas within the MDV including the Convoy Range (Bockheim and McLeod, unpublished), the Victoria Valley system (Bockheim and McLeod, unpublished), the Denton Hills (Bockheim and McLeod, unpublished), Taylor Valley (Bockheim et al. 2008a, b), Wright Valley (McLeod et al. 2008a), and the Quartermain Mountains (Bockheim, unpublished). Data from the regional soil maps were generated from digitized 1:50,000 and 1:250,000 USGS topographic maps stitched to form a mosaic in a geographic information system (GIS). The areal distribution of each soil taxon by region was determined through the use of a GIS (Bockheim and McLeod 2008).

To assist in classification of soils at the subgroup level, 1:5 soil:distilled water extracts were prepared and major cations (Na, Mg, Ca, and K) and anions (Cl, SO_4, and NO_3) were measured (Soil Survey Staff 2004). Cations were detected using flame photometry (Na, K) and atomic absorption spectrometry (Ca, Mg). Sulfate was measured turbidimetrically, Cl potentiometrically (chloridometer) and NO_3 from either cation–anion balance or on an autoanalyzer. The dominance of particular salts was confirmed by X-ray diffraction of salt patches and pans (Bockheim 1990).

8.4 Results

8.4.1 Soil Map of Central Victoria Land

The provisional 1:10 million map of soils in central Victoria Land extends from the Mawson Glacier (76° S) to the upper Amundsen Glacier area (86° 30′ S), so that it includes a large portion of the southern TAM (McLeod et al. 2008a). The map contains 14 soil associations within the following categories: soils of subxerous areas with patterned ground; soils of subxerous within penguin colonies; soils of xerous and ultraxerous inland areas with dry permafrost and no patterned ground; soils of xerous and ultraxerous areas with dry

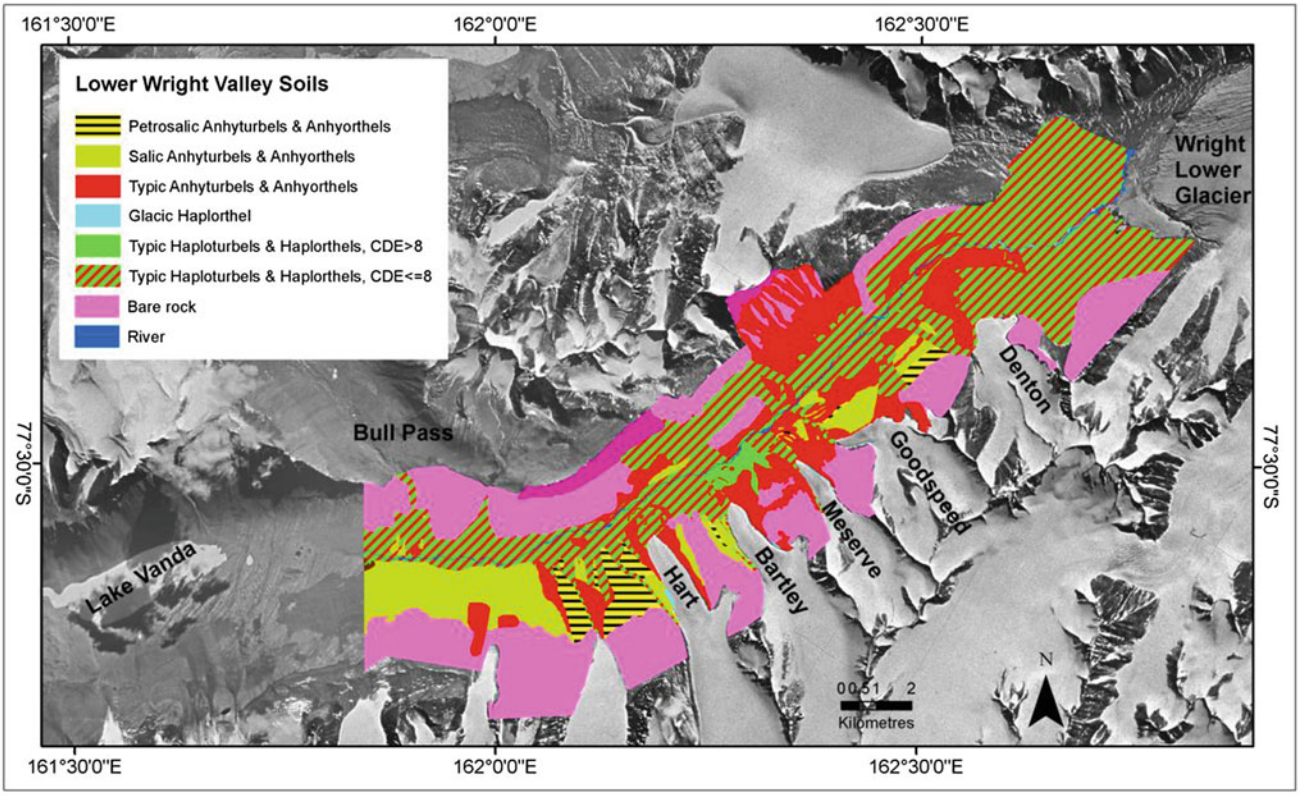


Fig. 8.6 Soil map of lower Wright Valley (McLeod 2012)

permafrost and patterned ground; soils of xerous and ultraxerous areas with dry permafrost, patterned ground and rock outcrops; soils of xerous and ultraxerous areas on nunataks and rock outcrops; and soils of xerous and ultraxerous areas with dry permafrost with an ice core (Fig. 8.3).

8.4.2 Soil Map of the McMurdo Dry Valleys

The 1:2 million map of soils in the MDV extends from the Drygalski Ice Tongue (75° 24′ S) to the Mulock Glacier (79° S) (Fig. 8.4). The map will be discussed by area, from the largest to the smallest, including Mount Discovery, the Denton Hills, the Convoy Range, the Victoria Valley system, Taylor Valley, Wright Valley, and the Quartermain Mountains.

8.4.2.1 Mount Discovery

Except at the higher elevations, soils in the Mount Discovery area are derived primarily from Ross Sea drift of late Quaternary age. The dark volcanic surfaces result in considerable melting and rejuvenation of ice-cemented permafrost. Typic Haploturbels (THt) are dominant (90 %) in the Mount Discovery area, followed by Glacic Haploturbels (GHt; 10 %) (Fig. 8.4, Table 8.1).

8.4.2.2 Denton Hills

Soils of valleys in the Eastern Foothills of the Royal Society Range are primarily THt (95 % of area) developed on Ross Sea drift (Fig. 8.4; Table 8.1). Ground ice is present throughout the region, particularly near Walcott Bay and the Koettlitz Glacier, and is accompanied by GHt. A small patch ($\sim$11 km^2) of pre-Ross Sea drift in upper Miers Valley contains dry-frozen permafrost with soils classified as Typic Haplorthels (THo).

8.4.2.3 Convoy Range

THo is the dominant soil in the Convoy Range (Fig. 8.4; Table 8.1). Debris-covered ice at several locations (<1 %) in the Convoy Range supports GHo. A small valley in the Coombs Hills (76.77982° S, 159.92305° E) contains Petrosalic Anhyorthels (PsAo). Lithic Haploturbels (LHt) occupy ice-free areas on nunataks in the region.

8.4.2.4 Victoria Valley System

According to recent glacial geological maps of the Victoria Valley system (Bockheim and McLeod 2013), GHo and GHt

Table 8.1 Distribution of soil subgroups in the McMurdo Dry Valleys

Location	Total	No. of soil pits	Area (km^2)									
			GAt	GHt	LAo	LAt	LHt	Ps/ PnAo	TAt	TAo	THo	THt
Mt. Discovery-Black Is.	996	0	–	95	–	–	–	–	7	–	–	894
Convoy Range-Coombs Hills,-Allan Nunatak	661	0	–	–	–	29	5	–	555	72	–	0
Denton Hills	753	19	–	8		–	–	–	–	–	3	742
Victoria Valley system	653	0	7.3	–	–	–	–	–	23	623	–	–
Taylor Valley	630	152	0	–	–	–	–	4	–	418	–	208
Wright Valley	486	281	–	3.5	–	–	–	–	–	424	–	58
Quartermain Range	397	98	14.5	–	–	–	–	18.4	130	218	–	16
Ferrar Valley	348	0	–	–	–	–	–	–	168	76	–	104
Ross Island	209	0	–	–	32	–	–	–	–	130	15	32
Other	1559	0	0	0	0	73	197	0	62	893	0	334
Total	6692	550	21.8	107	32	102	202	22.4	945	2854	18	2388
	% of total	100	0.3	1.6	0.5	1.5	3.0	0.3	14.1	42.6	0.3	35.7

GAt Glacic Anhyturbels, *GHt* Glacic Haploturbels, *LAo* Lithic Anhyorthels, *LAt* Lithic Anhyturbels, *LHt* Lithic, Haploturbels, *Ps/PnAo* Petrosalic/ Petronitric Anhyorthels, *TAt* Typic Anhyturbels, *TAo* Typic Anhyorthels, *THo* Typic, Haplorthels, *THt* Typic Haploturbels

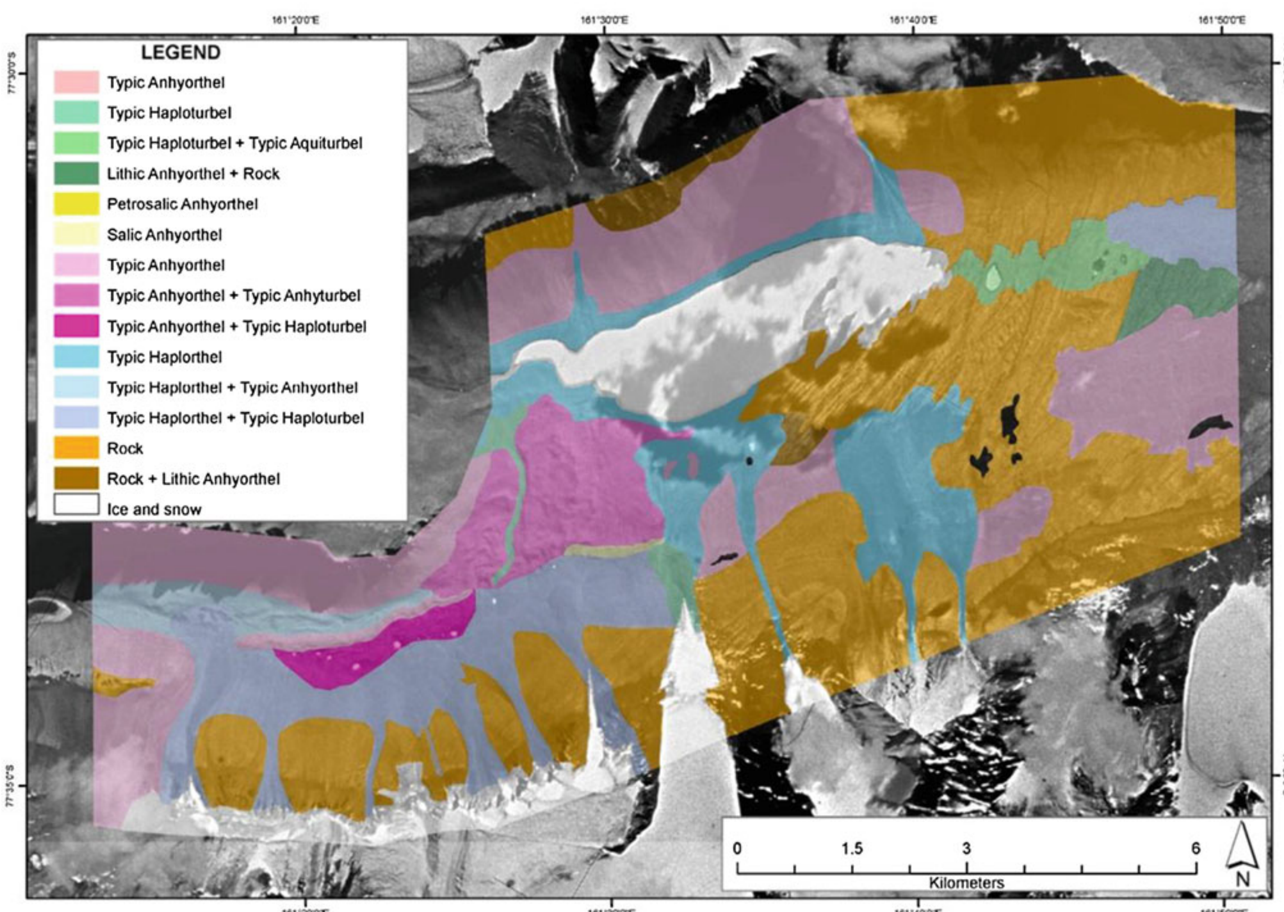


Fig. 8.7 Soil map of central and upper Wright Valley (McLeod et al. 2008c)

Fig. 8.8 Typic Anhyorthels landscape (*top*) and soil (*bottom*) from the Rhone Platform, Taylor Valley (site 75-06) (photos by J. Bockheim)

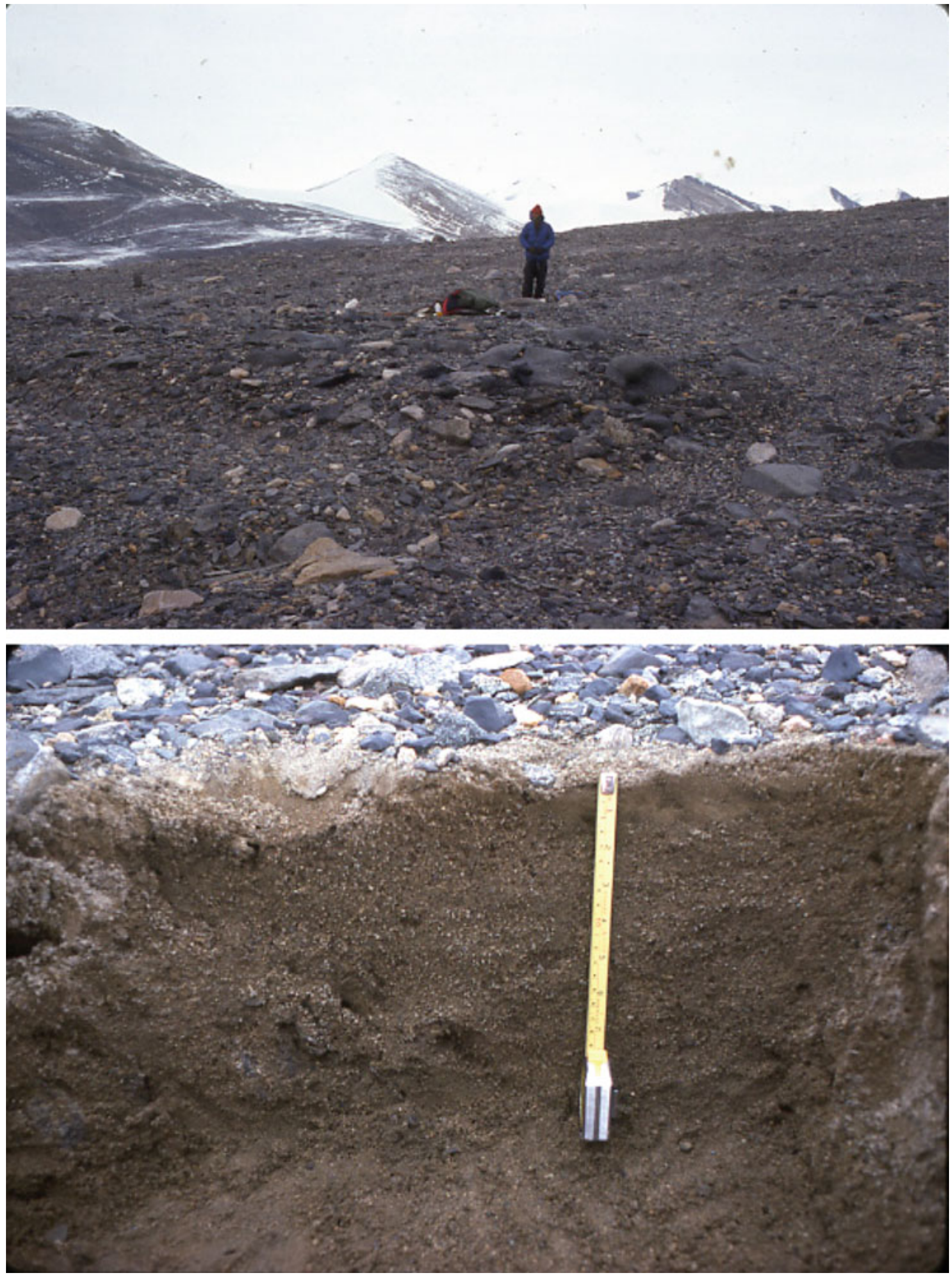


Fig. 8.9 Typic Haploturbels landscape (*top*) and soil (*bottom*) from Nussbaum Riegel, Taylor Valley (site 75-14) (photos by J. Bockheim)

(~1 % of total area) occur on ice-cored Holocene-aged drift at the margin of the Victoria Lower Glacier and near Webb Lake in Barwick Valley (Fig. 8.4; Table 8.1). THo (~39 %) are present on Packard and Vida drifts and their associated deposits of late to mid-Quaternary age adjacent to the Victoria Lower Glacier, Victoria Upper Glacier, and the Webb Glacier. Bull drift of mid- to early Quaternary age and the silt-enriched Insel drift of Pliocene age contain Typic Anhyorthels (TAo) interspersed with Salic Anhyorthels (SAo; ~60 % of total area).

8.4.2.5 Taylor Valley

According to a soil map of Taylor Valley (Bockheim et al. 2008a), GHt (0.7 % of area) occur on Alpine I drift of Holocene age. However, this small area of a soil-map unit cannot be shown on the 1:2 million-scale soil map. Soils in eastern Taylor Valley contain ice-cemented permafrost in the upper 70 cm of the solum and are strongly cryoturbated (THt) (35 % of area; Fig. 8.5; Table 8.1). The ice-cement results from melting of snow in the eastern part of the valley and the comparatively young geomorphic surfaces such as the late-Quaternary-aged Ross Sea, and Alpine II drifts. TAo (44 % of area) occur on Taylor III drift further up-valley in areas of dry-frozen permafrost. Soils on Taylor III in upper Taylor Valley often have relict patterned ground and presumably once contained ice-cemented permafrost.

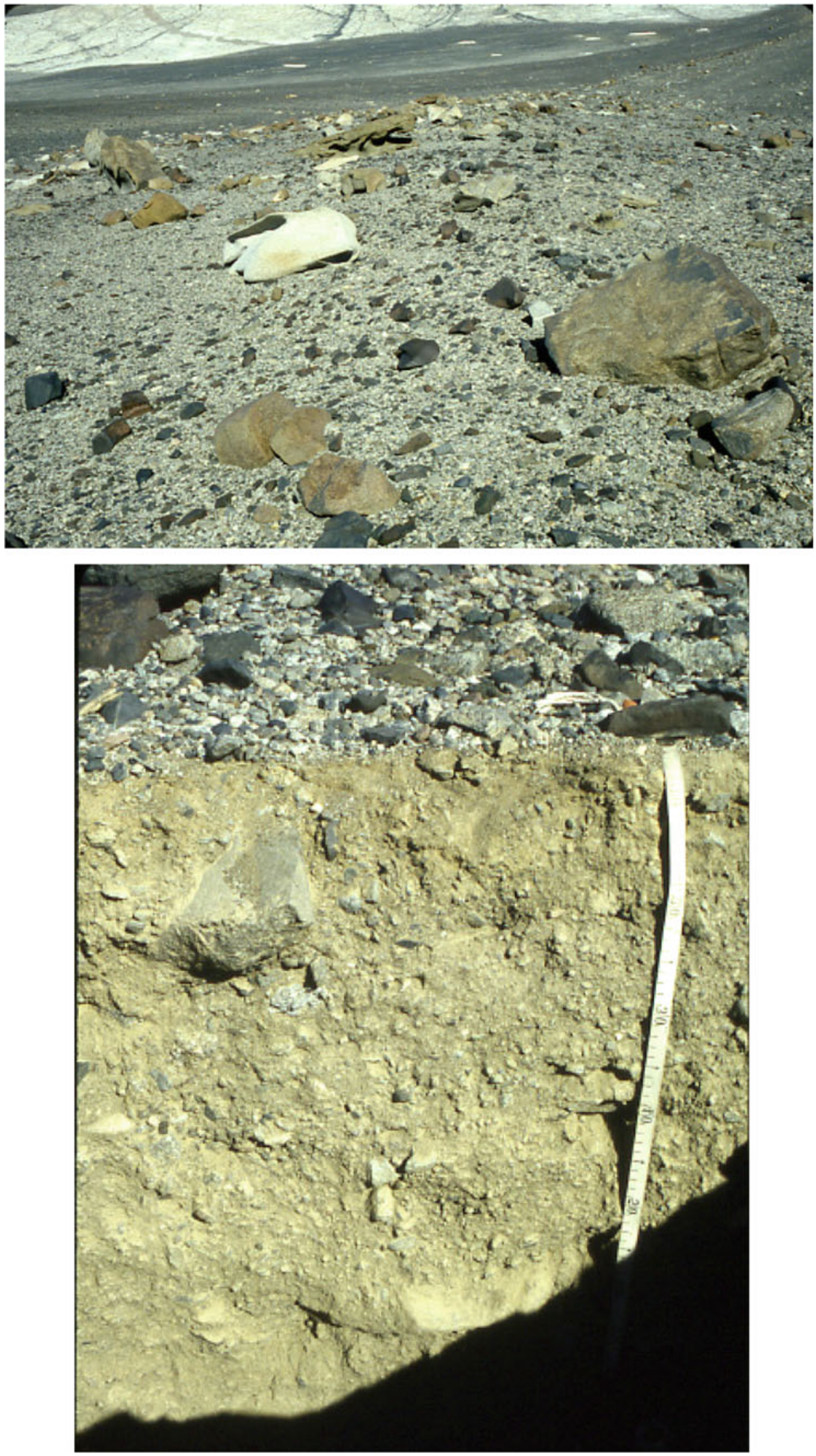


Fig. 8.10 Typic Anhyturbels landscape (*top*) and soil (*bottom*) from Conrow Glacier area, central Wright Valley (site 79-10) (photos by J. Bockheim)

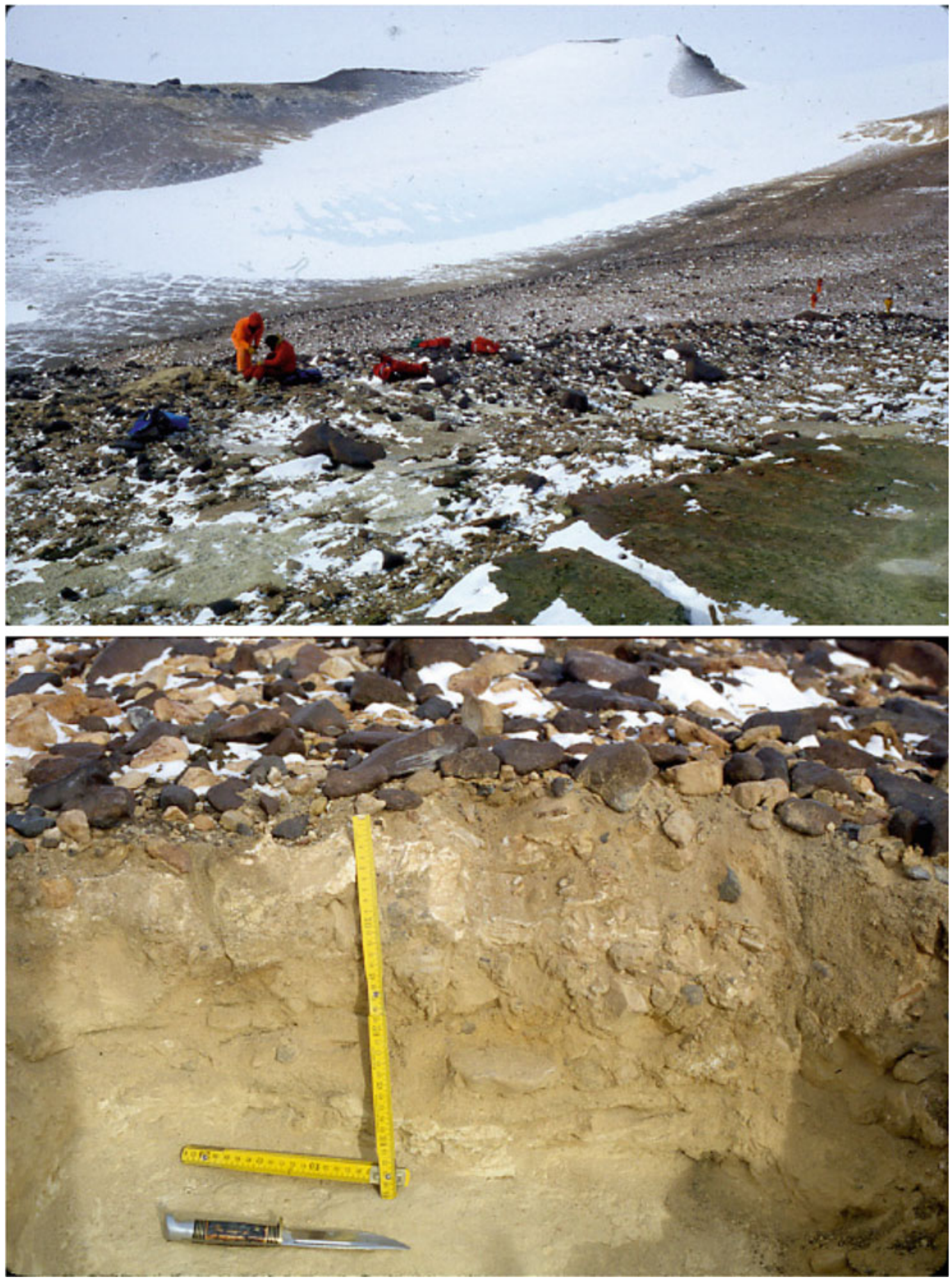


Fig. 8.11 Lithic Haploturbels landscape (*top*) and soil (*bottom*) from upper Arena Valley, Quartermain Range (site 80-09). The knife rests on sandstone bedrock (photos by J. Bockheim)

SAo (2.7 %) occur on Taylor IV drift of Pliocene age on Andrews Ridge (77° 38′ S, 162° 50′ E), above 1000 m along Alpine glaciers on the north valley wall, and in Pearse Valley. SAo also occur on Alpine III and IV drifts of Pliocene age near Alpine glaciers on the south valley wall. Soils with salt-cemented horizons (PsAo) are of limited extent (0.6 % of area) in Taylor Valley and are restricted to Taylor IV drift on the Rhone Platform (77° 42′ S, 162° 20′ E) and in Pearse Valley and on Alpine IV surfaces near the Sollas (77° 42′ S, 162° 35′ E) and Stocking (77° 43′ S, 161° 50′ E) Glaciers. Because of scale issues, the distribution of SAo and PsAo cannot be shown on the 1:2 million-scale soil map of the MDV.

8.4.2.6 Wright Valley

McLeod et al. (2008b) prepared a 1:50,000-scale soil map of Wright Valley. Soil maps are included here for lower Taylor Valley (Fig. 8.6) and central-upper Wright Valley (Fig. 8.7). GHt ($\sim$1 %) occur adjacent to Holocene-aged Alpine glaciers, including the Wright Lower Glacier and Alpine glaciers along the south valley wall (Fig. 8.6; Table 8.1). In addition, hummocky drift to the east of the Loop Moraine contains buried ice in places (Bockheim 1979b). THt comprise 12 % of the area and occur in the floodplain of the Onyx River, on deposits of late Quaternary age, including the Brownworth, Loke, and hummocky drifts (H1), and on Trilogy drift, which is considered by Hall and Denton (2005)

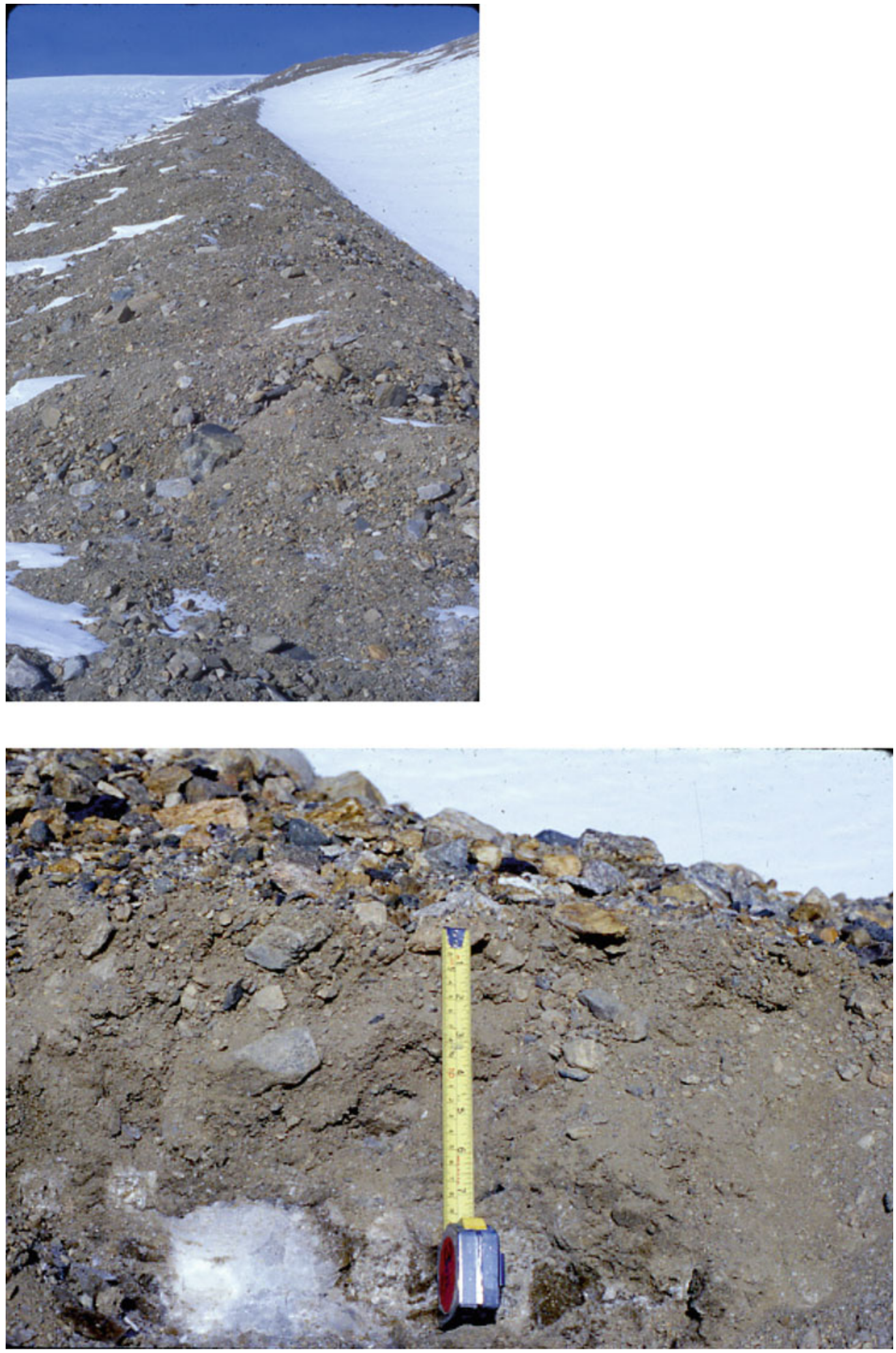


Fig. 8.12 Glacic Haploturbels landscape (*top*) and soil (*bottom*) on Alpine I moraine, Goodspeed Glacier, Wright Valley (site 77-36) (photos by J. Bockheim)

to be of mid- to early Quaternary age (Bockheim and McLeod 2006). TAo (80 %) occur on deposits of mid- to late-Quaternary age, including hummocky (H2) and Alpine II drifts. SAo (~3 %) occur on Onyx and Wright drifts of likely early Quaternary age; and PsAo (~4 %) exist on deposits of Pliocene age, including Valkyrie, Alpine III and IV, and Loop drifts (Fig. 8.7). Central Wright Valley may contain the largest occurrence of soils with saltpans in Antarctica. Soils on the oldest deposits, the silt-rich Peleus drift (>3.9 Ma), are anomalously poorly developed and are classified as SAo or TAo.

8.4.2.7 Quartermain Mountains

Small lateral valleys in upper Beacon Valley contain extensive (~4 %) ground ice and have GHt (Fig. 8.4; Table 8.1). THt (33 %) are present on Taylor II drift adjacent

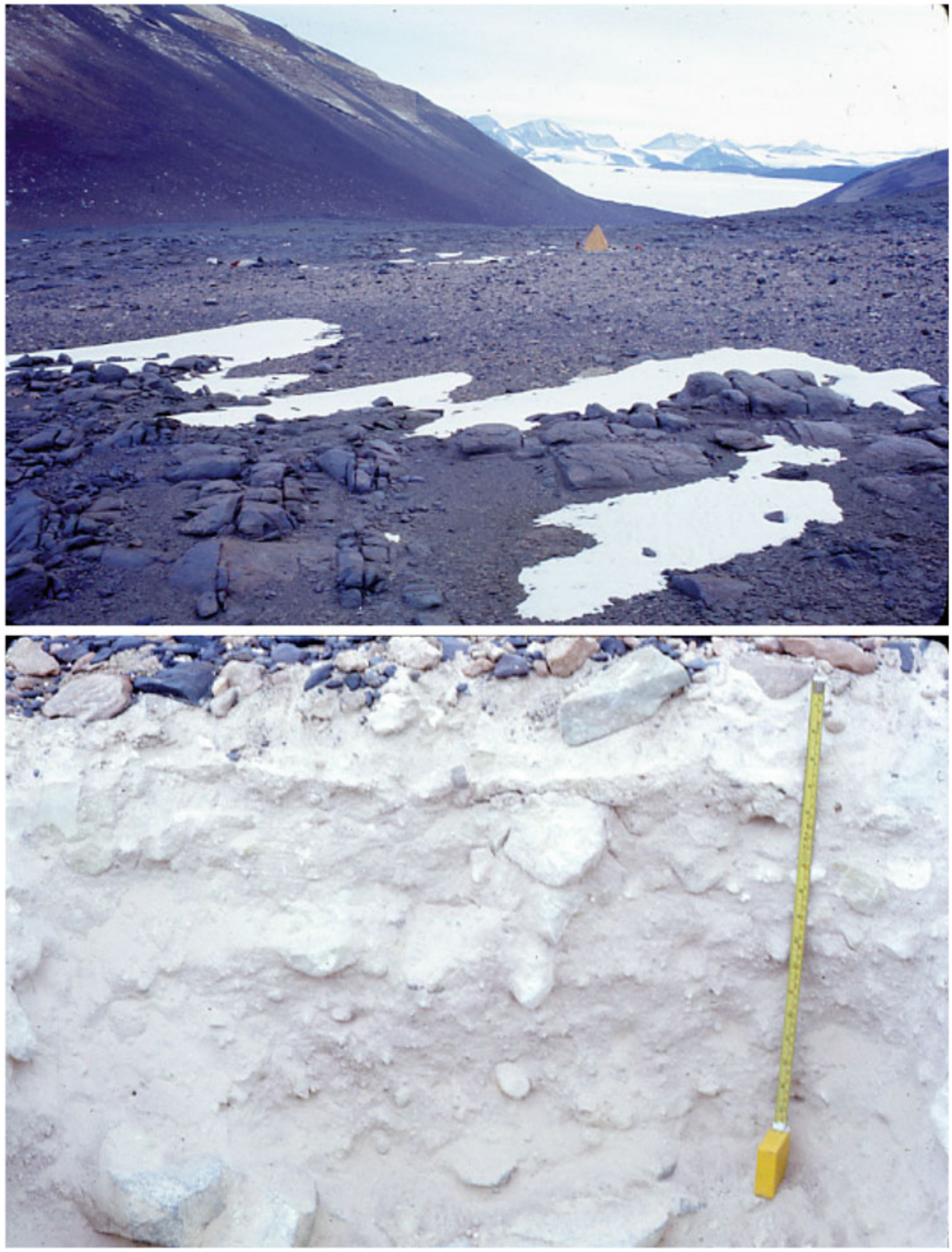


Fig. 8.13 Lithic Anhyorthels landscape (*top*) and soil (*bottom*) in upper Arena Valley, Quatermain Range (site 76-43). The base of the retrac tape is resting on sandstone bedrock (photos by J. Bockheim)

to the Taylor Glacier in both valleys and on rock glacier deposits from the Ferrar Névé in Beacon Valley. Soils on Taylor III and IV drifts in both valleys are predominantly TAo (70 %), but Gypsic Anhyorthels (GyAo) and Petronitric Anhyorthels (PnAo; 5 %) may occur locally, possibly as relict soils of older glacial deposits.

Arena Valley is unique in Antarctica in that despite being a small valley, it contains drifts ranging from 113 to 117 ka (Taylor II, Bonney drift) to >11.3 Ma (Altar till) (Marchant et al. 1993a). Soil mapping is complicated by the fact that some advances of the Taylor Glacier left only boulder belts and relict soils are common in inter-moraine areas (Bockheim 1982). The oldest drifts in the area, comprised of silt-enriched Quartermain, Brawhm, Arena, and Altar tills of Miocene age (Marchant et al. 1993a), are classified predominantly as Typic Anhyorthels.

8.4.3 Soil Map Units in McMurdo Dry Valleys

8.4.3.1 Typic Anhyorthels

TAo (40 %) are the dominant soil in the MDV, occupying xerous and ultraxerous regions in areas where dry-frozen permafrost is pervasive. TAo occur on geomorphic surfaces of mid-Quaternary age and also may exist on highly erosive

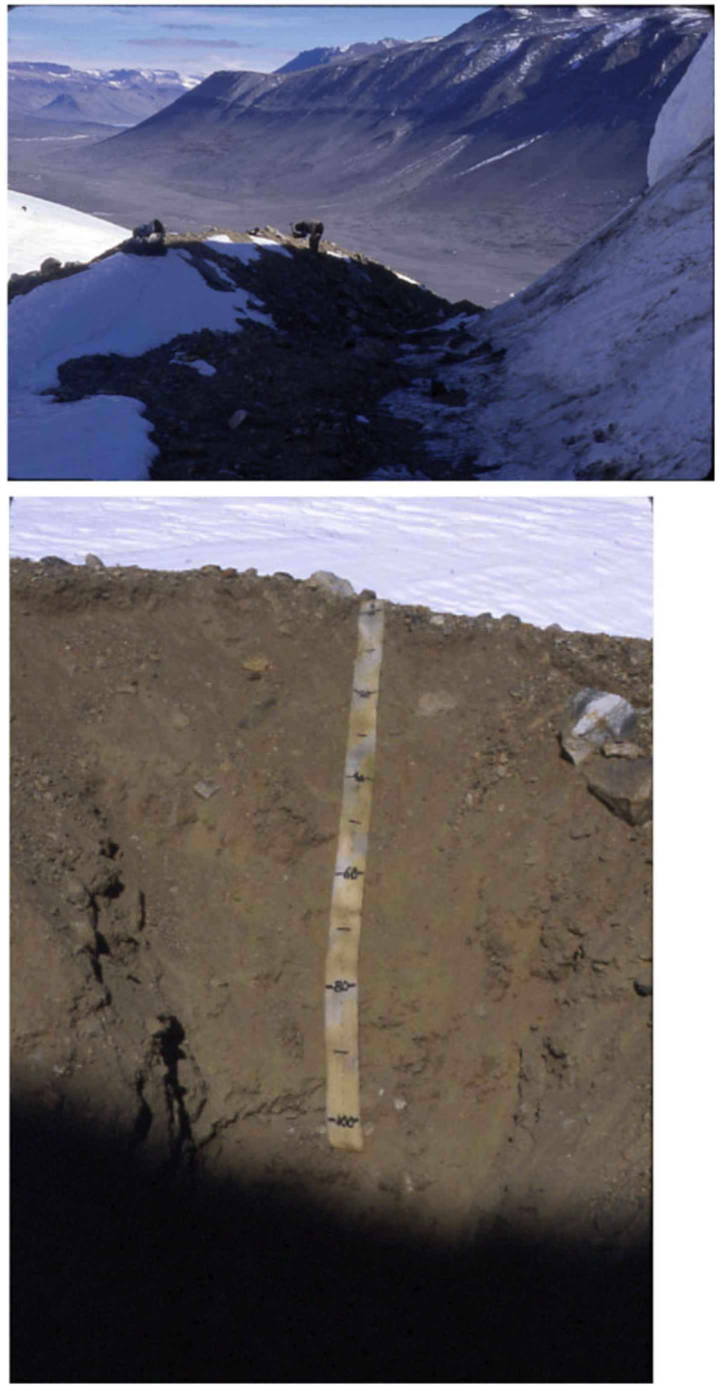


Fig. 8.14 Glacic Anhyturbels landscape (*top*) and soil (*bottom*) along the Goodspeed Glacier, Wright Valley (site 89-09). The glacic layer (buried ice) occurs below the tape (photos by S.C. Wilson)

silt-enriched soils of Pliocene and Miocene age. Pedon 75-06 (Fig. 8.8) is a deeply oxidized (54 cm) soil with stage 3 salts on Taylor IVa drift (1.6–2.5 Ma). The surface boulder frequency on early Quaternary drifts commonly is low.

8.4.3.2 Typic Haploturbels

THt (38 %) occupy soils in the subxerous zone containing ice-cemented permafrost within the upper 70 cm along the McMurdo Sound coast on surfaces primarily of late Quaternary age. Figure 8.9 shows a THt on the Nussbaum Riegel in central Taylor Valley. The microrelief is influenced by high-centered, nonsorted polygons that render the soils poorly developed. Ice-cemented permafrost exists at a depth of 25 cm.

8.4.3.3 Typic Anhyturbels

TAt are present on 13 % of the exposed soil area of the MDVs and occur primarily in ultraxerous regions along the

Fig. 8.15 Petrosalic Anhyorthels landscape (*top*) and soil (*bottom*) in the Conrow Glacier area, central Wright Valley (site 83-41) (photos by S.C. Wilson)

Polar Plateau. Pedon 79-10 (Fig. 8.10) occurs in an area that formerly contained patterned ground near the Conrow Glacier in central Wright Valley.

8.4.3.4 Other Soil Taxa

The remaining 7 % of the MDV ice-free area contains Lithic Haploturbels (LHt) in coastal areas where bedrock is within 50 cm of the surface, GHt in areas along the coast with ground ice, Lithic Anhyturbels (LAt), Lithic Anhyorthels (LAo), PsAo on old surfaces in the central Wright Valley and Arena Valley, and THo along floodplains of rivers and in penguin rookeries on Ross Island. Landforms and soils of these soil map units are contained in Figs. 8.11, 8.12, 8.13, 8.14, 8.15, 8.16, and 8.17.

8.4.4 Chemical and Physical Properties of Soils in the McMurdo Dry Valleys

Soils of the MDV contain very low SOC concentrations (0.035 ± 0.052 %; Beilke and Bockheim (2013)), are alkaline (pH 7.4 ± 1.0), sodic (exchangeable Na percentage = 79 ± 22), have abundant coarse fragments >2 mm (53 ± 19 %), contain dominantly sand in fine-earth (<2 mm) fraction (89 ± 7.4 %), and have low soil moisture contents (1.2 ± 1.5 %; Bockheim, unpublished) (Table 8.2). For this reason, soils of the MDV have been called Ahumic soils of the Cold Desert system (Tedrow and Ugolini 1966).

The dominant anion in 1:5 soil:water extracts depends on proximity to open water of McMurdo Sound (Fig. 8.18).

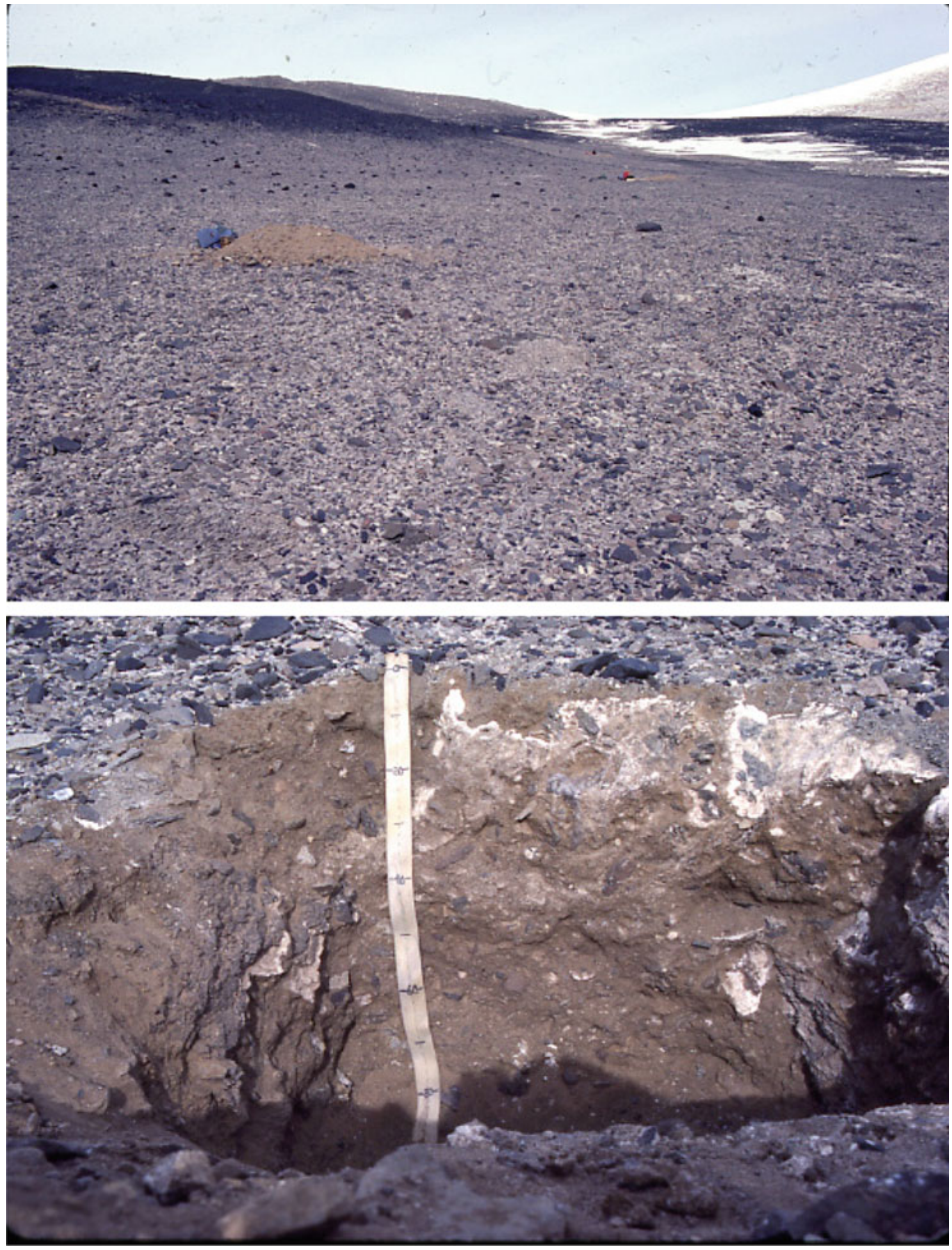


Fig. 8.16 Petronitric Anhyorthels landscape (*top*) and soil (*bottom*) adjacent to the Meserve Glacier, central Wright Valley (site 84-47) (photos by S. C. Wilson)

Chloride is dominant in soils of the lower parts of the MDV, sulfate occurs in an intermediate zone, and nitrate is pre-eminent in soils along the polar plateau.

8.5 Discussion

8.5.1 Soil-Forming Factors in the McMurdo Dry Valleys

Soils of the MDV can readily be distinguished on the basis of morphological properties, particularly the amount and distribution of soluble salts and the degree of chemical weathering. These changes are reflected in their position in *Soil Taxonomy* (Soil Survey Staff 1999), whereby GHt, THt, and TAt are found on the youngest (Holocene) surfaces, THo and TAo occur on surfaces of intermediate age (mid- to early-Quaternary), and SAo and PsAo exist on geomorphic surfaces of early Quaternary and older ages. PnAo may be limited to Taylor IV surfaces in Arena Valley (Fig. 8.19).

Soils on the oldest (Pliocene and Miocene-aged) surfaces derived from silt-rich drifts present an enigma to our model of soil evolution in the MDV. The silt-rich drifts include the Insel drift in Victoria Valley system (Calkin 1971), Peleus till in Wright Valley (Prentice et al. 1993), Asgard and Inland Forts tills in the Asgard Range (Marchant et al. 1993b), and

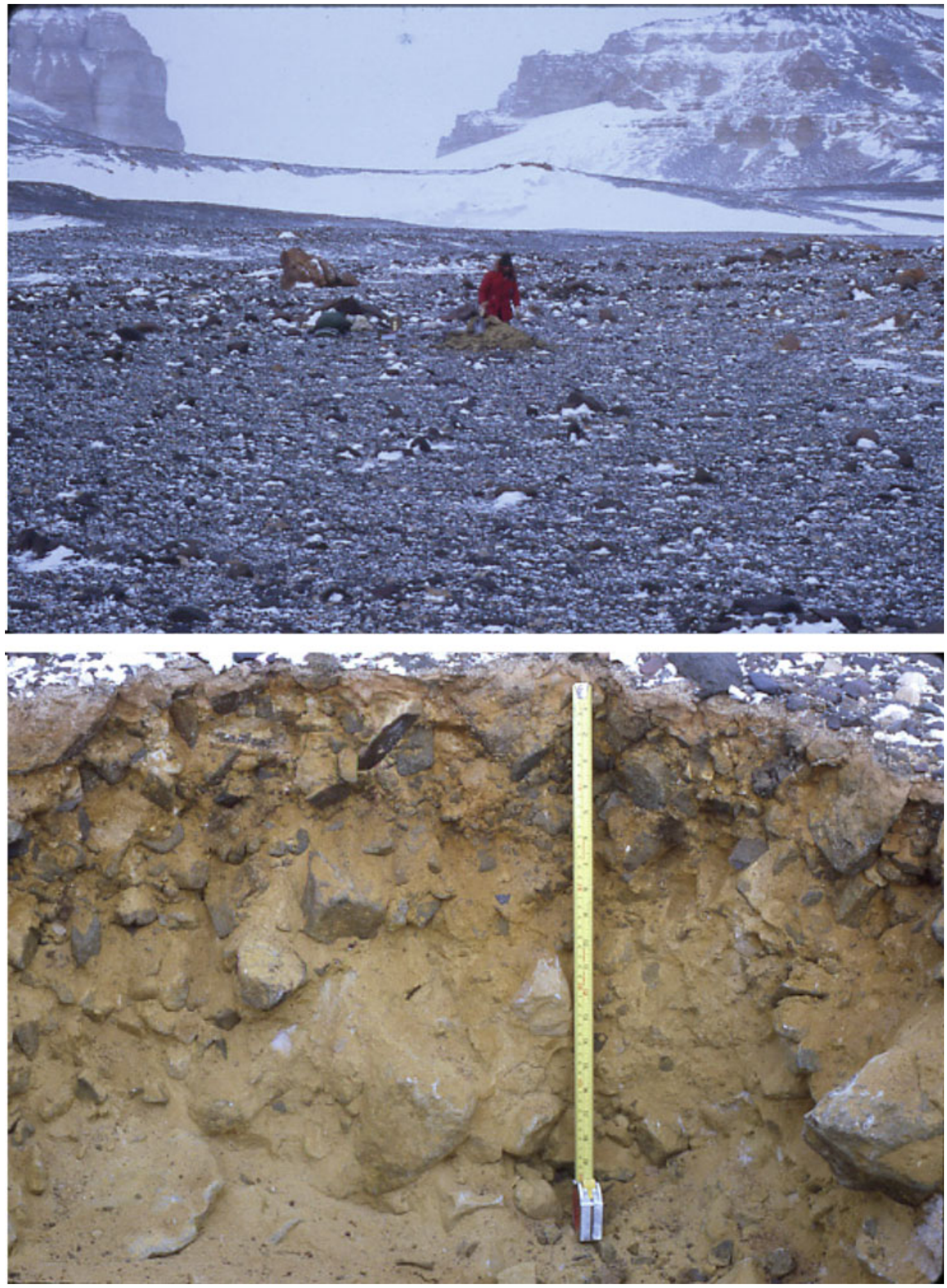


Fig. 8.17 Typic Haplorthels landscape (*top*) and soil (*bottom*) adjacent to the Conrow Glacier, central Wright Valley (site 79-09) (photos by J. Bockheim)

the Arena and Altar tills in the Quartermain Mountains (Marchant et al. 1993a). These drifts are derived from sediments of the Beacon Supergroup that contain primarily quartz and low amounts of weatherable minerals. Moreover, these soils may have been subject to considerable deflation by wind erosion since deposition. Therefore, traditional soil properties used to identify weathering stages are not applicable for these materials.

8.5.2 Soil-Forming Processes in the McMurdo Dry Valleys

In the MDV the dominant soil forming processes are salinization, desert pavement formation, and sublimation of ice-cement in permafrost, yielding dry-frozen materials (Bockheim 1990). Salinization refers to the progressive accumulation of soluble salts in the profile (Campbell and Claridge

Table 8.2 Chemical and physical properties of selected soil taxon from the McMurdo Dry Valleys

Horizon	Depth (cm)	EC (dS/m)	pH	Na^+	Ca^{2+}	Mg^{2+}	K^+ (mmol$_c$/L)	Cl^- (mmol$_c$/L)	SO_4^{2-}	NO_3^-	Ex. Na (%)	Fe_d (%)	>2 mm (%)	Sand (%)	Silt (%)	Clay (%)
			75-06 Typic Anhyorthels													
Bw1	1–12	4.7	6.6	508.9	0.94	0.93	0.11	4.34	488	18.6	99.6	0.18	55	90	2.7	7.3
Bw2	12–18	1.56	6.6	163.1	0.49	0.43	0.05	1.37	156	6.7	99.4	0.16	45	96.9	2.3	0.8
Bw3	18–54	1.2	5.3	124	0.42	0.3	0.06	1.04	117.8	5.9	99.4	0.17	85	94.4	3.3	2.3
Cn	54–115	0.33	6.4	32.6	0.26	0.17	0.01	0.24	32.2	0.6	98.6	0.14	25	96.3	2.3	1.4
			75-14 Typic Haploturbels												–	–
D	0–1	0.84	8.3	6	0.94	0.35	–	5.5	2.1	0	82.3	–	nd	–	–	–
Cn1	1–5	0.88	9.2	7	0.11	0.19	–	5.1	1.7	0.5	95.9	–	nd	–	–	–
Cn2	5–25	0.2	7.5	1.5	0.02	0.05	–	1.2	0.1	0.2	95.3	–	nd	–	–	–
Cf	25+	0.135	6.9	0.9	0.13	0.11	–	0.6	0.3	0.2	79.2	–	nd	–	–	–
			76-43 Lithic Anhyorthels													
D	0–1	1.05	5.9	25.7	8.5	4.9	0.8	0.8	11.7	27.277	64.4	–	nd	93	4	3
Bw	1–7	5	7.4	116.4	47.2	40.3	2.4	4.7	79.4	122.08	56.4	–	nd	79	16	5
Bwz	7–15	26	7.8	967.9	13.5	130.8	5.8	8.9	78.1	1031	86.6	–	nd	72	17	11
Cn1	15–33	1.25	8.4	30.9	3.5	15.6	2.2	6.3	3.4	42.495	59.1	–	nd	81	16	3
Cn2	33–52	0.75	8.8	15.2	3.9	9.9	1	4.2	3.6	22.138	50.7	–	nd	85	13	2
			76-52 Typic Haplorthels													
D	tr	2.3	8.4	58.7	7.2	16.6	3.1	65.2	9.2	11.377	68.5	–	80	92	5	3
Bw	0–12	4.75	8.5	147.9	5.5	44.4	7.2	154	22.9	28.107	72.1	–	55	85	10	5
Bwy	12–20	11	8.8	584	8.9	65.8	7.5	28.2	208.3	429.75	87.7	–	58	84	9	7
Cn1	20–47	1.45	8.7	39.1	3.5	11.5	4.3	26.1	1.4	30.926	67	–	33	86	12	2
Cn2	47+	0.8	8.7	21.3	3.1	5.8	2.3	1.5	1.6	29.463	65.5	–	nd	89	8	3

(continued)

Table 8.2 (continued)

Horizon	Depth (cm)	EC (dS/m)	pH	Na^+	Ca^{2+}	Mg^{2+}	K^+ ($mmol_c/L$)	Cl^- ($mmol_c/L$)	SO_4^{2-}	NO_3^-	Ex. Na (%)	Fe_d (%)	>2 mm (%)	Sand (%)	Silt (%)	Clay (%)
			77-36 Glacic Haploturbels													
Cn	0–8	0.62	8.2	2.8	2.3	1.3	0.2	4.4	0.8	0.49	42.4	0.124	nd	97.6	0.8	1.6
Cf	8–16	0.6	7.7	2.5	2.3	1.4	0.2	4.3	0.8	0.48	39.1	0.196	78	97.2	0.3	2.5
Wf	16+	0.069	7.4	0.2	0.5	0.1	0	0.2	0.9	0.006	25.9	–	0	–	–	–
			79-10 Typic Anhyturbels													
Bw	0.5–10	2.4	6.7	10	18	2.1	0.2	5.4	20	2.3	33	–	58	–	–	–
Cn1	10–64	5.2	6	42	7.9	5.8	0.4	36	8.5	9.5	74.9	–	75	–	–	–
Cn2	64–100	2.2	6.5	19	0.8	1.8	0.2	17	2.3	2.3	87.4	–	49	–	–	–
			83-41 Petrosalic Anhyorthels													
Cn	0–14	5.3	7.3	47.3	13	1.6	0.6	32.4	18.8	1.67	75.8	–	65	–	–	–
2Bwzb	14–28	80	7.8	1088.8	36.9	110.9	2.6	747.6	227.3	77.03	87.9	–	53	–	–	–
2Bwb	28–70	9.3	7.1	100.4	14.2	10.1	1	78.1	28.3	1.79	79.8	–	43	–	–	–
3Bwb	70–120	3.6	6.4	16.2	9.3	13.5	1.6	17	17.3	1.59	39.9	–	35	–	–	–
			84-47 Petronitric Anhyorthels													
Bw1	0–4	4.8	7	21.9	34.4	7.6	1.1	18.2	45.9	3.64	33.7	–	14	–	–	–
Bwz1	4–20	80	7.1	820.4	16.1	83.7	7.5	947.8	157.6	23.63	88.4	–	40	–	–	–
Bwz2	20–42	31	6.9	302.2	6.4	55	6.6	269.2	50.4	20.05	81.6	–	48	–	–	–
Bw2	42–85	4.4	6.7	30.3	2.3	7.4	2.7	30.6	7.7	4.75	71.1	–	78	–	–	–
	Mean	**9.2**	**7.4**	**167**	**8.5**	**20.3**	**2.2**	**79**	**56**	**61**	**72**	**0.16**	**53**	**88.7**	**7.6**	**3.7**
	Stdev	**19.8**	**0.99**	**295**	**11.5**	**33.8**	**2.5**	**210**	**101**	**193**	**22**	**0.026**	**19**	**7.4**	**5.8**	**2.7**

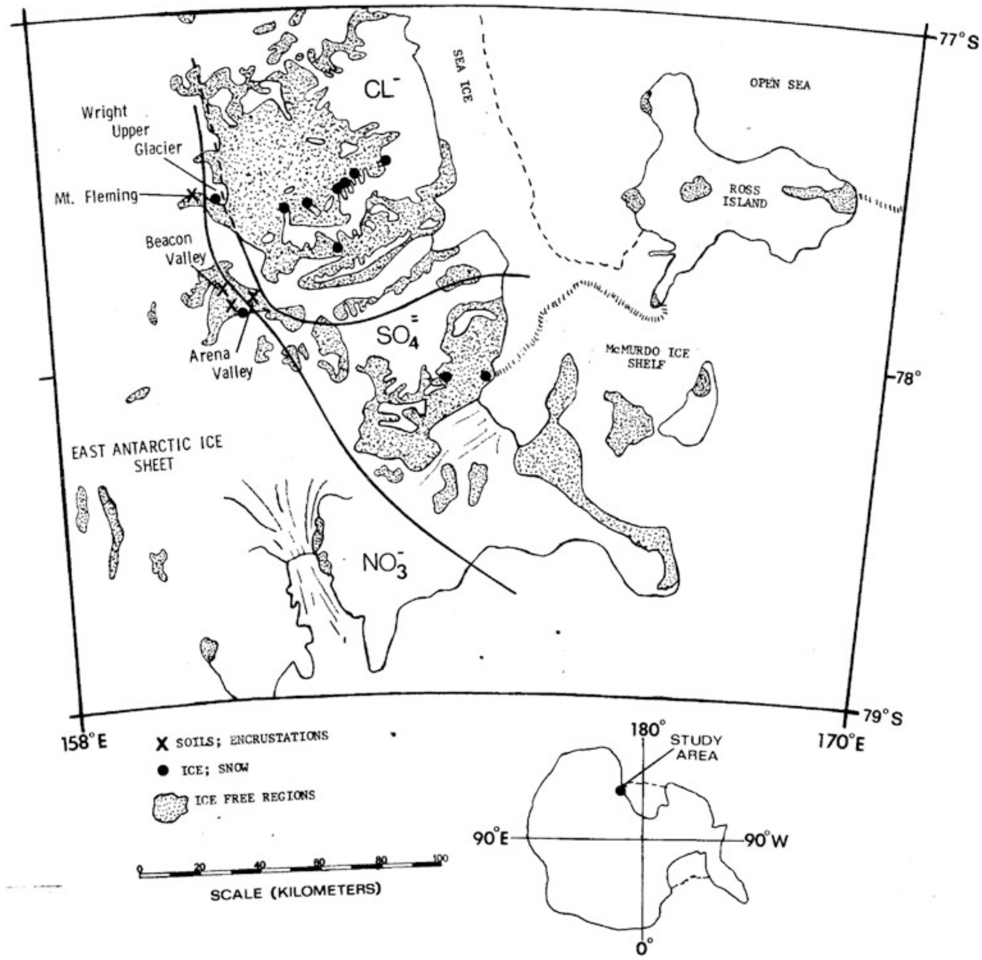


Fig. 8.18 Zonation of salts in the McMurdo Dry Valleys; dominant anion in 1:5 soil:water extracts in the McMurdo Dry Valleys (Bockheim 1997)

Fig. 8.19 Soil evolution in the McMurdo Sound region (Bockheim and McLeod 2006)

1975; Bockheim 1982, 1990; Bockheim and McLeod 2006). Desert pavement formation is reflected by the progressive weathering of clasts on the surface and development of a vesicular beneath the pavement (Bockheim 2010a). In the hyperarid climate of the MDV, since the Pliocene, ice-cement in permafrost has undergone sublimation, yielding dry-frozen materials (Bockheim 1990). Rubification becomes an important process in soils of middle Pleistocene age and older (Bockheim and McLeod 2006).

8.5.3 Utility of Soils in Reconstructing the Neogene History of Central Victoria Land

Soils have been useful in the MDV in numerical dating of drifts, correlation of drifts, understanding the behavior of cold-based glaciers, and testing hypotheses regarding the possible existence of former high-level lakes.

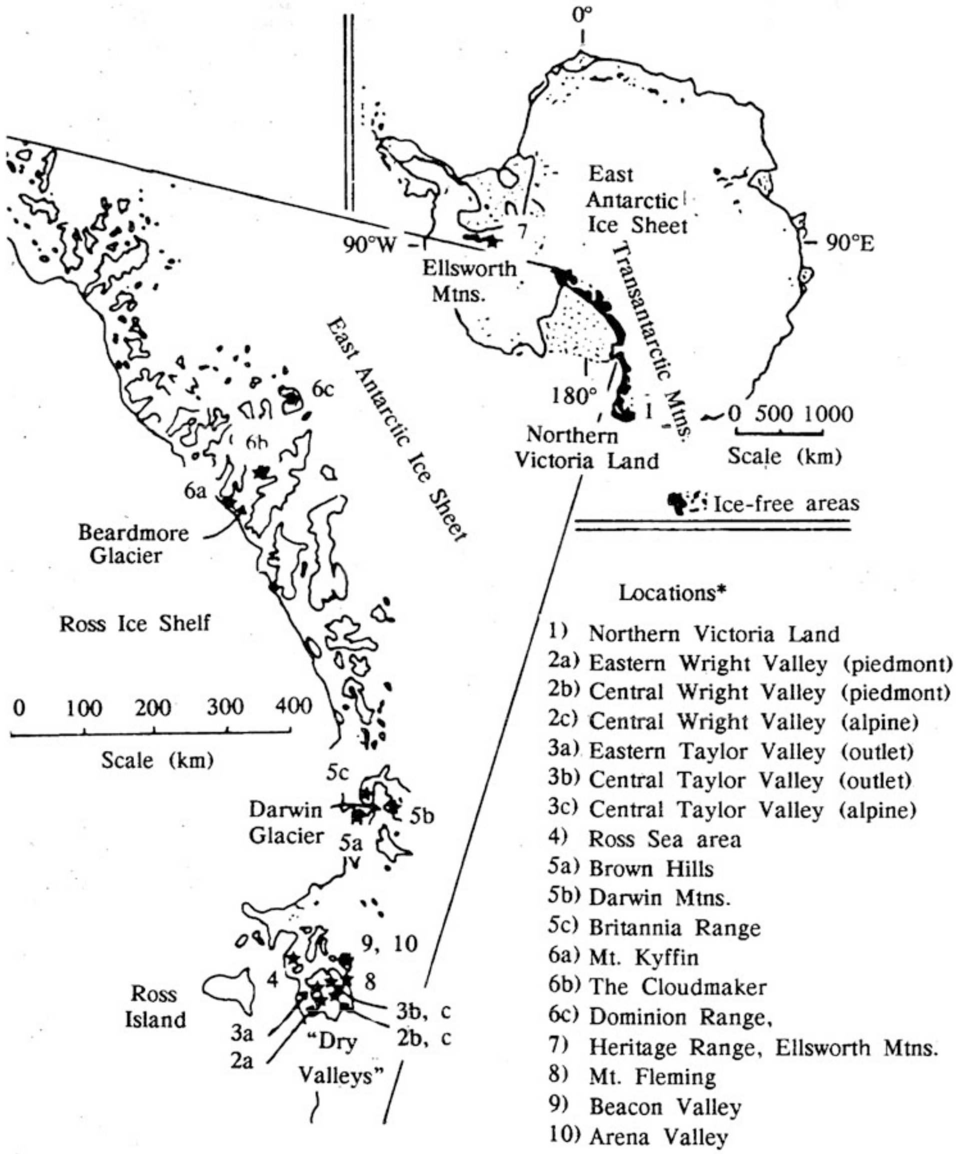


Fig. 8.20 Soil chronosequences of the Transantarctic Mountains (Bockheim and Wilson 1993). Chronosequence number 1 is considered in Chap. 7, numbers 5a through 6c in Chap. 9, and number 7 in Chap. 10

8.5.3.1 Soil Chronofunctions and Dating Glacial Deposits

A soil chronosequence is an array of related soils in a geographic area that differs primarily as a result of the soil-forming factor, time; a chronofunction is the mathematical solution of the relationship:

$$S = f(t)cl, o, r, p \tag{8.1}$$

where the soil (S) and the properties that define it are functions of time (t), with the variables of climate (cl), organisms (o), relief (r), and parent material (p) remaining relatively constant. Using data from 32 chronosequences from 27 areas contained in the published literature, Bockheim (1980) showed that a single logarithmic model, $Y = a + b\ 10X$, yielded the highest correlation coefficients, when soil property, (Y), was correlated with time, (X), using linear regression techniques. He later sampled soils from 18 chronosequences in central and southern Victoria Land, 10 of which are in the MDVs (Fig. 8.20). For all of the chronosequences, there were highly significant correlations between time and soil properties, including depths of staining, maximum color development equivalence, visible salts,

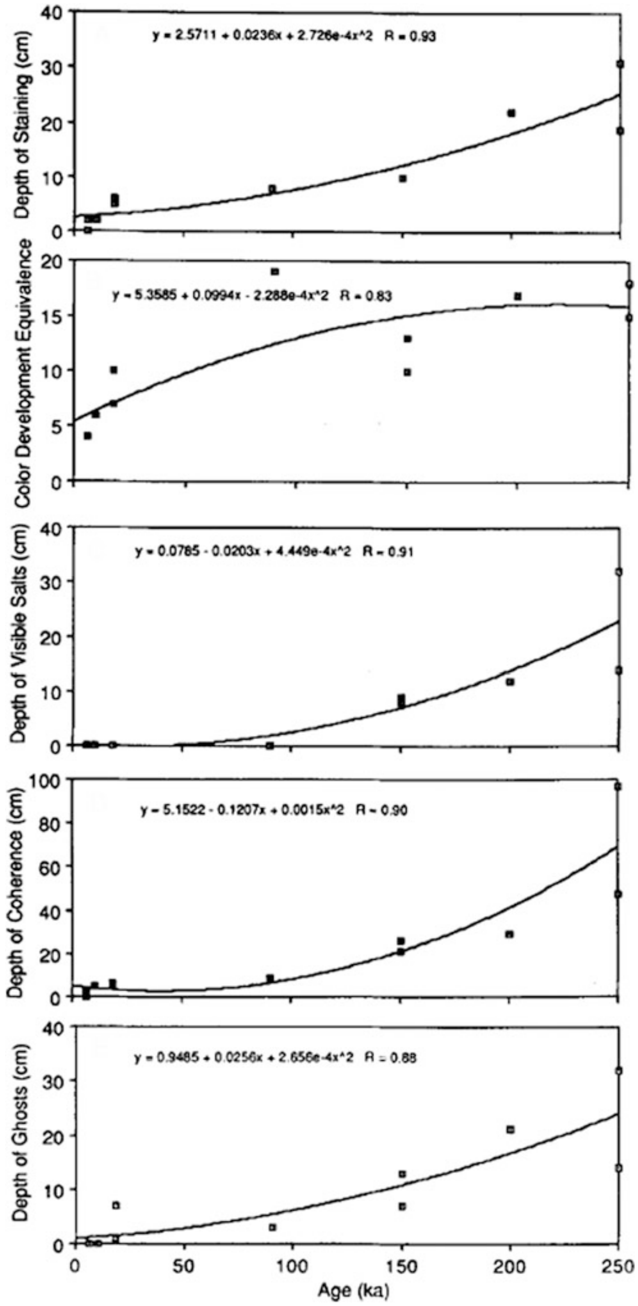


Fig. 8.21 Examples of soil chronofunctions from the central and southern Transantarctic Mountains (Bockheim 1990)

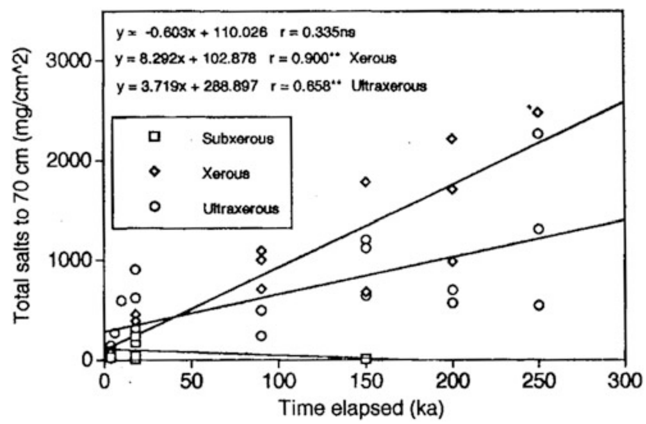


Fig. 8.22 Profile content of soluble salts in relation to time for three climatic zones in the central Transantarctic Mountains (Bockheim and Wilson 1993)

coherence, and ghosts (Fig. 8.21). Climate plays an interacting role in the slope of the regression lines relating soil property to time. For example, the profile accumulation of soluble salts (to a depth of 70 cm) was greatest in xerous soils, followed by ultraxerous soils, with the least amounts in subxerous soils along the coast (Fig. 8.22).

Changes in morphological soil properties with time are readily visible in the chronosequence from lower Wright Valley (Fig. 8.23). The figure depicts soils on a Late Glacial Maximum surface (A), mid- to late Quaternary (H1) aged hummocky drift (B), early Quaternary (Wright) drift (C), Pliocene-aged Valkyrie drift (D), Pliocene or older Alpine IV drift (E), and a strongly weathered soil below the white 3.9 My Hart Ash (F). The figures clearly show an increase in profile development of cohesion, salts, and depth of oxidation in relation to time.

Changes in the degree of development of the desert pavement are readily observable in a chronosequence of soils derived from sandstone and dolerite drifts from the Taylor Glacier in Arena Valley (Fig. 8.24). The dominant size range of clasts decreases with time of exposure, ranging from 16 to 64 mm on Holocene and late Quaternary surfaces (A) to 8–16 mm on surfaces of middle Quaternary and older age (B, C, D, E, and F). The proportion of clasts with ventifaction increases progressively through time from 20 % on drifts of Holocene and late Quaternary age (A) to 35 % on Miocene-aged drifts (E, F). Desert varnish forms rapidly, especially on dolerite clasts, with nearly 100 % cover on surfaces of early Quaternary and older age. Macropitting occurs only on clasts that have been exposed since the Miocene (E, F).

The morphology of patterned ground changes through time as ice within polygon fissures sublimates (Fig. 8.25). In central Beacon Valley, images obtained from a digital

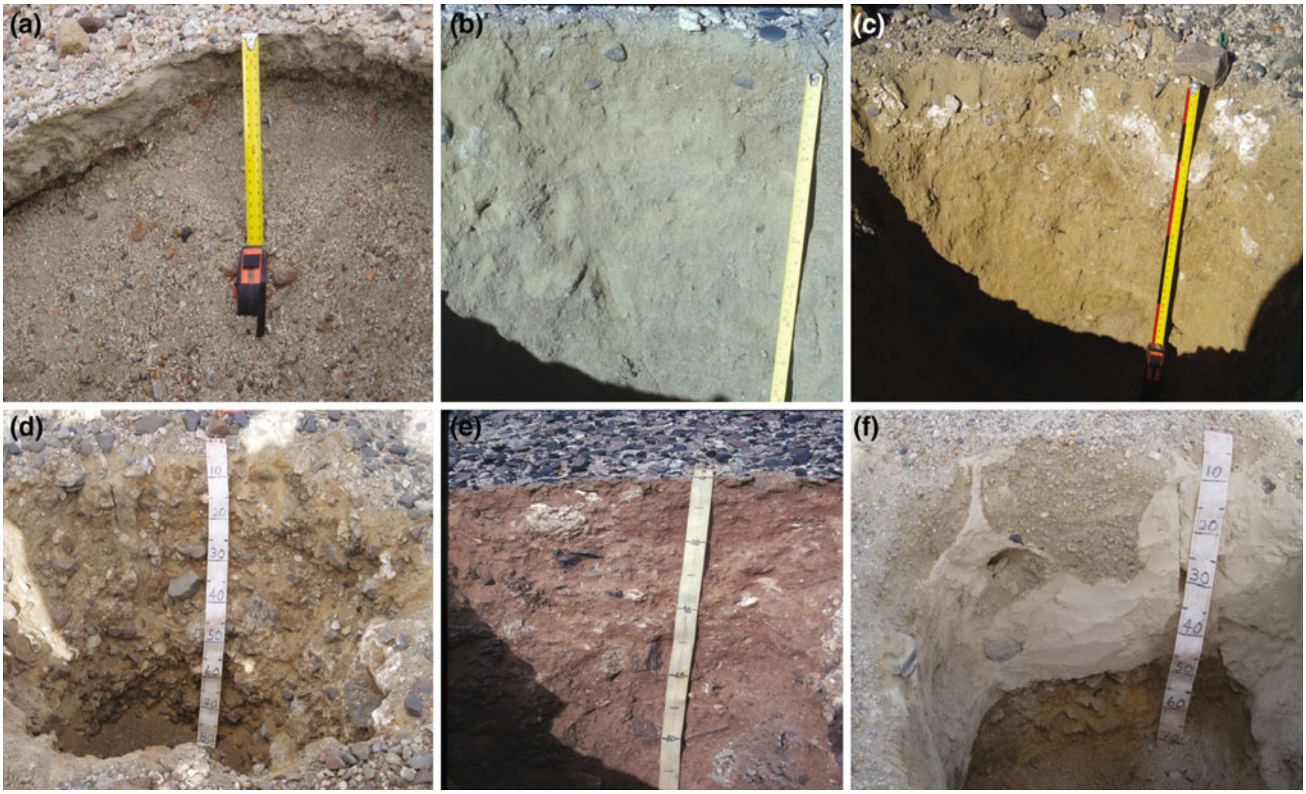
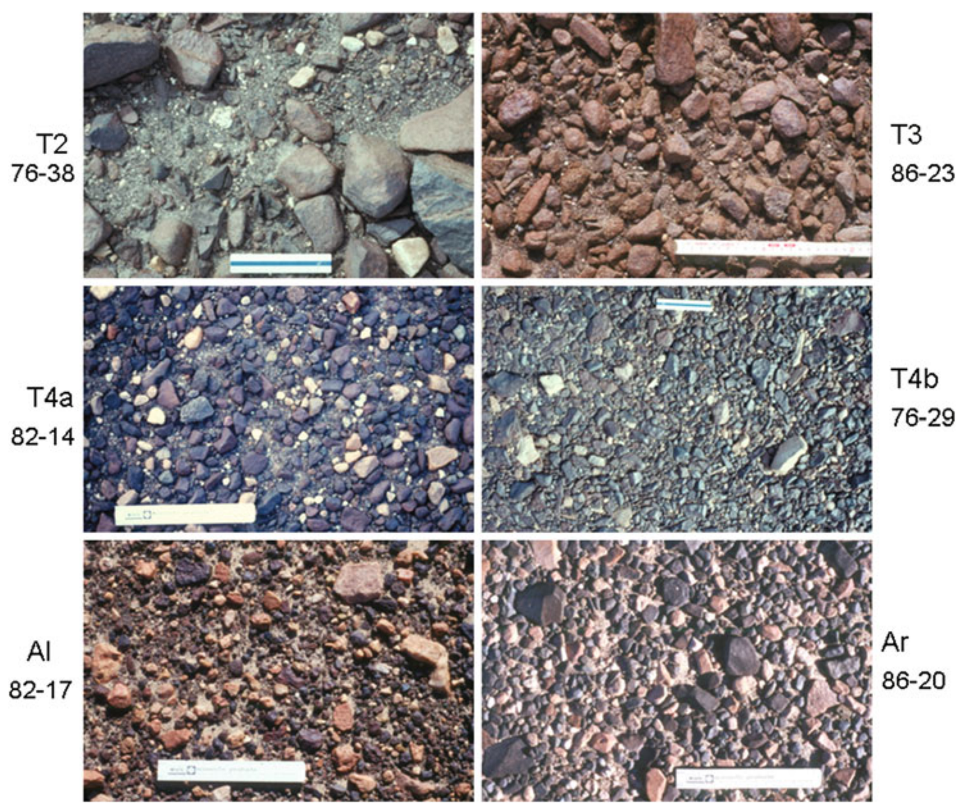


Fig. 8.23 Representative soils in Wright Valley, including **a** a soil on a Late Glacial Maximum surface, **b** a soil on mid- to late Quaternary (H1)-aged hummocky drift, **c** a soil on early Quaternary (Wright) drift, **d** a soil on the Pliocene-aged Valkyrie drift, **e** a soil on the Pliocene or older Alpine IV drift, and **f** a groundsoil and buried soil on the 3.9 My Hart Ash (Bockheim and McLeod 2006)

Fig. 8.24 A chronosequence of desert pavements derived from sandstone and dolerite drifts from the Taylor Glacier in Arena Valley: **a** Taylor 2 drift (pedon 76-38); **b** Taylor 3 drift (pedon 86-23); **c** Taylor 4a drift (pedon 82-14); **d** Taylor 4b drift (pedon 76-29); **e** Altar drift (pedon 82-17); and **f** Arena drift (pedon 86-20) (Bockheim 2010a)



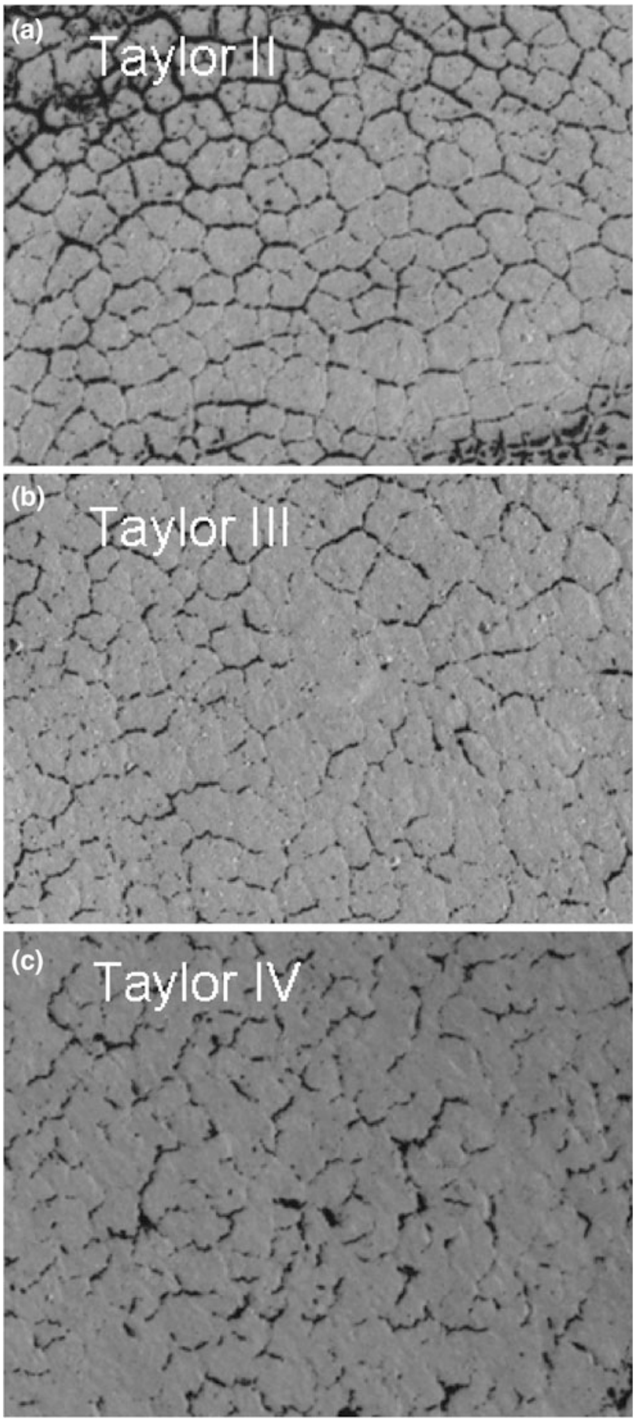


Fig. 8.25 Selected areas of patterned ground from the Beacon Valley digital elevation model for three drift sheets on the valley floor showing the increasingly diffuse expression of high-center, sand-wedge polygons with time in Beacon Valley: **a** regular pentagonal and hexagonal polygons on Taylor II drift in lower Beacon Valley (from oblique aerial photo); **b** poorly expressed polygons on Taylor III drift in lower Beacon Valley; and **c** diffuse polygons on Taylor IV drift in central Beacon Valley. The apparent lineations on Taylor III and IV surfaces may reflect prevailing wind ablation from the southwest to northeast (Bockheim et al. 2009)

elevation model show the increasingly diffuse expression of high-center, sand-wedge polygons with time on three drift sheets on the valley floor, including regular pentagonal and hexagonal polygons on Taylor II drift (A), poorly expressed polygons on Taylor III drift (B), and diffuse polygons on Taylor IV drift (C). The apparent lineations on Taylor III and IV surfaces may reflect prevailing wind ablation from the southwest to northeast (Bockheim et al. 2009).

8.5.3.2 Soils and Correlation of Drifts

The fact that soils show a regular progression in development with time enables their use in correlating drifts between or among valleys affected by a similar glacial sequence. This has enabled us to develop a "master relative chronology" for the MDV (Table 8.3). The chronology is based on an examination of 431 sites on moraines with approximate ages that range from mid-Holocene to Miocene. The chronology enables investigators to estimate relative ages of landforms based on the properties listed, which include depths of staining, cohesion, visible salts, and ghosts (pseudomorphs), depth to ice-cemented permafrost, salt stage (Fig. 2.11; Table 2.5), weathering stage (Table 2.4), thickness of salt pan, desert pavement development index, degree of patterned ground formation, and soil subgroup.

Table 8.4 shows a provisional correlation of drifts in the MDV based on data contained in Table 8.3. These data confirm that the outlet glaciers (Taylor, Wright Upper, Hatherton, Beardmore) and Alpine glaciers (Wright Valley) have acted out-of-phase with grounded ice in the Ross Sea (Wilson Piedmont Glacier) and that outlet glaciers in the MDV behaved similarly in response to changes in climate that accompanied the glacial–interglacial cycles.

8.5.3.3 Soils and Glacial Dynamics

Since the Pliocene, most of the glaciers in the MDV have been cold-based (dry-based), meaning that they are frozen to their bed. These glaciers advance over frozen aprons at their termini so that they are able deposit drift with minimal impact to the underlying surface. Figure 8.26 provides evidence for overriding by cold-based glaciers in Arena Valley. The upper soil (above the diabase ventifact in the center of the image) is of Taylor IV age (>1.0 Ma, <7.4 Ma) and the buried soil is of Quartermain age (>11.3 Ma).

Bockheim (2010b) examined soil preservation and ventifact recycling from dry-based and wet-based glaciers at 609 sites in the central and southern TAM. Buried soils were most common from deposition by dry-based glaciers (44 of 51 pedons). Fifteen percent of the pedons contained recycled ventifacts in relict and buried soils that ranged from late Quaternary to Miocene in age, particularly in drift from dry-based glaciers (56 of 77 pedons). Overall, 84 % of the buried soils and 78 % of the pedons with recycled ventifacts originated from dry-based glaciers. The proportion of soils with

Table 8.3 Master relative chronology for drifts in the McMurdo Dry Valleys

Drift unit	Approx. age	No. of sites	Staining	Max. CDE[a]	Coherence	Depth (cm) Vis. Salts	Ghosts	Ice cement	Salt stage[b]	Weathering stage[c]	Thickness salt pan (cm)	DPDI[d]	HCP index[e]	Soil sub-group[f]
					Taylor Valley (Bockheim et al. 2008a)									
Alpine I	<3.7 Ky	3	0		11	0	0	16 (core)	0	1	0			GHt, THt
Ross Sea	12.4–23.8 Ky	7	0		28	5	0	34	1.1	1.6	0			THt
pre-Ross	>12.4–23.8 Ky	3	0		23	0	0	25	1	1.7	0			THt
Alpine II	113–120 Ky	32	10		21	7	8	>40	1.5	2.1	0			THt-TAo
Taylor II	113–120 Ky	14	3		18	3	6	>45	1.2	2.1	0	17		TAo-THt
Taylor III	208–375 Ky	27	18		>46	21	9	>85	2	2.7	0	17		TAo
Taylor IVa	1.6–2.1 My	28	38		>48	33	15	>44	3.4	4.2	4	22		TAo, SAo
Taylor IVb	2.7–3.5 My	18	33		>49	29	15	>46	2.8	4	4	21		TAo
Alpine III-IV	2.7–3.5 My	4	41		>47	41	14	>47	3.3	3.5	7			TAo
					Wright Valley (Bockheim and McLeod 2006)									
Alpine I	<3.7 Ky	5	0 (0)		5 (4)	0 (0)	0 (0)	12 (8)	0 (0)	1 (0)	0	16		GHt
Lacustrine	Holocene	1	0		5	1	0	50	0	1	0	nd		GHt
Brownworth	>49 Ka	5	0 (0)		23 (26)	3 (5)	0 (0)	48 (18)	1 (0)	1 (0)	0	nd		THt
Hummocky, H1	Late Quaternary	13	7 (8)		19 (22)	19 (21)	2 (5)	55 (18)	1 (1)	2 (1)	0	19		THt
Loke	Mid- to late Quaternary	2	0		31	17	0	33	1	2	0	23		THt
Hummocky, H2	Mid- to late Quaternary	7	33 (32)		>34	9 (19)	13 (7)	>97	2 (2)	3 (1)	0	20		TAo
Alpine II	<3.3 Ma	24	15 (7)		35 (23)	18 (18)	4 (5)	>65	2 (1)	3 (1)	0	18		TAo
Trilogy	Early mid-Quaternary	5	13 (22)		21 (29)	1 (1)	7 (12)	39 (7)	1 (1)	2 (2)		22		THt
Onyx	<3.3 Ma	10	29 (15)	10	45 (25)	32 (22)	13 (8)	>82	3 (2)	4 (1)	8	21		TAo, SAo
Wright	<3.4 Ma	11	>27	12	>30	22 (17)	16 (16)	>90	3 (2)	4 (1)	8	19		TAo, SAo
Valkyrie	Pliocene?	3	>44	12	>94	>40	39 (27)	>94	5 (1)	5 (0)	26	19		PsAo
Alpine III	<3.5 Ma	15	>43	12	>56	48 (15)	21 (19)	>103	4 (1)	6 (1)	16	23		PsAo
Alpine IV	>3.7 Ma	18	>55	12	>100	>63	19 (11)	>100	6 (1)	6 (0)	22	24		PsAo

(continued)

Table 8.3 (continued)

Drift unit	Approx. age	No. of sites	Staining	Max. CDE[a]	Coherence	Depth (cm) Vis. Salts	Ghosts	Ice cement	Salt stage[b]	Weathering stage[c]	Thickness salt pan (cm)	DPDI[d]	HCP index[e]	Soil sub-group[f]
Loop	Pliocene or Miocene	4	>60	13	>88	44 (9)	9 (4)	>88	5 (1)	6 (1)	12	22		PsAo
Peleus	>3.7, <5.4 Ma	6	24 (13)	6	>100	17 (4)	10 (5)	>100	4 (1)	5 (1)	8	20		TAo
					Arena and Beacon Valleys (Bockheim 2007)									
Taylor II	117 Ka	18	10		14	2	11	>28	1	2	0	19		TAo
post-Taylor III	>117, <200 Ka	1	17					>100	1	2	0	nd		TAo
Taylor III	200 Ka	15	25		52	19	16	>78	2.4	3	3	23		TAo
pre-Taylor III	>200 Ka	5	37		68	30	10	>60	4.2	4	15	nd		PnAo
Taylor IVa	>1.0, <2.2 Ma	13	42		38	28	29	>77	4.6	4.8	14	24		PnAo
Taylor IVb	>2.2, <7.4 Ma	13	42		39	33	27	>66	5	5.7	14	26		PnAo
Taylor IV, undiff.	>1.0, <7.4 Ma	10	28		47	16	12	>52	3.9	4.5	10	nd		TAo
Arena	>11.3 Ma	6	30		56	10	6	>75	3.2	4.2	6	26		TAo
Altar	>11.3 Ma	12	32		51	12	35	>47	3.9	4.6	10	26		TAo
Quartermain II	>11.3 Ma	2	35		>95	37	4	>90	4.5	5.5	14	26		TAo
		360												
					Victoria Valley System (Bockheim and McLeod 2013)									
Ice-cored	*[Alpine I]*	2	0	4	6	0	0	15	0.5	1.5	0		3.7	GHo-GHt
Packard	*[Taylor II]*	25	3	9	24	6	2	34	1.2	2.8	0		3.3	THo-THt
Vida	*[Taylor III]*	13	18	16	50	16	17	58	1.7	3.3	0		1.9	THo
Bull	*[Taylor IVb]*	14	32	15	64	28	21	>69	2.5	4.8	0		<0.5	TAo, SAo
Insel	*[Peleus, Arena, Altar]*	17	26	20	57	17	7	>57	2.7	4.7	0		<0.5	THo, TAo
		71												

[a]Color development index (Buntley and Westin 1965)
[b]Bockheim (1997)
[c]Campbell and Claridge (1975)
[d]*DPDI* desert pavement development index (Bockheim 2010a)
[e]Maximum height of polygon, divided by mean width of contraction fissure
[f]*GHt* Glacic Haploturbels, *GHo* Glacic Haplorthels, *THt* Typic Haploturbels, *THo* Typic Haplorthels, *TAo* Typic Anhyorthels, *SAo* Salic Anhyorthels, *PsAo* Petrosalic Anhyorthels, *PnAo* Petronitric Anhyorthels

Table 8.4 Provisional correlation of glacial deposits in the Transantarctic Mountains (Bockheim 2010a)

Geologic time scale	Taylor V. Taylor Gl.	Wright V. Alpine	Wright V. Wilson Pied. Gl.	Arena V. Taylor Gl.	Beacon V. Taylor Gl.	Hatherton Glacier	Beardmore Glacier	Numerical Dating
Holocene late Quaternary	–	A1	–	–	–	Hatherton	Pl	3.7 Ky
	–	–	B	–	–	Br1, Br2	Be	10 Ky
	T2	A2a	–	T2	T2	–	–	117 Ky
	–	–	H1	–	–	D	M	–
	T3	A2b		T3	T3	–	–	200 Ky
Middle Quaternary	–	–	Loke, H2	–	–	I	pre-M	–
	–	–	T	–	–	–	–	–
Early Quaternary	T4a	–	–	T4a	T4a	–	–	1.0–1.1 My
	T4b	–	–	T4b	T4b	–	–	1.1–2.2 My
Pliocene	–	–	O, W	–	–	pre-I	Do	<3.4 My
	–	A3	–	–	–	–	–	<3.5 My
	–	–	V	–	–	–	–	–
	–	A4	–	–	–	–	–	>3.7 My
	–	–	Lp	–	–	–	–	–
	–	–	P	–	–	–	–	–
Miocene	–	–	–	–	–	–	S	7.7 My
	–	–	–	Al, Ar	Al	–	–	>11.3 My
References	Brook et al. (1993); Wilch et al. (1993); Higgins et al. (2000)	Hall and Denton (2005)	Hall and Denton (2005)	Marchant et al. (1993a)	Bockheim (2007)	Bockheim et al. (1989)	Denton et al. (1989); Ackert and Kurz (2004)	

Drift names: *A* Alpine, *Al* Altar, *Ar* Arena, *B* Brownworth, *Be* Beardmore, *Br* Britannia, *D* Danum, *Do* Dominion, *H* Hummocky, *Ha* Hatherton, *I* Isca, *L* Loke, *Lp* Loop, *M* Meyer, *P* Peleus, *Pl* Plunket, *O* Onyx, *Q* Quartermain, *S* Sirius, *T* Trilogy, *V* Valkyrie, *W* Wright

recycled clasts on a particular drift was greatest where the ratio of drift thickness to soil thickness ("recycling ratio") was the least.

These data illustrate the effectiveness of Antarctic dry-based glaciers in preserving underlying landforms and deposits, including soils. Moreover, the data imply that Antarctic glaciers have been recycling clasts for the past ca. 15 Ma. These findings have important implications in selecting surface boulders for cosmogenic dating.

8.5.3.4 Soils and Former High-Level Lakes

According to Hall et al. (2000), a high-water-level (336 m) lake, Glacial Lake Washburn, existed throughout Taylor Valley during the Last Glacial Maximum (LGM) and early Holocene, ca. 18.6–6.0 ka. They projected that this lake was 38 km^2 in area and had a maximum depth of 300 m. Hall et al. (2001) and Hall and Denton (2005) proposed the existence of Glacial Lake Wright, a high-water level (550 m) lake, during the LGM and early Holocene, ca. 2.7–25.7 ka in

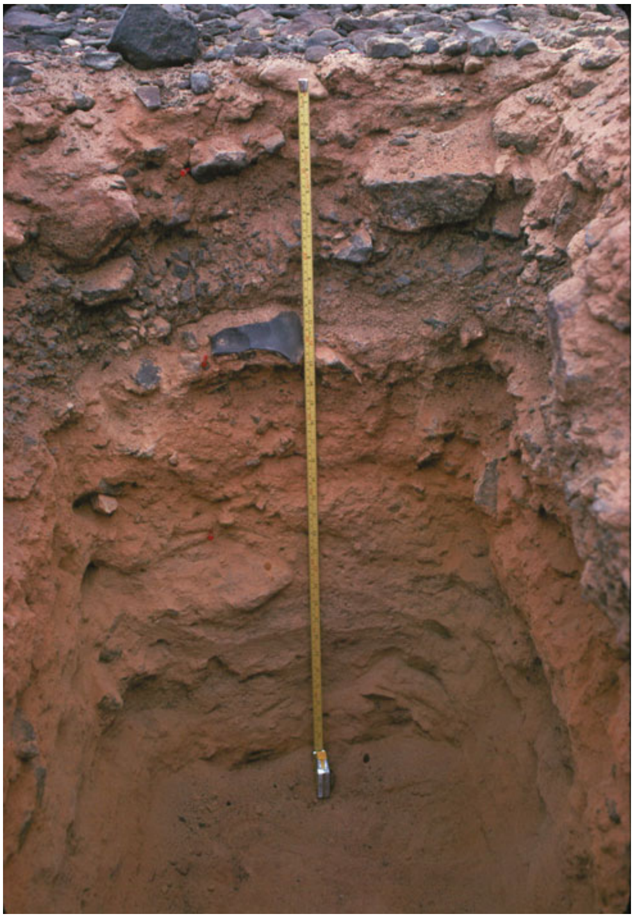


Fig. 8.26 Evidence for overriding by cold-based glaciers in Arena Valley. The upper soil (above the diabase ventifact in the center of the image) is of Taylor IV age (>1.0 Ma, <7.4 Ma) and the buried soil is of Quartermain age (>11.3 Ma)

Wright Valley. They proposed that this lake was 212 km^2 in area and had a maximum depth of 470 m. Hall et al. (2002) suggested that a 185-m deep lake may have engulfed most of the Victoria Valley system between 20 and 8.6 ka. The primary evidence for high-level lakes is the presence of deltas containing cyanobacterial mats that have been radiocarbon dated.

Bockheim et al. (2008b) and Bockheim and McLeod (2013) hypothesized that soils above the uppermost paleolake levels should be more strongly developed and contain more salts than soils below. In central, Taylor and Wright Valleys, soils on equivalent-aged drifts above and below the conjectured upper limits of Glacial Lakes Washburn (336 m) and Wright (550 m), respectively, are all well developed with no appreciable differences in their properties (Fig. 8.27). Moreover, there were no significant differences in the slopes of regression equations relating soil property to age of the parent materials above and below the high-water lake levels (Fig. 8.28). Other than small alluvial fans with algae at all elevations, they found no evidence of former lake sediments nor did they find high-level strandlines except for strandlines on the north valley wall ca. 50 m above Lake Vanda, ice-shove features, or paleo-shore features. In Victoria Valley, a regression analysis of depth of visible salts against elevation yielded a very poor adjusted R^2 of 0.27 (Bockheim and McLeod 2013). They argued that lakes of the magnitude and duration proposed by Hall et al. (2002) would have dissolved and redistributed salts in the soils.

8.6 Summary

Soils in central Victoria L, the MDV, and selected valleys have been mapped at scales of 10 million, 1:2 million, and 1:250,000 or 1:50,000, respectively. The dominant soil units from largest to smallest in area include Typic Anhyorthels, Typic Haploturbels, and Typic Anhyturbels, which comprise 93 % of the soils mapped. Soils of the MDV contain very low SOC concentrations, are alkaline, are sodic, have abundant coarse fragments, contain dominantly sand in fine-earth fraction, and have low soil moisture contents. Time is the key factor for soil-forming influencing soil development in CVL. From the mid-Holocene to the Pliocene, soils lose moisture from sublimation which lessens cryoturbation and enables salt to form. Climate controls the rate of soil formation along a longitudinal gradient from the coast to inland valleys to uplands. Parent materials influences soil properties, but relief and organisms play a minimal role except in penguin rookeries along the coast.

The dominant soil-forming processes are salinization, desert pavement formation, and sublimation of interstitial ice which converts ice-cemented permafrost into dry-frozen permafrost, and rubification. Soils have been useful in the MDV in numerical dating of drifts, correlation of drifts, understanding the behavior of cold-based glaciers, and testing hypotheses regarding the possible existence of former high-level lakes.

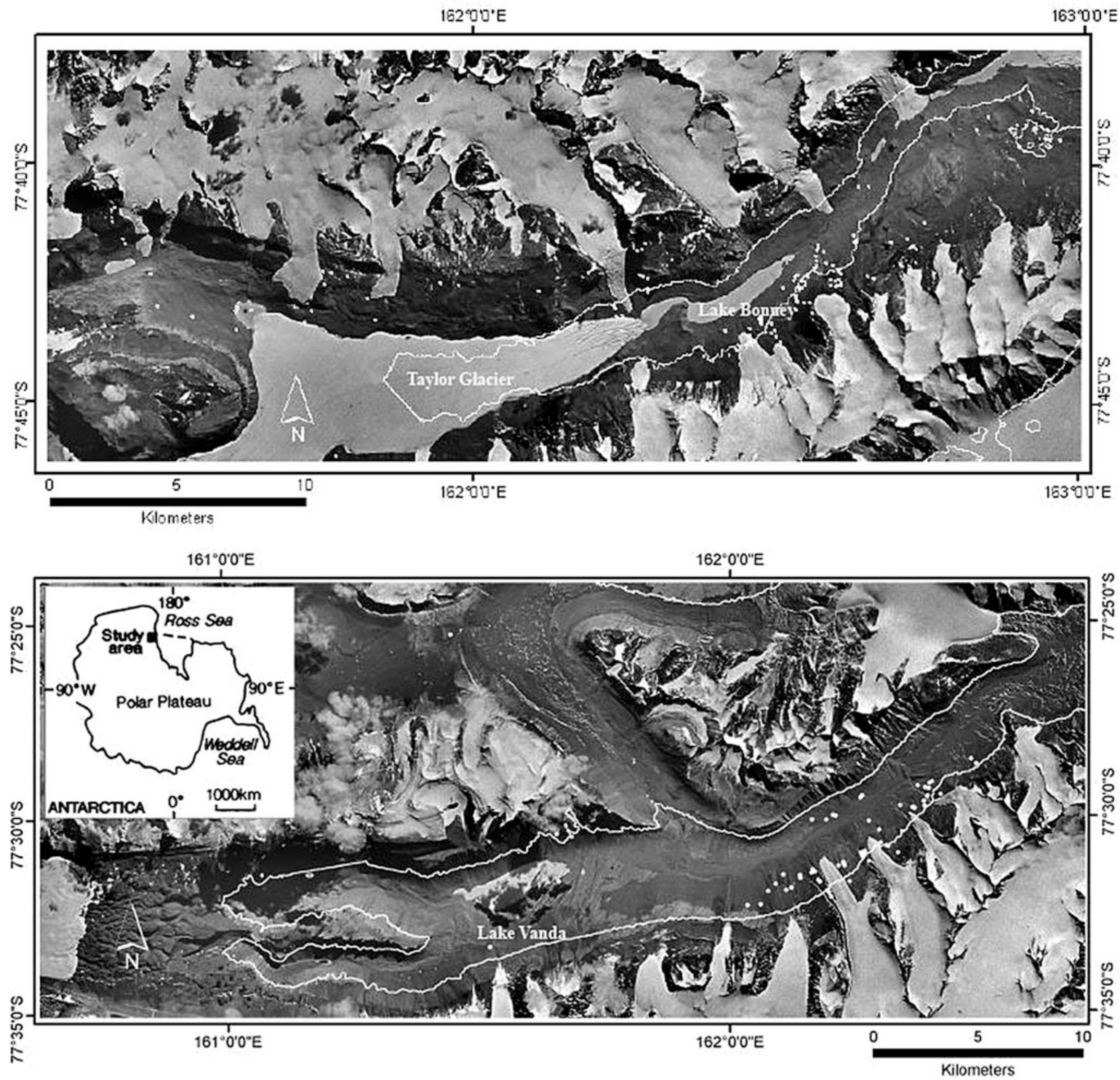


Fig. 8.27 Location of soil pits above and within the proposed upper elevations of Glacial Lakes Taylor and Wright by Hall et al. (2000, 2001). Maps from Bockheim et al. (2008b)

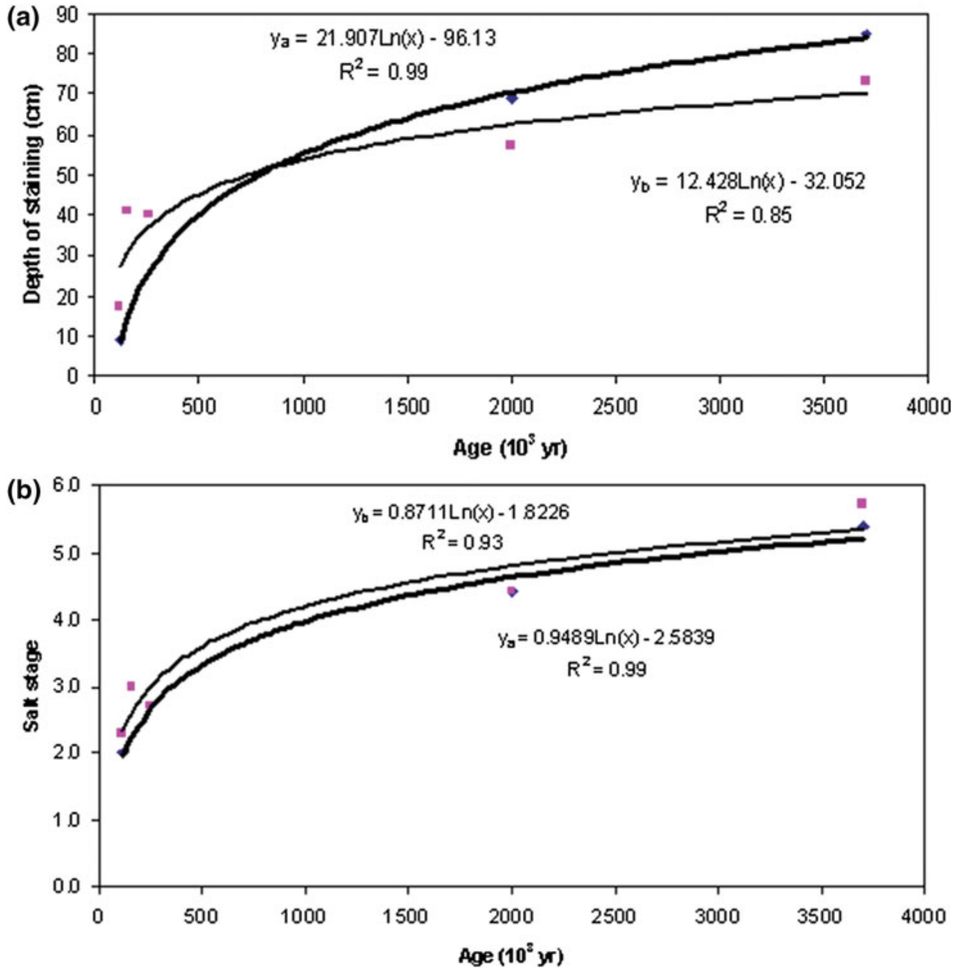


Fig. 8.28 Depth of staining (*top*) and salt stage for soils above (Ya) and below (Yb) the 550 m contour of Wright Valley (Bockheim et al. 2008b)

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9 Soils of Southern Victoria Land, the Southern Transantarctic Mountains

James G. Bockheim and Malcolm McLeod

9.1 Introduction

In this book we consider the southern Transantarctic Mountains (TAM) to include that portion of the TAM from the Mulock Glacier (79° S) to the southernmost part of the range, Mt. Howe (87° 19′ S). The major ice-free areas in the southern TAM from north to south include the Britannia Range-Darwin Glacier region, the Beardmore Glacier region, the Shackleton Glacier region, and the Reedy and Scott Glaciers region (Fig. 9.1).

The Thiel Mountains, Pensacola Mountains, and Shackleton Range are in Region 5a and, because there is insufficient soils information for these area, a brief summary is provided in Appendix 3.

The TAMs form a natural barrier between the land-based East Antarctic ice sheet and the marine-based West Antarctica ice sheet and records the primary record of Cenozoic glaciations of Antarctica (Mercer 1968; Denton et al. 1989; Bockheim et al. 1989). Soils have been studied in the southern TAM not only for reconstructing the glacial history of the region (Claridge and Campbell 1968; Bockheim et al. 1989; Denton et al. 1989; Bockheim et al. 1990), but also for their biological characteristics (Cameron 1971; Parker et al. 1982). According to these studies, surface-boulder weathering and soil properties are important for differentiating drift sheets and assigning relative ages of glacial deposits. In addition to isolated lichens and mosses, viable microorganisms, including yeasts, aerobic heterotrophic bacteria, and algae, occur in these soils, including the underlying permafrost.

The objectives of this chapter are (1) to provide three fifth-order reconnaissance soil maps of the TAM; and (2) to discuss the soil map units in terms of landform evolution, pedogenesis, and as a habitat for soil organisms.

9.2 Study Area

Site factors for the key ice-free areas in the southern TAM are given in Table 9.1. The mean annual air temperature of the southern TAM ranges between −20 and −40 ºC (Fig. 2.5), and the average annual accumulation of water-equivalent precipitation ranges from <10 to 150 mm year^{-1} (Fig. 2.4). Vegetation in the southern TAM is limited to an unknown number of species of nonmarine algae, some fungi, one liverwort, and cryptogams, including about 50 species of mosses and approximately 200 species of lichens (Seppelt et al. 2010).

The bedrock geology sequence of the southern TAM includes metasedimentary rocks of the Ross Sea System (upper Precambrian and lower Paleozoic), igneous rocks of the Paleozoic Ross Orogeny and Granite Harbour Intrusives (Paleozoic), extensive erosion during formation of the Kukri Peneplain (Ordivician), deposition of the Beacon Sandstone during the Triassic, intrusion of the sandstones by the Ferrar Dolerites during the Jurassic, and deposition of the McMurdo Volcanics from the Pliocene to the present (Gunn 1963; Barrett 1981).

The geomorphology of the southern TAM is dominated by glacial landforms, including erosional and depositional features (e.g., moraines, till plains, outwash plains), periglacial landforms (e.g., patterned ground, gelifluction lobes, rock glaciers), aeolian landforms (sand dunes, megaripples), and nunataks that project through the West and East Antarctic ice sheets. The glacial deposits result from ice-flow switching and East/West Antarctic ice sheet roles in glaciation of the western Ross Sea (Greenwood et al. 2012). The deposits range from Miocene to modern in age but are dominated by those deposited over the past 2 million years

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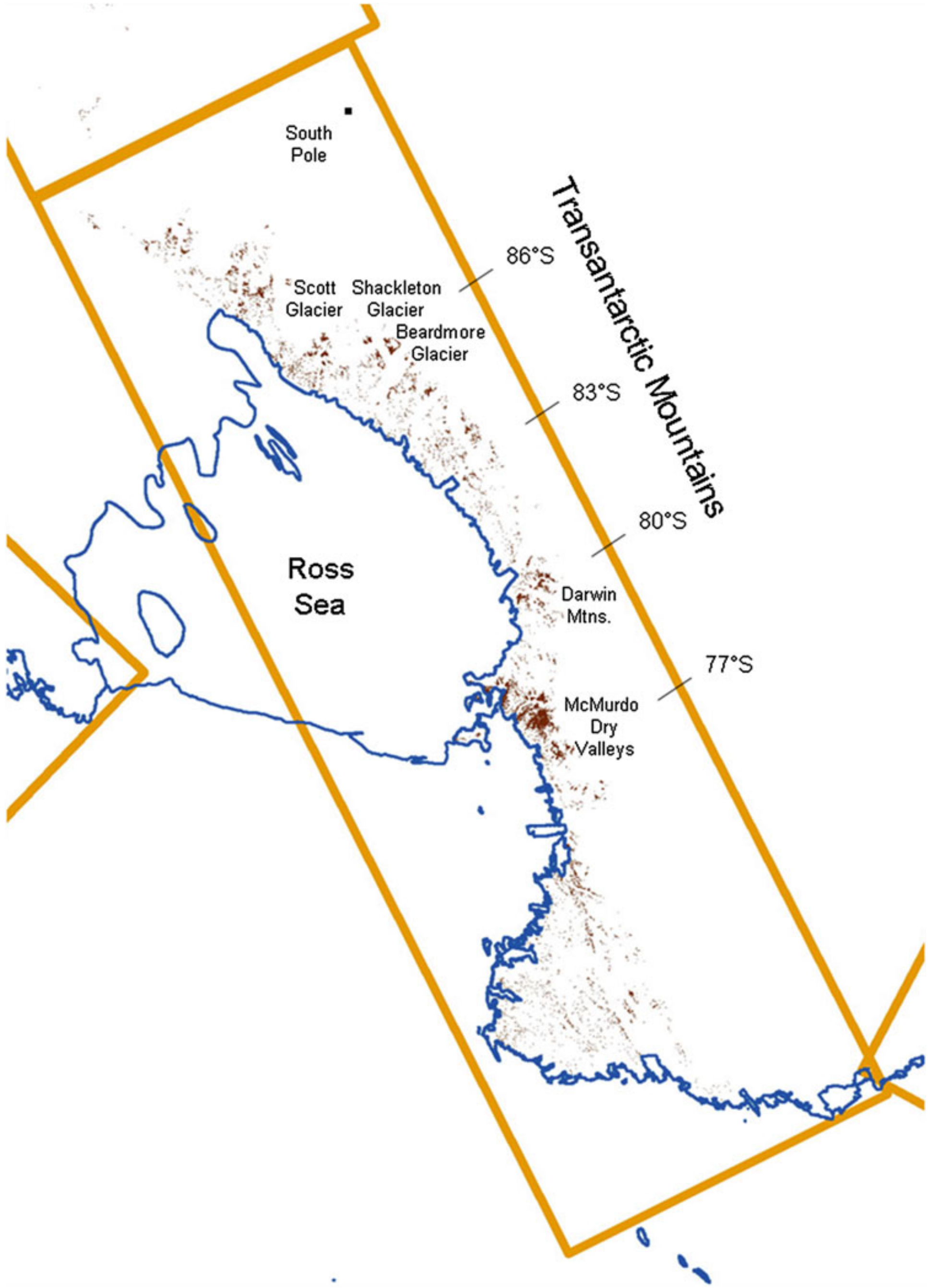

Fig. 9.1 Ice-free areas of the Transantarctic Mountains

during the Quaternary Period. During the Quaternary Period, major outlet glaciers in the TAM thickened due to damming of grounded ice in the Ross Embayment contemporaneously with Northern Hemisphere glaciations (Mercer 1968; Mayewski and Goldthwait 1985a, b; Bockheim et al. 1989; Denton et al. 1989, 1991). Drift from the Last Glacial Maximum (LGM) is dated at 18–24 Ka (Hall and Denton 2000) and occurs in the mouths of most of the major valleys in the central and southern TAMs (Denton and Marchant 2000). Drifts ranging from late Pleistocene to the Pliocene and older have been mapped in the upper portions of the valleys. Deposits of the Sirius Group, which occur throughout the southern and central TAM, represent a massive overriding of the TAM by a wet-based glacier(s) sometime prior to 5 My BP (Ackert and Kurz 2004). A correlation of drifts identified in the TAM and their approximate ages is given in Table 9.2.

The entire area is underlaid by continuous permafrost (Bockheim 1995), about 55 % of which is ice cemented and 43 % dry frozen (Bockheim and McLeod unpublished).

Table 9.1 Site factors for soils of the southern Transantarctic Mountains

Property	Darwin Glacier	Beardmore Glacier	Shackleton Glacier	Scott Glacier
Number of pedons	122	88	28	71
Time of sampling	1964–5, 1977–8	1985–6	1964	1970-1
Latitude (S)	79° 45′–80° 30′	83° 30′–85° 15′	84° 35′–85° 35′	85° 30′–87° 20′
Longitude (E)	155–160° E	164–172° E	173–180° W	146–154 30′ W
Elevation range (m)	300–2200	400–2700	1300–2700	250–2750
Parent materials	Till from Beacon ss-Ferrar dolerite	Till from Beacon ss-Ferrar dolerite	till from Beacon ss-Ferrar dolerite	
Age range of deposits	mid-Holocene to pre-Quaternary	mid-Holocene to pre-Quaternary	mid-Holocene to pre-Quaternary	mid-Holocene to pre-Quaternary
1:250,000 topo map sheets	Carlyon Glacier, Turnstyle Ridge, Cape Selborne, Mt. Olympus	Mt. Elizabeth, The Cloudmaker, Buckley Island, Plunket Point, Mt. Kathleen, Mt. Rabot	Shackleton Glacier, Liv Glacier, Mt. Wisting	Mt. Goodale, Nilsen Plateau, D'Angelo Bluffs, Leverett Glacier, Mt. Blackburn
References	Bockheim et al. (1989); Campbell and Claridge (1967)	Denton et al. (1989); Bockheim et al. (1990)	Claridge and Campbell (1968)	Campbell and Claridge, unpubl.

Table 9.2 Correlation and approximates ages of drifts in the southern Transantarctic Mountains

		Scott–Amundsen–		
Darwin[a]	Beardmore[b]	Shackleton[c]	Reedy[d]	Approximate age
Britannia I	Plunket			Holocene (10 ky)
Britannia II	Beardmore	Amundsen	Reedy III	Last glacial maximum (14–28 ky)
Danum	Meyer	Shackleton	Reedy II	Late Quaternary (∼200 ky)
Isca	Dominion	Scott	Reedy I	Pre-late Quaternary (∼900 ky)
pre-Isca		Queen Maud		Early Quaternary to late Pliocene (1.2–2.4 My)
	Sirius			Miocene or older (>5 My)

[a]Bockheim et al. (1989)
[b]Denton et al. (1989); Ackert and Kurz (2004)
[c]Mayewski and Goldthwait (1985a, b)
[d]Mercer (1968)

Ground/buried ice comprises probably at least 2 % of the area. Permafrost form is related to climatic zone, age of sediments, and local site factors (Bockheim 1995; Campbell and Claridge 2006; Bockheim et al. 2007). Ice is present in ice-cored alpine moraines and coastal tills of Holocene age in hummocky drifts of late Quaternary age (ca. <115 ka); however, it is also present in Miocene-aged sublimation till upper Beacon Valley. Ice-cemented permafrost is present not only in coastal areas (subxerous climatic zone) and in sediments of late Quaternary age, but also in soils of pre-Quaternary age in ultraxerous regions along the polar plateau. Dry-frozen permafrost exists along the floors and lower sidewalls of larger ice-free valleys (xerous climatic zone) in sediments of pre-late Quaternary age. Dry-frozen permafrost, which may be unique to Antarctica, appears to form from sublimation of moisture in ice-cemented permafrost over time. Active-layer depths are 40–80 cm in coastal areas and <20 cm along the polar plateau (Bockheim et al. 1989; Denton et al. 1989; Bockheim et al. 1990).

9.3 Methods

9.3.1 Field

We utilized field data from 287 pedons at four locations in the southern TAM, including the Darwin-Byrd Glaciers area (60 pedons by J. Bockheim; 40 pedons by I. Campbell and

G. Claridge), the Beardmore Glacier area (88 pedons by J. Bockheim), the Shackleton Glacier area (28 pedons by I. Campbell and G. Claridge), and the Scott-Reedy Glaciers area (71 pedons by I. Campbell and G. Claridge). Soil pits were excavated to at least 100 cm, unless ice cement or large boulders prevented digging to that depth. The following soil properties were measured in the field. The depth of staining refers to the thickness of the layers showing the strongest hues and chromas from oxidation of iron-bearing minerals and corresponds to the bottom of the Bw horizon. The depth of coherence refers to the thickness of consolidated soil from accumulation of weathering products such as salts and iron oxides; below the depth of coherence, soil readily caves into the pit. The depth of visible salts refers to the maximum depth for which salt encrustations beneath clasts, salt flecks, and salt cementation are readily visible to the naked eye.

Bockheim (1990) developed a six-stage sequence in which the form of soluble salts was related to total dissolved salts from electrical conductivity (EC) measurements and soil age, including 0 = no visible salts, 1 = salt encrustations beneath clasts, 2 = salt flecks covering <20 % of the horizon area, 3 = salt flecks covering >20 % of the horizon area, 4 = weakly cemented salt pan, 5 = strongly cemented salt pan, and 6 = indurated salt pan. The depth to ice or ice-cemented permafrost was also determined. The active (seasonal thaw) layer in the study areas varies between 10 and 50 cm; material below this depth that is not cemented by ice contains dry-frozen permafrost, i.e., perennially frozen materials lacking sufficient interstitial water to cause cementation.

The weathering stage is an overall representation of the landscape/material based on the degree of surface-boulder weathering, soil morphology, and patterned ground and permafrost forms (Campbell and Claridge 1975), including 1 = unstained angular boulders, no horizonation (Cn), stage 0 or 1 salts, ice cement within 70 cm of surface, and patterned; 2 = lightly stained subangular boulders, weak horizonation (Cox), stage 2 salts, may have ice cement, patterned ground; 3 = distinct polish and rounding of boulders, some cavernous weathering, distinct horizonation (Bw), stage 3 salts, moderately deep profile; 4 = strongly developed cavernous weathering, ventifaction, very distinct horizonation, stage 4 salts, deep profile; 5 = low surface boulder frequency, well-developed desert pavement, very distinct horizonation, stage 5 salts, deep profile; and 6 = low surface boulder frequency, well-developed desert pavement, macro pits in dolerite, very distinct horizonation, stage 6 salts, shallow to deep profile with bedrock possibly occurring in the lower solum.

Soils were classified into the Gelisol order to the family level (Soil Survey Staff 2010); mineral soils showing cryoturbation are classified as Turbels; mineral soils without obvious cryoturbation are Orthels. Both suborders are divided into great groups on the basis of soil climate and other soil properties. Whereas soils along the Ross Sea and Weddell Sea coasts are moist during the summer months, soils of central and upper valleys have anhydrous conditions (i.e., the mean annual precipitation is less than 50 mm year^{-1} water equivalent). Soils in coastal regions are classified as Haploturbels or Haplorthels and those in the upper valleys are Anhyturbels or Anhyorthels. The latter soils are further subdivided into subgroups based on the presence of soluble salts (e.g., salic, nitric, "petrosalic," and "petronitric").

9.3.2 Laboratory

Several measurements had been performed in the laboratory to supplement data taken in the field. EC was determined on 1:5 soil:distilled water extracts using a conductivity bridge and cell (U.S. Salinity Laboratory Staff 1954). Profile quantities of salts (mg/cm^2) to a depth of 70 cm were calculated from the formula (Bockheim 1979):

$$\begin{aligned}\text{Profile salts} = &\ \text{Electrical conductivity (dS/m)}\\ &\times \text{thickness (cm)} \times 4.8\end{aligned} \tag{9.1}$$

No corrections were made for coarse fragments >2 mm as they readily accumulate salts. Salts are reported to 70 cm, because this depth represents the maximum extent of staining; moreover, ice cement below this depth does not markedly affect cryoturbation and patterned ground formation.

9.3.3 Soil Mapping

Digitized and georectified 1:250,000-scale topographic maps from the U.S. Geological Survey were used as base maps for the entire area. For the southern TAM, 25 maps were seamlessly joined. Soil boundaries were drawn by hand on mylar sheets overlying the topographic maps using the criteria listed in Table 9.3 as a data layer on the topographic maps.

Previous mapping experience in the Darwin Glacier region (Bockheim et al. 1989) and the Beardmore Glacier region (Denton et al. 1989; Bockheim et al. 1990) enabled us to draw soil polygon boundaries on the 1:250,000 topographic maps throughout the southern TAM. In coastal regions Typic Haploturbels (THt) and the association of THt and Typic Haplorthels form on patterned ground that appears on topographic maps in a shaded stippled pattern (Table 9.3). Glacic Haploturbels have a narrow, white

Table 9.3 Criteria used to delineate soil map units from 1:250,000 topograhic maps and physiographic legend for soils of the southern Transantarctic Mountains

Soils of the coastal regions	
Formed on patterned ground	
Typic Haploturbels	THt
Soil association of Typic Haploturbels + Typic Haplorthels	THt +THo
Formed on rock glaciers or medial moraines	
Glacic Haploturbels	GHt
Formed on nunataks or rock outcrops	
Lithic Haploturbels + Lithic Haplorthels	LHt + LHo
Formed in areas with patterned ground and rock outcrops	
Soil association of Lithic and Typic, Haplorthels and Haploturbels	THt + LHt + THo + LHo
Soils of the inland areas	
Formed on patterned ground with evidence of moisture (e.g., proximity to glacial meltwater runoff, lake, or stream). Ice cement at less than 70 cm.	
Soil association of Typic Haploturbels + Typic Haplorthels	THt +THo
Formed on patterned ground with no ice-cemented permafrost in upper 70 cm	
Typic Anhyorthels + Typic Anhyturbels soil association	TAo +TAt
Formed on larger areas with no apparent patterned ground	
Typic Anhyorthels	TAo
Formed on rock glaciers and adjacent areas	
Glacic Haploturbels and Typic Haploturbels soil association	GHt + THt
Formed on rock outcrops/nunataks	
Lithic Anhyturbels	LAt
Formed on larger nunataks that include some unconsolidated sediments with patterned ground	
Lithic Anhyturbel + Typic Anhyturbel soil association	LAt + Tat + TAo + LAo
Formed on larger nunataks that include some unconsolidated sediments with no patterned ground	
Lithic Anhyorthels + Typic Anhyorthels	LAo +TAo

Note nitric, "petronitric," salic, "petrosalic," gypsic, petrogypsic subgroups of soils occur in small areas that cannot be shown at a 1:250,000 scale

stippled pattern on medial moraines and rock glaciers underlain with ground ice. Nunataks in coastal regions support Lithic Haploturbels and Lithic Haplorthels.

In inland areas, the THt–THo soil association occurs in areas with patterned ground and adjacent to streams (Table 9.3). Typic Anhyturbels (TAt) and Typic Anhyorthels (TAo) occur in inland areas with patterned ground, but where the surface of ice-cemented permafrost has been shown to occur below a depth of 70 cm. The ubiquitous TAo exist in areas with no apparent patterned ground. Rock glaciers and adjacent areas contain Glacic Anhyturbels and TAt. Nunataks with abundant snow and ice nearby were interpreted to contain Lithic Anhyturbels (LAt). Larger nunataks with flattened tops were interpreted to contain an association of LAt and TAt. The physiographic legend for soils of the TAMs is also given in Table 9.3. The areas of each soil map unit were determined using a geographic information system (ArcGIS 9.2).

Our confidence in soil mapping was evaluated using four criteria: (i) the concentration of pedons described in a given area, (ii) the similarity of the physiography to a benchmark area in the McMurdo Dry Valleys, (iii) the presence of patterned ground on air photographs, and (iv) earlier soil studies in the area (Table 9.4).

9.4 Results

9.4.1 Areas of Ice-Free Regions

Major ice-free areas along the main stem of the southern TAM from north to south include the Darwin-Byrd Glaciers region (2,000 km^2), the Beardmore Glacier region (2,700 km^2), the Shackleton Glacier region (1,200 km^2), and the Reedy–Scott Glaciers region (3,000 km^2). Collectively, these four regions comprise 8,900 km^2, which accounts for

Table 9.4 Criteria used for evaluating confidence in soil mapping in the southern Transantarctic Mountains

Criteria for evaluating confidence in soil mapping
(1) Soil profile density: 6 = very high; 4 = medium; 2 = low; 0 = none (2) Similarity of physiography to that of a benchmark area: 3 = high; 2 = medium; 1 = low; 0 = none (3) Presence of patterned ground on air photographs: 3 = high; 1 = medium; 0 = none (4) Previous soil studies in area: 2 = some; 1 = minimal; 0 = none
Confidence of soil mapping by region
Darwin Glacier – 6 + 3 + 3 + 0 = 12
Beardmore Glacier – 6 + 3 + 3 + 0 = 12
Shackleton Glacier – 2 + 3 + 0 + 0 = 5
Scott Glacier – 2 + 3 + 0 + 0 = 5

about 37 % of the total ice-free area of the TAM (24,200 km^2) and about 18 % of the total ice-free area (49,500 km^2) of Antarctica.

9.4.2 Distribution of Soil Taxa and Soil Map Units

The distribution of soil taxa was determined from (1) the initial data set and (2) from soil maps of each of the five regions. The initial data set contained primarily TAo (51 %) and TAt (16 %), with lesser amounts of Glacic Anhyturbels (GAt) (7 %), THt (6 %), and Lithic Anhyorthels (LAo) (5 %) (Table 9.5). Collectively, these soil subgroups comprised 85 % of the data set.

Reflective of the low moisture status of cold desert soils (Campbell et al. 1997), 68 % of the soils were classified as Orthels, i.e., soils showing minimal cryoturbation, and 32 % as Turbels (Table 9.5). Eleven percent of the soils had glacic horizons (i.e., a buried ice or ground ice layer within 100 cm of the surface); 6 % had a lithic contact within 100 cm of the surface, and 9 % of the soils had a salt-enriched layer, either a salic, nitric, "petrosalic," or "petronitric" horizon.

9.4.3 Description of Soil Taxa and Map Units

9.4.3.1 Typic Anhyorthels

The distribution of soil taxa was determined from (1) the initial data set and (2) from soil maps of each of the four regions. TAo are the predominant soil map unit in the TAMs accounting for 291 of the 665 pedons classified (44 %) but only 15 % of the total map area of the four regions. This soil map unit is located primarily along valley floors and sidewalls and in upland areas (Fig. 9.2).

TAo occur on geomorphic surfaces ranging from the late Pleistocene to Pliocene or older in age. The weathering stage is intermediate and averages 2.6 (Table 9.6). High-centered polygons may occur on some sites, but these surfaces usually are free of patterned ground. The depth to ice-cemented

Table 9.5 Frequency distribution of soil subgroups examined in the southern Transantarctic Mountains

		Number of pedons					
Soil subgroup	Symbol	Darwin	Beardmore	Shackleton	Scott	Total	% of total
Typic Anhyorthels	TAo	39	48	13	34	134	46.7
Typic Haplorthels	THo	0	0	0	3	3	1.0
Lithic Anhyorthels	LAo	0	5	0	7	12	4.2
Lithic Haplorthels	LHo	0	0	0	1	1	0.3
Glacic Haplorthels	GAo	0	3	0	6	9	3.1
Nitric Anhyorthels	NAo	2	2	2	3	9	3.1
Salic Anhyorthels	SAo	2	0	0	0	2	0.7
Petronitric Anhyorthels	PnAo	3	2	3	0	8	2.8
Petrosalic Anhyorthels	PsAo	2	0	0	0	2	0.7
Typic Anhyturbels	TAt	30	8	6	6	50	17.4
Typic Haploturbels	THt	13	7	0	7	27	9.4
Lithic Anhyturbels	LAt	2	1	1	0	4	1.4
Lithic Haploturbels	LHt	0	0	0	1	1	0.3
Glacic Haploturbels	GAt	6	9	3	3	21	7.3
Nitric Anhyturbels	NAt	0	2	0	0	2	0.7
Petronitric Anhyturbels	PnAt	0	1	0	0	1	0.3
Petrosalic Anhyturbels	PsAt	1	0	0	0	1	0.3
Total		100	88	28	71	287	100

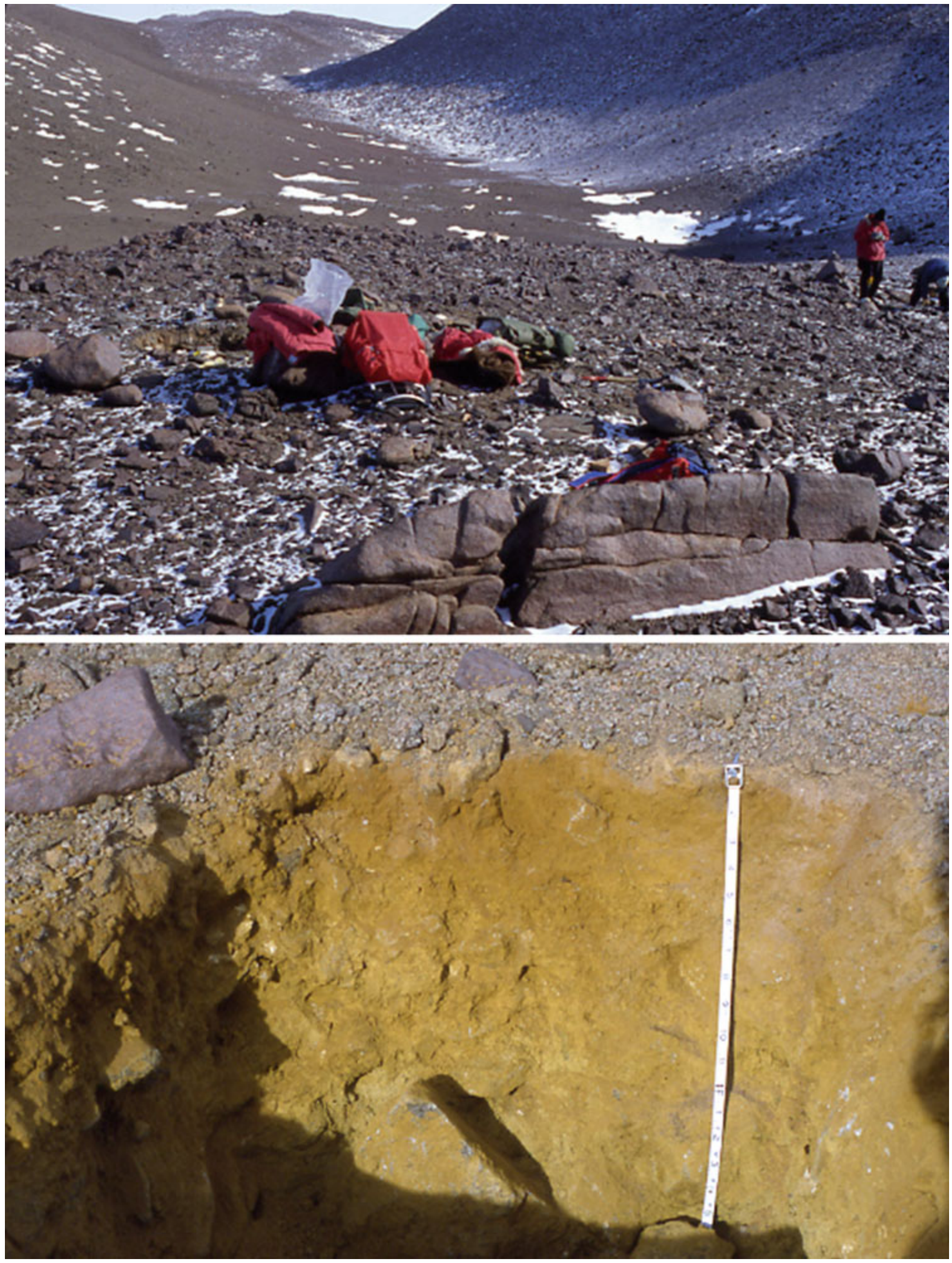

Fig. 9.2 Landform and soil (TAo) in the Darwin Mountains (pedon 78-41) (photos by J. Bockheim)

permafrost is greater than 100 cm on nearly two-thirds of the sites. The occurrence of "dry-frozen" permafrost is consistent with the existence of anhydrous conditions in these soils.

A typical profile contains a moderately well-developed desert pavement over a Bw horizon that averages 16 cm in thickness (range = 0–80 cm) that is weakly coherent, enriched in dolerite and sandstone ghosts, and contains salt encrustations or occasionally a few salt flecks. The salt stage is intermediate at 2.2; the average EC of the salt-enriched horizon is 5.5 dS/m; and the profile contains around 900 mg/cm^2 of salts to a depth of 70 cm (Table 9.6). Salt pans occur in about 25 % of these soils, but the thickness and/or salt concentration are insufficient for them to be classified in nitric, salic, "petronitric," or "petrosalic" subgroups.

9.4.3.2 Typic Anhyturbels

This is the second most abundant soil map unit in the southern TAM, accounting for 17 % of the pedons examined and for 43 % of the total map area of the region. This soil map unit is located primarily in xerous and ultraxerous regions (Fig. 9.3).

TAt occur on geomorphic surfaces ranging from the late Pleistocene to Pliocene or older in age. The weathering stage

Table 9.6 Average values of key properties of soil subgroups in the southern Transantarctic Mountains

Soil subgroup	No. Pedons	Depth to or thickness (cm)						Max. CDE[a]	Salt Stage	Weathering stage	Max. EC (dS/m)	Salts to 70 cm (mg/cm^2)	NO_3^- ($mmol_c/L$)	Cl^-
		Ground ice	Staining	Coherence	Vis. Salts	Ghosts	Ice cement							
Typic Anhyorthels	125	>100	15	>26	17	11	>64	20	2.2	2.6	5.4	915	23	2.7
Typic Haplorthels	3	>100	24	>48	14	18	>53	18	2.5	3.7	7.3	1258	3.1	0.22
Lithic Anhyorthels	12	>100	6	34	18	2	>39	19	2.0	2.0	26	1389	–	–
Lithic Haplorthels	1	–	–	–	–	–	–	–	–	–	–	–	–	–
Glacic Haplorthels	9	27	0	3	0	0	27	14	0	1.0	–	–	0.8	0.6
Nitric Anhyorthels	7	>100	28	21	36	16	>95	22	4.3	4.4	13.5	3154	248	3.5
Salic Anhyorthels	2	>100	>105	>105	93	25	>105	24	4.0	5.0	40	5815	–	–
Petronitric Anhyorthels	7	>100	32	>100	48	24	>100	24	4.5	5.1	27	3000	367	10
Petrosalic Anhyorthels	2	>100	14	48	19	18	>85	23	4.0	3.0	5.5	1550	–	–
Typic Anhyturbels	39	>100	11	>23	9	8	>39	21	1.5	2.1	2.5	585	13	2.8
Typic Haploturbels	16	>100	0	15	0	0	31	16	0.0	1.0	3.6	210	1.2	2.0
Lithic Anhyturbels	2	>100	44	58	44	7	>58	18	4.0	4.0	2.3	678	–	–
Lithic Haploturbels	1	–	–	–	–	–	–	–	–	–	–	–	–	–
Glacic Haploturbels	17	20	0	3	0	0	20	11	0	1.0	0.19	39	6.3	2.2
Nitric Anhyturbels	2	>100	16	12	16	20	>75	20	4.0	3.5	–	–	10	1.8
Petronitric Anhyturbels	1	>100	28	>110	18	21	>110	24	5.0	5.0	–	–	450	1.4
Petrosalic Anhyturbels	1	>100	>105	>105	93	25	>105	24	4.0	5.0	48	9,000	–	–

[a]CDE Color-development equivalents (Buntley and Westin 1965)

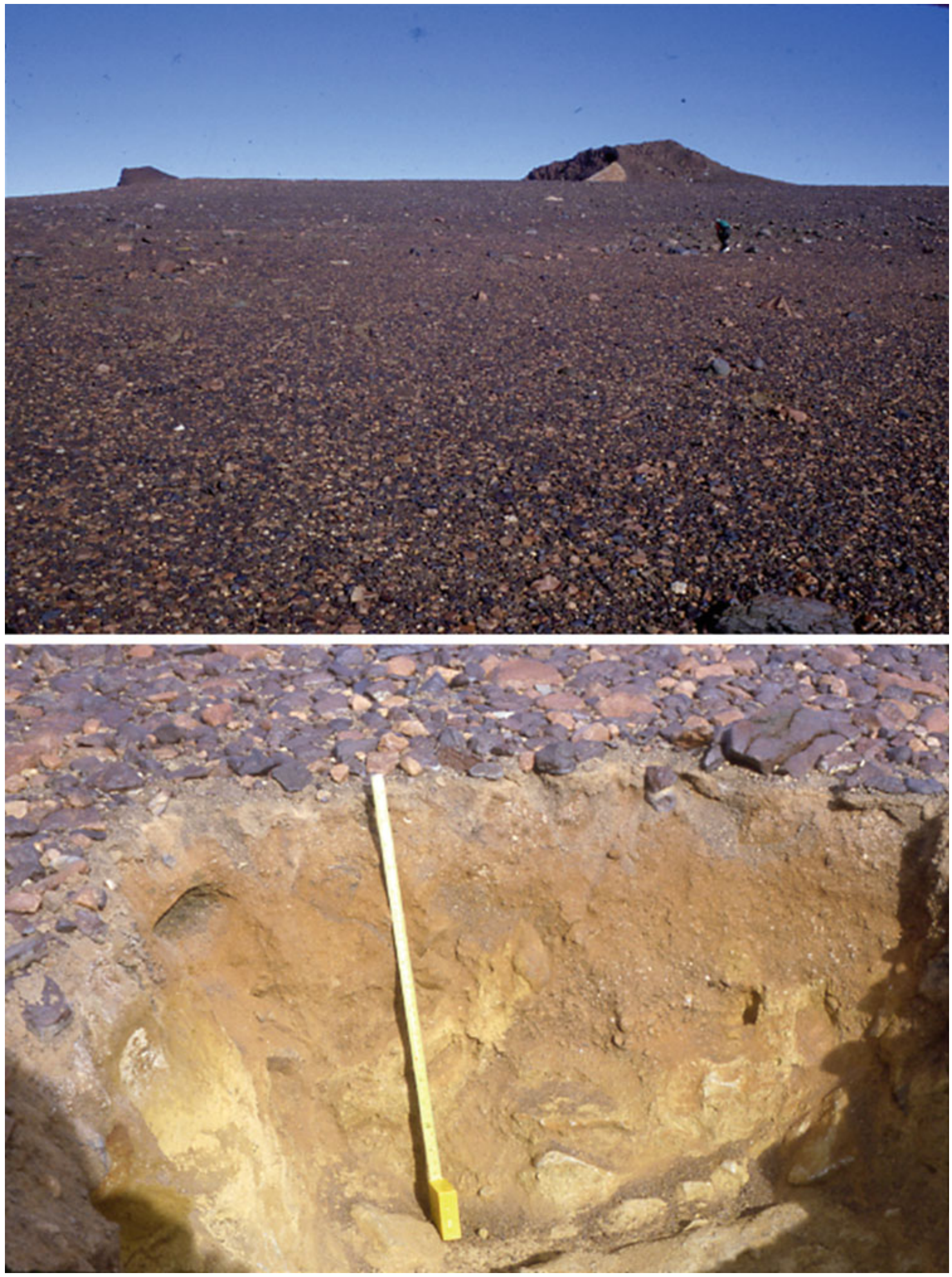

Fig. 9.3 Landform and soil (TAt) in the Darwin Mountains (pedon 78-34). Note the cryoturbated sandstone material residuum within the diorite-rich till (photos by J. Bockheim)

averages 2.0 (Table 9.6). Patterned ground is ubiquitous on landforms containing TAt, particularly flat-centered and high-centered polygons and occasionally frost boils. Some TAt contains sand wedge casts. Ice-cemented permafrost occurs within 50 cm of the surface in about half of the profiles investigated.

A typical TAt profile includes a desert pavement over a Bw horizon that is 11 cm thick (range = 0–48 cm), weakly coherent, enriched in dolerite and sandstone ghosts, and contains salt encrustations or occasionally a few salt flecks (Fig. 9.3). The salt stage is 1.5; the average EC of the salt-enriched horizon is 2.5 dS/m^2; and the profile contains around 600 mg/cm^2 of salts to a depth of 70 cm (Table 9.6). Salt pans are occasionally found in these soils.

9.4.3.3 Glacic Anhyorthels and Glacic Anhyturbels

Glacic Anhyturbels and Anhyorthels are common soil map units in the TAMs, comprising about 5.4 % of the pedons described and 1 % of the regions (Fig. 9.4). These soils occur on ice-cored drift adjacent to most, if not all, of the outlet and subsidiary glaciers in the region. These surfaces

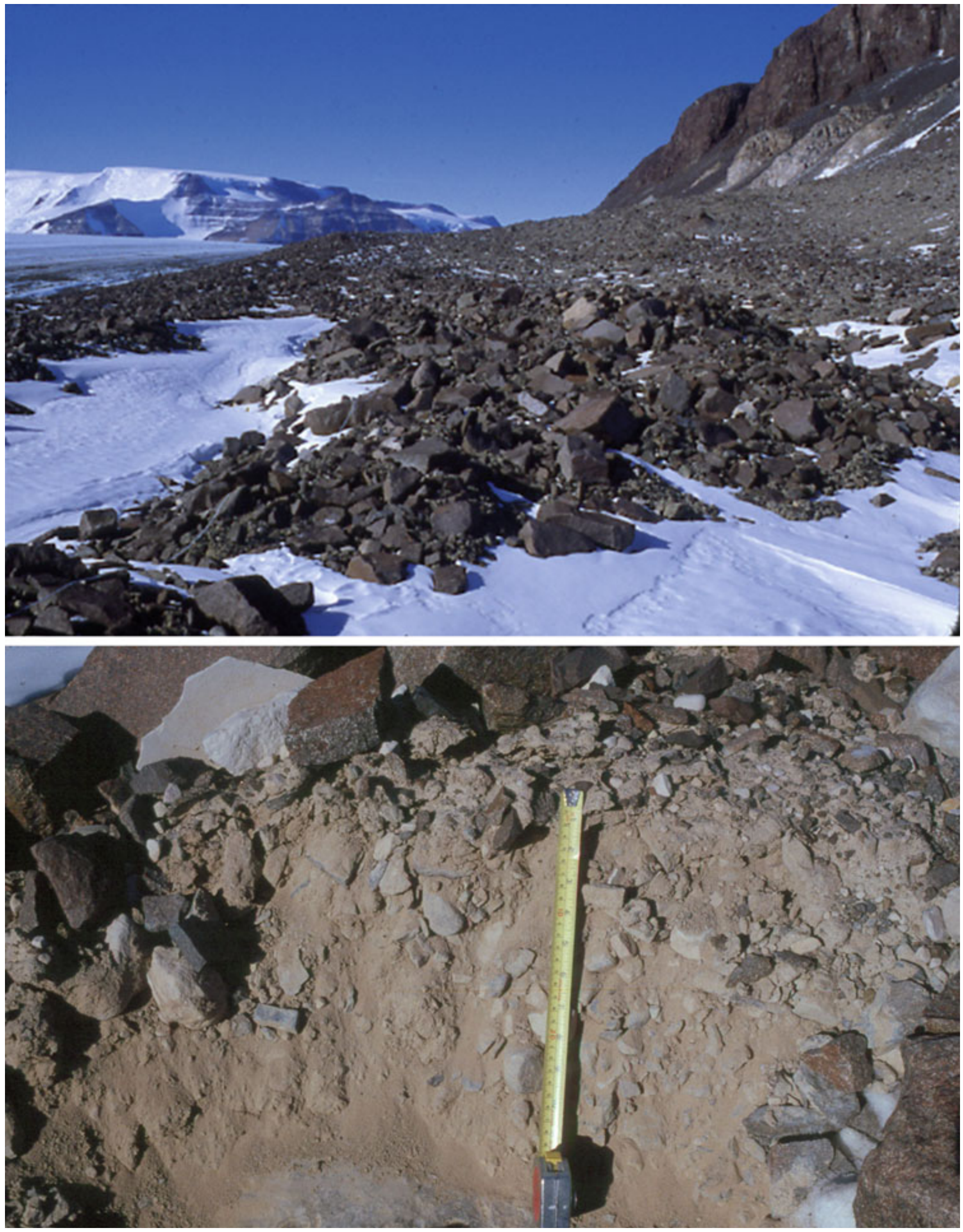

Fig. 9.4 Landscape and soil (Glacic Anhyturbels) in the Britannia range, Hatherton Glacier area (pedon 78-15) (photos by J. Bockheim)

are of late Pleistocene age. The weathering stage is 1.1 (Table 9.6). Patterned ground is common, particularly in the form of high-centered polygons. The glacic layer occurs at depths of 7–50 cm from the surface (average = 21 cm) and is >30 cm thick.

A typical Glacic Anhyturbel profile includes a weakly developed desert pavement over a Cn horizon that has minimal staining, is weakly coherent, and has either no salts or thin salt encrustations beneath clasts. The salt stage is 0.2; the average EC of the salt-enriched horizon is 0.32 dS/m (Table 9.6); and the profile contains around 60 mg/cm^2 of salts to a depth of 70 cm.

9.4.3.4 Typic Haploturbels and Typic Haplorthels

Typic Haploturbels and Typic Haplorthels comprise 10 % of the pedons examined and 11 % of the mapped areas, primarily along edge of the Ross and Weddell Seas regions (Fig. 9.5). These soils occur predominantly on drift from the LGM in coastal localities where the mean annual water-equivalent precipitation is 150–200 mm year^{-1}.

Patterned ground is common on these soil map units, primarily as flat-centered polygons. Ice-cemented permafrost occurs within 31 cm of the surface (Table 9.6). Because these soils are young and poorly developed, they have an

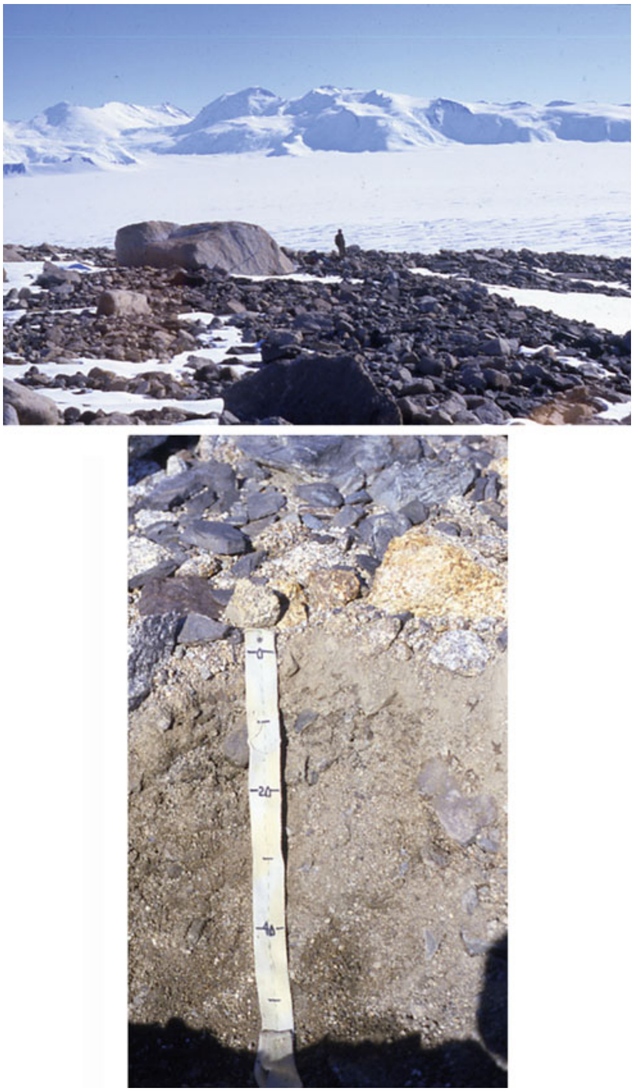

Fig. 9.5 Landscape and soil (Typic Haploturbels) at Mount Kyffin, lower Beardmore Glacier area (pedon 85-12SW) (photos by S.C. Wilson)

average weathering stage of 1.0. A typical Typic Haploturbels profile includes a weakly developed desert pavement over a Cox horizon that has either no salts or weak salt encrustations beneath clasts. The salt stage is 0.6; the average EC of the salt-enriched horizon is <0.2 dS/m; and the profile contains <100 mg/cm^2 of salts to a depth of 70 cm.

9.4.3.5 Nitric and Salic Anhyorthels and Anhyturbels

These soils comprise 7.8 % of pedons described but because they comprise a small area they are not shown on the soil maps. These soils are usually of mid- to early Pleistocene or older in age. These soils generally lack patterned ground and feature dry-frozen permafrost in the upper 1 m. Consistent with their age, these soils are deeply stained (average = 27 cm), are coherent to depths in excess of 1 m, and have a weathering stage that averages 4.4 (Table 9.6). The salt stage averages 4.3, and the salt pan averages 12 cm in thickness. The average EC of the salt-enriched horizon is 41 dS/m; and the profile contains an average of 5,500 mg cm^{-2} of salts to a depth of 70 cm. A Nitric Anhyorthel landform and soil are depicted in Fig. 9.6.

9.4.3.6 Petrosalic and Petronitric Anhyorthels and Anhyturbels

We found 63 (9.5 % of soils classified) of these highly salt-enriched soils in the TAM, primarily on Pliocene and older surfaces. Their distribution is too limited to show on maps at scales of 1:5 million. The weathering stage averages 4.3 (Table 9.6). Only relict patterned ground is found on some surfaces, and fossil sand wedges may occur in these soils. These soils contain dry-frozen permafrost in the upper 1 m, and the profiles often contain <3 % moisture content throughout. The soils are strongly deliquescent and initiate considerable breakdown of coarse fragments in the zone of salt enrichment.

A typical profile contains a strongly developed desert pavement over a thin (ca. 10 cm) highly stained Bw horizon, and the salt pan which averages 15 cm in thickness. This pan may be weakly cemented, strongly cemented, or indurated. Whereas in the McMurdo Dry Valleys, the cementing salt is commonly NaCl, $NaNO_3$ often causes cementation in the southern TAMs. The salt stage averages 4.3; the average EC of the salt-enriched horizon averages 45 dS m^{-1}, and the profiles contain an average of 5,600 mg/cm^2 of salts to a depth of 70 cm.

9.4.3.7 Lithic Anhyorthels, Lithic Anhyturbels, Lithic Haplorthels, and Lithic Haploturbels

Although we found only 26 lithic soils (soils with bedrock within 50 cm of the surface), they are probably very common on nunataks and in steeply sloping areas of the southern TAM (Fig. 9.7). Lithic soils account for 30 % of the soils mapped in the region. Because of their location, soils with lithic contacts are often quite old. We investigated several LAo derived from thin Sirius drift over sandstone and dolerite bedrock in the upper Beardmore Glacier region. On average the salt and weathering stages averaged 2.3 and 2.4, respectively (Table 9.6).

9.4.3.8 Rockland and Other Land Types

As much as 20 % of the ice-free areas of the southern TAM are composed of exposed bedrock, rather than soils. However, our method of soil mapping did not allow us to distinguish these land types.

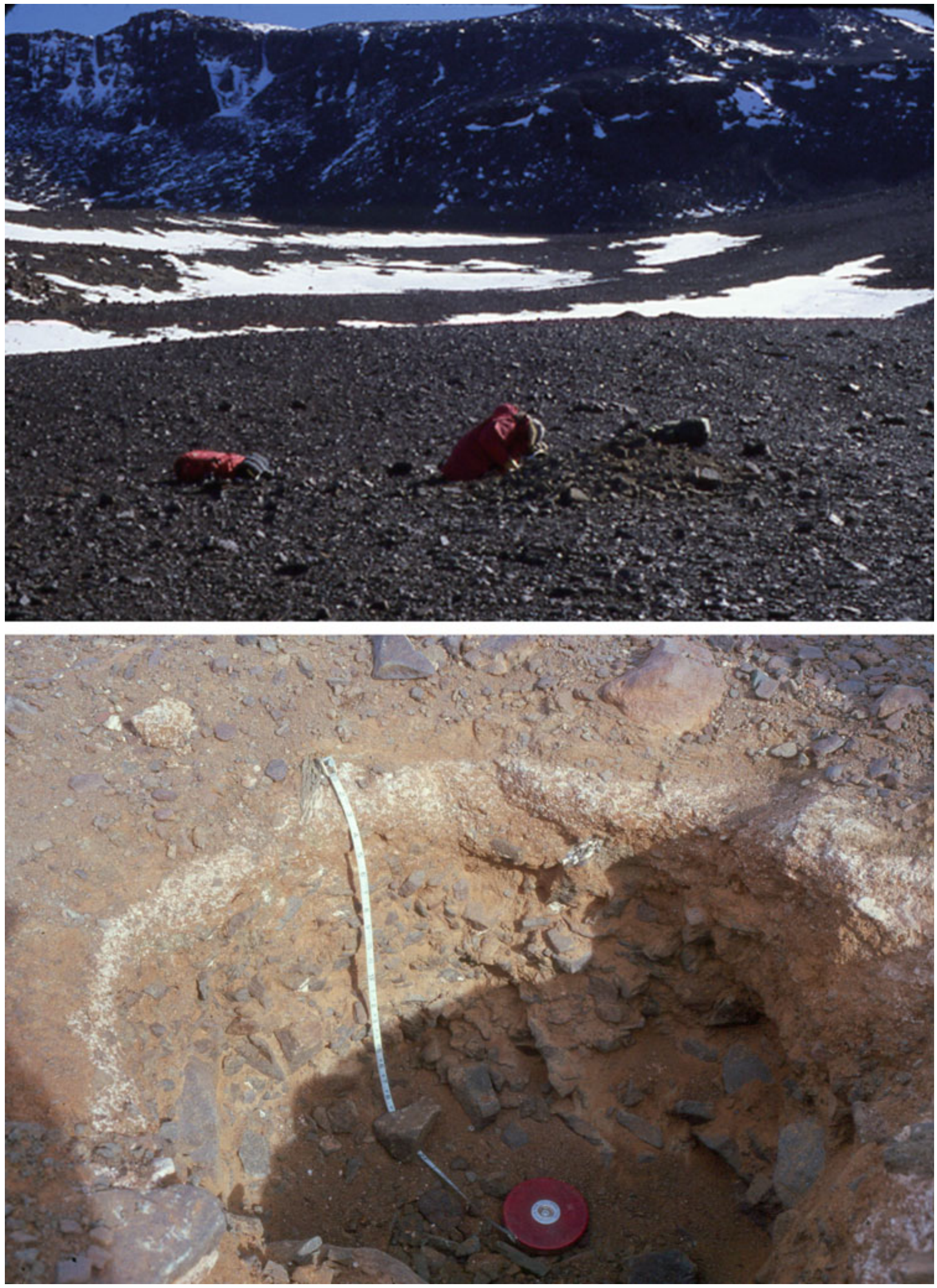

Fig. 9.6 Landform and soil (Nitric Anhyorthel) from the Britannia range, Hatherton Glacier area (pedon 78-47) (photos by J. Bockheim)

9.4.4 Soil Maps

Reconnaissance soil maps of the four study areas are provided in Fig. 9.8, 9.9, 9.10 and 9.11.

9.4.5 Soil Map Accuracy and Validation

Using the criteria in Table 9.4, we estimate confidence in soil mapping to be 12 in the Darwin-Byrd and Beardmore Glacier regions and 3 in the Shackleton and Scott Glaciers regions. By way of comparison, our confidence in soil maps in the Taylor and Wright Valleys of the McMurdo Dry Valleys is 12 and 14, respectively.

9.5 Discussion

9.5.1 Soils and Landscape Evolution

There is a correspondence between landform type and soil taxa (Table 9.7). Haplorthels and Haploturbels occur on

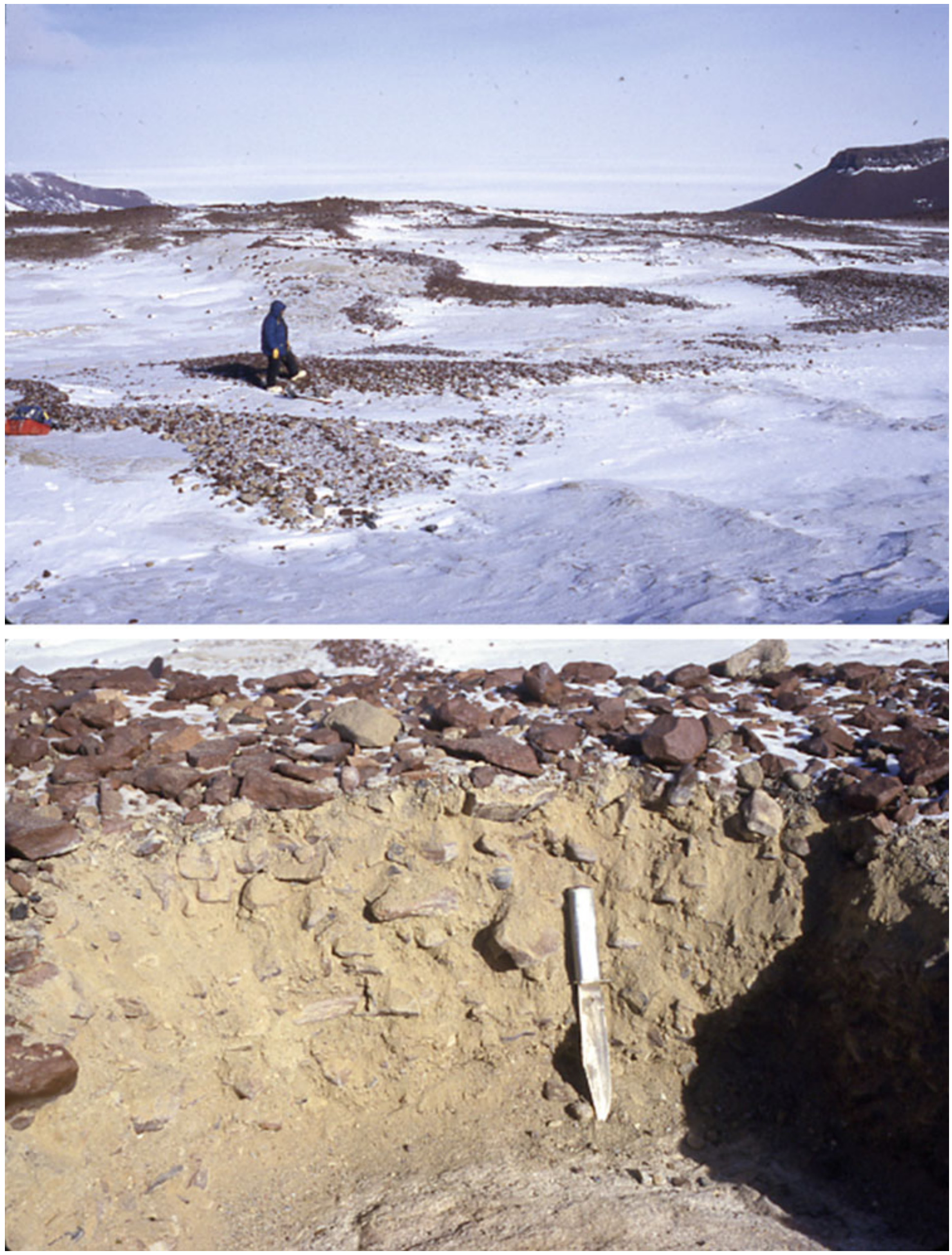

Fig. 9.7 Landscape and soil (Lithic Anhyorthels) on the Mt. Falla platform, Beardmore Glacier area (85-12JGB) (photos by J. Bockheim)

landforms in coastal and inland areas where water is available, e.g., adjacent to streams, lakes, and other hyporheic areas. In contrast Anhyorthels and Anyturbels occur along basin floors and in upland valleys that receive less than 50 mm of annual water-equivalent precipitation and have soil moisture contents of <3 %, ca. anhydrous conditions.

Typic Haplorthels occur on alluvial fans, deltas, alluvial flats, adjacent to braided streams, and ice-marginal streams where the sediments are coarse textured, e.g., sand and gravel. Similarly, THo occur on talus slopes and debris flows that contain abundant cobbles and stones, and THt exist in glacial drainage channels and on active rock glaciers and pattern ground. Glacic soil subgroups occur alongside alpine glaciers and on medial moraines and active rock glaciers. Lithic soil subgroups exist on rock outcrops and on nunataks throughout the study areas. All of the soil taxa may occur on ground, end, lateral, and disintegration moraines, but TAo are most common.

The soils show a developmental sequence from the coast inland (Bockheim and McLeod 2006; Bockheim and McLeod 2008). The developmental sequence contains Glacic Haploturbels on mid-Holocene surfaces, Typic Haploturbels on landforms from the LGM, TAo on late Quaternary surfaces, Salic and Nitric Anhyorthels on deposits of mid- to early Quaternary age, and “Petrosalic/Petronitric” Anhyorthels on late Tertiary surfaces.

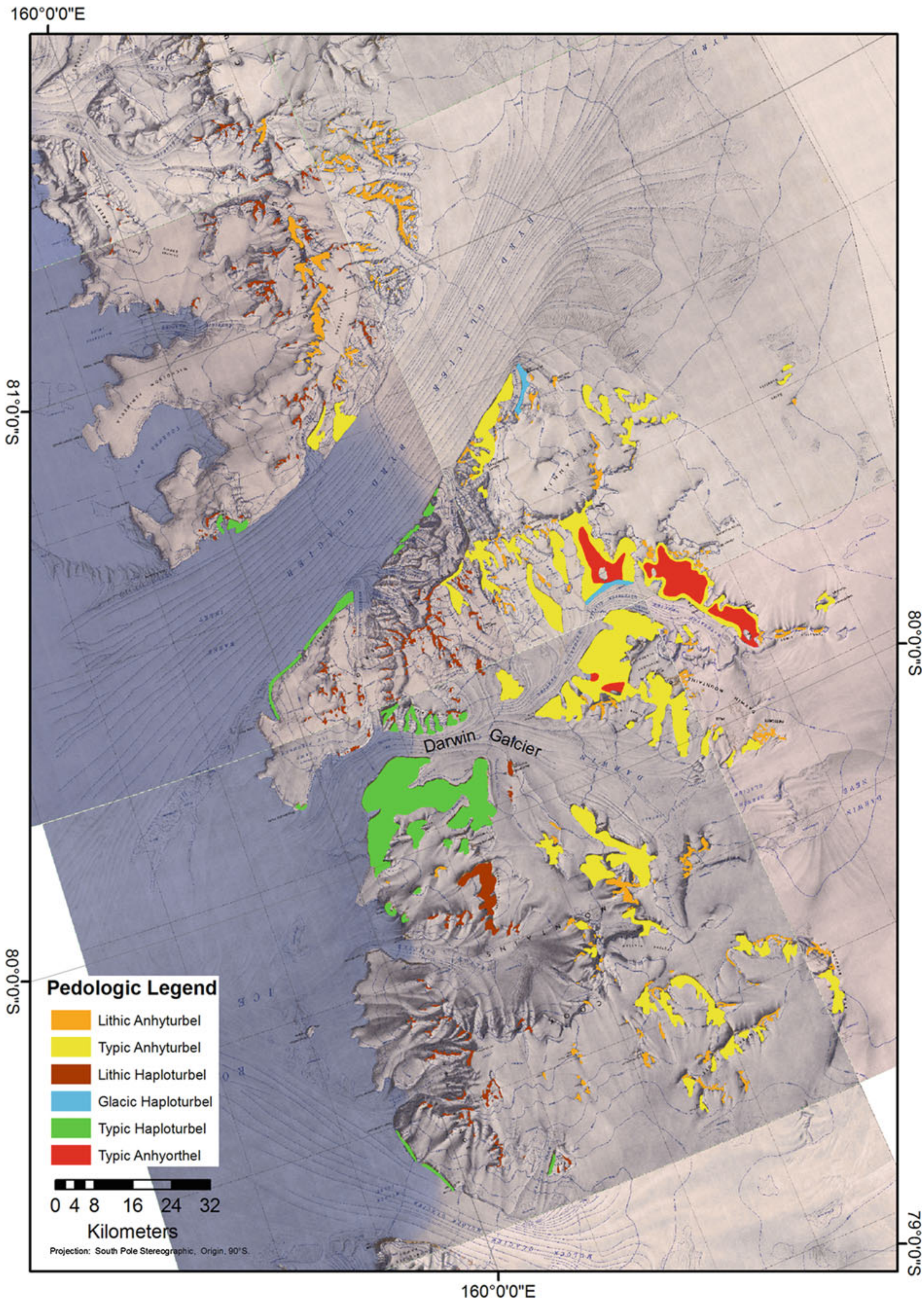

Fig. 9.8 Reconnaissance soil map of the Darwin Glacier area

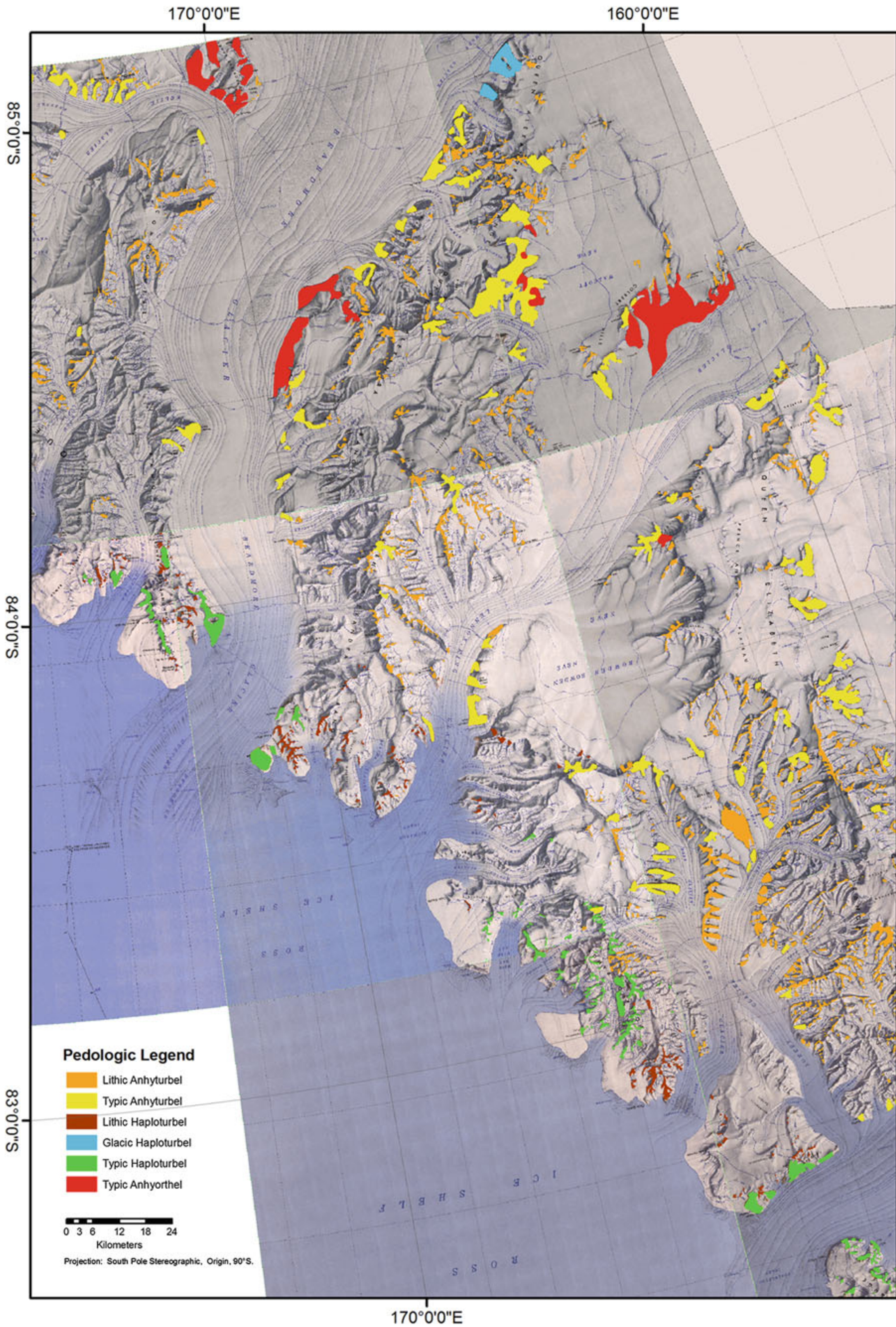

Fig. 9.9 Reconnaissance soil map of the Beardmore Glacier region

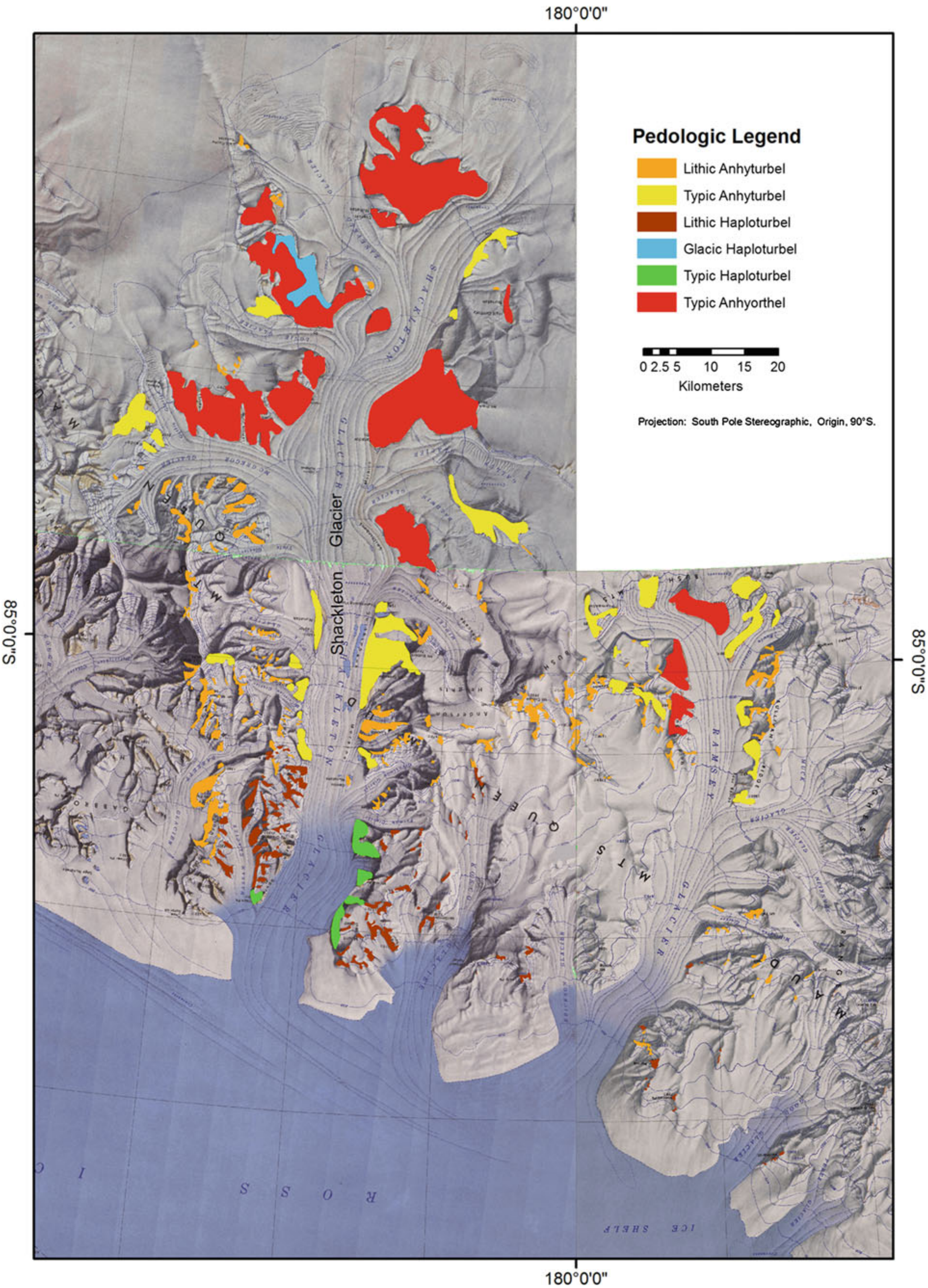

Fig. 9.10 Reconnaissance soil map of the Shackleton Glacier area

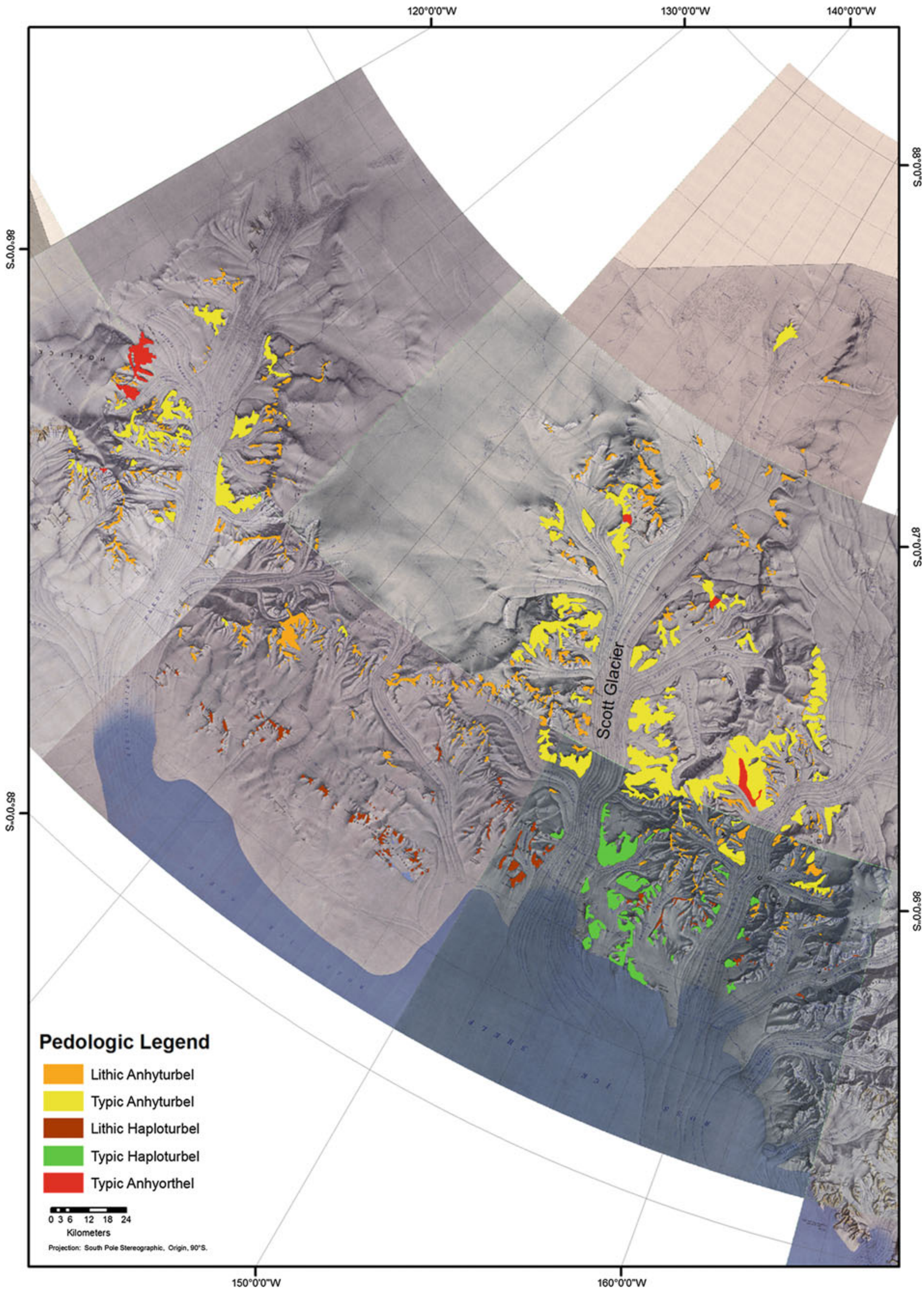

Fig. 9.11 Reconnaissance soil map of the Reedy–Scott Glacier area

Table 9.7 Soil taxa in the southern Transantarctic Mountains in relation to landform

Soil great group/ subgroup	Abbreviation	Common landforms	For soil organisms[a]
Haplorthels			
Glacic	GHo	Alpine glacier	+
Typic	THo	Alluvial fan, alluvial flat, alpine glacier, braided stream, debris flow, delta, ice marginal stream, talu-slope, moraine	+
Haploturbels			
Glacic	GHt	Alpine glacier, medial moraine, rockglacier (active)	+
Lithic	LHt	Rock outcrops	=
Typic	THt	Glacial drainage channel, patterned ground, rockglacier (active), moraine	+
Anhyorthels			
Lithic	LAo	Dikeland, horn, nunatak	=
Salic	SAo	Moraine	−
Petrosalic	PsAo	Moraine	−
Gypsic	GpAo	Moraine	−
Petrogypsic	PgAo	Moraine	−
Nitric	NAo	Moraine	−
Petronitric	PnAo	Moraine	–
Typic	TAo	Alluvial fan, alluvial flat, basin floor, cirque, debris flow, delta, disintegration moraine, dune, giant ripple, kame, inactive rockglacier, sand sheet, talus slope, volcanic ash, moraine	=
Anhyturbels			
Lithic	LAt	Rock outcrops, nunataks	=
Salic	SAt	Moraine	−
Petrosalic	PsAt	Moraine	−
Gypsic	GpAt	Moraine	−
Petrogypsic	PgAt	Moraine	−
Nitric	NAt	Moraine	−
Petronitric	PnAt	Moraine	−
Typic	TAt	Alpine glacier, disintegration moraine, patterned ground, rockglacier (active, inactive), moraine	=
Aquiturbel			
Typic	TQt	Blockfield	+

[a]Favorability for organisms: + favorable, = possibly favorable, − unfavorable

9.5.2 Pedodiversity

The concept of pedodiversity has not received much attention in Antarctica. Bockheim (2007) developed a "pedodiversity index" that was derived from the number of soil subgroups divided by the geographic area. Despite its comparatively small size (68 km^2), Arena Valley had an unusually high pedodiversity index (PDI) of 0.19 for Arena Valley, which contrasted with values of 0.05–0.026 for other regions in the McMurdo Dry Valleys. The southern TAM have a low pedodiversity, because of the large ice-free areas and despite the strong longitudinal, latitudinal, and elevational gradients therein. Pedodiversity indices ranged between 0.0017 and 0.0050, which is less than in the MDV (Chap. 8), where values range between 0.026 and 0.05.

9.5.3 Soil Taxa and the Occurrence of Organisms

Water is the limiting factor controlling the distribution and diversity of organisms in continental Antarctica, including cryptogams (Adams et al. 2006), microarthropods (Kennedy 1993), nematodes (Powers et al. 1998; Courtright et al.

Table 9.8 Soil organisms in relation to soil properties and taxa, McMurdo Dry Valleys

Organisms	Locations	Favorable soil properties	Reference	Soil taxa[a]
Prokaryotes, algae, yeasts, filamentous fungi, lichens and mosses, protozoa, tardigrades, rotifers, nematodes, arthropods	Granite Harbor, Cape Royds, lower Taylor Valley, Garwood V., Miers V., Marble Point, Cape Evans	Abundant soil moisture, abundant soil organic C, few salts	Adams et al. (2006)	THt, GHt, THo, TAo
Nematoda, tardigrades, rotifers, microarthropods	Lower Taylor Valley	Abundant soil moisture	Kennedy (1993)	THt, THo
Nematodes	Lower Taylor Valley	Abundant soil moisture, abundant soil organic C, N, few salts	Powers et al. (1998)	THt, THo
Nematodes	Lower Taylor Valley, Wright V., Labyrinth, Lake Vanda, Lake Brownworth, Victoria V.	Abundant soil moisture, abundant soil organic C, few salts	Courtright et al. (2001)	THt, THo, TAo
Nematodes	Bull pass	Abundant soil moisture, abundant soil organic C, N, few salts	Poage et al. (2008)	TAo, THo

[a]Determined from map by Bockheim and McLeod (2008) and Bockheim et al. (2008): THt Typic Haploturbels; GHt Glacic Haploturbels; THo Typic Haplorthels; TAo Typic Anhyorthels

2001), and microorganisms (Bamforth et al. 2005). More specifically, microbial and soil invertebrate abundance are significantly related to vegetation and vegetation-associated soil properties (e.g., water content, organic C, total N) (Powers et al. 1998; Yergeau et al. 2006). There is often a negative correlation with the number of soil invertebrates and soil salinity (Powers et al. 1998; Courtright et al. 2001; Poage et al. 2008). Microfauna (nematodes, rotifers, and tardigrades) are found on nunataks in Antarctica (Sohlenius et al. 1996). In some cases their dispersal may be due to wind (Michaud et al. 2012).

In Table 9.8 we show the favorability of soil taxa identified in the TAMs with regards to the occurrence of soil organisms. The most favorable soil taxa are the Haplorthel and Haploturbel great groups and soils with glacic horizons. The least favorable soil taxa are those containing abundant salts, i.e., salic, "petrosalic," gypsic, petrogypsic, nitric, and "petronitric" subgroups.

9.6 Summary

The ice-free area of the southern TAM is 8,900 km^2. We prepared fifth-order reconnaissance soil maps (1:10 million scale) for the TAM (3 map sheets). Soils of the southern TAM are dominantly Orthels (68 %), reflecting the hyperarid soil climate and low amount of cryoturbation. The dominant soil map unit was TAo, which occur on a variety of landforms, including alluvial fans and flats, basin floor, cirques, debris flows deltas, dunes, giant ripples, kames, inactive rock glaciers, talus slopes, and ground and constructional moraines. As in temperate regions, soils and landforms coevolve in the TAM. The soil pattern represents an age-related sequence of soils that includes Glacic Haploturbels (mid-Holocene), Typic Haploturbels (LGM), TAo (late Quaternary), Salic/Nitric Anhyorthels (mid- to early Quaternary), "Petrosalic/Petronitric" Anhyorthels (late Tertiary). Soils were assessed for their suitability for organisms. Haplorthels and Haploturbels appear to be the taxa that most commonly contain cryptogams, microarthropods, nematodes, and microorganisms.

Acknowledgments This study was encouraged by the Transantarctic Mountains workshop held on September 6–9, 2006 at the Byrd Polar Research Center, The Ohio State University (http://www-bprc.mps.ohio-state.edu/workshops/tam_2006.php). We are grateful to D.H. Elliot and W.B. Lyons, for their encouragement. This research was partially supported by the U.S. National Science Foundation, Office of Polar Programs, Antarctic Sciences (JGB) and by the New Zealand Foundation for Research, Science and Technology and Antarctic New Zealand (MM)

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10 Soils of Ellsworth Land, the Ellsworth Mountains

James G. Bockheim and Carlos E.G.R. Schaefer

10.1 Introduction

The Ellsworth Mountains occur along the southern edge of the Ronne-Filchner Ice Shelf in West Antarctica (Fig. 2.1) and are subdivided by the Minnesota Glacier into the Heritage Range to the east and the Sentinel Range to the west (Fig. 10.1). The Sentinel Range contains the highest peaks in Antarctica, including the Vinson Massif (4,897 m). The Ellsworth Mountains extend for 350 km with a NNW-SSE trend and are bounded by longitudes 78° and 87° W and latitudes 80° 30′ and 77° 15′ S.

The Ellsworth Mountains have an ice-free area of 2,095 km^2, which constitutes 4.2 % of the total (49,500 km^2) Antarctica (Fig. 2.2, Table 2.1). The Ellsworth Mountains are important for studying the glacial history of Antarctica, because they occur near the present-day grounding line between the West Antarctic Ice Sheet and the Ronne-Filchner Ice Shelf (Denton et al. 1992; Bentley and Anderson 1998).

Previous soils studies are limited to 22 pedons by Bockheim and Leide (1980) and Denton et al. (1992), 23 pedons by I.B. Campbell and G.G.C. Claridge (http://www.landcareresearch.co.nz./databases), and 30 pedons by Schaefer et al. (unpublished) from the 2012/2013 Brazilian Antarctic Expedition.

The objectives of this study are to (1) delineate the key soil taxa in ice-free areas of the Ellsworth Mountains, (2) evaluate the importance of the soil-forming factors and processes in the development of these taxa; and (3) interpret the pedodiversity and suitability of the soil taxa as a habitat for organisms.

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10.2 Study Area

The climate of the Ellsworth Mountains is strongly controlled by proximity to the Ronne-Filchner Ice Shelf and elevation. The mean annual air temperature at the 1,000 m level is estimated to be −25 °C (Fig. 2.5), and the average annual accumulation of water-equivalent precipitation likely ranges from 150 to 175 mm $year^{-1}$ (Fig. 2.4).

The dominant bedrock types from oldest to youngest include the Precambrian Minaret Group (marble), the middle to late Cambrian Heritage Group (sedimentary rocks), the upper Cambrian to Devonian Crashsite Group (predominantly quartzites), the Permo-Carboniferous Whiteout Conglomerate, and the Permian Polestar Formation (marine and terrestrial tillites) (Webers et al. 1992) (Fig. 10.2).

Denton et al. (1992) observed two major glacial erosion features in the Ellsworth Mountains. Exposed mountains show classic features of alpine glacier erosion, including horns, arêtes, and sharp spurs. These features are especially evident in the Sentinel Range but are also present in the Heritage Range. A second glacial erosional feature is a glacial trimline etched into alpine rides and spurs throughout the Ellsworth Mountains. Bedrock ridges above the trimline are serrated; those below the trimline lack serrations and have glacial polish and striations. Drift patches and erratics occur below the trimline. They concluded that the extensive alpine glacial erosion of the Ellsworth Mountains antedated etching of the trimline. The trimline and striations show major thickening of the West Antarctic ice sheet subsequent to this erosion. During this thickening, ice surface elevations increased from 1,300 to 1,900 m. Although they proposed two models, the surface boulder weathering and soil features suggest that the expansion of ice was during the Late Wisconsin/Holocene.

The entire area is underlaid by continuous permafrost of unknown thickness. Based on data collected from 22 pits, 41 % of the sites contained dry permafrost below 70 cm, 27 % had ice-cemented permafrost within 70 cm of the surface, 27 % had bedrock within 70 cm, and 5 % contained an ice core

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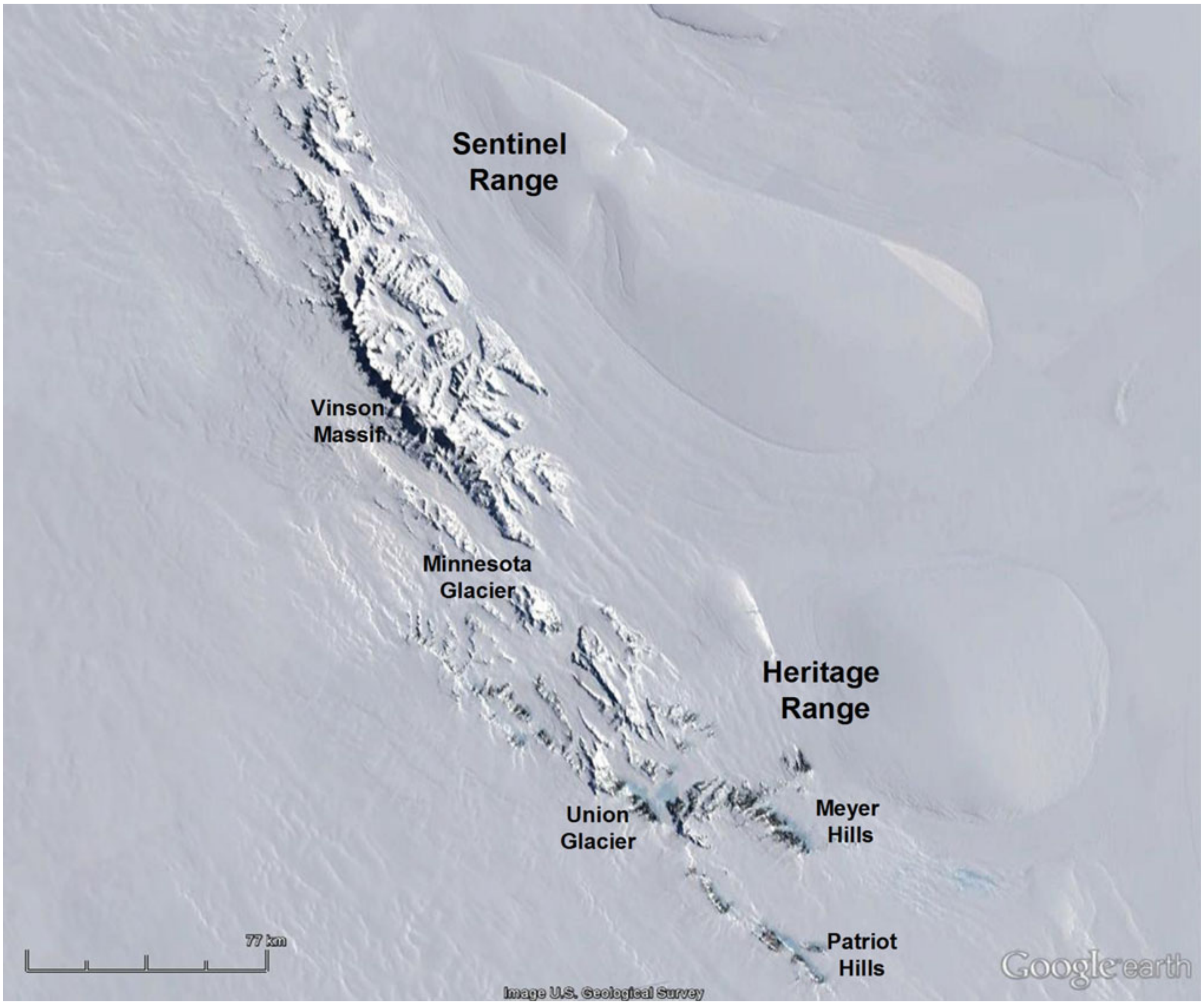

Fig. 10.1 Land satellite image of the Ellsworth Mountains with key site locations

(Bockheim, unpublished). Dry-frozen permafrost, which may be unique to Antarctica, appears to form from sublimation of moisture in ice-cemented permafrost over time. Active layer depths in drift sheets of the Ellsworth Mountains range from 15 to 50 cm (Bockheim, unpublished).

Occasional lichens and mosses were observed, especially in the Heritage Range. Unlike the McMurdo Dry Valleys, Collembola and Acari are absent in the Ellsworth Mountains (Spain 1971). Bacteria are remarkably different in the Ellsworth Mountains than in the more northerly sites and include mainly methylotrophic bacteria due to low nutrient inputs and high ultraviolet radiation levels in the summer (Yergeau et al. 2007).

10.3 Methods

10.3.1 Field

Field data include 22 pedons collected throughout the Ellsworth Mountain in 1979 and 30 pedons collected by Schaefer's team in 2012/2013. The pits by Bockheim were selected throughout the study area; the pits by Schaefer focused on elevational sequences in three key ice-free areas and various soil parent materials: Crashsite Group from Mt. Dolence (Enterprise Hills), the Minaret Group from Rhodes Bluff (Elephant Head), and the Heritage Group from the Edson Hills.

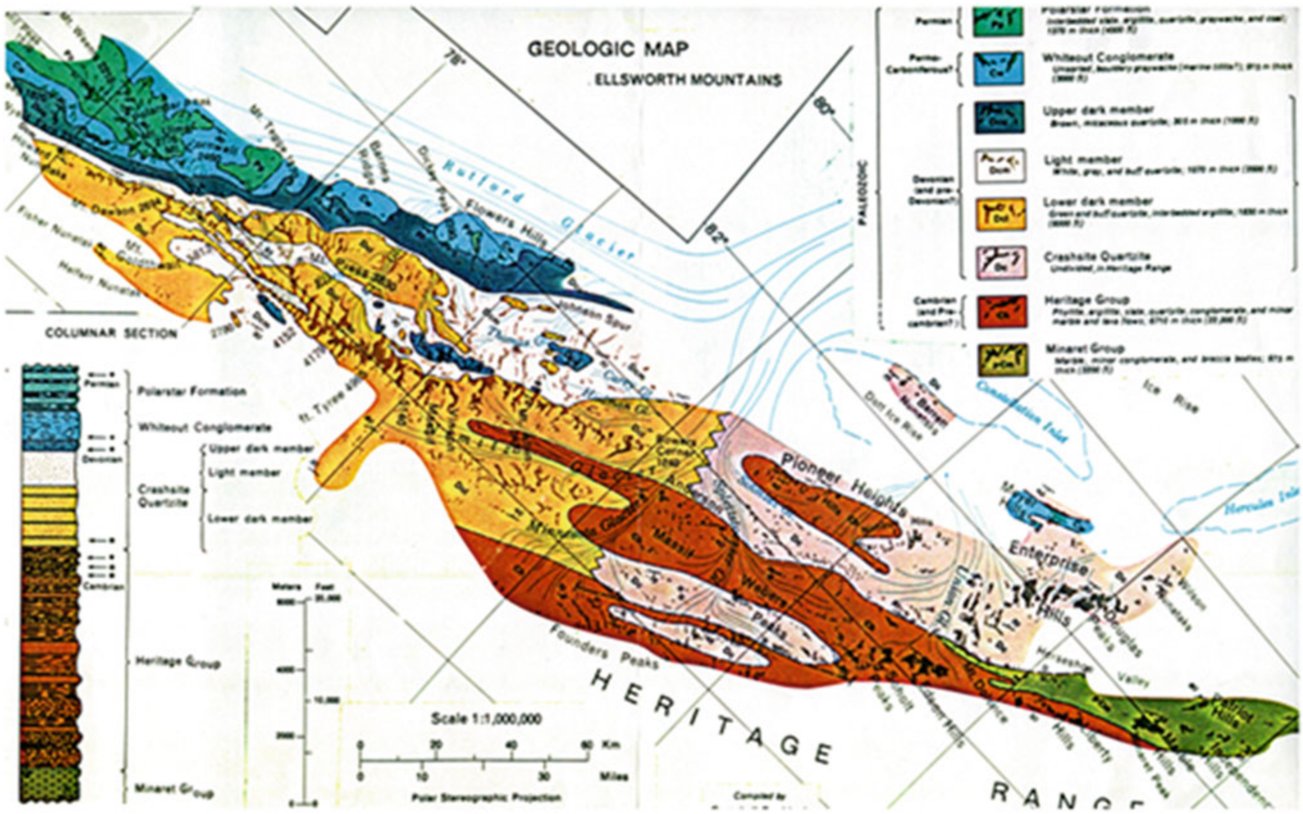

Fig. 10.2 Bedrock geology of the Ellsworth Mountains the *dark green colors* refers to the Polestar Formation (interbedded slate, argillite, quartzite, greywacke, coal); the *dark blue color* to the Whiteout Conglomerate (greywacke); the *light blue color* to the Upper dark member (micaceous quartzite); the white pattern to the Light member (quartzite); the *yellow color* to the Lower dark member (quartzite interbedded with argillite); the *pink color* to the Crashsite Quartzite; the *red color* to the Heritage Group (phyllite, artillite, slate, quartzite, conglomerates, marble); and the *light green color* to the Minaret Group (marble, conglomerate, breccia)

Soil pits were excavated to at least 100 cm, unless ice-cement, large boulders, or bedrock prevented digging to that depth. The following soil properties were measured in the field. The depth of staining refers to the thickness of the layers showing the strongest hues and chromas from oxidation of iron-bearing minerals and corresponds to the bottom of the Bw horizon. The depth of coherence refers to the thickness of consolidated soil from accumulation of weathering products such as salts and iron oxides; below the depth of coherence, soil readily caves into the pit. The depth of visible salts refers to the maximum depth for which salt encrustations beneath clasts, salt flecks, and salt cementation are readily visible to the naked eye.

The six-stage sequence described in Chap. 8 in which the form of soluble salts was related to total dissolved salts from electrical conductivity measurements and soil age, was employed in this study. The depth to ice or ice-cemented permafrost was also determined. The active (seasonal thaw) layer in the study areas varies between 15 and 50 cm; material below this depth that is not cemented by ice contains dry-frozen permafrost, i.e., perennially frozen materials lacking sufficient interstitial water to cause cementation. The weathering stage is an overall representation of the landscape/material based on the degree of surface boulder weathering, soil morphology, and patterned ground and permafrost forms (see Chap. 8).

Soils were classified into the Gelisol order to the family level (Soil Survey Staff 2010); mineral soils showing cryoturbation are classified as Turbels; mineral soils without obvious cryoturbation are Orthels. Soils with ice-cemented permafrost within 70 cm of the surface are classified as Haplorthels or Haploturbels. Soils with dry-frozen permafrost below 70 cm are classified as Anhyorthels or Anhyturbels. Soils in lithic subgroups have bedrock within 100 cm of the surface.

10.3.2 Laboratory

Several measurements were performed in the laboratory, including electrical conductivity (EC), pH, and major cations and anions in 1:5 soil:distilled water extracts (Embrapa 1997; U.S. Soil Survey Laboratory 2004). Profile quantities of salts (mg cm^{-2}) to a depth of 70 cm were calculated (see Chap. 9).

10.4 Results

10.4.1 Areas of Ice-Free Regions

The Sentinel and Heritage Ranges contain ice-free areas of 1,000 and 1,100 km^2, respectively, for a total of 2,100 km^2. This accounts for 4.5 % of the total ice-free area (49,500 km^2) of Antarctica. The largest ice-free areas include the Marble Hills, Liberty Hills, and Douglas Peaks in the Liberty Hills area, the Watlock Hills, Mt. Twiss-Carnell Peak, Maagoe Peak, Soholt Peak, Edson Hills, Enterprise Hills, and Mt. Dolence in the Union Glacier area, Mt. Hale and Mt. Epperly in the Vinson Massif area, and Mts. Dalrymple-Goldthwait in the Newcomer Glacier area.

10.4.2 Distribution of Soil Taxa

The distribution of soil taxa was determined from the initial data set, which contained primarily Typic Anhyorthels (TAo) (45 %), followed by Typic Haplorthels (THo) (23 %), Lithic Anhyorthels (LHo) (18 %), Lithic Haplorthels (LAo) (9 %), and Glacic Haplorthels (GHo) (5 %; Table 10.1). Four percent of the soils had glacic horizons (i.e., a buried ice layer within 100 cm of the surface); and 32 % had a lithic contact within 100 cm of the surface. Despite the comparatively high amounts of water-equivalent precipitation (estimated to be 150–175 mm year^{-1}) and the existence of patterned ground in some areas, there was minimal evidence of cryoturbation or cryodesiccation. Therefore, most of the soils are classified as Orthels.

10.4.3 Description of Soil Taxa

10.4.3.1 Typic Anhyorthels

Typic Anhyorthels (TAo) are a predominant soil map unit in the Ellsworth Mountains accounting for 6 of the 22 pedons classified (27 %). This soil taxon is located primarily along valley floors and sidewalls and in upland areas (Fig. 10.3). Typic Anhyorthels occur on geomorphic surfaces ranging from the Holocene to pre-LGM in age. The weathering stage is intermediate and averages 2.6 (Table 10.2). High-centered polygons may occur on some sites, but map unit usually is free of patterned ground. The depth to ice-cemented permafrost is greater than 70 cm. The occurrence of "dry-frozen" permafrost is consistent with the existence of anhydrous conditions in these soils.

A typical profile contains a moderately well-developed desert pavement over a Cox or Cn horizon that is weakly coherent, contains few ghosts and salts other than encrustations below surface clasts (salt stage = 1) (Fig. 10.3; Table 10.2). The average EC of the salt-enriched horizon is 2.0 dS/m; and the profile contains an average of 628 mg cm^{-2} of salts to a depth of 70 cm (Table 10.3). A salt pan was observed in one pedon (79-30), which may have been derived from a "window" of pre-Ellsworth drift.

Table 10.1 Distribution of soil map units in the Ellsworth Mountains

Soil taxon	Described number (%)
Typic Anhyorthels	6 (27)
Lithic Anhyorthels	8 (36)
Typic Haplorthels	3 (14)
Lithic Haplorthels	4 (18)
Glacic Haplorthels	1 (5)
Other	0
Total	22 (100)

10.4.3.2 Lithic Anhyorthels and Lithic Haplorthels

Lithic subgroups have bedrock within 50 cm of the surface. Lithic contacts occur in 54 % of the soils examined (Table 10.1). Because of their location, soils with lithic contacts may be quite old. On average the salt and weathering stages averaged 1.6 and 2.1, respectively (Table 10.2). The profile contains an average of 236 mg cm^{-2} of salts to a depth of 70 cm (Table 10.3). A typical landform and soil is shown in Fig. 10.4.

10.4.3.3 Typic Haplorthels

Typic Haplorthels comprise 14 % of the pedons examined (Table 10.1). These soils occur on drifts of all ages and where snowmelt contributes moisture to the profile. Ice-cemented permafrost occurs within 70 cm of the surface (Table 10.2). These soils have an average weathering stage of 2.0. A typical Typic Haplorthels profile includes a weakly developed desert pavement over a Cox or Cn horizon that has salt encrustations beneath surface clasts (Fig. 10.5). The salt stage is 1.8; the average EC of the salt-enriched horizon is <0.2 dS/m; and the profile contains 408 mg cm^{-2} of salts to a depth of 70 cm (Table 10.3).

10.4.3.4 Glacic Haplorthels

Glacic Haplorthels comprise 5 % of the soils classified in the Ellsworth Mountains (Table 10.1). These soils occur on ice-cored drift in the Cagle Peaks area and in the Edson, Liberty, Marble, Patriot, and Independence Hills of the Heritage Range. These surfaces are of Holocene age. The weathering

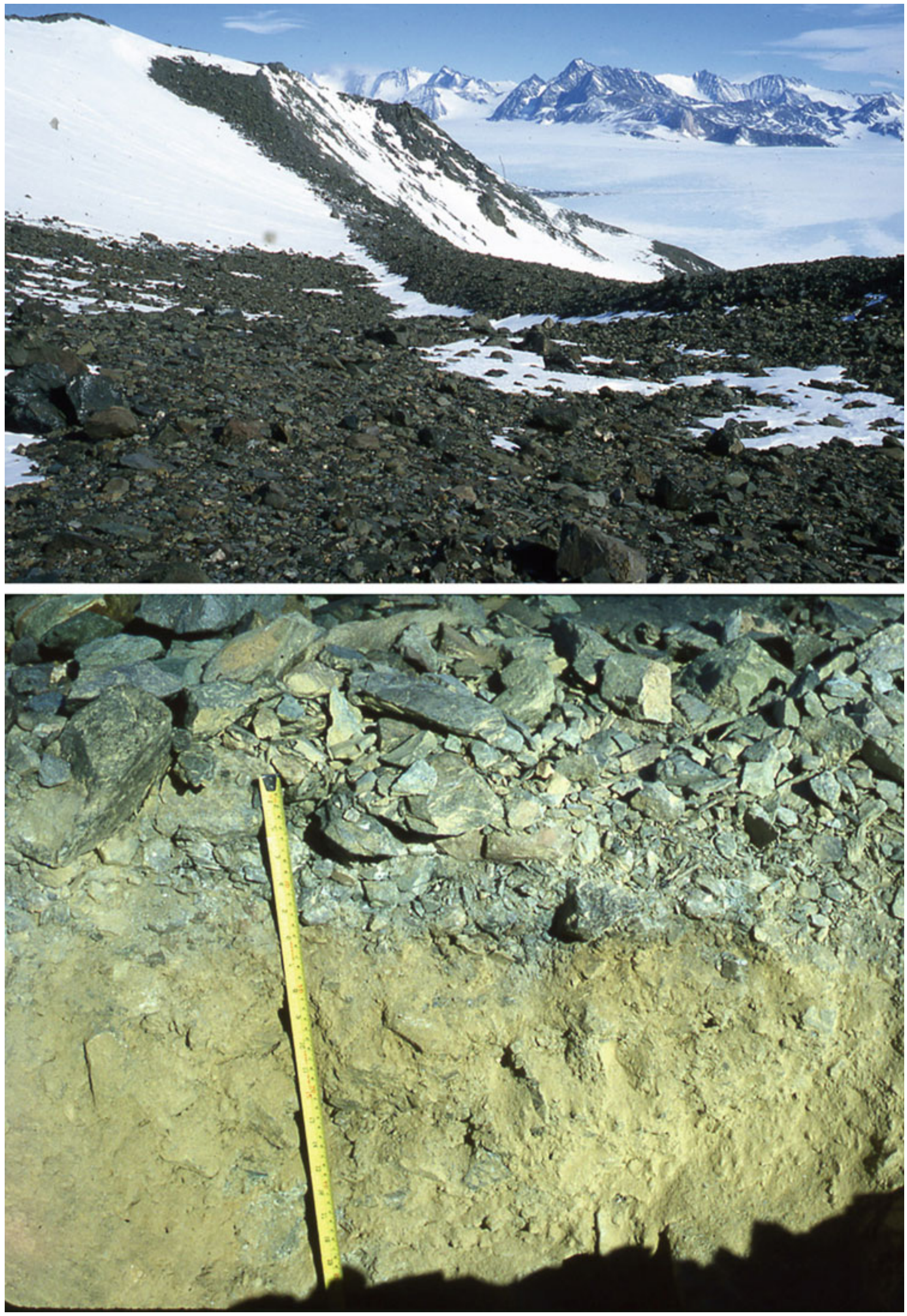

Fig. 10.3 Glacial drift (*above*) and Typic Anhyorthel (*below*) in the Edson Hills, Heritage Range (site 79-16) (photos by J. Bockheim)

stage is 1.0 and the salt stage is 0 (Table 10.2). Patterned ground is common, particularly in the form of high-centered polygons.

A Glacic Haplorthel profile includes a weakly developed desert pavement over a Cn horizon that has minimal staining, is weakly coherent, and has either no salts or thin salt encrustations beneath clasts. The salt stage is 0; the average EC of the salt-enriched horizon is 0.05 dS/m (Table 10.2); and the profile contains only 2 mg cm^{-2} of salts to an extrapolated depth of 70 cm (Table 10.3).

10.4.3.5 Rockland and Other Land Types

As much as 50 % of the ice-free areas of the Ellsworth may be composed of exposed bedrock, rather than soils. However, our method of soil mapping did not allow us to distinguish these land types.

Table 10.2 Morphology of soils on drift and moraines in the Ellsworth Mountains

Pedon No.	Location	Elev. (m)	Slope (°)	Geomorphic surface	Rock type	Weathering stage[a]	Salt stage[b]	Solum thickness (cm)	Depth of coherence (cm)	Depth of ghosts (cm)	Depth to ice cement (cm)	Soil subgroup[c]
79-15	Edson Hills	1000	4	Moraine crest	Phyllite	1	0	0	57	0	>57	LAo
79-16	Edson Hills	1100	1	Moraine crest	Phyllite	2	0	0	>80	0	>80	TAo
79-17	Edson Hills	900	2	Moraine crest	Quartzite	1	0	0	0	1	>70	TAo
79-18	Anderson Massif	1880	0	Residuum	Volcanics	3	1	13	13	13	>25	TAo
79-19	Dobratz Glacier	1300	5	Moraine crest	Quartzite	1	1	0	42	0	>42	LAo
79-20	Edson Hills	1200	0	Moraine crest	Quartzite	3	4	0	59	0	>90	TAo
79-21	Welcome Nunatak	1476	0	Ground moraine	Quartzite	1	1	0	25	0	>25	LAo
79-22	Edson Hills	1200	0	Ground moraine	Quartzite	2	1	0	17	0	>17	LAo
79-23	Edson Hills	1100	6	Moraine crest	Quartzite	2	1	0	50	38	50	THo
79-24	Mt. Dolence	1200	0	Ground moraine	Quartzite	1	0	0	17	0	17	THo
79-25	Mt. Dolence	1100	10	Moraine crest	Quartzite	2	4	0	>75	0	>75	TAo
79-26	Mt. Twiss	1200	0	Moraine crest	Quartzite	2	4	6	6	0	>75	TAo
79-27	Dickey Peak	1390	8	Ground moraine	Conglomerate	2	3	0	18	0	18	LHo
79-28	Flowers Hills	1200	0	Ground moraine	Conglomerate	2	1	0	20	0	>20	LHo
79-29	Flowers Hills	600	0	Ground moraine	Conglomerate	1	1	0	20	0	20	THo
79-30	Miller Peak	1600	0	Ground moraine	Quartzite	2	4	0	15	0	15	THo
79-31	Mt. Twiss	1400	6	Moraine crest	Quartzite	2	4	0	>100	0	>100	TAo
79-32	Mt. Twiss	1200	0	Ice-cored moraine	Quartzite	1	1	0	0	0	8	GHo
79-33	Meyer Hills	600	0	Ground moraine	Quartzite	2	1	0	14	0	33	THo
79-34	Marble Hills	1300	10	Ground moraine	Marble	2	1	0	>100	0	>100	TAo
79-35	Parrish Peak	950	0	Moraine crest	Quartzite	2	1	0	>75	5	>75	TAo
79-36	Cagle Peaks	1300	0	Ground moraine	Quartzite	2	1	0	33	0	>100	TAo

[a,b,c] indicate statistically significant differences ($p < 0.05$) in values based on analysis of variance

10.5 Discussion

10.5.1 Soil Development

Three key parameters appeared to control soil formation in the Ellsworth Mountain: parent material, topography, and soil age.

10.5.1.1 Topography

Toposequence on Crashsite Quartzite from the Enterprise Hills

Quartzite is the dominant metamorphic rock outcropping at the Heritage Range. The Mt. Dolence dry valley is the largest ice-free slope of the Enterprise Hills, varying from

Table 10.3 Chemistry of 1:5 soil–water extracts from soils in the Ellsworth Mountains, Antarctica

Profile #	Weathering stage	Horizon	Depth (cm)	EC (dS/m)	Salts to 70 cm (mg/cm^2)	$mmol_c/L$								
						pH	Na^+	Ca^{2+}	Mg^{2+}	K^+	Cl^-	SO_4^{2-}	NO_3^-	HCO_3^-
79-32 Spletts. Gl	1	Cf	3–8	0.1		7.4	0	0.3	0	0	0.01	0.2	0.009	0.1
		Wf	8+	0.1	2	7.3	0.1	0.2	0	0	0.11	0.12	0.02	0.1
79-15 Edson Hills	2	Cn1	0.5–20	1.6		7.2	1.2	20	1.6	0.05	0.85	18	1.4	0.06
		Cn2	20–39	2.3		7.2	1.2	32	2	0.06	1.4	30	1.1	0.1
		2Cn	39–57	1.5	587	7.1	1.3	19	1.2	0.04	0.39	18	0.93	0.1
		2R	57											
79-17 Edson Hills	2	Cn1	0.5–15	0.18		7.9	0.52	1	0.1	0.02	0.03	1	0.05	0.3
		Cn2	15–40	1		7.3	2.7	7.6	1.3	0	0.25	8.4	1.2	0.1
		Cn3	40–70	0.9	262	7.4	2.4	7.4	1.2	0.03	0.25	9.3	1	0.1
79-19 Carnell Pk.	2	Cn	1–25	1.4		7.3	2.6	14	2.4	0.12	1.5	12	2.3	0.1
		2Cox	25–42	1	375	6.8	2.7	5.9	1.7	0.08	1.4	5.6	1.9	0.0
		2R	42											
79-21 Welcome Nun.	2	Cn	0.5–13	0.5		7.3	0.4	4.1	0.23	0.08	0.03	4.6	0.003	0.1
		Cr	13–24	0.2	39	7.3	0.3	0	0.13	0.04	0.03	1.2	0.006	0.1
		R	24											
79-25 Mt. Dolence	2	Cox1	0.5–10	0.1		9.2	0	0.3	0.18	0.07	0.01	0.08	0.01	6.3
		Ckk	10–20	0.1		8	0.1	0.7	0.23	0.1	0.03	0.54	0.01	0.4
		Cox2	20–30	1		8.4	1.5	6.4	2	0.36	2.3	6.3	0.69	1.0
		Cn1	30–53	1.6		8	1.6	15	2.7	0.41	2.1	15	1	0.4
		Cn2	53–75	1.7	372	8.1	4.4	12	1.8	0.44	3.6	9.3	2.1	0.5
79-26 Mt. Twiss	2	Bkk	0–6	0.2		7.7	1	0.7	0.1	0.2	0.08	1	0.64	0.2
		Cn1	6–43	2.6		7.3	4.7	31	3	0.5	2.2	32	2.1	0.1
		Cn2	43–75	2.6	805	7.1	3.8	31	2.3	0.4	1.7	31	2.4	0.1
79-27 Dickey Pk	2	Cox	0.5–18	0.3		7.4	0.4	4.2	0.8	0.1	0.09	2.4	0.02	0.1
		2Cr	18+		27									
79-33 Meyer Hills	2	Cox1	1–6	0.6		8.2	0.3	2.7	0.8	0.1	0.96	4.6	0.16	0.6
		Cox2	6–14	0.1		7.6	1.4	0.2	0.2	0.1	0.45	0.5	0.26	0.16
		Cn	14–33	0.1		7.8	0.2	0.2	0.1	0	0.01	0.1	0.004	0.25
		Cf	33+	0.1	24	8.4	1.9	0.3	0.1	0	0.08	0.09	0.03	1
79-34 Marble Hills	2	Cn1	2–17	2.7		7.4	3.2	33	2.8	0.2	2.7	31	2.1	0.1
		Cn2	17–60	0.8		8.5	2	3.7	1.9	0.1	2	2.9	2.1	1.3
		Cn3	60–100	0.6	412	8	1.3	2.9	1.2	0.1	1.4	2.1	2.8	0.4
79-35 Seal Gl.	2	Cox	2–25	3.2		8	7.8	34	2.8	0.4	2.9	33	6.4	0.4
		Cn1	25–37	2.5		7.1	6	33	3.2	0.5	2.9	31	4.3	0.05
		Cn2	37–75	2.5	924	7.3	4.7	25	2.3	0.4	2.4	22	4.1	0.08
79-36 Cagle Pk.	2	Cn1	3–33	1.9		7.3	2.7	20	1.8	0.2	1.6	14	1.3	0.08
		Cn2	33–67	2.7		7.2	3.7	31	3.3	0.3	2.5	34	2	0.06
		Cn3	67–100	2.7	780	7.2	3.8	32	3.1	0.3	2.4	31	2.5	0.06
79-18	3	Bw	0.5–13	2.2	132	7.5	1.2	32	0.47	0.17	0.39	30	0.06	0.13
		R	13–25											

(continued)

Table 10.3 (continued)

Profile #	Weathering stage	Horizon	Depth (cm)	EC (dS/m)	Salts to 70 cm (mg/cm^2)	$mmol_c/L$								
						pH	Na^+	Ca^{2+}	Mg^{2+}	K^+	Cl^-	SO_4^{2-}	NO_3^-	HCO_3^-
79-20 Edson Hills	3	Cn	0.5–7	1.7		7.7	0.6	22	1.6	0.16	0.58	17	0.04	0.2
		Cz	7–18	1.6		7.5	0.4	18	1.1	0.12	0.48	19	0.16	0.13
		2Cox1	18–37	2.8		7.5	3.6	33	4	0.18	5.1	30	2.1	0.13
		2Cox2	37–59	2.7		7.2	4.4	24	4.9	0.2	5.9	19	3	0.06
		2Cox3	59–90	3	840	7.4	4.5	32	4.3	0.18	5.4	29	2.6	0.1
79-30 Miller Pk	3	Cz	0.5–15	11		5.4	162	14	28	0.8	1.9	173	11	0
		Wf	15+		792									

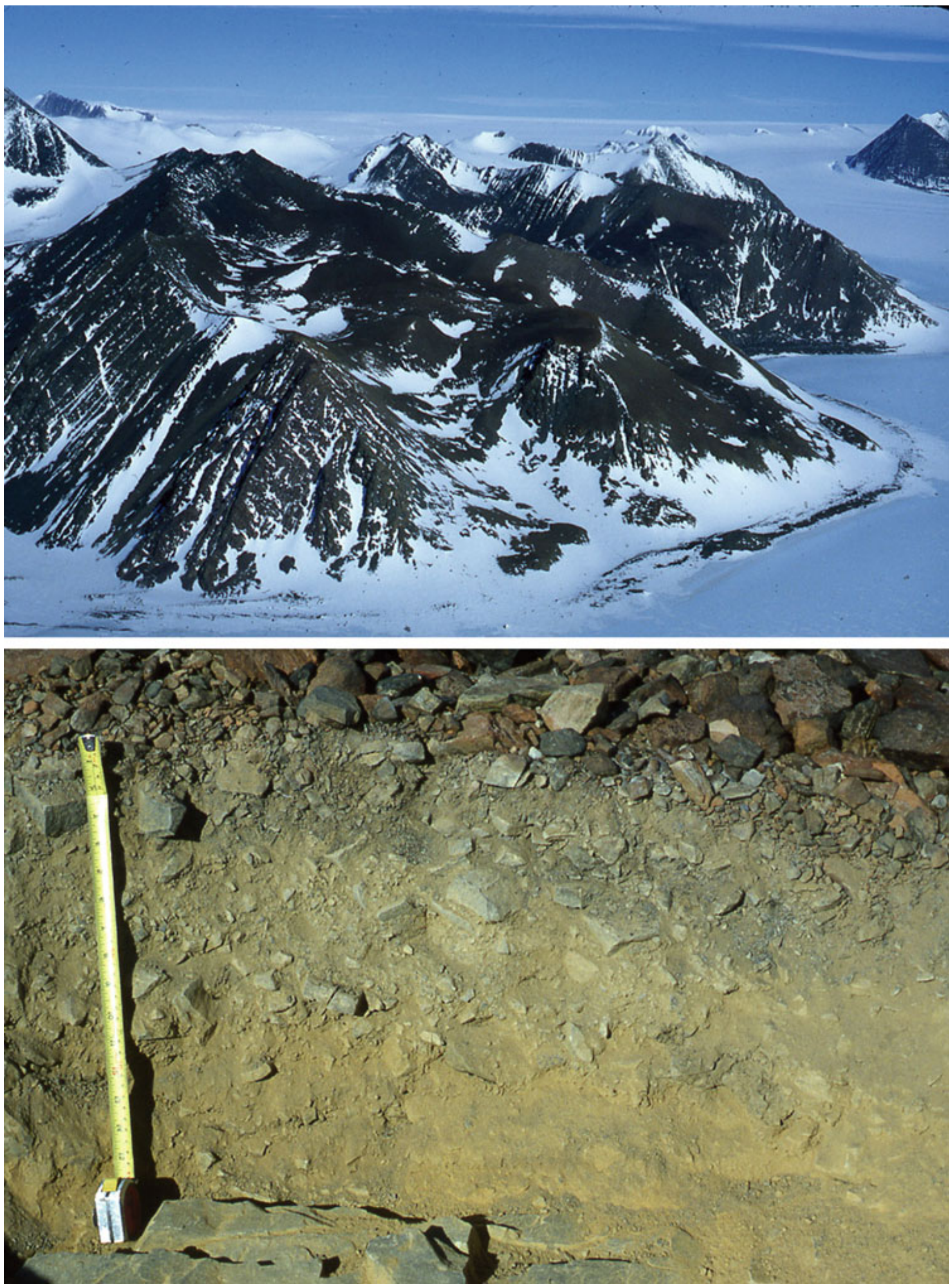

Fig. 10.4 Dobratz Glacier (*top*) and Lithic Anhyorthel derived from quartzite (*bottom* site 79-19) (photos by J. Bockheim)

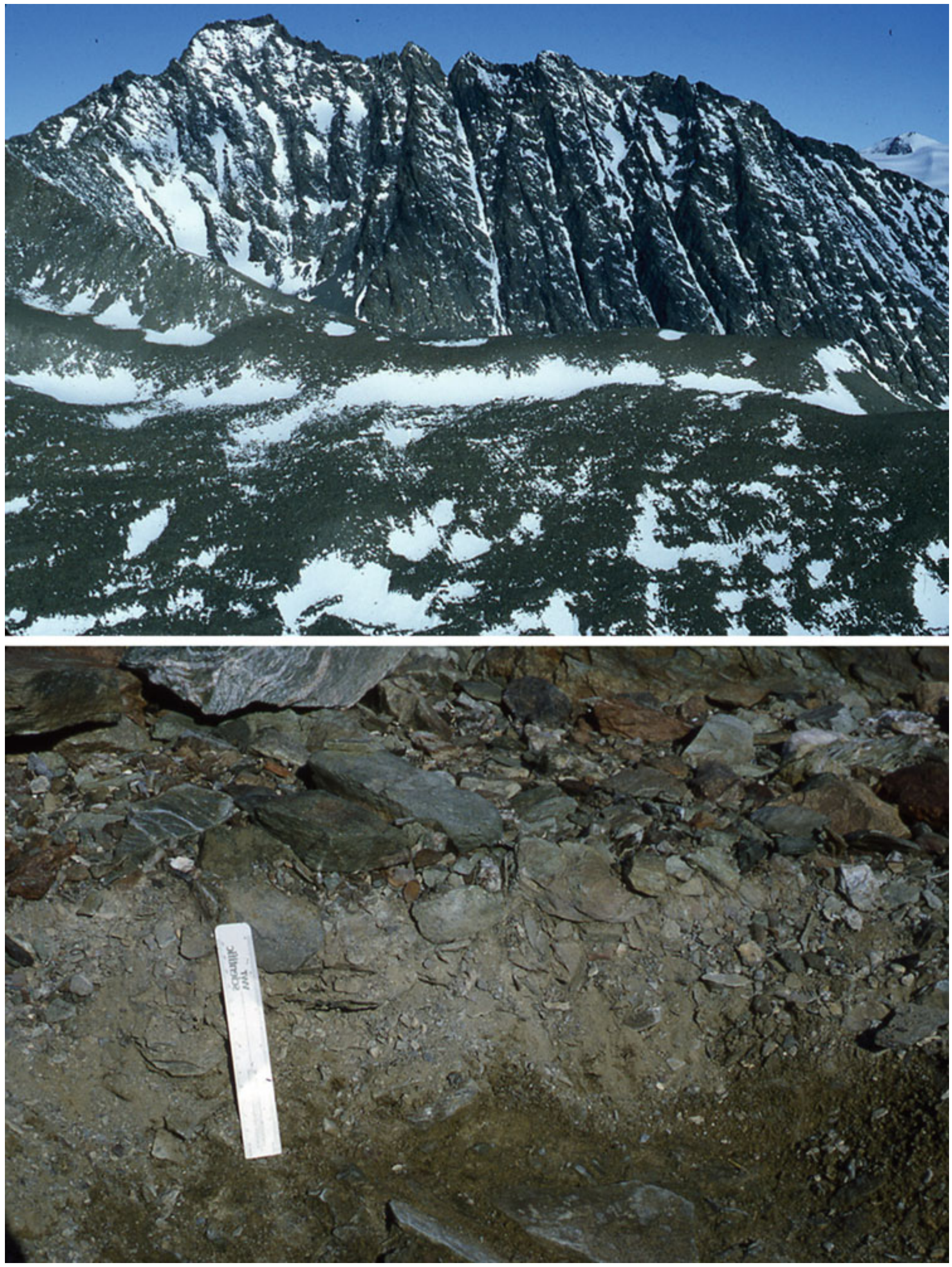

Fig. 10.5 Dolence Peak (*above*) and Typic Haplorthel with ice-cemented permafrost at 17 cm (photos by J. Bockheim)

800 up to 1950 m, where steep slopes with pinnacles of quartzite show no evidence of overriding glaciation (Fig. 10.6). This toposequence (EH 1–EH 6) thus represents soil formation on the most resistant rocks of the Ellsworth Mountains. The six soils range in altitude from a higher, stable surface, at 1300 m, just below the trimline, down to the Union Glacier margin at 880 m.

The most important morphological variation observed along the toposequence was an increase in depth from 15 cm at the higher elevations to 30 cm at the lower elevations. The amount of silt and fine sand (0.2–0.05 mm) was greater in soils at the higher elevations, especially in the uppermost horizon, than at the lower elevations; however, clay concentrations did not change along the toposequence, with values of 6 % or less (Table 10.3). The greater silt and fine sand concentrations at the higher elevations were attributed to eolian deposition, as the sand grains in these soils were wind polished and well sorted.

The following chemical properties decreased in soils with a decrease in elevation: electrical conductivity, exchangeable Ca, Na, Mg, and K, and cation-exchange capacity. These changes likely reflect elevational variations in atmospheric and weathering inputs. All of the soils were alkaline, with a pH in excess of 7.66 at the surface; pH normally increased

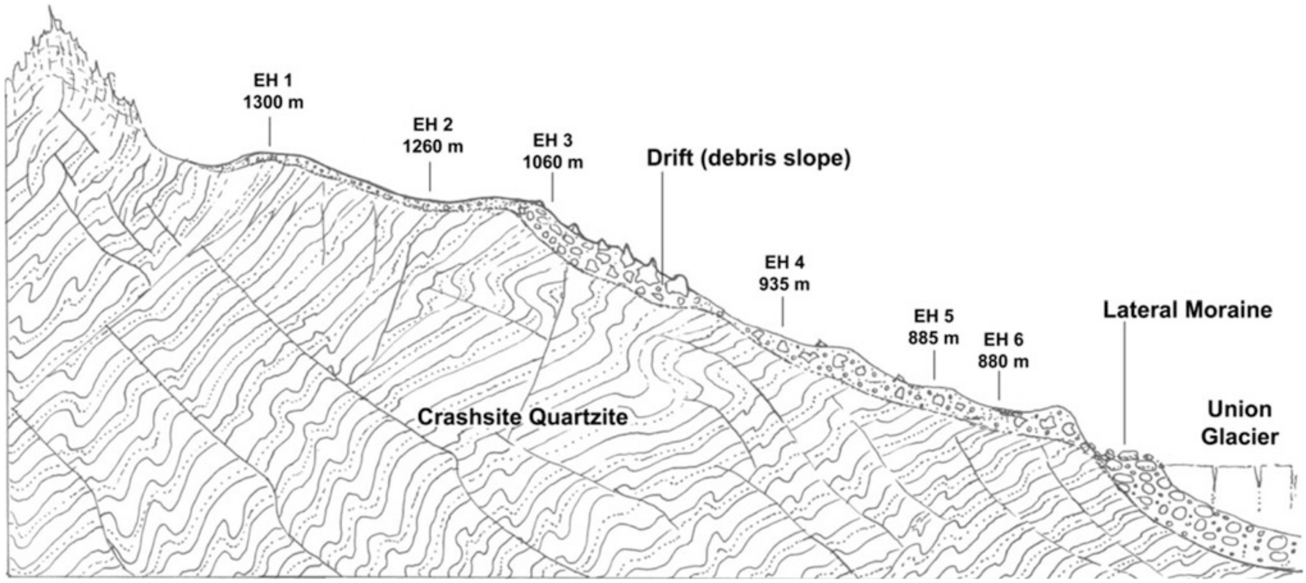

Fig. 10.6 Enterprise Hills toposequence of soils developed on green/gray quartzite from Mt. Dolence (EH 1) down to the Union Glacier margin (EH 6). The Enterprise Hill drift can reach 3 m deep, according to field observations and probing (vertical scale on diagram is not real)

with soil depth (except for EH2). Consistent with cold desert soils from elsewhere in Antarctica (Chaps 3, 7–9, and 11), soil organic carbon contents were very low, and did not account for any increase in acidity. The Mehlich-extractable P concentrations were quite variable and could represent impurities in quartz gains, since other accessory minerals were present in minor amounts.

The relatively high P levels warrant further investigation, since P is contributed in only minor amounts from atmospheric deposition, and biotic contributions are likely insignificant. The variations in P amounts across short distances (e.g., between EH5 and EH6) suggest large variations associated with the parent rock. The P adsorption capacity is low, as indicated by high P remaining values, and in some cases (e.g., EH2) is equal to the amount of P in the test solution (mg L^{-1}). From this, we infer that weathering rates must be very low. Whereas Lithic Anhyorthels were the dominant soils on the higher surfaces (EH 1 and EH2), Typic Anhyorthels and Typic Anhyturbels were present on the lower surfaces.

Toposequence on Limestone/Breccias at Rhodes Bluff

This toposequence is one of the rare sites in the Ellsworth Mountains, and possibly throughout all of Antarctica, where limestone forms an entire dry valley floor in a typical cirque bordered by breccias from one side and a quartzite crest on the other (Fig. 10.7). Only the bottommost soil ELE 3 (870 m) showed a mixed influence of quartzite pebbles and rock fragments, although most fragments were made of limestone and breccias.

The colors of these limestone soils are pale to pinkish red (2.5 YR), in strong contrast with whitish colors of the surrounding soils on Quartzite. These oxidized colors are not related to any present-day weathering degree, since these soils are very round and little weathered. This can be misleading, when one takes a general criteria for assessing weathering stages, as proposed by Campbell and Claridge (1987). Rather, the reddish tinge is directly related to the presence of Permian hematite bodies of brecciated limestone cave-like deposits, suggesting a Permian paleokarst landscape, with paleosols debris filling crevasses following carbonate dissolution. The clay contents are very low throughout, even compared with soils on quartzite, and silt contents increased upslope the sequence. The great amount of coarse sand is due to physical weathering of limestone, forming gravelly soils, where fine sand is in low frequency. The silt content should be attributed to the metasedimentary nature and ease of splitting.

Soils on limestone are chemically distinct from those on quartzite for having a much lower available P background (<0.8 mg dm^{-3}) and a greater P adsorption capacity, estimated from lower P remaining values, compared with toposequence from Mt. Dolence. In general, pH are alkaline, but with lower contribution of soluble salts, since Ca amounts are lower, as well as exchangeable Mg and K, suggesting less contribution of mica impurities in these limestone and marbles. CEC is comparably lower than that of quartzites; the SOC is very low, though slightly greater than that on quartzite. Similarly to the toposequence on quartzite, CEC and CE increased upslope, indicating that upland soils are more weathered than soils on mixed drift, as ELE3.

The most striking feature of limestone soils is the relatively low contents of exchangeable Ca, indicating that these

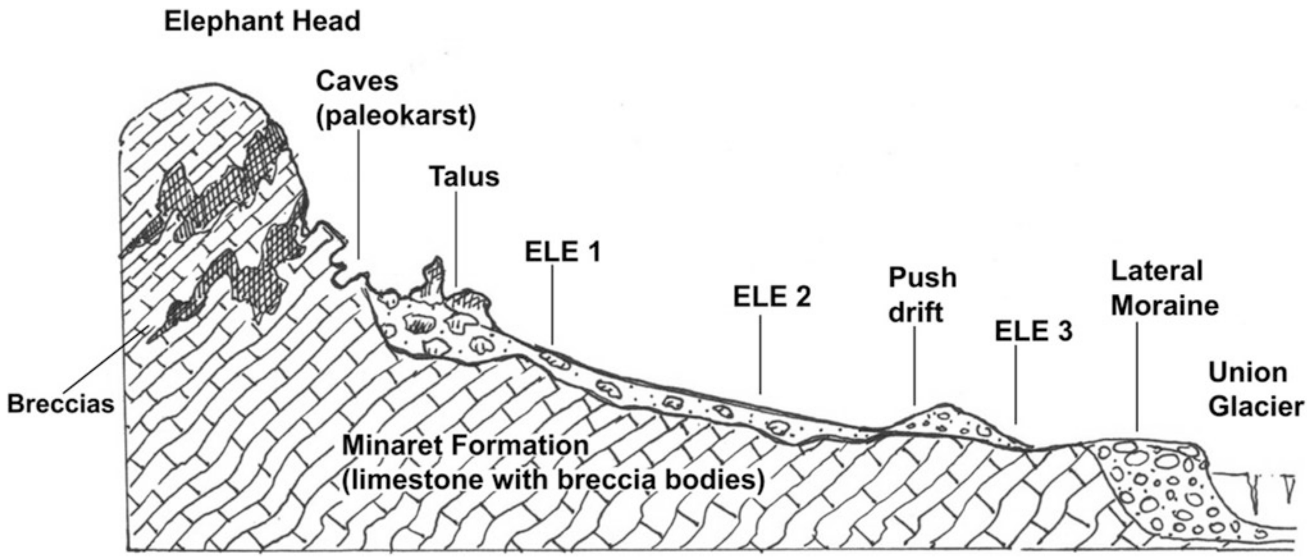

Fig. 10.7 Elephant Head (Rhodes Bluff) toposequence of soils (ELE1, 990 m—ELE2, 979 m—ELE3, 870 m) developed on limestone debris and drift between Elephant Head Talus and down to the Union Glacier margin, bordered by lateral moraines. The local drift can reach 4 m deep, according to field observations and probing (*vertical scale* on diagram is not real)

calcitic limestones are little weathered, so that most soluble and exchangeable forms are attributed to atmospheric inputs, rather than chemical dissolution under the present polar climate.

10.5.1.2 Time

We identified soils of three weathering stages, including ice-cored drift of likely Holocene age (weathering stage 1), Ellsworth drift of possible last glacial maximum (LGM) age (WS 2), and "windows" of older drift in selected locations (Denton et al. 1992).

10.5.1.3 Parent Material and Landform

There were minimal differences in the chemistry of 1:5 soil-water extracts of soils derived from six different bedrock types in the Ellsworth Mountains (Fig. 10.8). Ca^{2+} and SO_4^{2-} were the dominant cation and anion, respectively. Similarly, there were few differences in soil morphology among the different parent materials where these materials were of comparable age. A major reason for the lack of differences in soils on different parent materials can be attributed to the young age (ca. 18 kya) of the soils.

There is a correspondence between landform type and soil taxa. Haplorthels occur on landforms in areas where water is available, e.g., in snowmelt areas. In contrast Anhyorthels occur along benches and in upland valleys that receive less than 50 mm year^{-1} of annual water-equivalent precipitation and have soil moisture contents of <3 %, ca. anhydrous conditions. Glacic soil subgroups occur alongside glaciers and on medial moraines. Lithic soil subgroups exist on rock outcrops and on nunataks throughout the study area. All of the soil taxa may occur on ground, end, lateral, and disintegration moraines, but the TAo subgroup is most common.

10.5.2 Pedogenetic Processes

Because of the young nature of the soils, they do not show the strong developmental sequence observed in the Sør Rondane (Chap. 3) or Transantarctic Mountains (Chaps. 8 and 9). However, the developmental sequence contains Glacic Haploturbels on mid-Holocene surfaces, Typic Haploturbels on landforms from the last glacial maximum, and Typic Anhyorthels on slightly older surfaces. The Ellsworth Mountains offer great potential for studying soil formation on a variety of parent materials. Soils on Ellsworth drift are derived from quartzite, phyllite, marble, volcanics, and conglomerate.

The dominant soil-forming processes in the Ellsworth Mountains are desert pavement formation from deflation of fine materials and rock weathering and accumulation of $CaSO_4$ salts (calcification). Processes observed in older soils of Antarctica, such as rubification, salinization, and carbonation, were not observed in the Ellsworth Mountains.

10.5.3 Pedodiversity

Bockheim (2007) developed a "pedodiversity index" that was derived from the number of soil subgroups divided by the geographic area. In view of its comparatively large size, the Ellsworth Mountains have a low pedodiversity index

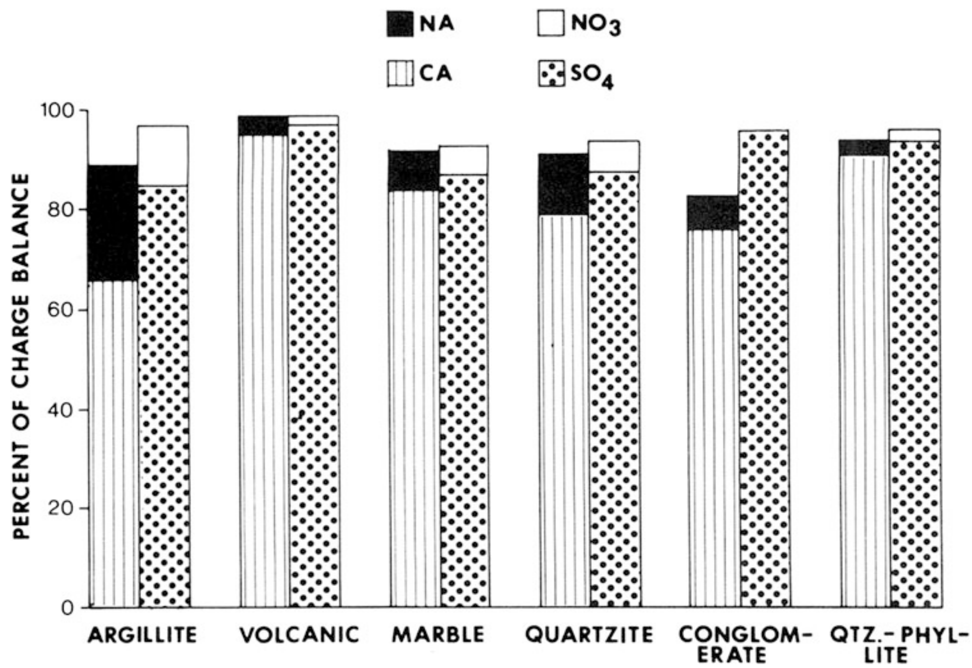

Fig. 10.8 Chemistry of 1:5 soil–water extracts of soils derived from six different bedrock types in the Ellsworth Mountains (from Denton et al. 1992)

(PDI) of 0.005, which contrasts with values of 0.026–0.05 for the McMurdo Dry Valleys but is comparable to values of 0.0017–0.0050 for the southern Transantarctic Mountains.

10.5.4 Soil Taxa and the Occurrence of Organisms

Water is the limiting factor controlling the distribution and diversity of organisms in continental Antarctica. There are very few ponds and streams in the Ellsworth Mountains. Based on findings in the Transantarctic Mountains (Chaps. 8 and 9), the most favorable soil taxa for microorganisms in the Ellsworth Mountains are soils in the Haplorthel great group.

10.6 Summary

Ellsworth Land has an ice-free area of 2,095 km^2, which constitutes 4.2 % of the total for Antarctica. The Ellsworth Mountains are separated by the Minnesota Glacier into the Heritage Range to the east and the Sentinel Range to the west. The Sentinel Range contains the highest peaks in Antarctica. The Ellsworth Mountains are unique in terms of the variety of soil parent materials, which include till and colluvium derived from marble, quartzites, conglomerates, argillites, phyllites, volcanics, and tillites. The entire area is underlaid by continuous permafrost of unknown thickness. Active layer depths range from 15 to 50 cm.

Because the soils are primarily of Late Glacial Maximum and Holocene age, they are poorly developed. The dominant soil-forming processes in the Ellsworth Mountains are desert pavement formation from deflation of fine materials and rock weathering and accumulation of $CaSO_4$ salts (calcification). Processes observed in older soils of Antarctica, such as rubification, salinization, and carbonation, were not observed in the Ellsworth Mountains. Soil taxa can be ranked (from greatest to least in terms of area): Typic Anhyorthels, Typic Haplorthels, Lithic Anhyorthels, Lithic Haplorthels, and Glacic Haplorthels.

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11 Soils of Marie Byrd Land

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11.1 Introduction

The whole area of the Marie Byrd Land (MBL) is more than 200,000 km^2. It stretches between 158° 00′ W and 103° 24′ W and includes five coastal areas (from west to east): the Saunders Coast, the Ruppert Coast, the Hobbs Coast, the Bakutis Coast, and the Walgreen Coast (Fig. 11.1). Ice-free areas are rare in this region (total area of discrete mountain ranges and nunataks within the MBL is about 700 km^2 (1.4 % of Antarctica's total ice-free area)). Small oases and nunataks are relatively abundant in the western part within the mountain chains of the Ford Range on the Ruppert Coast, the Washington and the Alexandra Ranges of the Edward VII Peninsula (the Saunders Coast).

The eastern part of the MBL contains fewer ice-free areas: the Flood Range and the Executive Committee Range in the inner part of the Hobbs Coast and the remote mountains of the inner part of the Walgreen Coast (the Crary, the Toney, the Murphy mountains, and some nunataks). The northernmost ice-free area is the Siple Mountain (73° 20′ S; 126° 05′ W; 3,100 m a.s.l.) on the Cape Dart of the Siple Island (eastern Hobbs Coast); the Rockefeller mountains (78° 05′ S; 155° 00′ W; ±430 m a.s.l.) on the Edward VII Peninsula of the western Saunders Coast are the southernmost. "Russkaya" scientific station is situated on the Berks Cape of the Hobbs Coast (74° 46′ S; 136° 48′ W) at the altitude of 124 m a.s.l. Small archipelago of the Lindsey Islands (73° 36′ S; 103° 01′ W) is situated just off the northwest tip of the Canisteo Peninsula, Amundsen Sea. The Hudson Mountains are located along the Walgreen Coast in Antarctica's western Ellsworth Land (74° 20′ S; 99° 25′ W).

MBL is one of the remotest and most difficult lands to access in Antarctica. No sovereign nation has even claimed this region of Antarctica. We have only recently begun to understand the soils of MBL, and the information is preliminary (Abakumov 2008, 2010a, b). MBL contrasts sharply with other regions of Antarctica. The mean annual precipitation is about 2,000 mm, which is 4–10 times higher than in other coastal regions of Antarctica (except possibly the western Antarctic Peninsula). One of the highest wind velocities measured on our planet was recorded here at 77 m/s. These differences in climate from other areas in Antarctica have resulted in differences in weathering and pedogenic processes as well.

The U.S. Navy mounted several expeditions to Antarctica in the period 1946–1959. They included aerial photography over portions of coastal MBL (Meunier 2006). The "USS Glacier" program explored the parts of the Walgreen Coast in 1960–66 and included parties of geologists and surveyors that were deployed to interior outcrops (McDonald 1962). The U.S. Byrd Coastal Survey during 1966–1969, led by F. A. Wade, conducted geologic mapping in the Alexandra and Rockefeller Mountains and the Ford Ranges and produced a series of 1:250,000 geologic maps of the region (Wade et al. 1977). Several geological expeditions explored MBL during the period 1978–1993. New Zealand geologists surveyed the Ford Ranges and Edward VII Peninsula in two expeditions 1978–1979 and 1987–1988. Exploration of the MBL Volcanic Province by U.S. geologists began in 1984–1985 (LeMasurier and Rex 1990; LeMasurier and Thomson 1990). The WAVE project (West Antarctic Volcano Exploration) focused on the volcanic province during the period 1989–1991. During the seasons of 1989–1990 and

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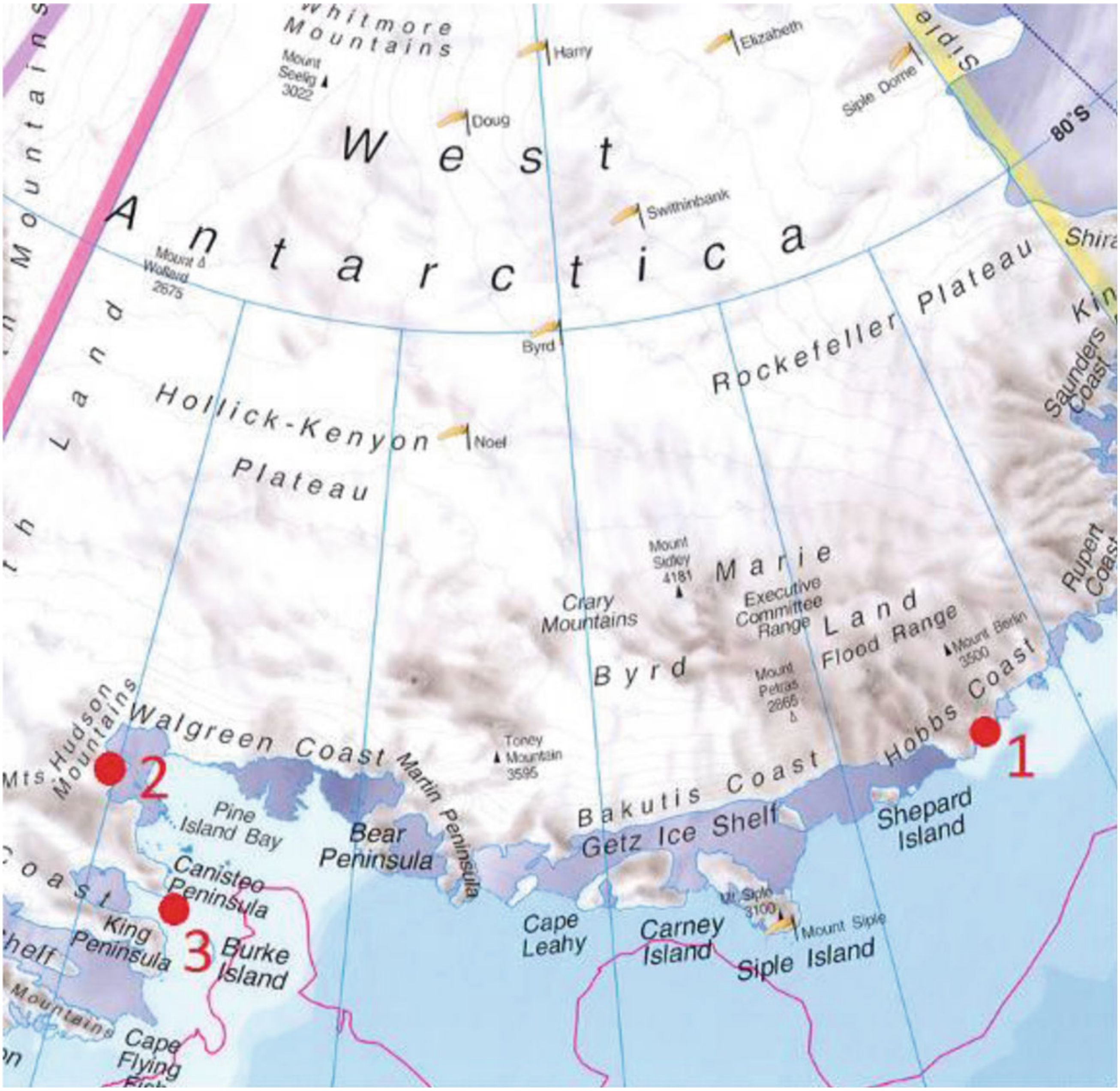

Fig. 11.1 Marie Byrd Land, West Antarctica. Key sites: *1* "Russkaya"; *2* "Hudson Mountains"; *3* "Lindsey Island" (*Source* http://mapsof.net/map/west-antarctica)

1990–1991 a geological party from the University of California, Santa Barbara explored several of the mountain ranges within the northern Ford Ranges of MBL (Luyendyk et al. 1992)]. GANOVEX VII, a multinational expedition led by Germany, visited Edward VII Peninsula in 1992–1993. Colorado College geologists led expeditions to the Ford Ranges in 1998–2001, and 2004–2007 (Fosdick Mountains).

"Byrd" station was originally established during the International Geophysical Year of 1957–1958, eventually became a summer field camp in 1972, and continued to support various research projects in West Antarctica thereafter. The original station ("Old Byrd") lasted about four years before it began to collapse under the snow. Construction of a second underground station in a nearby location began in 1960, and it was used until 1972. The station was then converted into a summer-only field camp until it was abandoned in 2004–2005.

"Russkaya" station of the Soviet Antarctic Expedition was opened on the Hobbs Coast on March 9, 1980. Wintering and seasonal staff carried out the meteorological observations, collected radiometric data, and provided snow and ice cover observations. A major part of the scientific activity included geomagnetical and geophysical observations and monitoring of Earth's sputniks. The only scientific activity in sense of biology was the observation and counting of local fauna species. Since March 12, 1990, "Russkaya" has been closed. Short visits to "Russkaya" were made by authors during the 2007–2008 and 2009–2010 field seasons. The data taken during these field seasons are basically discussed in this chapter. Several years ago the Republic of South Korea began to establish a scientific station close to "Russkaya".

The objectives of this study are to provide the first ideas on the issues of pedogenesis in this remote region (even in sense of Antarctica), to determine the unique pedogenic and weathering features that exist in view of the unique climate conditions of MBL, and to present the preliminary soil map of the "Russkaya" scientific station locale and to discuss its soil map units.

11.2 Study Area

11.2.1 Climate

Weather conditions of MBL are extremely severe and are resulted from a combination of low temperatures and high wind velocities. The mean annual air temperature at "Russkaya" averaged −12.4 °C during all observational periods. The warmest month is January, the coldest month is August. The absolute temperature minimum is −46.4 °C, and the absolute maximum is 7.4 °C. Mean annual precipitation is around 2,000 mm (water equivalent). However, it should be taken into account that precipitation occurs only in the form of snow. Under conditions of strong winds, it is possible that rain gauges could be partly filled with snow moving in the horizontal direction. It is also possible that some portions of snow could be blown out from rain gauges. Blizzards occur in the station area about 150 days a year; they include heavy snow fall and restricted visibility. Due to orographic features, easterly winds prevail. The mean annual wind speed at "Russkaya" station is 12.9 m/s. The maximum monthly mean wind of 18.1 m/s was registered in March; the minimum of 9.6 m/s was observed in January. The maximum wind speed (excluding January and February) fluctuates between 46 and 61 m/s. The maximum wind gust registered was 77 m/s. On one occasion, a wind speed of 50–60 m/s blew continuously for 16 days. The average number of days with wind speeds exceeding 15 m/s is 264, and there are 136 days a year with the wind speed exceeds 30 m/s. Southeasterly winds, which are typical for other areas of Antarctic coastline, are not stable here, possibly due to an abundance of snow fields and small glaciers and the relatively thick snow cover on sea ice.

At the "Russkaya" station the average barometric pressure at sea level (980.9 mbar) is the lowest pressure registered at coastline Antarctic stations. The annual pressure variation attains a maximum value in January and a minimum value in October. The maximum absolute pressure was 1019.1 mbar, and the absolute minimum of 923.4 mbar was lower than values registered at other coastal stations in Antarctica. The annual variation in absolute pressure at "Russkaya" station is much higher than at other Antarctic stations. The mean annual sunshine duration is 1191 h per year.

11.2.2 Elevation and Topography

Most ice-free areas of MBL are comprised of nunataks of volcanic origin. Their height above sea level increases from 500–1,200 m in the western part (the Ford Range, Fosdick Mountains, and Alexandra Mountains) to 2,500–3,500 m in the eastern part (the Executive Committee Range and Crary Mountains). The highest peak in MBL is Mount Sidley within the Executive Committee Range with an elevation of 4,181 m. MBL includes the lowermost point of Antarctic subglacial relief, the Bentley Subglacial Trench, which reaches 2,555 m b.s.l. This is also the lowest place on earth not covered by ocean (although it is covered by ice).

11.2.3 Permafrost Distribution, Thickness, and Form and Active-Layer Depths

The ice-free area in the vicinity of "Russkaya" station is about 4 km^2 and contains low, rocky hills with elevations about 150–200 m a.s.l. The bedrock is composed mainly of biotite–hornblende gneisses (Fig. 11.2). Gentle slopes are often terraced by former glacial processes. Thin layers of talus occur in local depressions. There are also several lakes in the area that are ice covered year-round. The upper several centimeters of the active layer is usually dry. The underlying permafrost is often ice-cemented, with massive and basal cryogenic structures. There are some cryogenic processes in the area, such as patterned ground and frost cracking. Frost mounds form locally on gentle slopes. On steep slopes, rectilinear forms of patterned ground turn to linear stripes. Small boulder stream-like bodies occur in the area. They seem to originate from the weathering of stretched minor intrusions of solid basic rocks rather than forming from slope processes.

The most striking feature of physical weathering at "Russkaya" station is the formation of schistose frost mounds that are oriented along the initial plane of the parent rocks (Fig. 11.3). These mounds are of biotite–hornblende gneisses of mainly angular form. The rock fragments are 0.5–1 cm in diameter in the center of the mound and from 5–7 cm up to 15–20 cm along the periphery. The next outstanding

Fig. 11.2 Environment of "Russkaya" scientific station. Hobbs Coast, Marie Byrd Land. Distribution of *Usnea Antarctica* (*black* clusters in the foreground), boulder stream-like body (*gray stripe* in the background). Interboulder area is filled with schistose debris from gneiss rocks. *Greenish* mottles on boulders in the *bottom-right corner* presumably contain a significant amount of copper (0.2–1 % of total weight)

weathering feature is the formation of aeolian remnants (Fig. 11.4). These remnants are 40–70 cm high. Their table-like or mushroom-shaped forms are determined by the solid ferriferous crusts on top of the boulders. Over time, aeolian processes remove the relatively less stable grains that are not cemented by ferrous oxides from the inner parts of the boulders. The crusts are 2–15 mm thick, brown colored, and in some cases are cracked. Salt encrustations are often associated with those cracks or along the edges of crusts.

The permafrost temperature in the borehole A5-09 at "Russkaya" station is −10.4 °C (mean annual value at 1.5 m). The active layer is shallow (0.1–0.2 m). Temperatures above 0 °C are quite rare here. According to year-round (2008–2009) measurements, the maximum surface temperature is around 6 °C and the minimum is −39 °C (Fig. 11.5). The thickness of permafrost is estimated at 300–400 m according to the 3–4 °C per 100 m ground temperature gradient.

11.2.4 Parent Materials and Age

MBL represents a region of thinned earth's crust that supports significant topography. Cenozoic faulting, Oligocene to Quaternary volcanism, and Miocene to recent glaciations formed the modern landscape. The bedrock geology of MBL includes the Cretaceous Byrd Coast Granite, the Mississippian and Devonian Ford Granodiorite, and the lower Paleozoic and Precambrian Swanson Formation and Fosdick metamorphic rocks (Wade et al. 1977). The MBL volcanic province is a late Cenozoic alkaline basalt-trachyte volcanic field on the Pacific coast of West Antarctica. Most of these volcanoes are partially buried beneath the West Antarctic ice sheet, but in some cases, a combination of tectonic uplift and lowering of ice level has exposed basal hydrovolcanic sections produced by eruptions in an englacial environment. Some of the largest and best preserved hydrovolcanic

Fig. 11.3 Schistose debris of biotite–hornblende gneisses with Usnea Antarctica (scale in 5 cm intervals)

structures are delta-like in form, with gentle distal slopes, and foreset bedded deposits composed of hyaloclastites, pillow breccias, pillow lavas, subaerial flows, and air-fall tephras.

Surface exposure ages of glacial deposits in the Ford Range of western MBL indicate continuous thinning of the West Antarctic Ice Sheet by more than 700 m near the coast during the past 10,000 years (Stone et al. 2003). Sampling rocks at various elevations within the Ford Ranges showed that the highest summits emerged about 10,400 years ago and the lower summits as recently as 3800 years ago. Thinning is presently continuing. Average exposure time of the Ford Range summits over the more distant past is less than 50 % while the lower elevations that are most recently exposed have been exposed less than 1–5 % of the time. This means that the ice extent in this region is at an extreme minimum and was probably even less than during the prolonged and very warm interglacial 400,000 years ago. More interior sites experienced lesser amounts of thinning. Isotopic analysis of ice from Byrd Station indicates that it was no more than 400 m higher during the last glacial maximum (Steig et al. 2001).

The Hudson Mountains contain many slightly eroded parasitic cones forming nunataks protruding above the Antarctic ice cap. The cinder cones apparently rest on three extensively eroded Miocene stratovolcanoes, including Teeters Nunatak, Mount Moses, and Mount Manthe. Subaerial basaltic lava flows dominate, but subglacial or subaqueous tuffs and lava flows are also present. A tephra layer from an eruption of a subglacial volcano in the Hudson Mountains was dated from ice thickness at about 2,200 yr BP. The presence of steam was reported at one of the Hudson volcanoes in 1974. Satellite data suggest that an eruption of Webber Nunatak took place during 1985, although this has not been confirmed (LeMasurier and Thomson 1990).

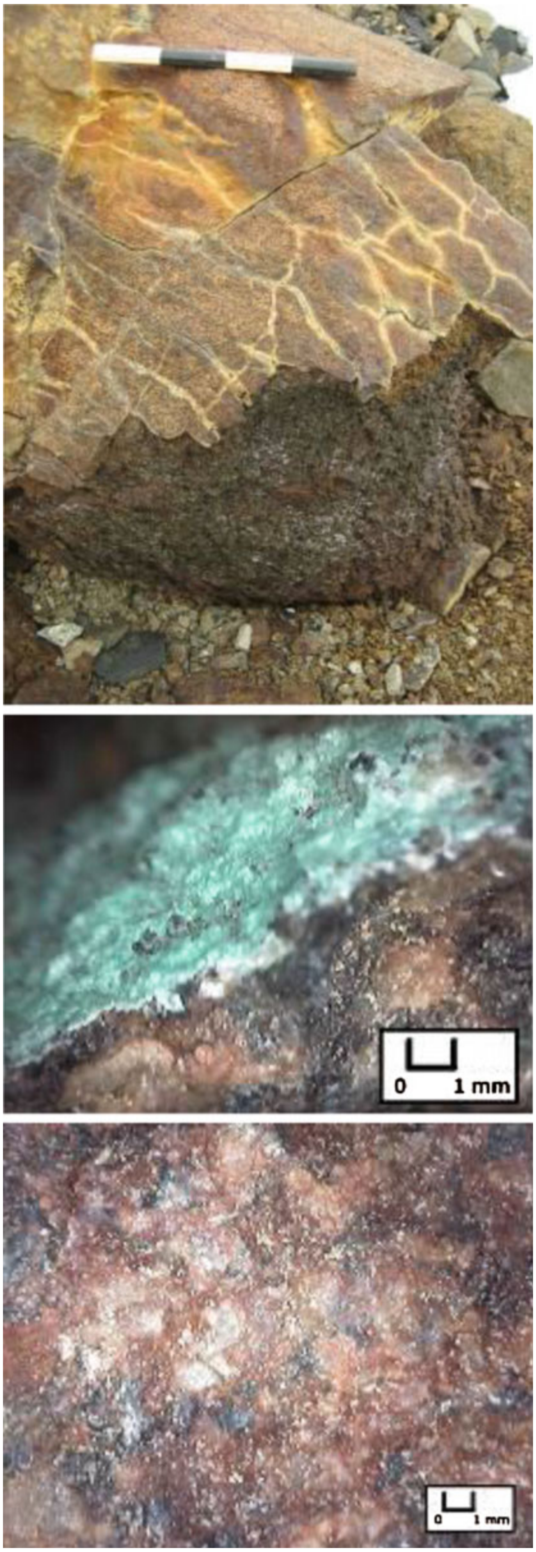

Fig. 11.4 Aeolian gneiss remnant with cracked ferriferous cap, *yellowish* mottles, and *white* sea-salt coatings (scale mark—5 cm) (*top*); *greenish* mottles on surface of debris with significant content of copper (0.5–1 % of total weight) (*middle*); ferriferous coating on bottom surface of debris (*bottom*)

11.2.5 Biota

The *Soviet Atlas of Antarctica* specifies that the only lichen species in the vicinity of "Russkaya" station is *Umbrilicaria decussata* (Atlas of Antarctica 1969). Recent investigations of Mikhail Andreev and Lyubov Kurbatova show that flora of the "Russkaya" station is the richest of the Russian stations, with 26 lichens and 4 bryophytes (Andreev and Kurbatova 2008). The most noteworthy are the lichens *Buellia pycnogonoides*, *Candelariella aurella*, *Cystocoleus ebeneus*, *Lecidella sublapicida*, *Pannaria caespitosa,* and *Placynthium asperellum*, previously unknown in continental Antarctica. The lichen *Ephebe multispora*, known only to Greenland, was also collected for the first time in Antarctica (Andreev and Kurbatova 2008). The vegetation cover at Russkaya is dominated by the lichens, *Usnea antarctica* and *Umbrilicaria decussate*, and some mosses (*Ceratodon purpureus* and *Schisticidium antarctici*.).

The projective cover degree of *Usnea antarctica* may reach 40–80 %, although the average is 25–40 %; Abakumov 2008). Thalli of lichens get snarled together in the upper layers of plant debris, providing a primitive structural "shield" that protects subsurface soil horizons from hard winds. Mosses are usually associated with the borders of frost mounds. They occupy space between relatively large fragments of debris, where water accumulation takes place and wind is lessened. Moss pads are often of black color in the center; living parts of green color are usually on the periphery of the pad. Pads often contain ingrown stones. In general, vegetation is more abundant and well developed on leeward slopes. The algae *Prasiola crispa* and the lichen *Lecania brialmonti*, which are nitrophilous and indicative of penguin rookeries, are locally represented here. Lake bottoms are covered by green algae coatings; sometimes floating bodies form here. The most abundant algae are *Cyanothece aeruginosa*, *Gloeocapsa* spp., *Oscillatoriaceae*, *Nostoc* sp., *Pseudococcomyxa simplex*, *Stichococcus bacillaris*, *Desmococcus vulgaris*, *Prasiola crispa,* and *Prasiococcus caicarius* (Broady 1989).

Diatoms were not found. The micromycetes, *Geomyces pannorum* and *Penicillium frequentans*, were isolated from local soils and debris. Soil mesofauna includes many species of tartigrades, several nematodes, infusoria, and flagellates (Fig. 11.6). The endemic antarctic rotifer *Phylodina gregaria* also occurs in soils at Russkaya. Special bacteriological investigations enabled isolation of Ralstonia, Sphingomonas, Solobium, Bacillus, and Micrococcus from soil samples collected in the station area and from the buildings (Abakumov et al. 2009).

Several fauna species are found at Russkaya; Weddell seals, Adelie penguins, and polar skuas are rare visitors to this area. On occasion emperor penguins and snow petrels have been observed.

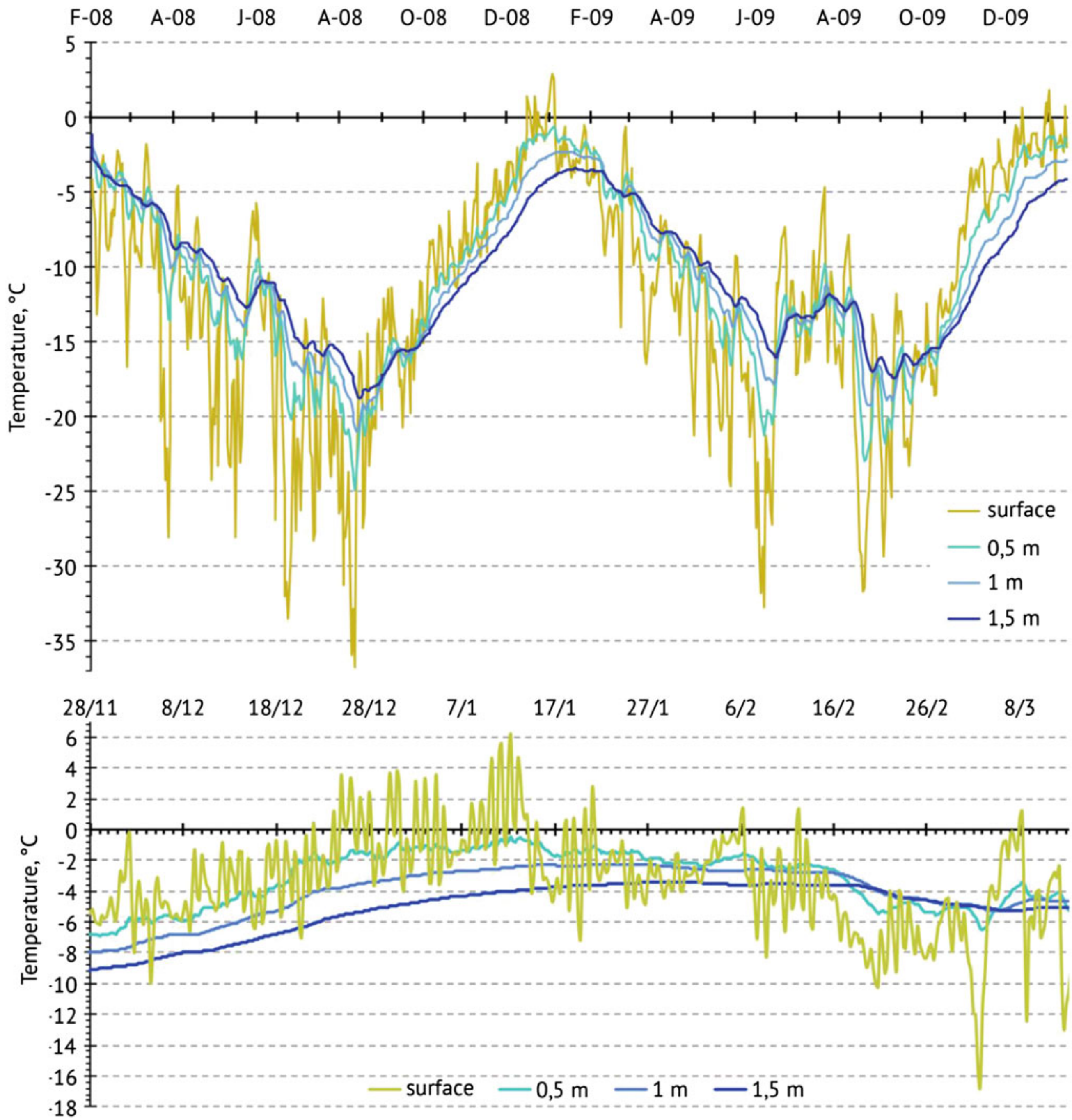

Fig. 11.5 Permafrost temperature variation at "Russkaya" station. Borehole A8-08 (period February 2008–January 2009). Mean daily temperatures (*top*) and period of positive temperatures (*bottom*)

11.3 Methods

11.3.1 Field—Soil Description, Soil Mapping

We collected field data from 15 pedons in the vicinity of "Russkaya" station, 3 pedons from the Lindsey Island, and 2 pedons from the Hudson Mountains. Unfortunately, no data are available for soils of other regions of Marie Byrd Land, especially from remote ice-free areas of the Executive Committee Range, the Flood Range, and the Ford Range. The soil-forming factors in these regions seem to significantly differ from those at the Berks Cape of the Hobbs Coast where "Russkaya" station is situated. In addition to

Fig. 11.6 Examples of mesofauna in soils of “Russkaya” scientific station, including the rotifer (*Phylodina gregaria*) (*top*) and the abundant tartigrades (*bottom*). Photo courtesy of Daniel Stoupin

major differences in soil climate, the abundance of alkaline volcanic rocks (in contrast to mainly acidic metamorphic gneisses of “Russkaya”) and significant increase of the altitude above sea level prevented authors from extrapolating their results to these remote ice-free areas. However, without doubt we can only assert that soils exist there also.

All the field procedures were carried out according to the “ANTPAS Guide” (Bockheim et al. 2006). Soil pits were excavated unless large boulders or solid rocks prevented further digging. GPS location and elevation of each site was determined. Some current weather conditions were recorded, including air temperature, wind speed and direction, form and intensity of precipitation, and background radiation. Site features were described, including structure and density of vegetation cover; depth of active layer, ice texture of permafrost (if present); the degree of boulder and debris weathering; and structure and dimensions of cryogenic forms of relief (MacNamara 1969; Campbell and Claridge 1975; Bockheim and Tarnocai 1998; Beyer et al. 1999).

The following soil properties were measured: 10 % hydrochloric acid test to distinguish carbonates in the soil profile; potassium ferricyanide test to detect redoximorphic features; “Cn” and “Cox” were used for distinguishing unoxidized and oxidized parent materials, respectively (Birkeland 1984). Soil temperatures have been measured year-round since 2008 every 6 h with a Hobo U12 data logger with an accuracy of ±0.21 °C. Sensors were installed at the surface and at 0.5, 1.0, and 1.5 m depths. Additional sensor was installed in 2010 in the borehole A8-08 at the depth of 0.2 m; two sensors were also installed in the soil profile in the pit LA55-Rs-01 at the depths of 0.05 (under the shallow cover of *Usnea antarctica*) and 0.2 m.

11.3.2 Laboratory—Characterization

The following laboratory methods were used to characterize different soil properties. Soil pH and major cations were measured in 1:5 soil: distilled water extracts (U.S. Salinity Laboratory 1954). Total organic carbon (TOC) was determined by Tuyrin dichromate oxidation method [1937] (almost the same as Walkley and Black). The fraction less than 2 mm in diameter (fine earth) was determined from dry sieving, and the particle-size distribution in the fraction less than 1 mm was determined by the pipette method. Absorbed water content was determined using Russian Governmental Standard-28268-89 method (Soils, 2005). The content of anthropogenic petroleum products in soils was measured using infrared spectrometer AN-2. The total content of biophyl elements, heavy metals, and rare earth elements in the mineral material of soil horizons was determined using X-ray crystal diffraction spectrometer Spectroscan-MAKS GV. Submicroscopic investigation of soils employed an electronic scanning microscope JSM-6610LV with a microanalyzer. The preliminary conclusions on the weathering stage of soil profiles were made following the criteria of Campbell and Claridge (1975).

11.3.3 Map Compilation and Database

A digitized 1:2,000-scale topographic map was used as base map for soil mapping in the vicinity of "Russkaya" scientific station. Each soil pit was located on a topographic map (Fig. 11.7). Soil boundaries were drawn over the topographic map.

11.4 Results

11.4.1 Location and Area of Major Ice-Free Regions

Major ice-free regions of the MBL are the Rockefeller Mountains (480 km^2) and the Alexandra Mountains (220 km^2) for a total ice-free area of 700 km^2 (Table 2.1). The ice-free area in vicinity of "Russkaya" scientific station is about 4 km^2.

11.4.2 Distribution and Description of Soil Taxa

Preliminary conclusions on the distribution of major soil units in the environment of "Russkaya" scientific station are made on the data taken during two short visits (5 days) to MBL in 2007–2008 and 2009–2010.

Soils were classified into the Gelisol order to the family level (Soil Survey Staff 2010). Mineral soils showing cryoturbation were classified as Turbels; mineral soils with no cryoturbation were classified as Orthels. Both suborders are divided into great groups on the basis of soil properties. Soils under the mosses or algae mats along streams or near lakes and snow patches are moist only during the summer months and were classified as Aquic Haploturbels or Aquic Haplorthels. Soils under lichens on relatively dry watersheds and slopes having anhydrous conditions were classified as Anhyturbels or Anhyorthels. Due to the lack of soil water regime data, we avoided classifying moist soils as Aquiturbels or Aquorthels. Soils that have bedrock within 50 cm of the mineral soil surface occur in Lithic subgroups. Small areas near Russkaya contain thin organic soils under former or modern penguin rookeries and are classified in the Histel suborder. These soils contain a significant amount of poorly decomposed organic ornithogenic material (up to 70–80 % by volume) and also have bedrock within 50 cm; therefore, they are classified as Lithic Fibristels.

The interpolation of the scarce field data while compiling the soil map let authors to assume the percentage of the area occupied by each soil unit. The most abundant soil map unit in the vicinity of "Russkaya" station is the soil association Lithic Anhyorthels + Lithic Anhyturbels (about 40 % of the total ice and snow-free area of the keysite). Less abundant are Aquic Haplorthels + Aquic Haploturbels (10–15 %). Lithic subgroup index may often also be referred to the latter pedons. Lithic Fibristels (in conjunction with Lithic Haplorthels) are of rarest soil map units (5–10 %).

11.4.2.1 Lithic Anhyorthels + Lithic Anhyturbels

This soil association occupies the greatest area (about 40 %) of Russkaya scientific station. These soils (Fig. 11.8) occupy relatively flat watersheds and medium slopes. *Usnea antarctica* dominates the vegetation cover, thalli may reach 3–5 cm in width and cover may reach 40–60 %. Mosses are rare and suppressed (2–4 cm in diameter; 1–3 cm thick). Most commonly, lichens occupy the space between large fragments of debris, in some cases binding the material of the uppermost horizons. Orthels prevail in this association; however, evidence for cryoturbation is rare and weakly expressed (rock orientation and sorting, slope stripes, vague stone pavement). Flat and low-centered polygons reach 1 m in diameter; debris dimension increases from 0.5–3 cm in the central part to 10–15 cm along the periphery. Cryoturbation processes can be observed in soil profiles that exceed 30–40 cm depth.

Boulders and large fragments of debris on the surface are often stained, sometimes are covered with dark brown ferruginous crusts and have greenish, yellowish and bluish salt encrustations and mottles; application of 10 % HCI showed no evidence of carbonates. The uppermost layers are always significantly more coarse-textured. The fine-earth (<2 mm) content increases with soil depth from 1–2 to 10–15 %. The coarse fragments of subsurface horizons have macro-, meso-, and micromorphological evidences of fine-earth and secondary minerals coatings. This material contains fragments of lichen thalli, an initial source of SOC. Soils are of neutral pH. Lightly stained material is obtained all the way down to the lithic contact. These pedons are of weathering stage 2–3 (Campbell and Claridge 1975) and have a salt stage of 0–1.

Permafrost is usually "dry-frozen" which is consistent with the anhydrous conditions in these soils. In some cases pore ice is obtained in the space between the fragments of debris. Some physical and chemical properties of Lithic Anhyorthels and Lithic Anhyturbels are given in Tables 11.1, 11.2 and 11.3.

Lithic Anhyorthels were also obtained in Hudson Mountains and here they have some special features (Figs. 11.9 and 11.10). Due to the vast distribution of pyroclastic deposits, debris is of black color and mainly cubiform. *Usnea antarctica* is also represented here, taking part in initial structuring of mineral material by fixing its upper layers. The fine-earth content increases downward and reaches 10–15 % in

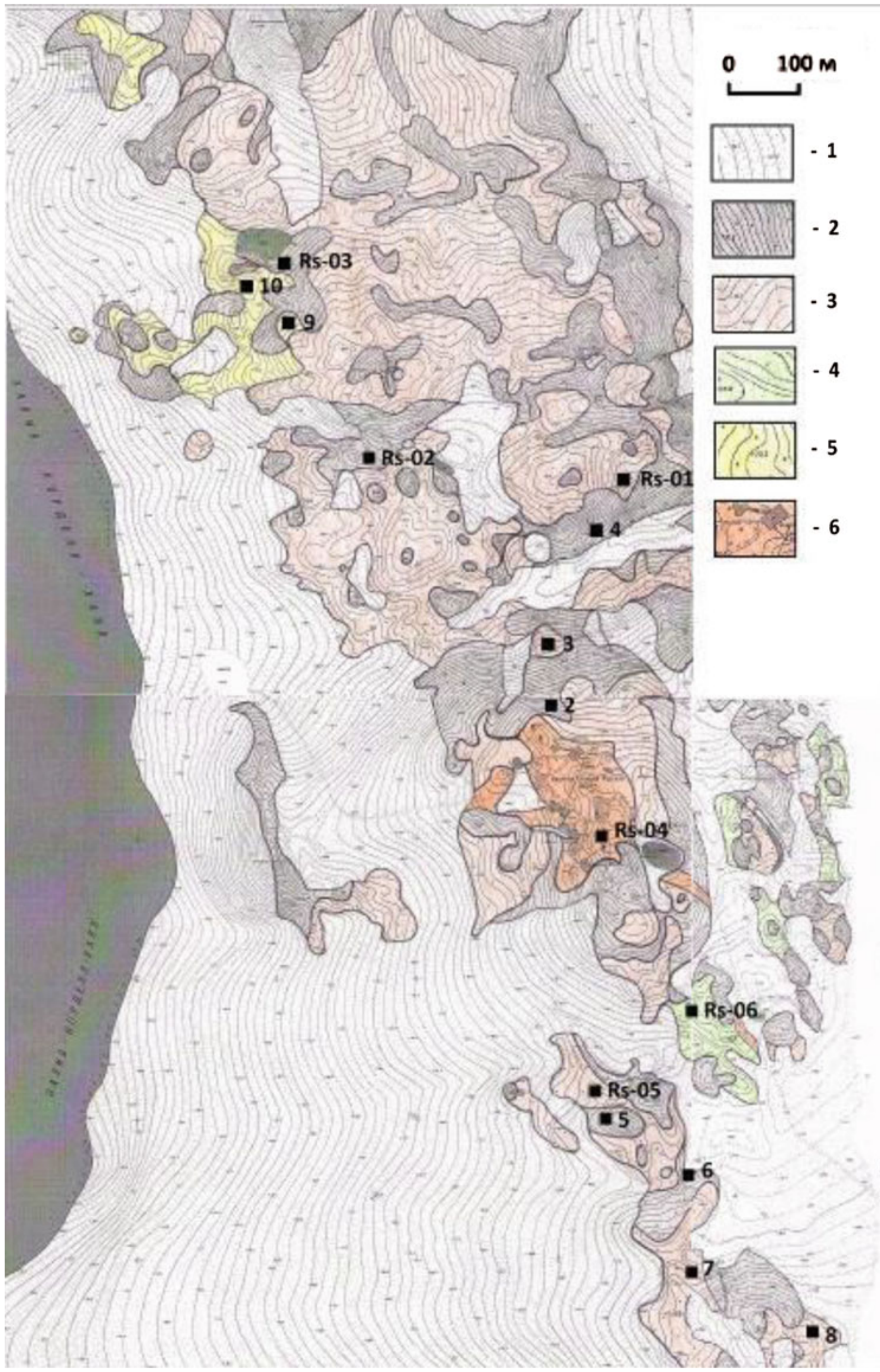

Fig. 11.7 Soil map of ice-free area in vicinity of "Russkaya" station.*1* Snow patches; *2* rocklands and remnants; *3* Lithic Anhyorthels + Lithic Anhyturbels; *4* Aquic Haplorthels + Aquic Haploturbels; *5* Lithic Haplorthels + Lithic Fibristels; *6* human-affected soils

lowermost horizons. The pH ranges from 6.6 to 8.7. Soils investigated in the Hudson Mountains have a lithic contact at 5 cm; the mineral material contains fragments of lichens. These pedons may probably be the most abundant in MBL, because of rocks and deposits of volcanic genesis. Morphological structure and some physical and chemical properties of Lithic Anhyorthels on pyroclastic deposits are given in Fig. 11.8 and Tables 11.1, 11.2 and 11.3.

Fig. 11.8 Lithic Anhyturbels. Pedon LA55-Rs-01 (scale marked in 5 cm intervals)

11.4.2.2 Aquic Haplorthels + Aquic Haploturbels

This soil association (Fig. 11.11) most often occupies depressions of relief and shallow slopes with overlying snow patches (10–15 % by area). These snow patches provide liquid water during thawing periods. This condition enables vegetation to proliferate; thalli of *Usnea antarctica* become larger (7–10 cm), moss polsters reach 10–15 cm in diameter and 7–12 cm thick, especially in areas where large rocks trap snow and liquid water. Moss polsters here have an interesting feature. Nearly all of the polsters have a brown-black center with small pinkish-white parasitic lichens on it; the peripherical part of the polster is green-brown. The plant cover may occupy 80 % of surface in such an environment. Turbels comprise a large part in a soil cover here. The thickness of rock debris reaches a maximum in depressions that average about 50–60 cm in depth. In these depressions, the moisture content is also the highest, so that cryoturbation processes can become more pronounced. Flat and low-centered cryogenic polygons reach 1.0–1.5 m in diameter. We suspect the existence of ice-rich permafrost in such conditions. This fact allows us to expect that some soils here will be classified as Gelisols in Typic subgroups. The fine-earth content in these soils is very high (up to 50–60 % in the lower parts of moss polsters and 30–40 % in the underlying horizons). The uppermost soil horizons (lower parts of moss polsters) are weakly acidic and the underlying mineral material is neutral in pH. In spite of relatively saturated conditions, even the lowermost soil horizons do not show evidences of an anaerobic regime. The potassium ferricyanide test did not enable recognition of ferrum protoxides. As with the previous soil association, the 10 % HCl test shows no evidence of carbonates. Yellowish and greenish salt encrustations and mottles are rarely obtained in these soils, probably due to the relatively more available liquid water. Staining of soil material is obtained here to a light degree. These pedons also have a weathering stage of 2–3 and a salt stage of 0. Some physical and chemical properties of Lithic Anhyorthels and Lithic Anhyturbels are given in Tables 11.1, 11.2 and 11.3.

11.4.2.3 Lithic Fibristels + Lithic Haplorthels

These soils (Figs. 11.12, 11.13, 11.14, 11.15 and 11.16) are of the rarest occurrence at Russkaya station (5–10 % by area). Penguin rookeries of MBL are among the southernmost in the world (the most southerly are *Pygoscelis adeliae* at Cape Royds, region 5b, 77° 32′ S). Small colonies of penguins produce a small but significant amount of soil organic matter. The thickness of soils on guano deposits never exceeded 15–30 cm. The guano deposits are underlaid by ice-rich, frozen coarse debris, and a lithic contact within 100 cm. Therefore, we used the Lithic subgroup for Fibristels of MBL, but we suppose that the existence of Typic Fibristels is possible. Small areas of these pedons were obtained in vicinity of Russkaya station, but the most impressive are the soils of Lindsey Islands.

Fresh organic material is light brown and after desiccation it forms a rubber-like mantle, which covers debris and shields it from removal of fine-earth material by strong winds. Besides fragments of debris, these soils contain a significant amount of bird remains, including carcasses, feathers, eggshell, etc. The average “organic matter/mineral matter” ratio in Lithic Fibristels is 80/20 % (Abakumov, 2008). The abundance of coarse angular debris fragments increases downward. If the rookery is inactive, cryogenic sorting of mineral material begins to move coarse fragments upward to the soil surface and bury the organic matter with time.

Penguin rookeries mainly occupy elevated areas and strongly influence the organic matter forms of Lithic Haplorthels that are covered by the nitrogen-fixing community of the algae *Prasiola crispa* and the lichen *Lecania brialmonti*. These pedons occupy gentle slopes and snow-free depressions. The abundance of meltwaters enriched with organics lead to the intensive development of vegetation cover. Lithic Haplorthels of Lindsey Island contain a significant amount

Table 11.1 Chemical properties of major soil units of MBL (Lupachev and Abakumov 2013)

Soil unit	Pit	Horizon	Depth (cm)	TOC_{org} (%)	pH_{H_2O}	Adsorbed cations, meq/100 g				Hydrocarbons (mg/kg)
						Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	
Lithic Anhyturbels	LA55-Rs-0I	OC	0–2	Not det.						
		C1	2–7	0.91	5.38	Not det.				
		C2	7–31	0.56	5.33	0.90	1.20	0.50	0.24	63.33 ± 2.81
		⊥R	31↓	0.37	5.41	Not det.				
	Hudson-1	OC	0–5	0.42	7.40	0.51		3.65		Not det.
	Hudson-2	OC	0–5	0.67	7.30	0.54		2.87		Not det.
Lithic Anhyturbels	LA55-Rs-03	OC	0–3	8.34	5.91	Not det.				
		C	3–15	1.96	5.95	Not det.				
	LA55-Rs-05	C1	0–1	Not det.	6.01	Not det.				
		C2	1–5	1.11	5.35	Not det.				
		C3	5–17	1.10	5.40	0.30	0.30	0.07	0.01	65.20 ± 3.12
	Rus4	C1	0–5	0.60	5.53	Not det.				
		C2	5–15	0.51	5.40	Not det.				
		C3	15–30	0.90	–	Not det.				
Aquic Haploturbels	LA55-RS-06	AO	0–4(7)	8.64	5.01	3.70	2.00	1.27	0.39	Not det.
		C	4–16	1.03	5.34	0.90	0.90	0.19	0.09	Not det.
Lithic Fibristels	Rus 10	O	0–5	10.57	6.50	Not det.				
		OC	5–15	0.70	5.90					
	Lindsey 1	O	0–5	18.23	7.20	0.35		0.25		Not det.
		C	5–15	1.29	6.70	0.21		0.15		Not det.
Human-affected soils	LA55-Rs-04	Average sample	0–5	1.77	4.98	Not det.				2205.95 ± 22.70

of coarse debris; the fine-earth content is small (5–15 %) and increases with soil depth. At the average depth of 10 cm, pore ice appears and is sometimes accompanied by ice cementation of the mineral material. The majority of these soils have a lithic contact within the 100 cm of the surface. Some physical and chemical properties of this combination of pedons are given in Tables 11.1, 11.2 and 11.3.

11.4.2.4 Rocklands and Snow Patches

About 40 % of the ice-free areas of "Russkaya" station environment is composed of exposed bedrock, rather than soils. However, given soil mapping did not allow us to clearly distinguish this land type. Although rocklands most of the high peaks, steep slopes, and boulder fields, Lithic Anhyorthels can occur even in these extreme conditions.

More detailed field and laboratory investigations may prove the existence of other soil units in this area and in other regions of the Marie Byrd Land. Aquorthels and maybe Aquiturbels (of Typic or Lithic subgroups) may exist close to snow patches and along lakeshores. Due to a limited time in the field, we were unable to distinguish Orthels or Turbels in the Typic subgroup. We obtained a lithic contact in 100 % of soil pits examined, but we suspect that there are depressions or shallow slopes where the accumulation of nonconsolidated debris takes place and thickness of soil profiles may exceed 100 cm.

11.5 Discussion—Pedogenic Processes and Landscape Evolution

11.5.1 Relation Between Soils and Landforms

There is a strong correspondence between landform and microrelief type and soil taxa. Deep intervalley depressions and windward ocean-facing slopes are occupied by relatively stable snow patches which produce a significant amount of meltwater each summer. The high peaks, steep slopes, and aeolian remnants occur as rock lands with no vegetation cover (probably except of sporadic and depressed lichens). Although we cannot be absolutely certain that soils do not exist on these geomorphological sites; we suppose that rare occurrence of Lithic Anhyorthels is possible here.

Table 11.2 Physical properties of major soil units of MBL, % (Lupachev and Abakumov 2013)

Soil unit	Pit	Horizon	Depth (cm)	Sum of fractions >1 mm (>3 mm)	Fine earth (<1 mm)	0.01 mm/ <0.01 mm	Field moisture	Hygroscopic moisture
Lithic Anhyturbels	LA55-Rs-01	OC	0–2	99.14 (98.37)	0.86	Not det.	0.61	Not det.
		C1	2–7	87.38 (63.44)	12.62	95.64/4.36	0.71	0.77
		C2	7–31	84.58 (55.70)	15.42	93.00/7.00	0.86	0.93
		⊥R	31↓	82.46 (54.68)	17.54	95.76/4.24	2.06	0.61
	Hudson1	OC	0–5	98.90 (95.32)	1.10	Not det.		0.67
	Hudson 2	OC	0–5	80.00 (77.24)	20.00	88.62/11.38	Not det.	0.99
Lithic Anhyorthels	LA55-Rs-03	OC	0–3	96.94 (87.11)	3.06	Not det.	Not det.	0.47
		C	3–15	96.94 (80.93)	3.06	Not det.	Not det.	0.27
	LA55-Rs-05	C1	0–1	98.48 (96.58)	1.52	Not det.	0.07	2.48
		C2	1–5	91.93 (50.49)	8.07	95.72/4.28	0.56	0.26
		C3	5–17	95.18 (73.21)	4.82	95.96/4.04	1.70	0.28
	Rus 4	C1	0–5	Not det.				0.55
		C2	5–15	Not det.				0.40
		C3	15–30	Not det.				0.60
Aquic Haploturbels	LA55-Rs-06	AO	0–4(7)	63.28 (30.86)	36.72	92.40/7.60	34.61	3.25
		C	4–16	83.95 (54.87)	16.05	91.00/9.00	3.26	0.73
Lithic Fibristels	Lindsey 1	C	5–15	98.00 (95.67)	2.00	Not det.		0.71
Human-affected soils	LA55-Rs-04	Average sample	0–5	95.60 (79.93)	4.40	93.36/6.64	Not det.	0.71

Table 11.3 Bulk contents of some elements in the profiles of major soil units of MBL (air-dried samples) (Lupachev and Abakumov 2013)

Soil unit	Pit	Horizon	Depth (cm)	Na_2O	MgO	P_2O_5	K_2O	CaO	Fe_2O_3	Al_2O_3	SiO_2	S	As	Pb	Hg
				(%)									(ppm)		
Lithic Anhyturbels	LA55-Rs-01	OC	0–2	Not det.											
		C1	2–7	1.75	3.16	1.04	0.30	8.19	7.88	15.23	54.29	0.08	22	43	0.07
		C2	7–31	1.88	2.63	0.82	0.37	5.87	6.19	13.88	60.21	0.14	16	43	0.05
		⊥R	31↓	2.00	3.15	1.23	0.38	7.33	8.71	16.99	55.47	0.15	32	61	0.07
Lithic Anhyorthds	LA55-Rs-03	OC	0–3	0.57	1.79	1.23	0.57	6.32	3.97	8.76	58.66	0.33	1	23	0.06
		C	3–15	0.79	2.52	1.04	0.36	8.85	4.51	11.97	54.76	0.13	9	28	0.07
	LA55-Rs-05	C1	0–1	1.19	1.97	0.38	0.26	5.19	5.05	9.95	60.70	0.18	17	42	0.08
		C2	1–5	0.72	2.32	0.44	0.16	7.93	5.65	13.23	54.74	0.06	21	46	0.09
		C3	5–17	0.91	2.56	0.52	0.21	7.89	5.72	12.91	55.56	0.05	15	40	0.05
Aquic Haploturbels	LA55-Rs-06	AO	0–4(7)	1.00	2.16	1.61	0.33	5.93	6.00	10.01	58.66	0.55	0.1	19	0.11
		C	4–16	1.11	3.02	2.23	0.57	9.25	8.83	17.03	49.61	0.09	1.9	56	0.11
Human-affected soils	LA55-Rs-04	Average sample	0–5	1.29	2.86	0.45	0.33	7.58	7.63	15.08	54.92	0.20	23	58	0.08

Fig. 11.9 Hudson Mountains

In the Russkaya area, soils on gentle slopes and under relatively closed vegetation cover, primarily *Usnea Antarctica*, are Lithic Anhyorthels and Lithic Anhyturbels. However, Orthels tend to be most prevalent, because of the lack of liquid water and the thin layer of unconsolidated materials that precludes cryoturbation processes. Moving further down slope into depressions we find Aquic Haplorthels and Aquic Haploturbels. These soils receive meltwater, and the thickness of the unconsolidated material is greater, but a lithic contact still exists within 100 cm of the surface. The vegetation cover includes different mosses with relatively thick polsters, even by comparison to other, less southern oases of continental Antarctica. Turbels play more significant part in this combination and even ice-cemented permafrost can be obtained in some cases.

The area of the Lithic Fibristels and Lithic Haplorthels association coincide with a unique set of geomorphological conditions. Penguin rookeries are common along the seashore on elevated benches that receive more solar radiation and hence heating. In these locations Lithic Fibristels form. Organic matter provided by penguins accumulates on slopes and in depressions where moisture can accumulate, forming Lithic Haplorthels. These soils have ice-cemented permafrost in the upper 70 cm.

11.5.2 Soil Taxa and the Occurrence of Organisms

There were no special investigations that dealt with the microbial and soil invertebrate abundance in relation to soil taxa. However, in high-latitude barrens the amount of animal and vegetation species is strongly dependent on the availability of water (e.g., dissolved organic C, total N, etc.). Different species of Tartigrades, nematodes, rotifers, infusoria, and flagellates seem to be most prevalent in Aquic Haplorthels (or Haploturbels) and in Lithic Haplorthels. The poorest sites for organisms are the rocklands and Lithic Anhyorthels (or Anhyturbels).

Fig. 11.10 Surface of Lithic Anhyorthels, Moses Mountain

Fig. 11.11 Aquic Haplorthels + Aquic Haploturbels. Pedon LA55-Rs-06 (scale marked in 5 cm intervals)

Fig. 11.12 Penguin rookeries on Russkaya station. Photo courtesy of Igor Gavrilov

11.5.3 Anthropogenic Influence

The human impact at Russkaya scientific station appears in two ways that are common to nearly all scientific stations in Antarctica: fuel spills and soil disturbance by heavy (mainly tracked) vehicles (Fig. 11.17). Preliminary analysis reveals deep and significant differences between "natural" and disturbed soils of Russkaya station. Particle-size distribution data show that soils that have not been influenced by human pressure are highly lithogenic and contain from 5–10 to 30 % of fine earth. This condition gives an opportunity for contaminants to migrate downward and after that laterally over the surface of the bedrock or permafrost table. Some soils that are transformed by human activity contain 40–50 and even 70 % of fine earth. In spite of the absence of pedogenic structure, this material may accumulate contaminants on its surface (water-holding capacity may reach 3–7 %). These disturbed soils contain 3–10 times more As, Pb, Cd, and Cs than unaffected soils. Soils under vehicle tracks or close to oil reservoirs also accumulate petroleum products—from 150 to 600 and even more than 2,200 mg/kg (average background concentration is 40–60 mg kg^{-1} (Tables 11.1, 11.2 and 11.3). Human impacts are discussed further in Chap. 15.

Fig. 11.13 Lithic Haplorthels under *Prasiola crispa* (Pedon #10)

Fig. 11.14 Surface of former penguin rookeries on Lindsey Island

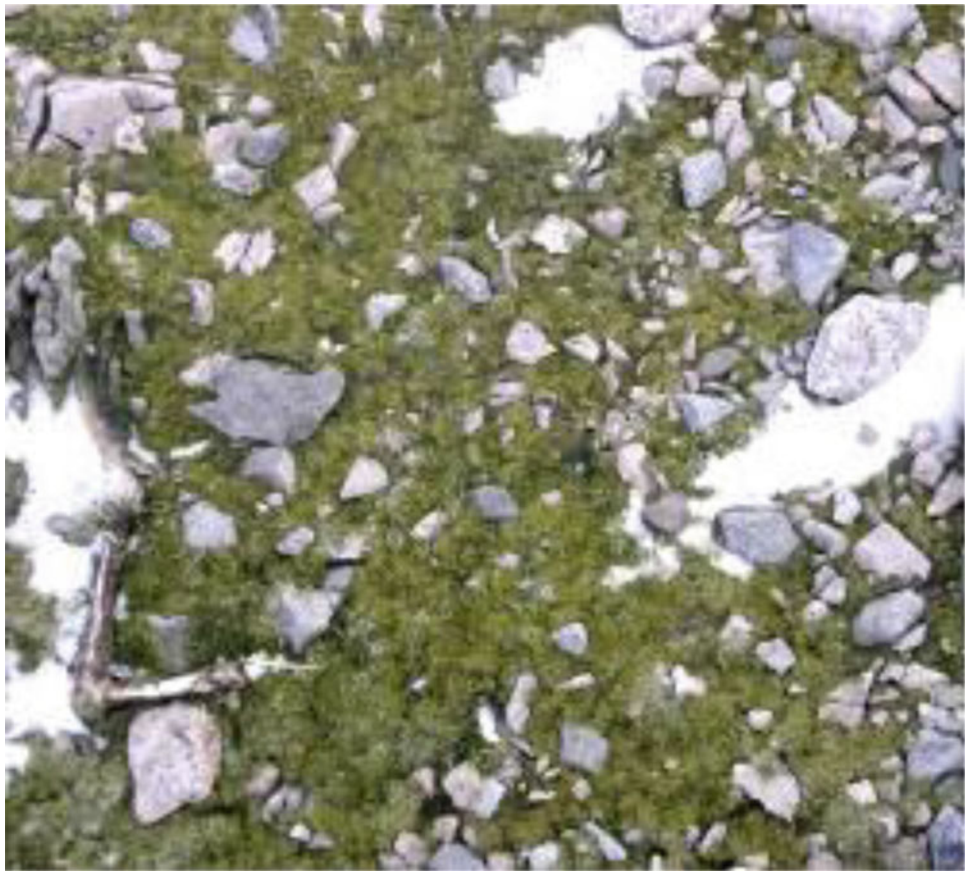

Fig. 11.15 Lithic Haplorthels under *Prasiola crispa* on Lindsey Island (Pedon #2)

Fig. 11.16 Lithic Fibristels on Lindsey Island (Pedon #1); depth of soil profile is 25 cm

Fig. 11.17 Human impact: an example of oil fuel spill at Russkaya station (*top*); road infrastructure and construction vehicles left by Russian polar explorers in the vicinity of Russkaya scientific station (*bottom*)

11.6 Summary

We have made a first attempt to analyze the soil diversity of one of the most remote areas of the world (and even of Antarctica)—the Marie Byrd Land. Investigation of 4 km^2 key site in vicinity of Russkaya scientific station allows us to prepare a provisional soil map of the region, but more importantly enable us to describe soil taxa distribution and their relation to landforms. The dominant soil unit is the association of Lithic Anhyorthels and Lithic Anhyturbels which occur on flat to gentle slopes. Rocklands and steep slopes comprise a significant proportion of the Russkaya area that do not support soils. The richest soils in terms of animal and plant species are Aquic Haplorthels (or Haploturbels); cryoturbation and stone sorting processes are best expressed in these soils. The most nutrient-rich, rarest, and unique soils of MBL are the association of Lithic Fibristels and Lithic Haplorthels in penguin rookeries with *Prasiola crispa* and *Lecania brialmonti*.

Acknowledgments The authors commemorate the inspiration of Russian soil studies in Antarctica—David Gilichinsky. We kindly acknowledge all of the members of the Russian Antarctic Expedition, especially Valery Lukin and Vyacheslav Martyanov, for invaluable help in conducting the investigations. We also thank Daniel Stoupin and Igor Gavrilov for photos. Investigations were partly taken with financial support of Russian Fund for Basic Researches (10-05-00079-a; 12-04-00680-a) grant of the President of the Russian Federation (MK-5451.2011.5); grant "U.M.N.I.K." (10016p/14298).

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12 Soils of Graham and Palmer Lands, Antarctic Peninsula

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12.1 Introduction

This chapter deals with the Antarctic Peninsula (AP) exclusive of the South Shetland and South Orkney Islands, which will be considered in Chap. 13, and the Joinville and James Ross Island group along the east coast of the AP, which will be considered in Chap. 14. It is disconcerting that so few soil investigations have been conducted along the AP, especially in view of the rapid warming along the western Antarctic Peninsula (WAP), which is expanding the ice-free area. The WAP is unique from other areas in Antarctica, because of its relatively temperate climate and the strong influence that biology plays in soil-forming processes.

Soils along WAP form on glaciofluvial plains, frost-shattered bedrock, patterned ground, peat beds, moraines, raised beaches and solifluction terraces. Entisols, Inceptisols, Gelisols and Histosols have been identified and possibly as many as 10 great groups exist. Cryoturbation, phosphatization, podzolization and melanization are active processes that have produced soils along the WAP that are unlike any others in the Antarctic region.

The AP has been divided into a northern portion, Graham Land, and a southern portion, Palmer Land; the AP is about 1,450 km long. Graham Land, which extends from the Trinity Peninsula (63° 30′ S) to Marguerite Bay (68° 30′ S) (Fig. 12.1), is a mountain chain less than 250 km wide and approximately 750 km long. The maximum elevation, 3,500 m, occurs within the Palmer Archipelago, which is an extinct island arc off the northwestern coast. Palmer Land extends from 68° 30′ S another 700 km to about 74° S where it joins Ellsworth Land (Chap. 10).

The east coast of the AP is subject to extremely dry and cold air masses that result in continental-type climates that are similar to those found in interior Antarctica. In contrast, the western coast of the peninsula is considerably warmer and wetter than the eastern coast due to the constant impact of low pressure systems moving eastward from the Bellingshausen Sea (Martin and Peel 1978).

The ice-free areas along the AP generally are nunataks lacking sediments or isolated coastal areas each comprising less than 2 km^2 (Fig. 12.1). The Antarctic Peninsula contains about 8,800 km^2 of ice-free area that includes Graham Land (2,500 km^2), Palmer Land (4,300 km^2), and Alexander Island (2,000 km^2) (Table 2.1).

The weather of the Antarctica Peninsula is dominated by the Polar Front, a thermal separation between air masses of the warmer mid-latitudes and the colder high-latitudes. As cold, dense air descends near the South Pole and radiates outward, concentric rings of low pressure develop and confront mid-latitude high pressures, creating a phenomenon known at the Southern Annular Mode. In the last 50 years the WAP has experienced some of the fastest warming on the planet, with a rate exceeding 3.4 °C per century (Vaughan et al. 2003). The dramatic breakups of ice shelves and rapid deglaciation in the region have been attributed to this rapid rise in temperature.

About 87 % of the 244 glaciers investigated on the AP are currently in retreat (Cook et al. 2005). Multiple factors likely contribute to the rapid warming and deglaciation of the Antarctic Peninsula, all of which are anthropogenic. Of primary importance are elevating levels of global carbon dioxide, now approaching 400 ppm$_v$, which warm the upper troposphere in the mid-latitudes. Secondly, warm waters from the Circumpolar Deep Water (CDW) may be upwelling along the continental shelf of the AP. Furthermore, changing

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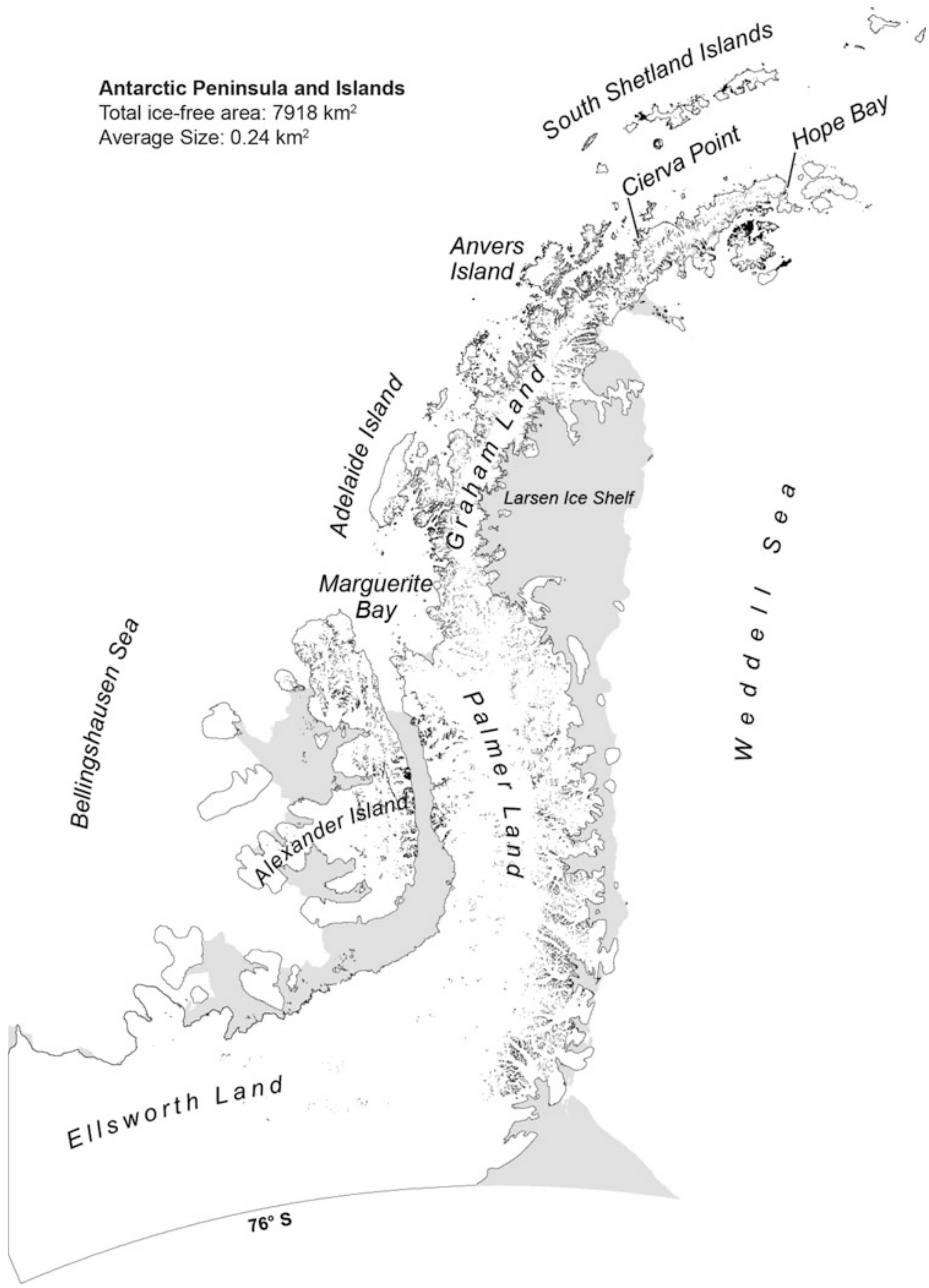

Fig. 12.1 Ice-free areas of the Antarctic Peninsula

atmospheric patterns may be bringing warmer air masses to the region (Vaughan et al. 2001). Another possible contributor is the destruction of ozone over Antarctica by chlorofluorocarbons to reduce the absorption of ultraviolet radiation, thereby cooling the lower stratosphere in the high-latitudes. A warmer troposphere in the mid-latitudes and cooler stratosphere in the high-latitudes causes a positive shift in the Southern Annual Mode causing a 15–20 % increase in the warm, moist westerly winds impacting the WAP (Turner et al. 2009). The reduction of winter sea ice is an additional factor which is likely a cause and effect of the rapid warming along the WAP (Smith and Stammerjohn 2001).

The objectives of this chapter are to delineate the role of soil-forming factors on soil development along the AP, summarize soils data in major ice-free areas from north to south, and identify the major soil-forming processes in the region.

Table 12.1 Chemical and physical properties of selected soils from Hope Bay, Trinity Peninsula

Horizon	Depth (cm)	>2 mm (%)	Sand (%)	Silt (%)	Clay (%)	pH H_2O	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	H+Al	CEC ($cmol_c\ kg^{-1}$)	BS (%)	Mehl-1 P ($mg\ dm^{-2}$)
							($cmol_c\ dm^{-2}$)							
HB2–Ornithogenic Haploturbels														
A	0–15/25	52	61	24	15	3.4	3.3	0.79	0.27	0.94	27.3	28.6	18	4437
Bwjjf	30/40–55	35	70	23	7	3.3	2.2	0.47	0.35	0.40	17.9	21.3	16	1606
Cf	100–210	41	50	30	20	6.2	3.5	1.4	0.48	0.12	0.8	6.3	87	353
HB5–Ornithogenic Haplohemists														
Oe	0–30	0	11	58	31	4.5	5.2	1.1	0.20	0.47	9.1	16.1	43	2953
HB11–Ornithogenic Gelorthents														
A	0–10	58	88	7	5	4.8	1.7	0.66	0.53	0.88	9.1	12.9	30	920
3Ab	35–60	62	94	3	3	4.9	0.54	0.36	1.3	0.79	7.2	10.2	29	396
3Cb	60–85	26	97	1	2	4.9	1.1	0.39	1.3	0.60	8.8	12.2	28	630
4Ab	85–120	73	94	4	2	4.8	1.1	0.48	1.2	0.85	7.8	11.1	32	1684

12.2 Soil Forming Factors

12.2.1 Geology

The AP is a mountainous continuation of the South American Andes. Most of the bedrock has an andesite/diorite composition that formed during the subduction of the Phoenix oceanic plate, which was a precursor to the Drake Plate (Barker 1982). Subduction and volcanism ceased along the AP as the ridges from spreading centers approached the subduction trench. The cessation of the spreading centers occurred along the southern AP from about 50 Ma and at about 4 Ma near Anvers Island (Barker 1982). Most of the surficial rocks exposed along the WAP were deposited during the late Mesozoic and early Cenozoic and can be categorized as either part of the Antarctic Peninsula Volcanic Group or Andean Intrusive Suite. The Antarctic Peninsula Volcanic Group is comprised of extrusive and pyroclastic deposits (e.g. agglomerates, tuffs and flows with inter-bedded terrestrial sediments) (Hammer and Moyes 1982). The Andean Intrusive Suite was a magmatic intrusion of the Antarctic Peninsula Volcanic Group and produced plutons of intrusive rocks (e.g. granites, granodiorites, gabbros) (Dewar 1970). Farther north, subduction of the Drake Plate under the South Shetland Islands is still occurring; frequent eruptions of Deception Island are a testimony to the active subduction below the South Shetland Islands. Ancient, marine eroded benches are found at several locations along the AP and are likely the product of uplifting during active subduction.

The ice sheets of the Antarctic Peninsula are currently about 500 m thick and either terminate on land or as floating ice sheets (in contrast to the grounded ice sheets surrounding the Antarctic interior) (Heroy and Anderson 2005).

12.2.2 Topography and Parent Materials

The WAP is a glacial/periglacial mountainous environment. The terrain is mostly craggy complex hillslopes that are either completely lacking sediments or covered by scree and till. Exposed bedrock that lack sediments is commonly glacially polished and/or striated. Simple slope complexities can be found on beach terraces, glaciolacustrine deposits and solifluction terraces. High-elevation marine-eroded benches lacking alluvial sediments are also common along the WAP. North-facing aspects, especially on steeper slopes, can exert a great influence on soil formation due to increased solar incidence; large, thick peat banks of the moss *Polytrichum alpestre* commonly form on intermediate drainage in these environments (Fenton and Smith 1982). Raised marine beaches which are common to the South Shetland Islands occur but are not prevalent along the AP.

12.2.3 Biota

High biologic activity occurs along the WAP due to a maritime climate and the upwelling of the nutrient rich CDW along the continental shelf of the WAP. Interestingly, most of the vertebrates that inhabit the ice-free terrestrial ecosystems of the AP feed directly on Antarctic krill (*Euphausia superba*) which are sustained by phytoplankton, and which in turn, are supported by nutrient-laden waters from upwelling by the CDW. The flow of nutrients into soils of the AP is, therefore, relatively simple and direct relative to other ecosystems with multiple inputs. For instance, the annual input of phosphorus to terrestrial Antarctica is about 15–20 thousand tons and is derived almost entirely from excreted krill in penguin rookeries (Myrcha and Tatur 1991).

Birds tend to have the greatest observable influence on the soils, particularly the rookeries of Adélie (*Pygoscelis adeliae*), Gentoo (*P. papua*) and Chinstrap (*P. antarcticus*) penguins and the nesting grounds of Brown (*Stercorarius antarcticus*) and South Polar skuas (*S. maccormicki*) and Southern Giant petrels (*Macronectes giganteus*). In the late 20th century, Adélie penguins were the most numerous of the penguin species at several locations along the WAP, but climate change is currently favoring Gentoo and Chinstrap penguin expansions (Turner et al. 2009). Penguin rookeries of hundreds to thousands of individuals can cause extremely high levels of soil carbon, nitrogen, and phosphorus. The soils formed under these conditions have unique physical and chemical properties and have been termed "ornithogenic" since their discovery by E.E. Syroechkovskii and F.C. Ugolini in the 1950s and 1960s (Everett 1976; Ugolini 1972). Ornithogenesis is best expressed at active penguin rookeries, but the process is recognizable in soils adjacent to active rookeries, at abandoned rookeries, and over the nesting grounds of non-penguin species.

Several species of seals exist along the WAP, but colonies of Antarctic Fur seals (*Arctocephalus gazelle*) and Elephant seals (*Mirounga leonina*) are the only species that cause any significant impact on the soils. Elephant seals can have especially dramatic effects where they "wallow"; this leads to high rates of soil compaction, erosion, and addition of nutrients through urine and fecal materials.

Vegetation occurs along the WAP in the form of algae, cryptogams (111 bryophytes species and about 400 lichen

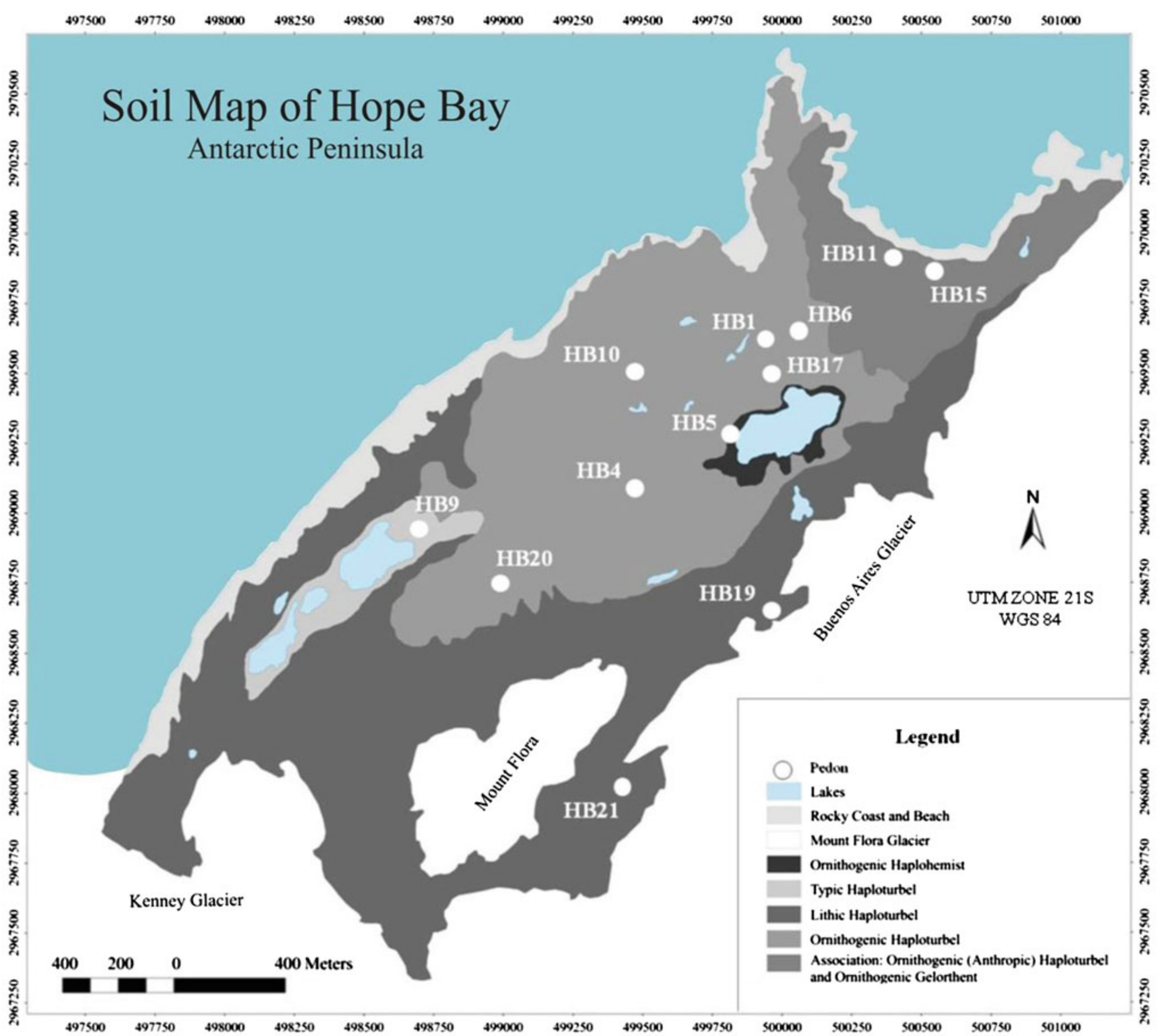

Fig. 12.2 Soil map of Hope Bay. Locations of the selected pedons in Fig. 12.3 are shown. Soil classification adapted from Soil Survey Staff (2010)

species), and phanerogams (two species) (Smith, 2005). Algae are found predominantly in the form of cyanobacteria, green algae (*Chlorophyta*) and diatoms. Although cynanobacteria and diatoms have been reported to dominate the soils, green algae, particularly *Prasiola crispa*, form continuous mats that can add considerable amounts of organic carbon to soils (Fermani et al. 2007; Rudolph 1965). Most Antarctic algae appear to be inhibited by low levels of inorganic nitrogen and moisture; algae are found in the greatest concentrations on moist areas indirectly impacted by birds (Arnold et al. 2003; Fermani et al. 2007).

Bryophytes are common along the entire WAP and form large (10 to over 1000 m^2) communities of “carpet-” and “turf-” forming mosses that may exceed depths of 40 cm. Thick turf-forming mosses (e.g. *Chorisodontium aciphyllum* and *Polytrichum alpestre*) are responsible for the formation of “peat banks”. In contrast to their counterparts in the northern hemisphere that form in poorly drained areas, peat banks on the WAP can develop on unsaturated rocky slopes. Carpet-forming mosses (e.g. *Brachythecium–Drepanocladus*) develop in poorly drained depressions and bedrock joints (Allen and Northover 1967). Fenton and Smith (1982) attribute the accumulation of peat in well-drained environments in maritime Antarctica to decreased decomposition due to low pH (3.5–4.5) and cold temperatures. Everett (1976) and Smith (1982) observed the development of permafrost in peats deeper than about 30 cm and concluded that permafrost likely causes higher moistures and stabilized slopes which in turn may favor peat formation. Other studies indicate that soil nutrient levels of maritime Antarctic soils may play a larger role in decomposition of organic matter than soil climate (Bokhorst et al. 2007; Davis 1981).

The only phanerogams are Antarctic hair grass (*Deschampsia antarctica*) and Antarctic pearlwort (*Colobanthus quintensis*). They are generally found in areas of high N and P from birds, although the severe trampling and harsh chemical conditions found in the active rookeries can prevent the plants from establishing. Recent rapid warming of the WAP has led to increased seed viability and germination of seeds in soil banks (Convey and Smith 2006; McGraw and Day 1997), and thus the population density of both species has increased of late, though no increase in their geographic range has been observed thus far. A descriptive model showing the effects of avians on soil development is given in Figs. 12.2, 12.3, 12.4, 12.5, 12.6, 12.7, 12.8.

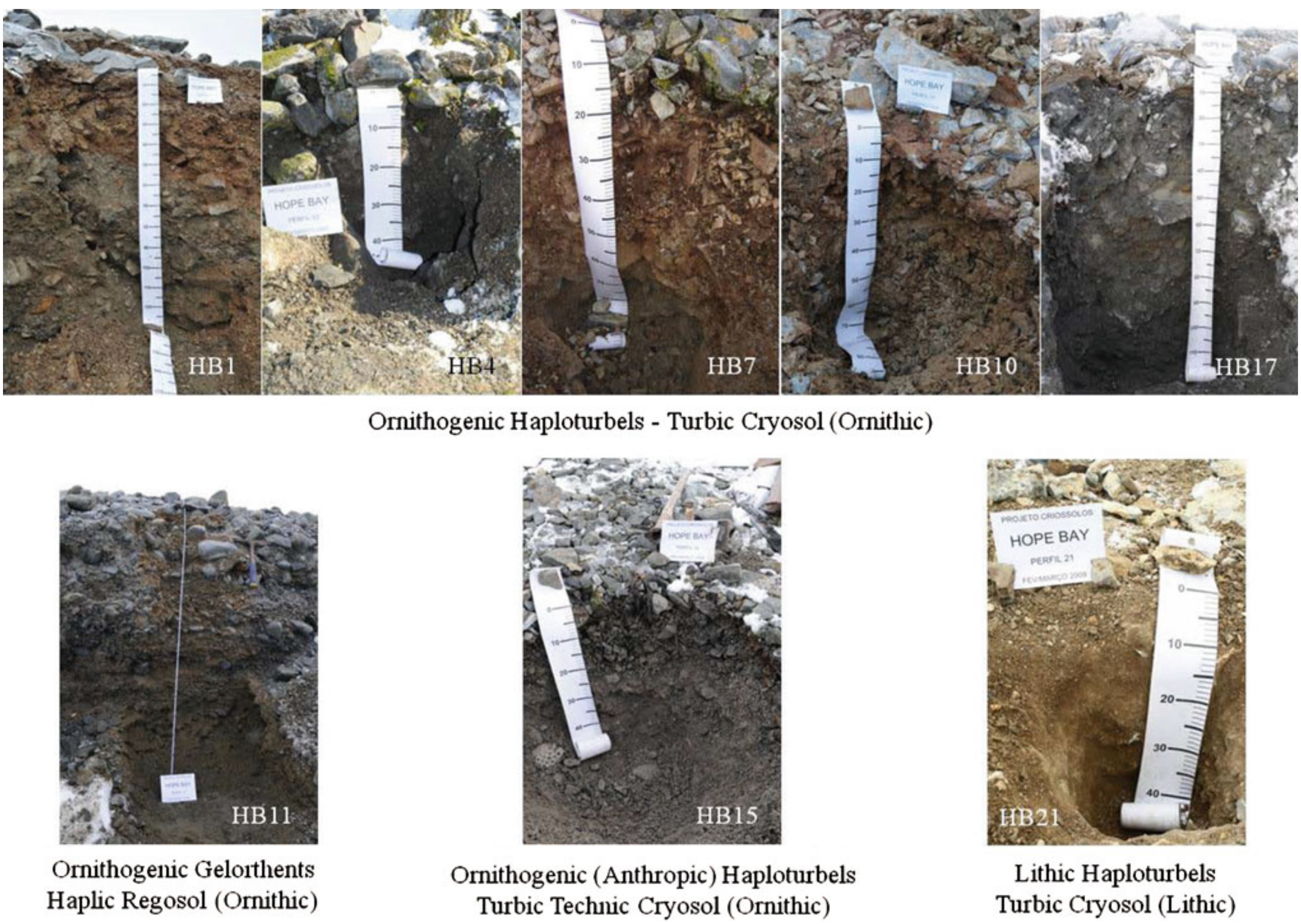

Fig. 12.3 Representative pedons at Hope Bay, Antarctic Peninsula

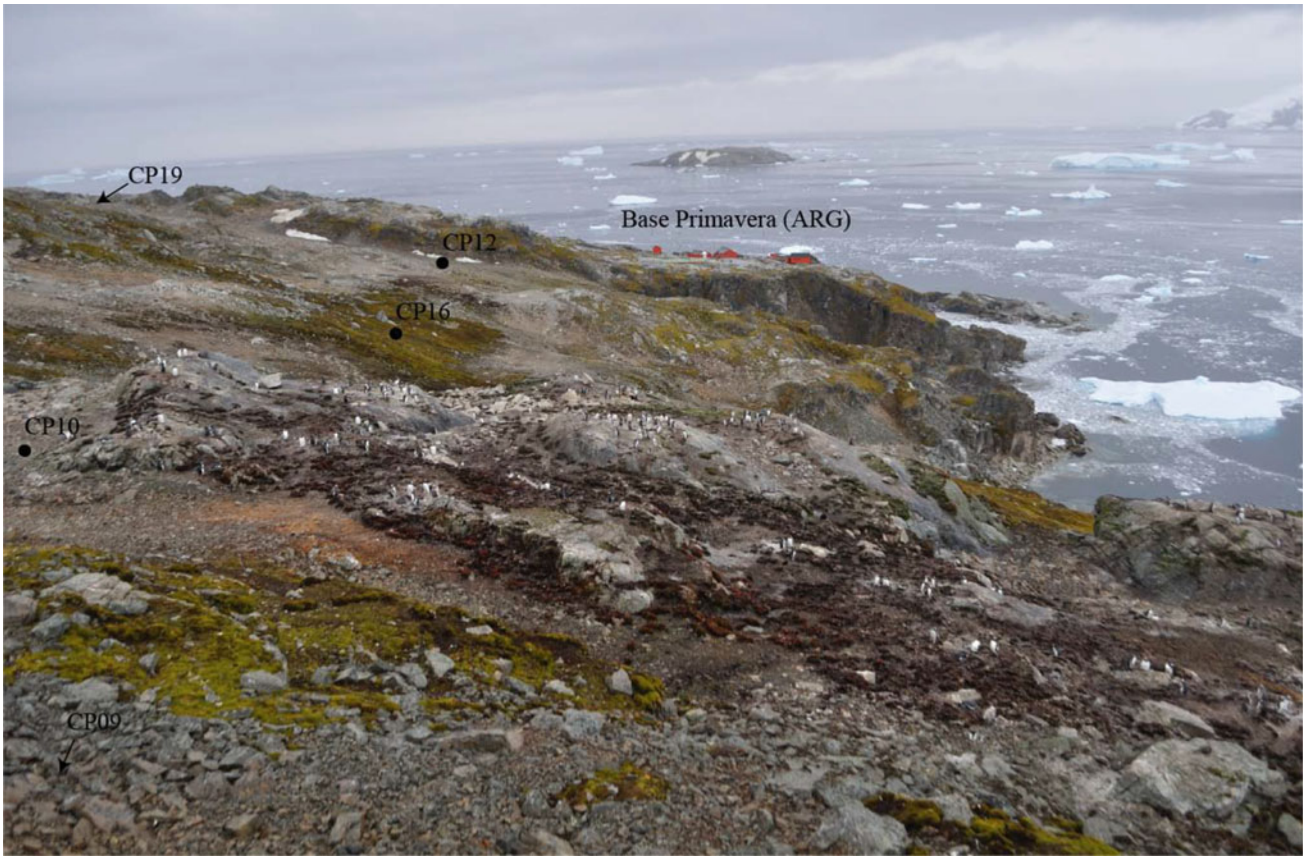

Fig. 12.4 Cierva Point looking west towards Base Primavera. ASPA 134 includes all the visible area except Base Primavera and its immediate surroundings. A large Gentoo penguin rookery covers most of the region. Till deposits, solifluction terraces and skree cover most of the slopes. Vegetated areas are beds of *P. alpestre*–*C. aciphyllum*, a nearly continuous moss bed covers the bedrock to the east

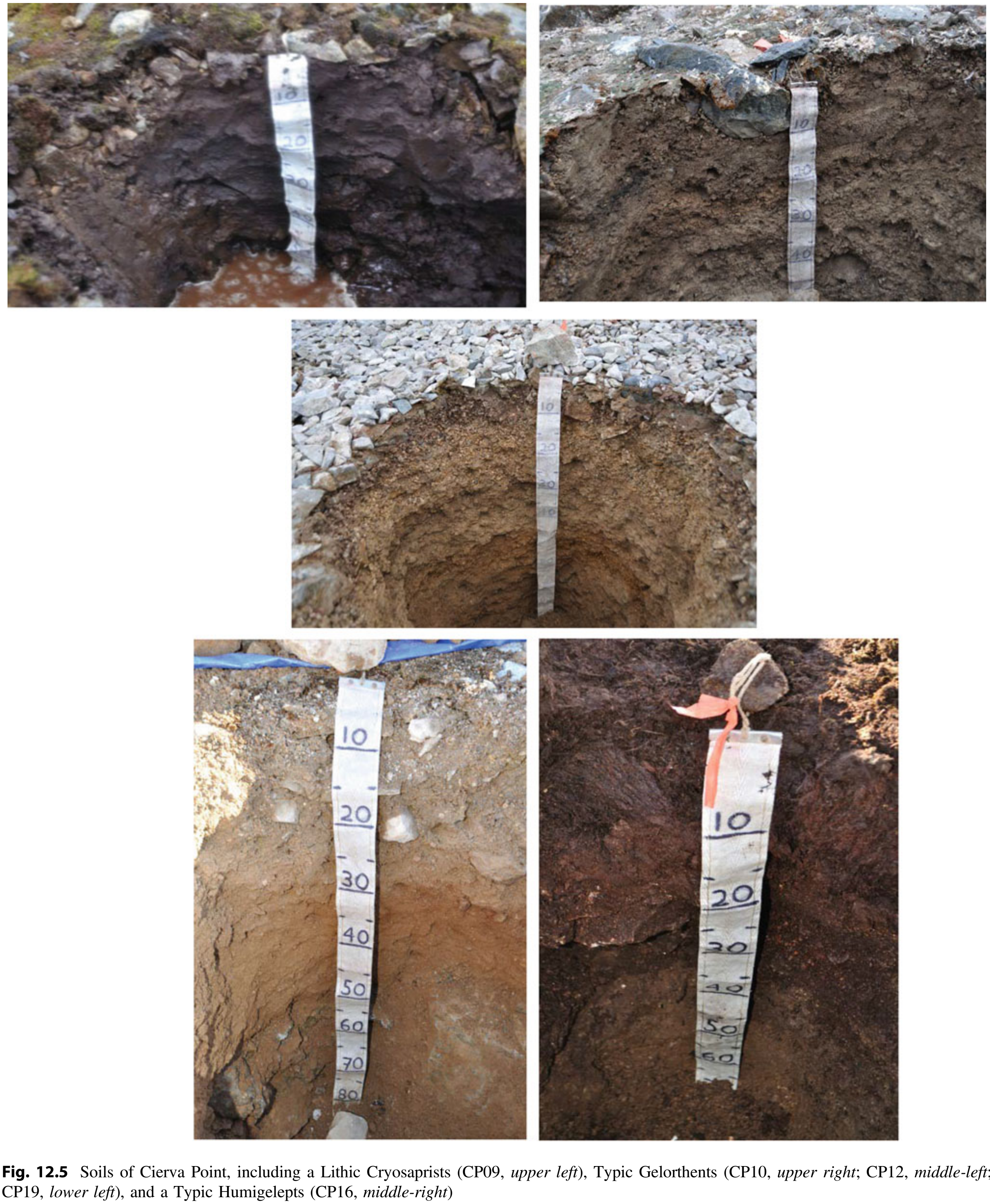

Fig. 12.5 Soils of Cierva Point, including a Lithic Cryosaprists (CP09, *upper left*), Typic Gelorthents (CP10, *upper right*; CP12, *middle-left*; CP19, *lower left*), and a Typic Humigelepts (CP16, *middle-right*)

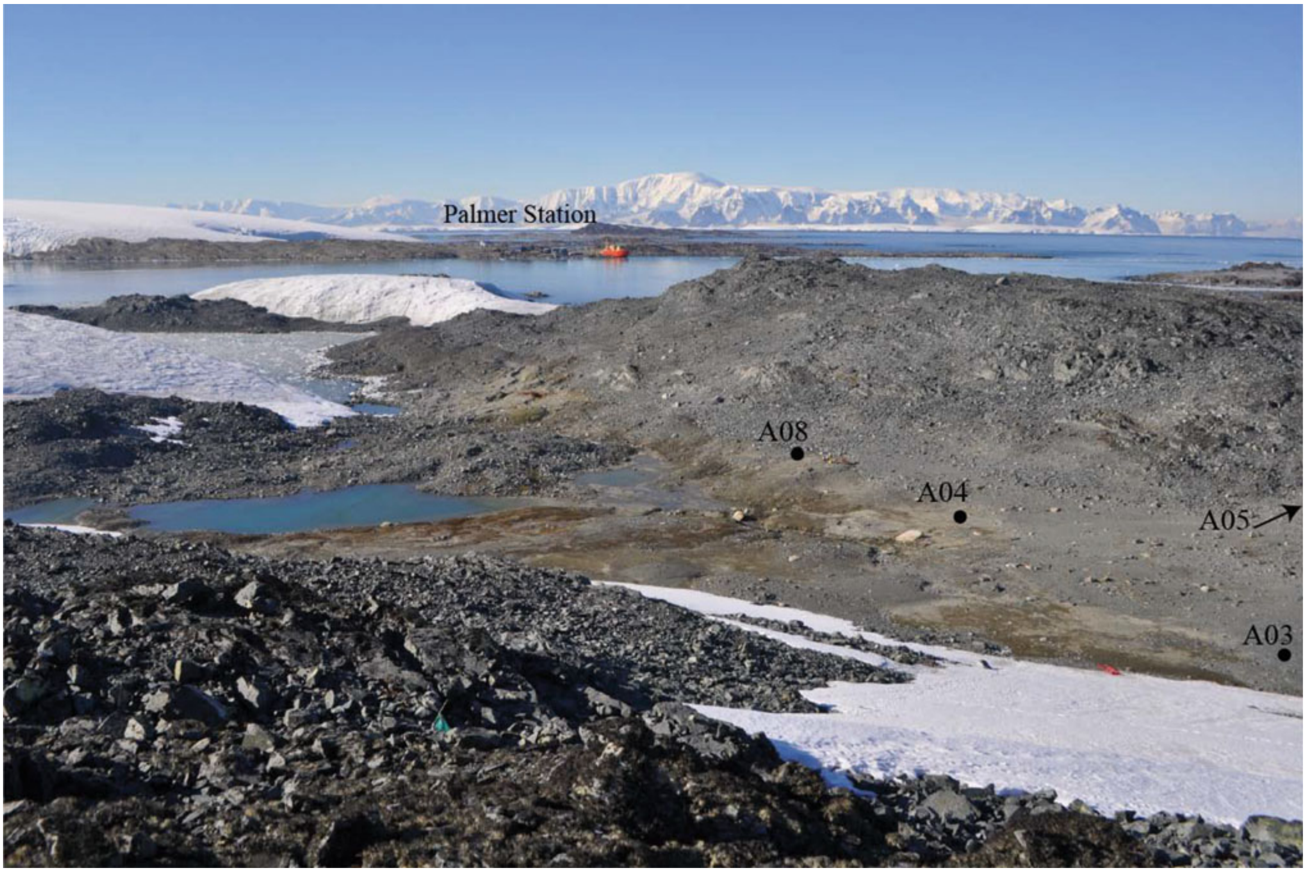

Fig. 12.6 Amsler Island looking southeast towards Palmer Station. The Marr Ice Piedmont is visible left of Palmer Station. Frost-shattered bedrock with skree covered slopes is visible in the foreground with a fluvio-glacial valley flanked by solifluction terraces below. The bedrock upland in the background covered by scattered till and frost-shattered bedrock

Fig. 12.7 Soils of Amsler Island, Palmer Archipelago, including Typic Gelorthents (A03, *upper left*; A08, *lower right*), a Typic Gelaquepts (A04, *upper right*), and a Lithic Humigelepts (A05, *lower left*)

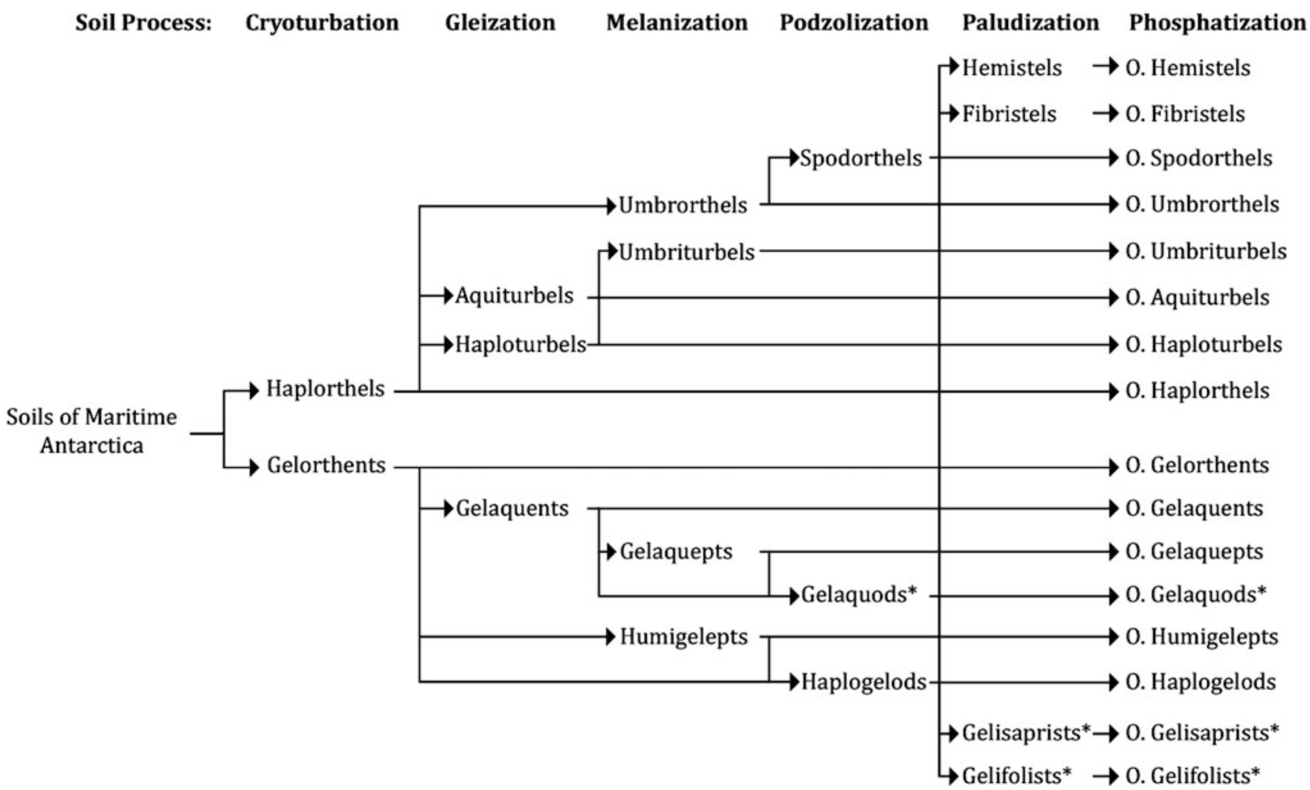

Fig. 12.8 Schematic of soil formation in Maritime Antarctica using *Soil Taxonomy* (Soil Survey Staff 2010). Asterisk indicates where the prefix "Gel" has replaced the prefix the "Cry"; Soil Taxonomy currently does not accommodate these soils. Spodorthels are proposed by Beyer and Bolter (2000) to identify Gelisols with spodic materials. O. abbreviates ornithogenic as proposed by Simas et al. (2007)

12.2.4 Climate

The Last Glacial Maximum in the AP occurred 22,000 years ago with grounded ice sheets extending to the continental shelf. By 18,500 years ago the ice sheets were retreating from the outer continental shelf, and by 13,000 years ago retreat from the inner continental shelf had begun. A climatic optimum occurred in the beginning of the Holocene with temperatures about 1.3 °C warmer than today. Recent ice-core records from James Ross Island off the northeastern tip of the AP show that warmer than present conditions occurred 12,000–9,000 years ago (Mulvaney et al. 2012). During this time period, ice sheets along the WAP may have retreated close to their current positions. Other proxy records from ice-cores, marine-cores, and terrestrial geomorphology support this interpretation (Bentley et al. 2009). Conditions similar to today existed from 9,000 to 2,500 years ago during the Mid-Holocene Hypsithermal, as evidenced by ice-core records and increased sedimentation and organic production from terrestrial environments (Bentley et al. 2009; Mulvaney et al. 2012). A period of cooler temperatures (~0.7 °C cooler) followed and persisted until at least 1,200 years ago and possibly as late as 600 years ago along the northern AP. Glacial advance likely occurred throughout much of the WAP during this cooler interval. The AP began to warm again 600 years ago, initially at a rate of 0.22 °C per century but increased to a rate of 1.56 °C per century over the last 100 years and to a rate of 2.6 °C per century over the last 50 years (Mulvaney et al. 2012).

Currently, the mean annual temperatures along the WAP is approximately −4.3 °C (data from Rothera, Faraday, Esperanza and O'Higgins stations) with positive mean monthly temperatures generally occurring between November and March (Jacka et al. 2004). Temperature data for the region were collected from about 10 stations with most records extending to the 1960s and 1970s (Jacka et al. 2004; Turner et al. 2009). Precipitation falls in the form of both snow and rain (mainly snow) with a mean annual precipitation (water-equivalent) of about 500 mm/year, with a range of about 300–1,000 mm/year.

12.3 Soils of the Western Antarctic Peninsula

The first soils investigation of the AP was conducted by Everett (1976) who described soils near Anvers Island, Paradise Harbor on the AP mainland, and in the South Shetland Islands. Following Everett's initial investigation, no soil investigations were conducted until the 21st century. Contemporary soil investigations were conducted at: Hope Bay on the extreme northern western end of the Peninsula (Pereira et al. 2013a; b); Cierva Point (Haus and Bockheim, in progress), and near the southern coast of Anvers Island (Haus and Bockheim, in progress; Strauss et al. 2009). Brief descriptions of the soils and terrestrial environment in Marguerite Bay region (Rothera Point, Adelaide Island, Avian Island, Emperor Island and Lagotellerie Island) are summarized from unpublished British Antarctic Survey (BAS) field notes in Antarctic Specially Protected Area (ASPA) reports. The soils of an Alexander Island nunatak were investigated by Engelen et al. (2008).

12.3.1 Hope Bay, Trinity Peninsula

Hope Bay (63° 25 S; 77° 01 W) occurs at the northern tip of the Trinity Peninsula (Fig. 12.1) and has an ice-free area of 3.3 km^2. The polar semi-desert climate is colder and drier here than at more southerly locations along the WAP; the mean annual air temperature at nearby Esperanza Station (1952–2010) is −5.1 °C, and annual precipitation is approximately 250 mm (Argentine Antarctic Institute). Air temperatures have been increasing at Hope Bay over the last half century by 0.4 °C per decade (Fig. 13–3). The Buenos Aires and Kenney Glaciers are actively retreating. Eight mosses and at least a dozen mosses have been identified at Hope Bay, but the colder, drier conditions limit the flora to sparse patches.

Hope Bay is composed of the metasedimentary Trinity Peninsula Group—Hope Bay Formation composed of marine siliciclastic turbidites and sandstones, the sedimentary Botany Bay Group—Mount Flora Formation containing sandstones, conglomerates and schists, and volcanic rock sequences, the Antarctic Peninsula Volcanic Group—Kenney Glacier Formation, which contains rhyolite-dacites, ignimbrites, conglomerates and cemented tuff (Birkenmajer 1993; SCAR 2002).

Paraglacial and periglacial processes drive geomorphology in the area, and landforms which cover nearly half of the ice-free areas reflect the widespread late Quaternary retreat of glaciers (Martín-Serrano et al. 2005), with short intervals of minor glacial advances. Permafrost is widespread and usually occurs at a depth of 0.3 m. Geomorphic features include patterned ground, thermokarst, glaciofluvial plains, moraines and ground moraines, gelifluction lobes, rock outcrops, talus cones, and modern and raised marine beach terraces. Patterned ground is concentrated around the "Five Lakes" valley where a stable and saturated active layer leads to the formation of pattern ground with conspicuous sorted polygons, nets, and some poorly developed circles. Glaciofluvial plains and thermokarst depressions are found along the Hut, Eagle and Five-lakes Creeks, and a large thermokarst exists below the Lake Boekella outlet.

A moraine system with several dammed lakes and buried ice occurs along the lateral border of the Buenos Aires glacier. Below the Buenos Aires and Mount Flora cirque glaciers, moraines are affected by thermokarst and lateral degradation that forms undulating, hummocky terrain. The terminal moraines of the Mount Flora cirque glacier are a complex series of successive crests of curved profiles, with several intervening depressions and pools fed by drainage channels of melting snow and ice from the upper slopes (e.g. Esmeralda Lake). Gelifluction lobes are active during the summer season and are found on moraines and talus cones located on Lake Boekella's periphery. Glaciofluvial deposits are typically reworked moraines, with finer textures subjected to water transport along drainage channels. Summer melting of the glacial ice-front leads to high discharge and glaciofluvial erosion and deposition. Till and colluvium deposits are widespread, particularly in the northern coast and at the foot of Mount Flora, where intense congelifraction feeds an extensive fan system of coalesced debris slopes and cones. Rock fragments are generally angular, with few cobbles, indicating short range transport and strong cryoclastic weathering. Raised marine beaches are generally up to 3 m deep, with pebbles and cobbles in a coarse sand matrix, and sedimentary structures from marine deposition. The penguin rookery is found on a large marine cut platform with a scattered number of large erratics of allochthonous source.

Approximately 125,000 pairs of Adélie penguins nest in a large rookery on the slopes of Hope Bay (SCAR 2002). Ornithogenic soils are widespread and well developed in and around the rookery. Presently the rookery occupies only a fraction of the area where ornithogenic soils occur, indicating that in the past, penguins were distributed far more widely across the site.

Hope Bay can generally be separated into two main soil areas: (1) stable and accessible ornithogenic soils below 60 m a.s.l.; and (2) shallow, young, lithic soils on rocky terrains, above 60 m (Pereira et al. 2013a; b). Three soil orders occur at Hope Bay: Entisols, Gelisols and Histosols, with the following predominate great groups: Haploturbels, followed by Gelorthents and a small area of Haplohemists. The soils are spatially distributed as follows (ornithogenic is used as an alteration to Soil Taxonomy): Ornithogenic Haplohemists (4.1 ha); Typic Haploturbels (10.0 ha); Lithic Haploturbels (177.0 ha); Ornithogenic Haploturbels (145.1 ha) and association of Ornithogenic Haploturbels + Ornithogenic Gelorthents (39.0 ha). Rocky coasts and beach deposits occupy 30.8 ha (Fig. 12.2).

Typic Haploturbels are associated with patterned ground, and Lithic Haploturbels are related to rock outcrops, talus cones and till (Pereira et al. 2013a). The ornithogenic soils occur on late Pleistocene to Holocene ground moraines, marine terraces, and rock outcrops, usually at altitudes less than 60 m above sea level. Ornithogenic soils are not observed on late Holocene glacial fronts, talus cones, till and debris slopes, recent paraglacial and periglacial landforms, including the area surrounding the "Five Lakes." Relict and contemporary ornithogenic soils are prone to periglacial erosion by thermokarst activity and can suffer thermoerosion and collapse. Human activities have accelerated erosion rates near Esperanza station (Yermolin and Silva-Busso 2007), and moraine slopes are now exposed by 3 m scarps facing the newly formed glaciofluvial plain, beneath. Subsequently, the area available for nesting is reduced, and several colonies had to move to new sites. Photographs of selected soils are in Fig. 12.3.

In general, all soils show moderate or weak structural development, varying mainly between subangular blocky and granular. Soils classified as ornithogenic show a clear or gradual transition from surface to subsurface horizons. Surface horizons have a dark gray to gray surface horizon with higher organic matter than bleached phosphatic B and/or C horizons. Non-ornithogenic soils (Typic Haploturbels) lack clear horizon differentiation due the absence of organic inputs and phosphatization reactions.

The soils are gravelly to very gravelly (average of 47 %), except for the Histosols (Table 12.1, HB5). The fine earth fraction generally has a sandy loam particle size with averages of 60 % sand, 25 % silt and 15 % clay. Higher clay concentrations and loam soils occur in some ornithogenic soils. Cryoturbation is in most soils, evidenced by wedges and involutions, wavy/irregular transitions between soil horizons, and also by the erratic distribution of clay and silt along the pedon. Furthermore, silty layers and expulsion of fine materials to the surface (frost heave) are common to most of the soils classified as Gelisols.

Even in areas with some stagnant water (Fig. 12.2; HB5 and HB9), no redoximorphic features were observed, as were described by Blume et al. (2002) and Simas et al. (2008) for similar hydromorphic soils of the South Shetland Islands. There was no evidence of salinization or podzolization, even in soils with high sand contents.

Soils at Hope Bay are mostly dystrophic, with highest levels of exchangeable Ca^{2+} and Mg^{2+}, followed by K^+ and Na^+ (Table 12.1). These results are comparable to those of Schaefer et al. (2004) and Simas et al. (2008) for Gelisols of the South Shetlands archipelago. Despite the high concentration of base cations found in some soils, the dystrophic character can be related to higher potential acidities (H^+ and Al) found in the Hope Bay soils. The pH of the soils averaged 5.5 and ranged from 4.2 to 7.3. The lowest pH values are found in the ornithogenic soils, which might be explained by acidification due to ammonium volatilization, nitrification and microbial degradation of guano. Organic carbon levels were highest in the ornithogenic soils and averaged 5.6 % (range of 0.7–21.7 %). All the ornithogenic soils of Hope Bay had very high Mehlich-1 extractable P levels and classify as "strongly ornithogenic" according to the criteria proposed by Simas et al. (2007).

The average total Ca, Mg and K contents were 2.6, 0.4, and 2.0 % respectively for ornithogenic soils, and 1.2, 0.4, and 2.2 % for the lithic soils. Total P averaged 2.88 % for ornithogenic soils, and 0.044 % for lithic soils (Pereira et al., 2013a). Average total Fe and Al were 2.7 and 2.0 %, respectively, for the ornithogenic soils, and 1.7 and 2.0 %, respectively, for the lithic soils. This reveals that these oxides are closely related to the parent material. However, the somewhat higher total Al contents at ornithogenic sites in comparison to non-ornithogenic sites (lithic soils), suggests larger precipitation of this oxide from "clay-sized" phosphates. The total heavy metal contents averaged 28.1 mg kg^{-1} (As), 6.0 mg kg^{-1} (Cd), 53.7 mg kg^{-1} (Cr), 125.3 mg kg^{-1} (Cu), 32.2 mg kg^{-1} (Pb), and 244.6 mg kg^{-1} (Zn).

Pereira et al. (2013b) observed clay-sized mineral assemblages typical of phosphatization, such as taranakite, minyulite, leucophosphite, struvite and fluorapatite; all of which were also found as microaggregates in the silt and sand fractions. Montmorillonite, vermiculite, K-feldspar and plagioclase were also observed in the clay fraction.

12.3.2 Cierva Point, Danco Coast

Cierva Point (64°10 S; 60°57 W) is an approximately 5 km^2, north-facing, ice-free bedrock promontory overlain by till, solifluction deposits, and screes (Fig. 12.4) that rises to a 300 m high ice-free ridge connecting Mounts Mojon and Escombrera. The area has an unusually high diversity of animal and vegetative life which led to its designation as ASPA No. 134 (SCAR 2006). The winter mean monthly air temperature is −5.2 °C (March–September, 2012), and the summer mean monthly air temperature is −1.2 °C (October–April, 2012). At least nine geomorphic surfaces are present at Cierva Point including bedrock depressions, fellfields, modern beaches, recent end moraines, ground moraines, *P. alpestre–C. aciphyllum* moss beds, *Drepanocladus* moss beds, scree slopes, and solifluction lobes. Solifluction lobes are especially common, and most of the north-facing slopes have a stepped appearance. The primary soil parent materials are till, scree or peat, and most show evidence of downslope movement. Permafrost is only present in the soils on a recently exposed end moraine containing buried ice east of the site, below the current ice-front. Granites, granodiorites, granophyres, and gabbro are the predominant rock types.

Seabird activity by penguins and skuas affect virtually all the soils of Cierva Point either directly through excreta or indirectly by runoff, aeolian deposition and vegetative growth enhanced by these birds. A large Gentoo penguin rookery with approximately 1,000 nesting pairs (Quintana et al. 2000) occupies nearly a third of the ice-free area at Cierva Point, with nests found up to 150 m in elevation. Several dozen South Polar skuas also nest on the surrounding peat beds, preying on penguin chicks. Other biological influence includes occasional visits from immature male Antarctic Fur seals.

Vegetation is abundant and diverse at Cierva Point and includes some 50 different moss species, 10 liverwort species, both phanerogams (*D. antarctica* and *C. quitensis*), and possibly more than 100 different species of lichens (Smith 1996). The green algae *P. crispa* is found throughout the active penguin rookery. The north-facing slopes below a marine cut platform at 80 m a.s.l. have very thick (>50 cm) beds of *P. alpestre–C. aciphyllum* that cover virtually all surfaces that are not trampled by the large gentoo penguin rookery. *D. antarctica* is commonly found in patches up to a few square meters adjacent to the rookery on stable solifluction terraces and on the surface of the peat beds.

The soils of Cierva Point were described by Haus and Bockheim in 2012 (unpublished), data for five selected pedons are given in Table 12.2, and images of the soils are in Fig. 12.5. Generally, the soils are often greater than 50 cm

Table 12.2 Data for selected soils from Cierva Point

Horizon	Depth (cm)	Color (Munsell)	Field texture class	pH	EC μS cm^{-1}	Total C (%)	Total N	Total P
CP09-Lithic Cryosaprists formed in muck from Drepanocladus on a bedrock depression 89 m a.s.l. with 0 % slope								
Oa1	0–18	2.5YR 2.5/1	Muck	5.3	14.4	12.24	0.88	0.49
Oa2	18–32	2.5YR 2.5/1	Muck	5.8	19.3	13.13	1.13	0.55
Oa3	32–45	2.5YR 2.5/1	Very gravelly muck	5.8	14.2	11.93	0.81	0.36
Oa4	45–80	2.5YR 2.5/1	Very cobbly muck	–	–	–	–	–
2R	80+	–	–	–	–	–	–	–
CP10-Typic Gelorthents formed in colluvium on a solifluction lobe 86 m a.s.l. with 3 % slope								
A1	0–10	10YR 3/3	Very gravelly loamy sand	4.3	174.9	1.87	0.20	0.46
A2	10–22	10YR 3/2	Very gravelly loamy sand	4.2	76.6	1.24	0.13	0.57
Bw	22–34	2.5Y 4/3	Very gravelly loamy sand	4.6	12.2	0.28	0.02	0.14
C	34–50	2.5Y 5/3	Very gravelly loamy sand	4.6	9.5	0.14	0.02	0.13
2R	50+	–	–	–	–	–	–	–
CP12-Typic Gelorthents formed in till on a solifluction lobe 68 m a.s.l. with 21 % slope								
A1	0–4	10YR 4/3	Gravel	6.3	628	15.89	3.99	4.72
A2	4–9	7.5YR 3/4	Gravel	3.8	890	13.31	2.45	1.25
A3	9–25	7.5YR 4/6	Very gravelly fine sandy loam	3.5	176	2.73	0.46	1.09
E	25–42	7.5YR 5/4	Very gravelly loamy sand	3.5	104	0.39	0.09	0.44
Bw1	42–53	7.5YR 5/6	Very gravelly loamy sand	3.4	73.1	0.34	0.06	0.32
Bw2	53–85	10YR 4/4	Very gravelly loamy sand	3.3	81.5	0.44	0.07	0.39
BC	85+	–	–	–	–	–	–	–
CP16-Typic Humigelepts formed in peat from P. alpestre and colluvium 45 m a.s.l. with 40 % slope								
Oi1	0–11	2.5YR 2.5/3	Peat	–	–	31.81	0.72	0.30
Oi2	11–19	2.5YR 2.5/4	Very stony peat	–	–	31.50	1.22	0.59
A	19–39	10R 2.5/2	Extremely gravelly coarse sand	3.4	52.4	4.88	0.34	0.45
Bw	39–62	5YR 3/3	Very cobbly sandy loam	3.6	44.5	0.87	0.08	0.43
BC	62–75	5YR 4/4	Extremely gravelly coarse sand	3.6	59.7	0.45	0.05	0.30
CP19-Typic Gelorthents formed in colluvium on a ground moraine 43 m a.s.l. with 7 % slope								
A	0–9	10YR 4/3	Extremely gravelly loamy sand	4.9	46.1	1.10	0.28	0.59
E	9–25	7.5YR 5/4	Very gravelly loamy sand	3.6	42.1	0.50	0.17	0.96
Bw	25–40	7.5YR 4/6	Very gravelly loamy sand	3.5	44.4	0.57	0.10	0.51
2BC	40–80	7.5YR 4/6	Cobble	–	–	–	–	–

deep even on strongly sloping colluvial hillsides. The fine-earth fraction of the mineral soils is mainly sands and loamy sands with gravelly to extremely gravelly modifiers. Organic materials are mostly *P. alpestre–C. aciphyllum* peat beds, but depressions covered by *Drepanocladus* consist of highly decomposed mucks. The mineral soils are generally brown to dark brown but several are stained reddish brown to dark red by the extensive peat beds of *P. alpestre–C. aciphyllum*, which are dark reddish brown to reddish black. Soil organic carbon ranges from less than a 0.5 % on freshly deposited till to 40 % in the organic materials with a median of 3.5 %. Cierva Point has three main soil orders: Entisols, Inceptisols and Histosols. Gelisols may be present near the retreating ice-front. The soils fall into the following *Soil Taxonomy* great groups: Cryofolists, Cryosaprists, Gelorthents, and Humigelepts. Humigelepts result from the formation of umbric epipedons rather than cambic horizons.

Weak podzolization has produced an E-B morphology on many of the solifluction terraces. Soil pH values are extremely acidic in general: values from 3.5 to 4.5 characterize nearly all soils occurring within the penguin rookery and below *P. alpestre–C. aciphyllum* moss beds. Only the freshly deposited till, modern beaches, ridgetop and muck-filled depressions had pH values above 5. The average total P of the Cierva Point soils is 0.7 %, and most soils within the penguin rookery have an average total P level greater than 1 %, with individual horizons often having greater than 3 % P. Living vegetation does not exist on the ornithogenic soils (with the exception of *P.crispa*), however, areas of decaying, in situ mosses indicate extension of the rookery grounds.

12.3.3 Anvers Island, Palmer Archipelago

A large concentration of ice-free areas (64° 46 S; 64° 04 W) with soils occurs along the southern coast of Anvers Island, and dozens of small islands extending into Bismarck Straight (e.g. Amsler, Hermit, Litchfield and Stepping Stones) (Fig. 12.6). Palmer Station (US) is located on Gamage Point, Anvers Island. The station reports approximately 742 mm precipitation and a mean annual temperature of −1.4 °C, with monthly means ranging from −6.6 °C (September) to 2.4 °C (January). The area is prone to some of the greatest rates of warming in Antarctica. There has been a 4.5 °C increase in mean annual air temperature since 1945, with June air temperatures at nearby Faraday Station increasing 6 °C over the same time period (Smith and Stammerjohn 2001). Rapid deglaciation of the Marr Ice Piedmont began in the last half of the 20th century, exposing (and in some cases re-exposing) more ice-free area each year. Although the region surrounding Palmer Station is frequently visited by researchers, the soils have only been observed on Amsler Island, Gamage Point, Litchfield Island, Point 8, and the Stepping Stones Islands. No published investigations of soil distribution and morphology are known.

Strauss et al. (2009) investigated a soil chronosequence on Point 8, located on Anvers Island 3.5 km east of Palmer Station, and the Stepping Stone Islands. The distance from the glacier front was used as a time marker. The glacial front started retreating from Point 8 sometime in the 1980s, while the Stepping Stone Islands, located approximately 1 km southeast of Point 8, have likely been ice-free for hundreds of years. The study indicated that insufficient time had elapsed to differentiate the soils on Point 8 but that pH decreased and organic matter increased from Point 8 soils to the Stepping Stone Islands soils. Detailed descriptions of the soils were not given, but the authors stated that soils consisted of an 8 cm thick mineral horizon derived from glacial till overlying granitic parent material. The Stepping Stones Islands soils consisted of an organic horizon of intermediate decomposition (2.5–4.0 cm thick) overlying sandy-loam glacial drift (Day et al. 2008).

A similar chronosequence occurs on Amsler Island and Litchfield Island, 1 km northwest of Palmer Station. Amsler Island has an area of 0.8 km^2 and a maximum elevation of 70 m. It became deglaciated in the last two decades, and only a narrow channel separates the island from the ice front. Litchfield Island has an area of 0.35 km^2 in area and a maximum elevation of 50 m; it is nearly 2 km from the ice front and appears to have been deglaciated for hundreds of years (Smith 1982). Both islands are composed of dark grey, fine-grained diorite with visible plagioclase crystals intruded by light colored, quartz rich, trondhjemitic rock from the Jurassic period (Hooper 1960). The islands are frequented by a number of seabirds including Adélie and Gentoo penguins, Brown and South Polar skuas, and Southern Giant petrels. Litchfield Island has a thick moss bank of *P. alpestre* and *C. aciphyllum*, although a recent influx of Antarctic Fur seals is extensively damaging the beds (Smith 1996). Geomorphic surfaces that occur on the islands include moraines, bedrock depressions filled with fine-textured material, outwash plains, lake basins and terraces, talus, patterned ground (poorly sorted stone circles, mudboils), solifluction terraces, and modern beaches. The soil parent materials are mainly till, glaciolacustrine materials, colluvium, and peat. Permafrost was not observed in soils of Amsler or Litchfield Islands, although Everett (1976) and Smith (1982) reported permafrost at depths between 20 and 30 cm in moss banks.

The soils of Amsler Island were described by Bockheim and Haus in 2011 and 2012 (unpublished); data for four selected pedons are given in Table 12.3 and photos of the soils are in Fig. 12.7. The soils are predominantly Typic Gelorthents that form in glacial till from ground moraine or glaciolacustrine materials. The till derived soils (Table 12.3, A08) are generally <50 cm deep but may be deeper where solifluction terraces have developed. The till is generally

Table 12.3 Data for selected soils from Amsler Island

Horizon	Depth (cm)	Color (Munsell)	pH	Clay	Silt	Sand	>2 mm	Total C	Total N	Total P
				(% of <2 mm fraction)				(%)		
A03-Typic Gelorthents formed in outwash on an ice dammed glacial lakebed 15 m a.s.l. with 1 % slope										
C1	0–10	2.5Y 5/2	6.0	5	7	88	79	0.26	0.05	0.07
C2	10–26	5Y 4/2	5.9	10	14	76	56	0.22	0.03	0.07
2C3	26–46	10YR 3/3	6.0	12	16	72	39	0.71	0.05	0.07
2C4	46–62	10YR 4/4	6.0	4	8	88	80	1.39	0.13	0.09
2C5	62–90	2.5Y 5/2	6.0	4	6	90	62	0.11	0.04	0.05
A04-Typic Gelaquents formed in outwash on an ice dammed glacial lakebed 19 m a.s.l. with 1.7 % slope										
C1	0–11	2.5Y 6/2	5.3	8	21	71	92	0.26	0.03	0.07
2C2	11–33	10YR 6/6	5.4	9	29	62	26	0.19	0.04	0.07
2Cg1	33–48	2.5Y 6/2	5.4	11	26	62	38	0.19	0.05	0.06
2Cg2	48–66	2.5Y 6/2	5.2	7	16	76	93	0.07	0.04	0.04
2Cg3	66–83	10YR 5/2	5.2	7	13	81	42	–	–	0.04
A05-Lithic Humigelepts formed in till on in-filled bedrock depressions 15 m a.s.l. with 7 % slope										
E	0–8	10YR 5/2	5.4	29	38	34	75	0.90	0.14	0.98
Bt	8–18	7.5YR 4/6	5.5	37	47	16	80	3.25	0.54	7.29
BC	18–44	7.5YR 4/6	5.4	32	44	24	87	2.15	0.36	5.37
2R	44	–	–	–	–	–	–	–	–	–
A08-Typic Gelorthents formed in colluvium on a solifluction terrace 16 m a.s.l. with 4.4 % slope										
C1	0–27	10YR 5/2	6.0	3	4	93	100	0.34	0.03	0.10
C2	27–48	10YR 6/2	5.9	5	6	89	98	0.54	0.06	0.04
C3	48–73	10YR 4/2	5.7	10	17	73	70	0.47	0.05	0.06

grayish brown and gravelly to extremely gravelly sands or loamy sands with no pedogenic alteration. A valley filled with diamicton overlying glaciolacustrine materials bisects the island, trending from the NW–SE. The glaciolacustrine materials are generally gravelly sandy loams that show evidence of slight rubification. The overlying mantle is light colored, coarser and 0–50 cm thick. Surface erosion has completely removed the mantle near drainage channels. In the northwestern half of the valley the underlying glaciolacustrine materials have sporadic and occasional lenses of 2–10 cm diameter decaying moss fragments. Hall et al. (2010) radiocarbon dated the moss fragments and obtained ages of 700–970 years B.P.; retreat of the ice-front exposed these soils within the last 50 years, which strongly suggests that the ice-front was at or behind its current position during deposition of the moss fragments. The southeastern part of the valley which became deglaciated during the last decade, features a unique deposit of glaciolacustrine materials with up to 25 % shell (likely limpet-*Nacella concinna*) fragments that Hall et al. (2010) found to be 3,700–5,500 years old. Re-exposed in situ, decaying moss was also described by (Smith 1982) in the same region.

The southwestern coast of Amsler Island lies adjacent to Litchfield Island and has presumably been deglaciated the longest. The most complex vegetation occurs on sites with associations of *D. antarctica* and *P. alpestre–C. aciphyllum*; immature male Antarctic Fur seals are commonly found on the site. Skuas are very common and several pairs nest on the site, aggressively defending their young from researchers during the summer months. The soils are generally very shallow and stony with a 0–10 cm thick layer of moss; however, well-developed Lithic Haplogelepts occur where materials have filled bedrock joints and depressions. These soils have a leached upper horizon overlying subsoils with high levels of SOC and total-P levels that can exceed 5 %, indicative of ornithogenic soils. It is unknown if these soils have also been re-exposed following glacial retreat and represent resurfaced paleosols. It seems unlikely that the high degree of development and extremely high levels of total P could have taken place in the limited time since deglaciation under the current environmental conditions.

Litchfield Island is defined as ASPA No. 113 (SCAR 2004). The soils have not been studied in detail, but the early work of Everett (1976) suggested that the majority of the soils are organic and can be divided into two groups: (1) poorly drained peats soils formed from the decaying remains of *Drepanocladus* moss carpets in bedrock depressions; and (2) somewhat poorly drained peat soils formed from the decaying remains of *P. alpestre–C. aciphyllum* on gently to strongly sloping bedrock hillsides (identified by Everett as Ranker soils). Both soils likely classify as Cryofolists, and analyses by Everett show that both soils have similar levels of SOC (∼39 %), total N (∼2 %) and total P (∼0.1–0.7 %), but that pH changes from an average of 5.2 in the poorly drained soils and 4.0 for the better drained *P. alpestre–C. aciphyllum* peat beds. Thin marine sands were observed underlying some peat deposits; there is no mention of tills or other glacial deposits and they are likely rare on Litchfield Island.

12.3.4 Marguerite Bay Area

Marguerite Bay (68° 30′ S, 68° 30′ W) is a large bay bounded Adelaide Island on the northwest, Graham Land to the north and east, and by Alexander Island to the south (Fig. 12.1). Rothera Station (UK) is located on a Rothera Point in the northern part of Marguerite Bay, and General San Martin Base (ARG) is located in eastern part of the bay on Graham Land. Several ice-free areas have been defined as ASPA in Marguerite Bay including: Rothera Point (68° 07 S; 67° 34 W), ASPA No. 129 (SCAR 2012b); Avian Island (67° 46 S; 68° 54 W), ASPA No. 117 (SCAR 2003a); Emperor Island (67° 52 S; 68° 42 W), ASPA No. 107 (SCAR 2003b); and Lagotellerie Island (67° 53 S; 67° 25 W), ASPA No. 115 (SCAR 2012a). Despite the relatively large ice-free area in the Marguerite Bay area, no soil investigations have been conducted there. Data and insights included herein are taken from unpublished British Antarctic Survey (BAS) field reports that are compiled into the ASPA management plans.

Rothera Point is located along the southeastern coast of Adelaide Island. The point is composed of diorite, granodiorite and adamellite of the Andean Intrusive suite. The soils are mainly “small pockets of glacial tills and sands on rock bluffs” (SCAR 2012b). Deeper soil materials were reported to form patterned ground as small circles, polygons and frost-sorted materials. Organic soils are apparently absent. Accumulations of limpet shells (*N. concinna*) were reported to produce calcareous soils. Lichens are the only significant vegetation, although a small population of *C. quitensis* was observed. Only a few nesting pairs of skuas were found on Rothera Point. The soil taxa of Rothera Point may include: Lithic Haplorthels or Haploturbels.

Avian Island is a low lying 0.49 km^2 island with a maximum height of only 40 m a.s.l. lying a few hundred meters off the southern coast of Adelaide Island (SCAR 2003a). The island is 1.2 km from the Teniente Luis Carvajal Base (Chile) which had a mean daily maximum and minimum temperature of 3 °C in February and −8 °C in August for 1962–1974. It has one of the largest Adélie penguin rookeries on the AP with 35,600 nesting pairs. An additional 670 pairs of Blue-eyed cormorants (*Phalacrocorax atricips*) also occupy the island. Other seabirds that visit the island include skuas, petrels, gulls and terns and thus the entire, appropriately named island is subject to ornithogenic influence. The island is composed of tuffaceaous sandstones, conglomerates and breccias of the Antarctic Peninsula Volcanic Group. Neither *D. antarctica* nor *C. quitensis* occur on the island but nine mosses and 11 lichens have been identified; mosses are mainly carpet forming species such as *Drepanocladus* that thrive in wet depressions. The green algae *P. crispa* is widespread on the island. The geomorphic landforms on the island are rock outcrops, frost-shattered bedrock with permafrost, ornithogenic soils, raised beaches, and possibly small isolated peat beds. Ephemeral ponds as large as 10,000 m^2 occur on Avian Island. The likely soil parent materials are frost-shattered residuum, marine alluvium, till, and peat. Ornithogenic soils are widespread and are likely associated with moderately well drained soils, possibly of marine origin. The soil taxa of Avian Island may include: Ornithogenic and Lithic Haplorthels or Haploturbels, Histels and Gelorthents.

Emperor Island has an area of 5 ha and is part of the Dion Islands in the northwestern part of Marguerite Bay (SCAR 2003b). The island is low lying with a maximum height less than 50 m. Geologically the island is part of the Antarctic Peninsula Volcanic group and is composed of andesitic to basaltic lavas and pyroclastics on the southern half and sedimentary and volcaniclastic rocks on the northern half. The vegetation appears to be similar to Avian Island; six mosses and 19 lichens have been identified, although neither of the phanerogams are present. A small 100–200 bird Emperor penguin colony exists on a southeastern peninsula. Other seabirds are generally small in number compared to Avian Island and include Adélie penguins, cormorants, gulls, and skuas. Very little is known about the soils and geomorphology of Emperor Island in part due to the sensitivity of the uniqueness of the small colony of Emperor penguins found there. Smith (1996) identified an ornithogenic soil covered with *P. crispa* near a cormorant colony in which topsoil has high concentrations of Na, Ca, Mg and P and a pH of 4.9. At the edge of the cormorant colony, pure guano 10–30 cm thick was observed, but the soils otherwise were poorly developed, occurring as pockets of “ornithogenic mud.” The soil taxa of Emperor Island may include: Ornithogenic and Lithic Haplorthels or Haploturbels, Histels and Gelorthents.

Lagotellerie Island has an area of 1.58 km^2 and is located in the northwestern part of Marguerite Bay off the coast of Graham Land (SCAR 2012a). The island has two peaks, 268 and 288 m a.s.l., and is mainly composed of quartz diorite with fossiliferous volcanics (agglomerates, lavas and tuffs) on the eastern end. The vegetation on the island is notable for its dense cover of *D. antarctica* and *C. quitensis*, which have been identified growing on terraces in patches of 10 m^2 on the northern part of the island. Both species produce abundant and viable seeds and have been found up to 120 m (*C. quitensis*) and 275 m (*D. antarctica*) in elevation. At least six moss species occur on the island as do numerous lichen species. Between 1000–2000 Adélie penguins, a few hundred Blue-eyed cormorants and several dozen skuas nest on the island. Antarctic Fur seals are also common on the northern slopes of the island.

The geomorphology of the southern part of Lagotellerie Island is rocky with cliffs, but the northern part has gentler slopes with scree, raised marine beaches, and series of terraces, possibly solifluction terraces (SCAR 2012a). Coarse sand and gravel, weathered from the quartz diorite bedrock, cover the slopes and fill gulleys and depressions. A saddle in the center of the island has an extensive deposit of sand and gravel with well-developed stone polygons, circles and stripes. Topsoils with loamy A horizons were identified on terraces with dense stands of *D. antarctica*. The soil taxa of Lagotellerie Island may include: Ornithogenic and Lithic Haplorthels or Haploturbels, Histels, Gelorthents, and possibly Humigelepts.

12.3.5 Alexander Island

Alexander Island (71°–73′ S, 68° W) is the largest island (43,250 km^2) in Antarctica and the second largest uninhabited island in the world next to Devon Island in the Canadian Arctic. The island is contained by the Wilkins, Bach, and George VI ice shelves and the northernmost tip extends into Marguerite Bay. Peaks in the north of the island rise to nearly 3,000 m a.s.l. The island is unique in that it lies at the boundary of the maritime Antarctic climate zone and the interior Antarctic climate zone. The island is approximately 95 % ice-covered but contains an ice-free area of about 2,000 km^2, primarily in the east (Ablation Point Massif, Fossil Bluff, Mars Oasis, Ares Oasis, Viking Valley, Coal Nunatak, Two Step Cliffs, and Citadel Bastion).

Climate data are sparse for the island. Whereas Clapperton and Sugden (1983) reported a MAAT of −9 °C and a mean annual precipitation of <200 mm/year, Hall (1997) recorded a MAAT of −7 °C during 1992–1993. The bedrock geology is similar to that reported for the Argentine Islands with mainly metasedimentary and metavolcanic rocks that are overlain by igneous rocks of the LeMan Group. Of interest is the presence of Cretaceous fossil forests with metamorphosed palaeosols at Fossil Bluff (Howe and Francis 2005). The island contains abundant glacial landforms and deposits, ice marginal lakes, melt pool, gelifluction landforms and patterned ground and valley-slope landforms (Clapperton and Sugden 1983). Hall (1997) described a series of "cryoplanation" benches in the Mars Oasis that have thermal contraction cracks in bedrock and salt-encrusted runnels. From Be^{10} ages, the northwest portion of the island showed a general trend of progressive ice-sheet thinning from 22 to 10 ka (Johnson et al. 2012). The ice-cap thickness on NW Alexander Island is at least 490 m. SAR-OSL dating of an elevated delta at Ablation Lake yielded an age of 4.6 ka, suggesting a fall in relative sea-level of 14.4 m since the mid-Holocene (Roberts et al. 2009).

According to Convey et al. (2011), the northern portion of Alexander Island may represent the southernmost occurrence flowering plants and moss-peat accumulation. Mosses, lichens, microbial mats, and grasses are common habitats on Alexander Island (Maslen and Convey 2006). From an analysis of geographic patterns of eukaryotic diversity in Antarctic soils, the Alexander Island site was three to four times less diverse than all of the other maritime sites to the north (Lawley et al. 2004).

From limited data, the soils of Alexander Island are arid, nutrient-poor, and exhibit lower mean temperatures than typical maritime soils found at more northern sites (Lawley et al. 2004; Yergeau et al. 2007a, b; Engelen et al. 2008). On Alexander Island, surface-soil samples yielded pH values of 7.0–7.9, electrical conductivity values of 27–291 μS/cm, field moisture contents of 2.6–12.4 %, and SOC concentrations of 0.16–1.5 % (Lawley et al. 2004; Chong et al. 2012). These data suggest that the dominant soils on Alexander Island are Haploturbels and Haplorthels but that Anhyorthels and Anhyturbels may occur on inland nunataks.

12.4 Soil Processes and Taxonomy

Soil processes of the WAP are mainly dependent on drainage, aspect, vegetation and animal activity. The dominant soil processes are: cryoturbation, gleization, melanization, podzolization, paludization, and phosphatization and will be discussed below. Soils along the WAP can be categorized as: ornithogenic, organic, podzolic, humic, hydromorphic, and immature soils. Figure 12.8 is a schematic for soil formation and classification in maritime Antarctica by *Soil Taxonomy* (Soil Survey Staff 2010).

Cryoturbation is the churning and involution of soil by frost action. Although not inclusive to cryoturbation the presence of permafrost within a meter of the soil surface is included here as part of a more general process of annual active layer freeze-thaw. Similar to the arctic, the permafrost of the maritime Antarctica and the WAP is ice-cemented and creates an impermeable barrier to soil water. Twentieth century literature assumed permafrost occurred within 2 m of the soil surface in the WAP, and Gelisols were considered to be predominant order (Beyer et al. 1999; Bockheim and

Ugolini 1990). Recent observations at Cierva Point and Anvers Island (Bockheim et al. 2013) indicate that the occurrence of permafrost in soils may be rare along the WAP.

Gleization and redoximorphism are the reduction of ferric iron to ferrous iron under anaerobic conditions. Aquic conditions and soils with redoximorphic features are found throughout the WAP, although redoximorphic features are not very well expressed in the soils. Aquic conditions usually result from episaturated conditions caused by lithic contacts in closed-bedrock depressions. Perched water over permafrost is not currently an active soil-forming factor but may have been in during a recent, cooler past. Saturated conditions most strongly affect soil forming processes by modulating suitable habitats for vegetation. Carpet-forming mosses are usually found on aquic soils whereas the turf-forming mosses and higher plants usually prefer soils that are well drained. Everett (1976) suspected soil development in the WAP "is conditioned principally by relief and drainage, and to a lesser extent by parent material, vegetation, and time." Consequently he divided soils into well-, intermediate-, and poorly-drained groups; ornithogenic and ranker (peat soils with intermediate drainage) soils were considered independent of drainage.

Melanization is the formation and incorporation of organic materials to the soil surface. In maritime Antarctica, melanization can occasionally produce a horizon with a base saturation less than 50 % and a sufficient depth of organic carbon (usually 18–25 cm) to form an umbric epipedon. Beyer et al. (1999) described three sources for the organic matter: (1) living vegetation such as mosses and lichens; (2) algal leachates; and (3) ornithogenic inputs. Bockheim and Ugolini (1990) described the zonal soil of the Subantarctic and maritime Antarctica as a "Brown" soil (i.e. Humigelepts or Umbrorthels) with an O-A-Bw profile. The difference between the two regions was a decrease in the O horizon and a lack of earthworms in maritime Antarctic soils.

Podzolization (i.e. the illuvial migration of Fe and Al humus complexes) and rubification (i.e. the oxidation of Fe from primary minerals that reddens soil) are processes responsible for the formation of "B" horizons. Currently, features associated with podzolization have not been described in the soils of the WAP. Beyer and Bolter (2000) described podzolic soils in maritime soils of East Antarctica and on King George Island on abandoned rookeries with a shallow dark gray AE horizon over a phosphorus rich, black, Bh horizon. They suggest the Great Group Spodorthels be included in *Soil Taxonomy* to classify these soils. "Podzolic" morphologies were described by Tatur (1989) on Torgersen Island in the Palmer Archipelago and were attributed to ornithogenic processes. Everett (1976) gives composite descriptions of well and moderately well drained soils along the WAP with slightly redder horizons that had developed a texture contrast as a result of translocations of fines through the profile (i.e. pervection); the influence of birds was again noted. Currently, it is difficult to say to what extent the processes of podzolization and rubification impact soils along the WAP, but it is likely that both are associated with ornithogenesis.

Paludization is the deep accumulation of organic materials and formation of organic horizons. Along the WAP and throughout maritime Antarctica, paludization is caused solely from the buildup of mosses, usually turf-forming mosses associations such as *P. alpestre–C. aciphyllum*. The formerly grouped "ranker" soils, Histels or Histosols in *Soil Taxonomy*, exemplify (or typify) soils formed by this process.

Phosphatization occurs when phosphorus rich guano, mostly from penguins, interacts with water and soils. Penguin excrement is divided into three fractions of varying color and chemistry: a white fraction comprised primarily of urates is about 27 % N and 0.1 % P; a red fraction that is compositionally 66 % chitin, originates from krill (*E. superba*) and has 9.6 % N and 2.5 % P; and a green fraction that is composed primarily of undigested algae and has 10 % N and 0.9 % P (Pietr et al., 1983). Fresh guano has a neutral pH and initial stages of degradation enrich the surface of penguin rookeries with urates, ammonium, chitin, struvite ($[NH_4]MgPO_4{\bullet}6H_2O$) and apatite ($Ca_5[PO_4]_3[OH, F, Cl]$) (Myrcha and Tatur 1991). Volatilization and nitrification of ammonium ions and various hydrolysis reactions cause phosphorus laden acidic solutions to percolate downwards, causing the following set of phosphate minerals to precipitate: leucophosphite ($KFe_2^{3+}[PO_4]_2[OH]{\bullet}2H_2O$); minyulite ($KAl_2[PO_4]2[OH]_{0.75}F_{0.25}{\bullet}4H_2O$); metavariscite ($Al[PO_4]{\bullet}2H_2O$); vashegyite ($Al_6[PO_4]_5[OH]_3{\bullet}22H_2O$); arctowskite ($Al_9[PO_4]_8[OH]_3{\bullet}27H_2O$); and vivanite ($Fe_3^{2+}[PO_4]_2{\bullet}8H_2O$) (Myrcha and Tatur 1991; Pietr et al. 1983; Simas et al. 2007; Tatur 1989).

A leached horizon is often observed immediately below the surface guano that is dominated by phosphates lacking Fe and Al (e.g. fluorapaptite (Ca_5PO_43F) and brushite ($CaHPO_4{\cdot}2H_2O$)) (Myrcha and Tatur 1991). Simas et al. (2007) found that nearly 50 % of the clay sized minerals found in the deeper soil layers of penguin rookeries on King George Island were crystalline phosphates with total phosphorus levels over 4 %. Tatur (1989) observed that even rookeries that have been abandoned for centuries to millennia still maintained a phosphatized chemistry. The unique characteristics of ornithogenic soils and their persistence in the environment have prompted several researchers to suggest "Ornithogenic" as an additional subgroup to Soil *Taxonomy* (Michel et al. 2006; Simas et al. 2007).

12.5 Summary

The soils of the ice-free areas of the WAP can generally be described as thin, rocky Lithic Gelorthents or Lithic Haplorthels formed in shallow till or frost-shattered rock. However, large areas of deeper and more developed soils have formed on glaciofluvial plains, patterned ground, peat beds, moraines, raised beaches and solifluction terraces. Processes influenced by birds, cryoturbation and mosses have produced soils with orthnithogenic, podzolic, gelic and umbric properties. Regional warming has raised temperatures all along the WAP, but the area surrounding Anvers Island appears to have warmed at a faster rate. The highest diversity and abundance of vegetation is likewise found in the same area and extending north along the Danco coast to Cierva Point (Smith 1996). Although the number of WAP soils investigations is limited, it seems likely that soil development also reaches a peak near the middle of the peninsula and weakens at the northern and southern latitudes. However, seabird activity does not seem be limited to any particular latitude along the WAP (excluding Alexander Island), and ornithogenic soils are common from Hope Bay to Marguerite Bay. Ornithogenic processes exert strong influences that alter the physical, chemical and morphological properties for decades to centuries, thus, conclusions concerning zonal soil development along the WAP are difficult.

Most ice-free areas along the WAP are devoid of soils and locations with soil deposits are relatively rare; however, the areas that do have soils support the largest terrestrial ecosystem in the Antarctic. Rapid regional warming has perturbed the distribution and ecology of several WAP species, and soil may act as the medium for these changes. For instance, the populations of phanerogams, mosses, and microbes have increased one to two orders of magnitude for Antarctica's only two phanerogams, *D. antarctica* and *C. quitensis*), throughout most of the ice-free areas of the WAP (Convey and Smith 2006). Increased seed viability due to more favorable soil conditions as well as germination of seeds and spores in soil banks are likely major contributors (Convey and Smith 2006; Mcgraw and Day 1997).

Bird populations are also changing, with the decreases in the numbers of Adélie penguins relative to increases in Gentoo and Chinstrap penguins being the most notable (Emslie et al. 1998). The exact mechanisms controlling penguin response to climate change is unknown. Adélie, Chinstrap and Gentoo penguins all nest in ice-free areas, but each species prefers varying degrees of slope, roughness, elevation and soil moisture. Thus, it is likely that soils play a pivotal role in penguin distribution along the WAP (Ainley et al. 1995; Emslie et al. 1998; Volkman and Trivelpiece 1981). The identification of relict ornithogenic soils is needed to help determine the role food supplies and nesting grounds have contributed to changing penguin patterns (Emslie et al. 1998).

Changes to terrestrial ecosystems both from warming and increased human impact carry the risk of introducing alien species to the WAP, which may have drastic consequences for numerous endemic species (Frenot et al. 2005). Currently, the subantarctic (region immediately north of the Antarctic Convergence) has 108 species of persistent (established but not spreading, as opposed to invasive spreading) alien vascular plants of mostly European origin which have been transported to the region by human activities. The fast growing grasses *Poa annua* and *P. pratensis* now occupy all the islands of the Subantarctic; *P. pratensis* is already established at Cierva Point, Antarctic Peninsula (Frenot et al. 2005). Increasing our understanding of terrestrial biologic functions will unquestionably benefit from an improved understanding of the soil environment and its functions.

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13 Soils of the South Orkney and South Shetland Islands, Antarctica

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13.1 Introduction

Soils of the South Orkney and South Shetland Islands along the northwestern Antarctic Peninsula (WAP) are important in the global soil system because they occur in (1) a transition zone between the maritime sub-Antarctica (e.g., Falkland Islands, South Georgia, South Sandwich Islands, Marion Island, Gough Island, Macquarie Island, Campbell Island) and the Antarctic Peninsula (Tedrow 1968; Bockheim and Ugolini 1990), (2) areas receiving considerable inputs of nutrients from birds (Michel et al. 2006; Simas et al. 2007b); (3) a region where permafrost distribution and continuity is variable, with a trend of following an altitudinal gradient resulting in a high pedodiversity with implications to soil classification; (4) an area with a proliferation of international research stations and tourism activities, and; (5) a region which has experienced the highest recorded increases in mean air temperature in the last 50 years, with oscillations around the 0 °C isotherm (Turner et al. 2005), with expected impacts on active layer thickness, physical, chemical, and biological processes, and landscape stability.

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Throughout the history of pedology in Antarctica, the western Antarctic Peninsula (WAP) was much less studied than ice-free areas in continental Antarctica (Campbell and Claridge 1987). Prior to 1980 studies in WAP emphasized soil nutrients and generally were restricted to the topsoil (Holdgate et al. 1967). Recent gradient analyses have focused on microbial (Tscherko et al. 2003; Chong et al. 2009; Ganzert et al. 2011; Dennis et al. 2012), biological (Bokhorst et al. 2008) and temperature aspects of soils (Guglielmin et al. 2008). During the last decade several studies have increased our knowledge of soil formation and distribution in ice-free areas of the South Shetlands Archipelago (Michel et al. 2006; Simas et al. 2006, 2007b, 2008; Schaefer et al. 2008; Francelino et al. 2011; Moura et al. 2012).

Due to the higher temperatures and precipitation, soils of the WAP are much different from those reported for other parts of Antarctica (Campbell and Claridge 1987; Simas et al. 2008; Bölter 2011). Frequent freeze-thaw cycles result in intense physical degradation of parent materials while higher water availability and biological activity increase biological and chemical weathering and total organic carbon contents, with neoformation of clay minerals, (Simas et al. 2006).

Our current understanding of pedogenesis in the WAP islands includes the following: (1) modern global soil taxonomic systems are insufficient to classify these soils; (2) there have been very few published soil maps of the region or parts of the region (Francelino et al. 2011; Moura et al. 2012) and for this reason the geography of the soils has not been elucidated; (3) soil evolution is dominated by chemical weathering as well as cryogenic processes (Simas et al. 2006; Navas et al. 2008); (4) the high pedodiversity is due to differences in parent materials, soil biological processes, and permafrost occurrence and distribution (Simas et al. 2008; Bölter 2011; Moura et al. 2012); (5) there is a poor understanding of soil organic C and N turnover despite large standing stocks of these elements (Bölter 2011; Simas et al. 2008; Mendonça et al. 2011); (6) soil-forming processes include argilluviation, sulfurization, and podzolization which do not commonly occur in Antarctica (Chen et al. 2000; Simas et al. 2006);

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(7) soil taxa are strongly related to geomorphic surfaces and permafrost distribution (Francelino et al. 2011); and (8) there is marked phosphatization and a dominance of amorphous material in the clay fraction of soils influenced by birds (Michel et al. 2006; Simas et al. 2006, 2007b).

Although recent publications highlight interesting and novel aspects of soil genesis in Antarctica, there has not been a comprehensive regional approach to describe the soils from the South Orkney and South Shetland Islands. The region experiences a notable impact of human activities due to the presence of many scientific stations. It is also an important tourist destination due to its proximity to South America. Therefore, the understanding of soil characteristics and distribution is important not only for the advance in soil science but also to support management and preservation of the region. In this regard, soil maps provide a very important base for planning human activities, as well as for ecological studies on terrestrial ecosystems. The objective of this chapter is to summarize the existing information on soils of the South Shetland and South Orkney Islands and to identify key research needs.

13.2 Study Area

The WAP islands are part of the Scotia Arc that crosses the Drake Passage to Tierra del Fuego and up the Andes chain, a distance of 4,350 km (Dalziel and Elliot 1971). The present study includes the South Orkney Islands (SOI) and the South Shetland Islands (SSI). The SOI (60° S 35′ S, 45° 30′ W) are composed of four major islands, Coronation, Laurie, Signy, and Powell, and numerous smaller islands, comprising a total area of 620 km^2 (Fig. 13.1). The maximum elevation is 1,266 m, Mt. Nivea on Coronation Island. The SSI (62° 0′ S, 58° 0′ W) are composed of 11 major islands and numerous smaller islands and have a total area of 3,687 km^2 (Fig. 13.2). The maximum elevation is 2,300 m, Mt. Irving on Clarence Island. The WAP islands contain 80–90 % ice cover so that the total ice-free area is approximately 645 km^2. The largest ice-free areas are Byers Peninsula on Livingston Island and Fildes Peninsula on King George Island.

Mosses, lichens, and algae are common in the WAP islands, along with two vascular plants, Antarctic hairgrass (*Deschampsia antarctica*) and Antarctic pearlwort (*Colobanthus quitensis*) (Greene and Holtom 1971). Penguins, seals, and seabirds are common in coastal areas and have had significant effects on soil development (Michel et al. 2006; Simas et al. 2007b).

There are two climate stations in the SOI, Signy and Orcadas, and eight in the SSI, six of which are on KGI and one each on Greenwich and Deception Islands (http://antarctica.ac.uk/met/READER/). The WAP experiences a sub-antarctic cold, moist, maritime climate with mean annual air temperature of −2.2 °C and mean summer air

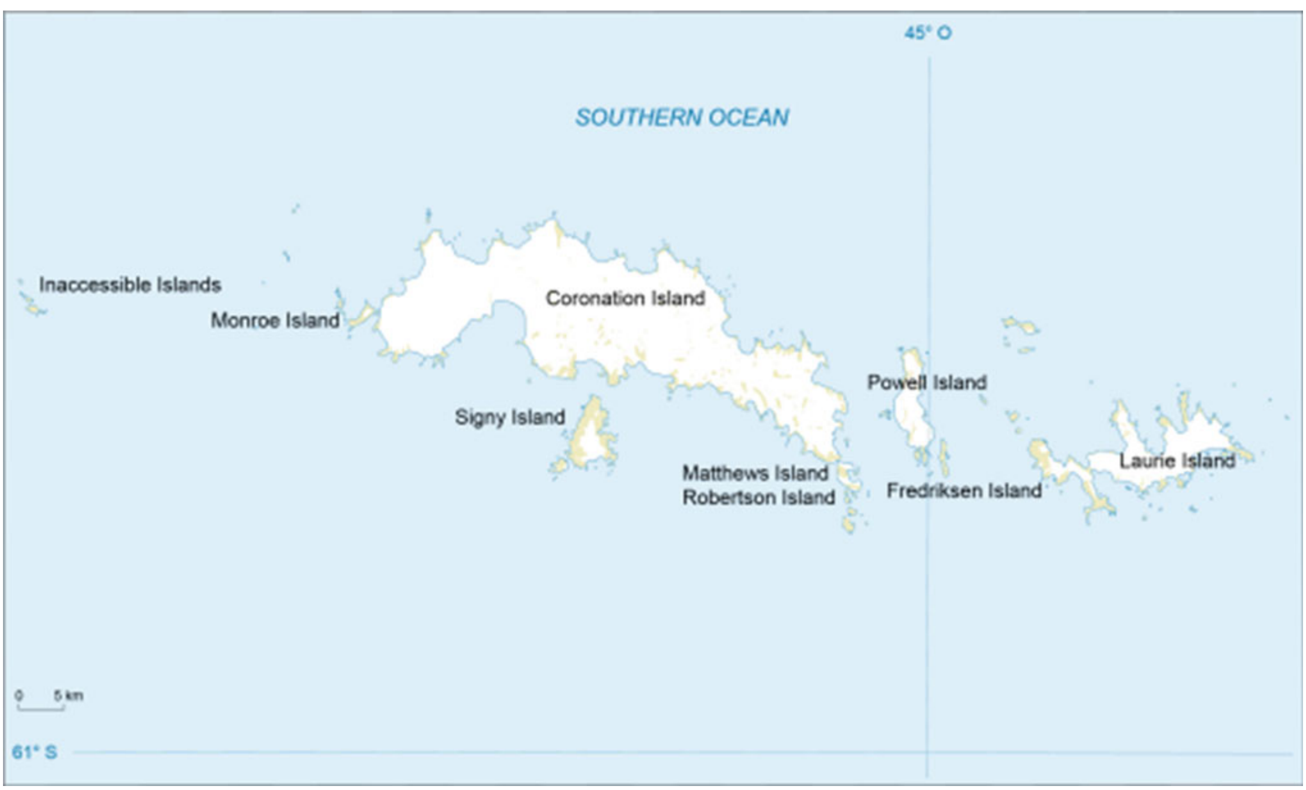

Fig. 13.1 Map of the South Orkney Islands (*Source* Wikipedia)

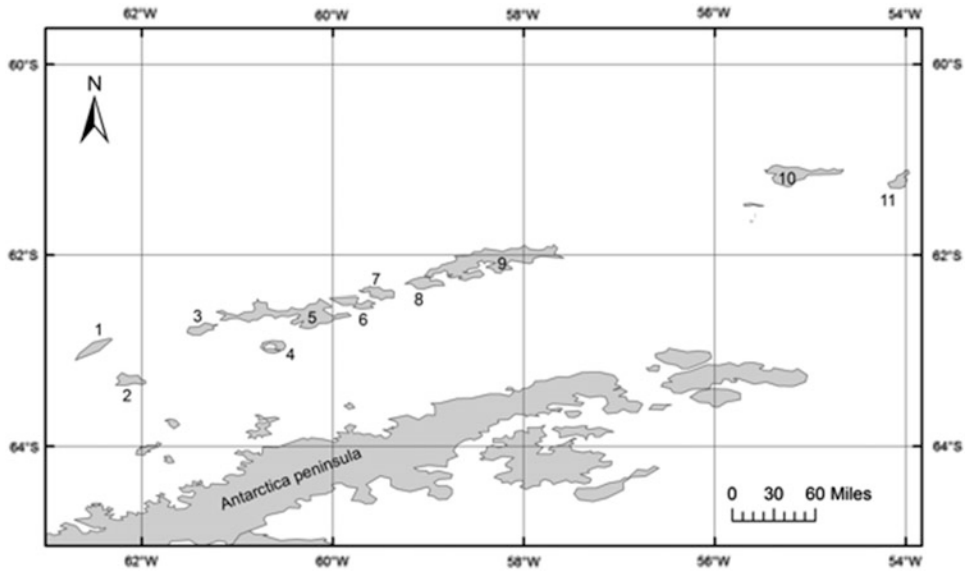

Fig. 13.2 Map of the South Shetland Islands Archipelago indicating the following Islands: 1-Smith; 2-Low; 3-Snow; 4-Decepcion; 5-Livingston; 6-Greenwich; 7-Robert; 8-Nelson; 9-King George; 10-Elephant; 11-Clarence

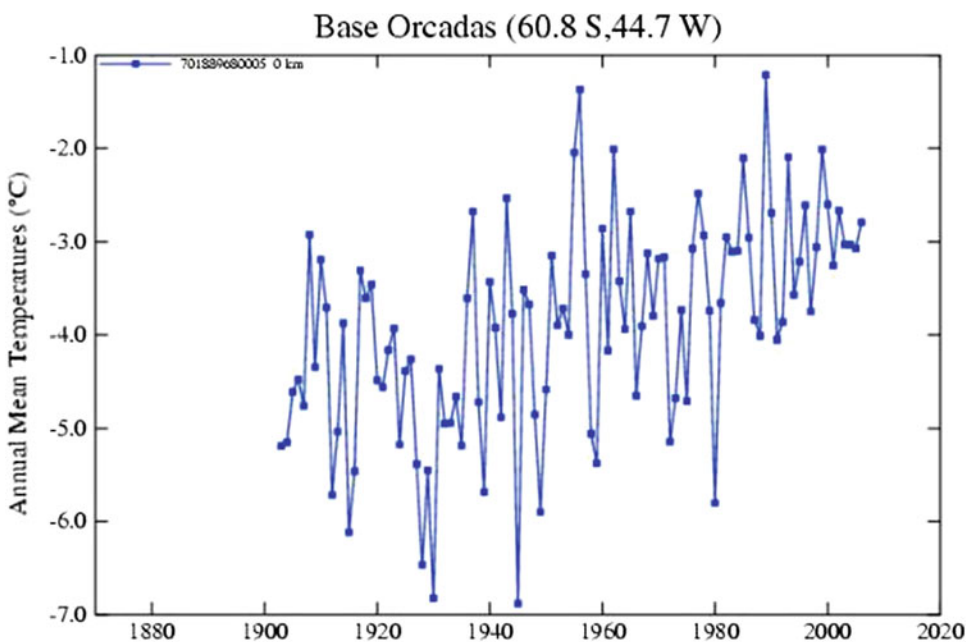

Fig. 13.3 Historical climate changes at Orcadas Base, Laurie Island, and South Orkney Group (*Source* Wikipedia)

temperatures above 0 °C for up to 4 months (data from 2000 through 2012, Teniente Rodolfo Marsh Martin Aerodrome Meteorological Station). Precipitation ranges between 350 and 1,000 mm per year, with rainfall occurring in the summer period.

In the current global changing climate scenario, it is estimated that this region has experienced increases in air temperature from 1 to 3 °C during the last 50 years (Turner et al. 2005), with important implications to ecosystems dynamics (King and Comiso 2003) because such increases occur close to the 0 °C isotherm and therefore affect the freezing and thawing of water. From 1901 to 2007, the mean annual air temperature at Orcadas Station has increased 2 °C (Fig. 13.3).

Soils in WAP form predominantly from volcanic substrates dating from the Late Palaeozoic, with the majority of the rocks of basaltic and andesitic nature. Quaternary marine sedimentary rocks as well as pyroclasts are also found in lesser extent. Such materials have been subjected to reworking due to advances and retreats of glaciers and periglacial activity during the last 9 ka BP when the first ice-free areas were exposed.

In a recent and comprehensive study of the regional geomorphology of the SSI, López-Martínez et al. (2012) suggest that at elevations below 20 m a.s.l. permafrost is absent or sporadic and periglacial landforms are poorly developed. Nival processes prevail and give rise to protalus ramparts, flat-floored and asymmetrical valleys. Physical weathering (salt, wet-drying and freeze-and-thawing) along with gravitational processes is also dominant under 20 m a.s.l. Active layer-related processes (e.g., frost creep, frost heaving and sorting, gravity and gelifluction) and landforms (debris lobes, cones and talus, gelifluction sheets and lobes, and patterned ground) prevail at intermediate altitudes (20–50 m a.s.l.). Permafrost-related processes (e.g., frost heaving, cryoturbation, and frost sorting) prevail at altitudes above 50 m a.s.l., resulting in stone stripes on the slopes and patterned ground (stone and earth circles and polygons, stone fields and frost mounds) on stable platforms. The periglacial environment of the South Shetlands in very active, especially between 30–100 m a.s.l. and is dependent on nivation, topography, lithology, and temperature oscillations (López-Martínez et al. 2012). This model has important implications for soil classification and ecosystems dynamics in the SOI and SSI, as the presence of permafrost affects chemical, biological, and physical processes and is determinant for Gelisols (Soil Survey Staff 1999, 2010) and Cryosols (IUSS, WRB 2006).

13.3 Methods

We compiled data from existing soil studies in the SOI and SSI with a focus on pedogenesis and soils geography. Data from dissertations and doctorate thesis not yet published internationally, as well as recent data from ongoing field work, are also presented and discussed. It total, data were collected from 365 pedons, of which 71 % were from KGI (Table 13.1).

Standard field methods were employed and are described in Everett (1976), O'Brien et al. (1979), Bölter (1995), Navas et al. (2008), and Francelino et al. (2011). Laboratory analyses commonly included pH, soil organic carbon (SOC), particle-size distribution, extractable P (Mehlich), and total N using methods generally described in Soil Survey Staff (2004). For some areas, notably those studied by Brazilian researchers, levels of exchangeable and extractable elements are presented in a volume basis due to the fact that routine soils analysis in that country frequently use a "scoop" of known volume to measure samples for extractions instead of a mass basis. Therefore, care must be taken when comparing data expressed in mass (mg kg^{-1}) and in volume basis (mg dm^{-3}).

Additional methods conducted on selected pedons or samples included exchangeable cations, clay mineralogy, total elemental analysis, petrographic analysis of a sand fraction, micromorphology, electrical conductivity, and extractable Fe, Al, and Si (Table 13.1). Soils were classified in *Soil Taxonomy* (Soil Survey Staff 2010).

13.4 Results

13.4.1 Soils from the South Orkney Islands

Publications on soils studies in the SOI are limited to the 20 km^2 Signy Island and appeared during the 1960s (Allen et al. 1967; Holdgate et al. 1967; Holdgate 1970). These studies emphasized the importance of cryogenic processes and the role of vegetation in pedogenesis. Holdgate et al. (1967) recognized eight broad soil groups (with our interpretations of great groups or subgroups in ST in parentheses), including soil on moraines (Gelorthents), (2) soils on patterned ground and solifluction slopes (Haploturbels, Gelaquents), (3) soils on schistose bedrock (Lithic Gelorthents), (4) soils on marble bedrock (Lithic Gelorthents), (5) soils beneath *Polytrichum-Dicranum* moss carpets (Fibristels), (6) soils beneath *Brachythecium-Acrocladium-Drepanocladus* vegetation (Gelaquents), (7) soils of grass patches (Humigelepts and Haplogelepts), and (8) ornithogenic soils (Haploturbels?). Holdgate et al. (1967) analyzed 170 topsoils from various soil groups, reporting low amounts of clay, extractable base cations, P, and N, with pH values ranging from 3.7 to 8.5, and SOC levels from 10 to 481 g kg^{-1} depending on the type and extent of vegetation cover. They emphasized that the soils on Signy Island showed minimal development.

Studies by the British Antarctic Survey in the 1960s reported active layer depths ranging from 0.4 to >2 m (Chambers 1966; Holdgate et al. 1967). Recent studies measured the active layer at depths from 0.86 to 2.3 m (Cannone et al. 2006; Guglielmin et al. 2008). The active layer depth is strongly dependent on vegetation and has increased 1 cm/yr since 1963 at Signy Island due to climate warming (Cannone et al. 2006).

13.4.2 Soils from the South Shetland Islands

Soils have been studied on six islands in the South Shetland Group, including King George, Ardley, Livingston, Deception, Penguin, and Elephant Islands.

Table 13.1 Soil dataset for WAP indicating the laboratory analyses used by different authors

Area	No. of profiles	Reference	Petr. sand	PSA	Exch. bases	pH	SOC	N	Ext. P	Clay min.	Micr.	EC	Tot. Elem.	BD	CEC	Fe_p. Al_p. Si_p	Fe_o. Al_o. Si_o	Fe_d. Al_d. Si_d
Elephant Is.	3	O'Brien et al. (1979)	x	x	x	x	x	x	x	x	x	–	–	–	–	–	–	–
Livingston Is. (LI)	11	Navas et al. (2008)	x	x	–	x	x	x	x	–	–	x	x	–	–	–	–	–
Byers Pen	23	Moura et al. (2012)	–	x	x	x	x	x	x	x	–	–	–	–	x	–	–	–
LI—Hurd Pen	19	Bockheim and Haus unpubl.	–	x	–	x	x	x	x	–	–	x	–	x	–	–	–	–
LI	8	Everett (1976)	–	x	x	x	x	x	x	–	–	–	x	–	–	–	–	–
Deception Is. (SSI)	28	Bockheim and Haus unpubl.	–	–	–	–	x	–	–	–	–	–	x	–	–	–	–	–
	5	Resck (2011)	–	x	x	x	x	–	x	x	–	–	–	–	x	x	x	x
King George Isl. (KGI)	13	Bölter (1995)	–	x	–	x	x	x	x	–	–	x	–	x	–	–	–	–
KGI—Fildes Pen	3	Chen and Blume (2000)	–	x	–	x	x	–	–	–	–	–	x	–	–	x	x	–
	31	Michel et al. (2014)	–	x	x	x	x	x	x	–	–	–	–	–	x	–	–	–
	4	Mendonça et al. (2013)	–	–	x	x	x	–	x	x	–	–	–	–	x	x	x	x
KGI—Ardley	17	Michel et al. (2014)	–	x	x	x	x	x	x	–	–	–	–	–	x	–	–	–
KGI—Keller Pen	26	Francelino et al. (2011)	–	x	x	x	x	–	x	–	–	–	–	–	x	–	–	–
KGI—Llano Point	4	Michel et al. (2006)	–	x	x	x	x	x	x	–	–	–	–	–	x	–	–	–
	6	This volume	–	x	x	x	x	–	x	–	–	–	–	–	x	–	–	–
KGI—Admiralty Bay	9	Simas et al. (2006)	–	x	–	x	x	–	x	x	–	–	–	–	–	x	x	x
	56	Simas et al. (2008)	–	x	x	x	x	x	x	x	–	–	–	–	x	–	–	–
	4	Schaefer et al. (2008)	x	–	–	x	x	–	x	x	x	–	x	–	–	–	–	–
KGI—Rakusa Point	10	Simas et al. (2007b)	–	x	x	x	x	x	x	x	x	–	–	–	x	x	x	x
KGI—Warszawa Pen	7	Bremen (2008)	–	x	x	x	x	x	x	x	–	–	–	–	x	–	–	–
KGI—Barton Pen	30	This volume	–	–	–	–	–	–	–	–	–	–	–	–	x	–	–	–
KGI—Potter Pen	18	Poelking (2011)	–	x	x	x	x	x	x	–	–	–	–	–	x	–	–	–
KGI—Barton Pen	30	Lee et al. (2004)	–	–	–	–	x	–	–	–	–	–	x	–	–	–	–	–
Total	**335**																	

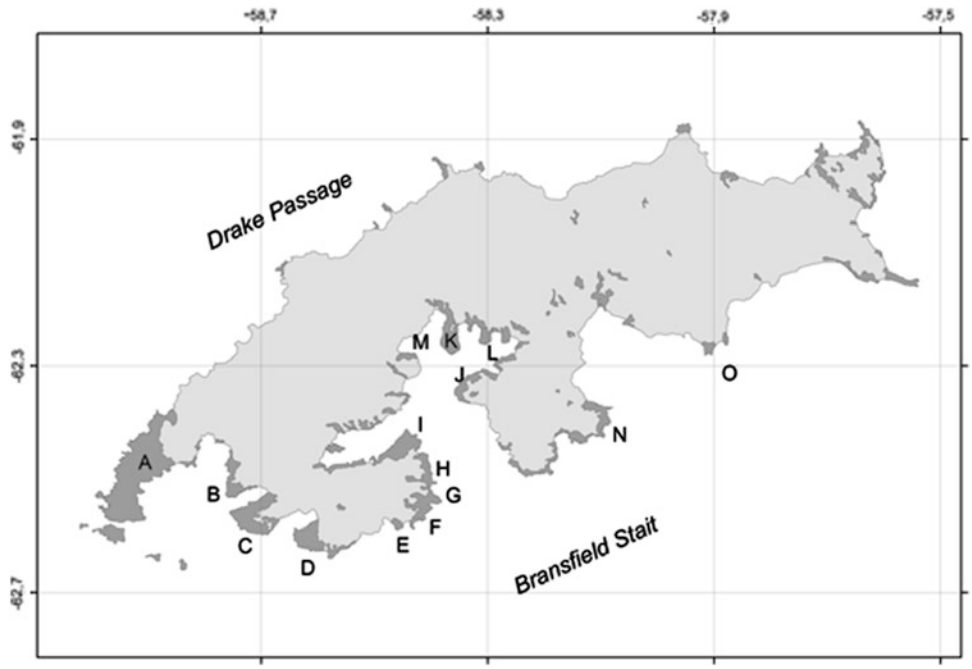

Fig. 13.4 Map of King George Island indicating the ice-free areas where soil studies have been conducted. A − Fildes Pen., B − Ardley, C − Barton Pen., D − Potter Pen., E − Telefon Pt,. F − Utchatka Pt., G − Agat Pt., H − Llano Pt., *I* Rakusa Pt., J − Hennequin Pt., K − Keller Pen., L − Ullman Pt., M − Crépin Pt., N − Lions Rump, O − Penguin Is

13.4.2.1 King George Island

Soils on KGI have been studied at Keller Peninsula, Admiralty Bay, Lions Rump, Potter Peninsula, Barton Peninsula, Fildes Peninsula, and Ardley Island (Fig. 13.4).

Keller Peninsula

Twenty-five pedons from the Keller Peninsula were examined on basaltic/andesite, acid sulfate materials, and sites affected by skuas (*Catharacta* sp.) (Simas et al. 2008). Data on physical and chemical properties of each soil are found in Francelino et al. (2011). The soils generally are shallow with a lithic or paralithic contact in the upper 1 m and have very high coarse fragment contents that confer a skeletic (or hyperskeletic) character.

The largest part of the peninsula is composed of basaltic-andesitic materials on which grayish soils develop without the influence of vegetation (Fig. 13.5). These soils have high pH (7.0–8.0) and high levels of exchangeable bases, providing a eutrophic character; extractable P varies from 119 to 468 mg dm^{-3}. SOC values are generally low (<2 g kg^{-1}), and soil texture varies from clay loam to sandy, with some soils containing up to 30 g kg^{-1} clay in the <2 mm fraction. The clay fraction is composed by hydroxy-interlayered smectite along with easily weatherable primary minerals such as pyroxenes and feldspars (Simas et al. 2008).

Although typical ornithogenic soils are not found on Keller Peninsula (Simas et al. 2008), small areas with some degree of influence by sea birds (mostly skuas—*Catharacta sp.*) are present on uplifted terraces and moraines usually at altitudes >45 m a.s.l., normally colonized by mosses, lichens, and higher plants (Fig. 13.5). These soils have a slightly acidic reaction with pH ranging from 5.5 to 6.2 and SOC values reaching 65 g kg^{-1} and dystrophic surface horizons). There is no pronounced increase in extractable P levels in relation to the basaltic/andesitic soils or formation of crystalline phosphate minerals in these soils.

Acid sulfate soils develop on sulfide-bearing andesites, showing yellowish colors (Fig. 13.6) and very acidic pH (4.3–5.0) (Simas et al. 2007b). Extractable P levels are much lower (19–83 mg dm^{-3}); the soils are depleted in bases and have a dystrophic character, with extremely high levels of Al^{3+}. Soil texture is normally sandy loam with very high silt contents (Simas et al. 2008). Jarosite and ferrihydrite occur in the clay fraction and account for high P adsorption capacity and pH-dependent charges (Simas et al. 2006).

Only 63.4 % of Keller peninsula is sufficiently stable to allow soil development (Francelino et al. 2011). The remaining area is composed of rock outcrops or unstable, steep slopes marked by solifluction, gravitational, and colluvial processes. Vegetation cover occurs on less than 3 % of the area (Francelino et al. 2011). Lichens and mosses prevail, but small areas with higher plants (Deschampsia Antarctica and Colobanthus quitensis) occur that are influenced by birds. Nine soil complexes were identified. Gelisols, Inceptisols, and Entisols are the primary soil orders in the area (Francelino et al. 2011). Gelisols only occur at altitudes higher than 20 m a.s.l., since permafrost is absent below this height (López-Martínez et al. 2012). Due to the strong cryoturbation, such as frost heave, sorting, thermal cracking, and patterned ground, the soils are classified as Turbels. The sulfuric qualifier was provisionally adopted in the Haploturbel suborder to differentiate acid-sulfate soils as suggested by Simas et al. (2008). Along slopes and moraines between 20 and 80 m a.s.l., these soils occur in association with Inceptisols and Entisols as permafrost is discontinuous.

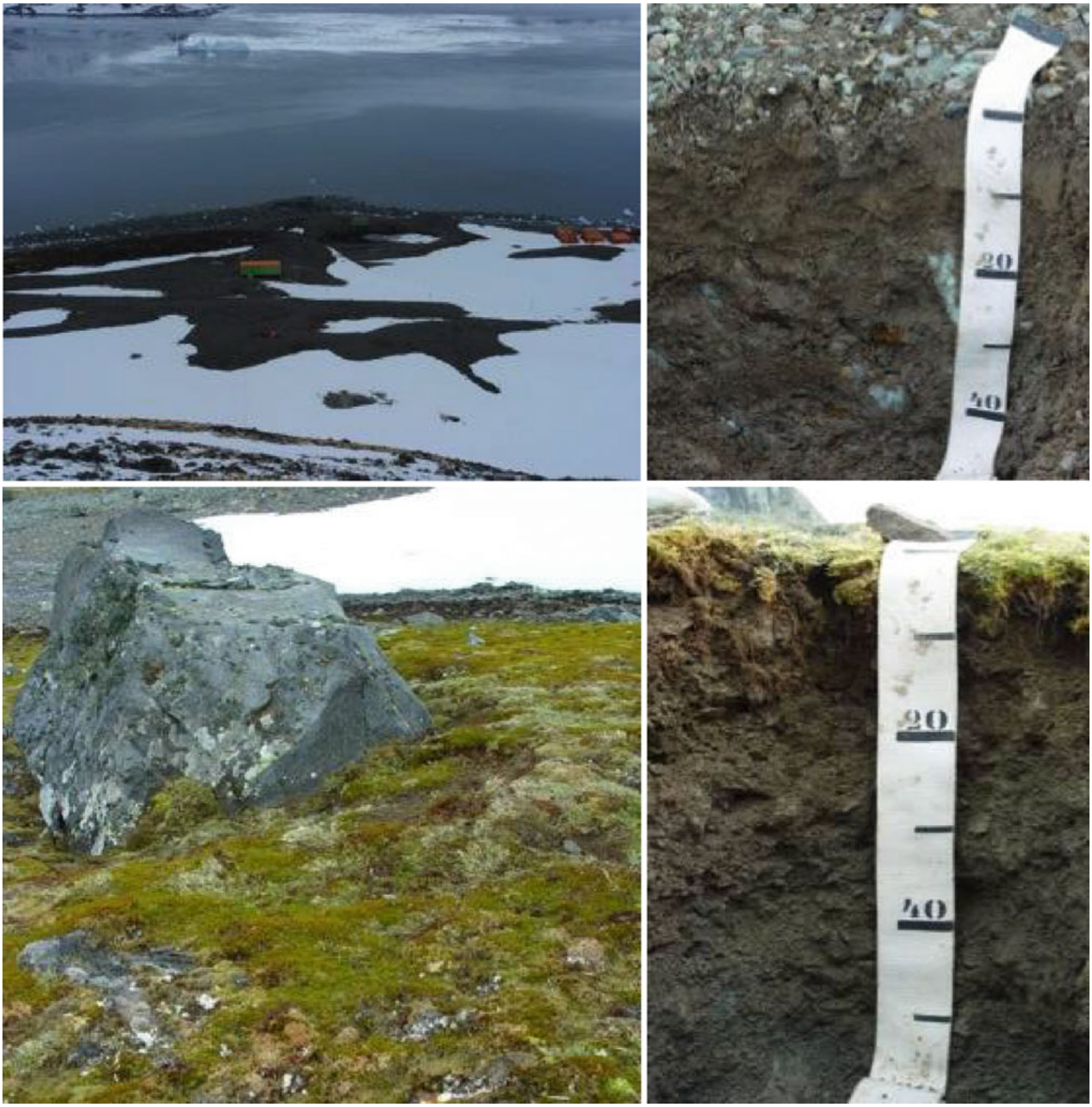

Fig. 13.5 Soil on basaltic/andesitic moraines close to the Brazilian Comandante Ferraz Station in the Keller Peninsula (*top*); and typical soil and site with incipient ornithogenic influence due to Skua nesting (*bottom*)

West Coast of Admiralty Bay

The west coast of Admiralty Bay has large areas affected by penguins and other flying birds that nest in ice-free areas, mainly at altitudes below 70 m a.s.l. Soil studies were first carried out by Polish researchers (Myrcha et al. 1983; Myrcha and Tatur 1991; Tatur and Barczuk 1983), with an emphasis on the characterization of pedogenic phosphate minerals present in ornithogenic soils. Several papers describe in detail the process through which guano and other materials deposited on land by birds (i.e., egg shells, bones, corpses, etc.) react with the underlying mineral substrate with neoformation of crystalline P minerals (Tatur 1989; Tatur and Myrcha 1993; Tatur et al. 1996; Simas et al. 2006). Amorphous and crystalline P minerals account for 30–70 % of the clay fraction in ornithogenic soils near the Polish Arctowski Station (Simas et al. 2006).

Simas et al. (2008) provided chemical data for ten pedons along an altitudinal sequence from 5 to 147 m a.s.l.at Rakusa

Fig. 13.6 Panoramic view of the eastern coast of Keller Peninsula showing large area affected by acid sulfate formation with characteristic *yellow colors*, easily distinguished from the predominant basaltic materials. On the *right*, a micro soil profile with acid sulfate soil overlaying by basaltic colluvium

Point. The soils have abundant gravel, show weak to moderate granular structure, and have a clay content varying from 7 to 20 g kg^{-1}. Ornithogenic soils occur up to 72 m a.s.l. and have pH values ranging from 3.5 to 5.9 and high SOC. The highest Mehlich-extractable P values occur in soils located from 45 to 72 m a.s.l., with values ranging from 828 to 4270 mg dm^{-3}. The ornithogenic influence decreases with increasing altitude, where upon the soils become eutric, with a high pH and low SOC.

Michel et al. (2006) reported similar results for five soils along and altitudinal sequence at Llano Point. Table 13.2 provides analytical data for four of these soils. Ornithogenic soils have a pH ranging from 4.1 to 5.0 and extractable P values up to a maximum value of 1,186 mg dm^{-3}. At the upper part of the landscape, no ornithogenic influence occurs, and the soils are eutrophic, with pH increasing from 5.9 in surface to 8.0 at depth. Extractable P levels varied from 182 to 394 mg dm^{-3} and are comparable to values for basaltic/andesitic soils at Admiralty Bay (Simas et al. 2007b).

Soils from Llano Point have SOC levels ranging from 1 to 154 g kg^{-1} for ornithogenic soils. These are lower than those reported by Simas et al. (2007b) for soils from Rakusa Point (40–440 g kg^{-1}). Permafrost occurs at depths of 50–70 cm under thick fibric horizons at altitudes ranging from 40 to 60 m a.s.l.

A first approximation of a soil map for an area of 1.2 km^2 at Llano Point and the surrounding U.S. Peter Lenny refuge is given in Fig. 13.7, as well as the detailed legend in Table 13.3. Haploturbels are the predominant soils, occupying the highest part of the landscape. Ornithogenic Turbels and Entisols occupy lower areas. Seven out of 14 soil units have an ornithogenic character.

Bremen (2008) studied seven soil profiles from the east part of the Warszawa Peninsula in areas influenced by penguin rookeries (Utchatka, Telefon and Agat Points; Table 13.4). At Telefon Point, values of extractable P reach the highest levels so far reported for soils from maritime Antarctica (8,410 mg dm^{-3}). The soils have organic horizons and high SOC levels. Occurring at elevations below 23 m a.s.l., the soils key out as Ornithogenic Gelorthents (five soils), Ornithogenic Sapristels (one soil). A Lithic Gelorthent occurs in an area unaffected by penguin rookeries. Figure 13.8 shows ornithogenic sites and phosphatized soil at Utchakta and Telefon Points.

Lions Rump

Almeida et al. (2010) sampled 13 pedons and identified three soil groups at Lions Rump, King George Island, including acid ornithogenic soils (two pedons), neutral ornithogenic soils (three pedons), and nonornithogenic soils (seven pedons). A soil map comprised of 2.3 kms of the Lions Rump area is shown in Fig. 13.9, and the legend is in Table 13.5. Soils from Lions Rump have relatively low amounts of clay (92 g kg^{-1}) and silt (24.9 g kg^{-1}) (Table 13.6). The soils are gravelly and become more skeletal at higher elevations when derived from Tertiary volcanic materials. The soil structure

Table 13.2 Physical and chemical properties of soils from Llano Point, western coast of Admiralty Bay, King George Island

	Depth	Coarse Sand[1]	Fine Sand[2]	Silt[3]	Clay[4]	Color	pH	P	K	Na	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	CEC	N	SOC	PSS[5]
	(cm)	(g/kg)					H_2O	(mg/dm^3)			($cmol_c/dm^3$)					(g/kg)		(%)
Profile 1—Typic Gelaquent (5 m, Marine Terrace 1st Level)																		
A	0–20	450	140	300	110	5YR4/3	6.2	117	153	206	15.0	17.7	2.4	7.0	41.0	0.8	22	2.4
C1	20–30	430	150	310	110	7.5YR5/2	6.3	125.3	154	214	18.5	19	1	4.8	43.7	0.6	30	2.3
C2	30–40	260	120	350	270	7.5YR5/2	6.4	236.6	169	226	22.1	19.5	0.2	3	46.1	0.5	39	2.2
Cg	40–50	540	60	200	200	5YR4/2	6.7	412.3	115	182	20.4	14.9	0.2	4.8	41.3	0.6	39	2.1
Profile 5—"Ornithogenic" Lithic Haploturbel (40 m, Moraine)																		
A	0–10	760	80	80	80	5YR3/4	4.5	258	145	188	2	2.2	3.1	16.5	21.9	1.1	115	9.5
BA	10–20	630	170	130	70	5YR4/3	4.8	494.5	179	210	1.8	1.4	5.8	23.1	27.7	0.6	22	8.7
B	20–30	570	190	170	70	7.5YR4/3	4.5	803.3	197	202	1.2	0.7	5.8	29.9	33.2	0.5	19	9.5
C	30–40	620	150	150	80	7.5YR5/4	4.3	1185.8	179	184	1.3	0.6	5.6	31.7	34.9	0.6	27	9.0
Cr	40–50	600	150	150	100	5YR4/4	4.5	981	143	125	1.9	1	8.5	31.8	35.7	0.6	41	4.3
Profile 6—Terric Fibristel (40 m, Moraine)																		
H1	30–20	460	200	220	120	7.5YR3/3	4.6	264	80	172	2.9	2.4	5.6	22.5	28.7	1.5	115	6.2
H2	20–0	520	210	170	100	5YR3/4	4.6	322.7	66	111	0.7	0.5	2.5	16.8	18.7	2.0	154	10.7
Bh	0–25	520	210	200	70	7.5YR3/3	4.5	293.5	56	79	0.9	0.4	1.9	15	16.8	1.8	133	9.2
Bhs	25–50	470	190	260	80	7.5YR4/4	5	418	282	170	0.2	0.1	0	20.8	22.2	0.4	26	50.6
C	50–70	390	180	320	110	5YR4/3	5.9	342.3	381	257	19.2	9.58	1.2	6.7	37.6	0.1	4.0	3.4
Cr	70–100	350	130	350	170	5YR5/2	6.9	357	367	301	21.1	10.2	n.d.	2.2	35.8	n.d.	1.0	3.9
Profile 7—Typic Psammoturbel (50 m, Moraine)																		
A	0–10	450	220	250	80	7.5YR4/3	5.2	177.6	129	214	5.2	6.9	6	16.5	29.9	0.7	45	4.7
B1	10–20	400	180	330	90	5YR5/4	5.3	219.2	117	206	3.2	4.1	8.5	21.4	30	0.7	44	5.2
B2	20–30	480	180	240	100	7.5YR4/4	5.1	465.2	89	186	1.7	1.7	11.4	0.8	5.3	0.7	35	5.0

[1]Coarse sand (0.2–2 mm)
[2]Fine sand (0.05–0.2 mm)
[3]Silt 0.002–0.05 mm
[4]Clay <0.002 mm
[5]PSS–Percentage of Sodium Saturation

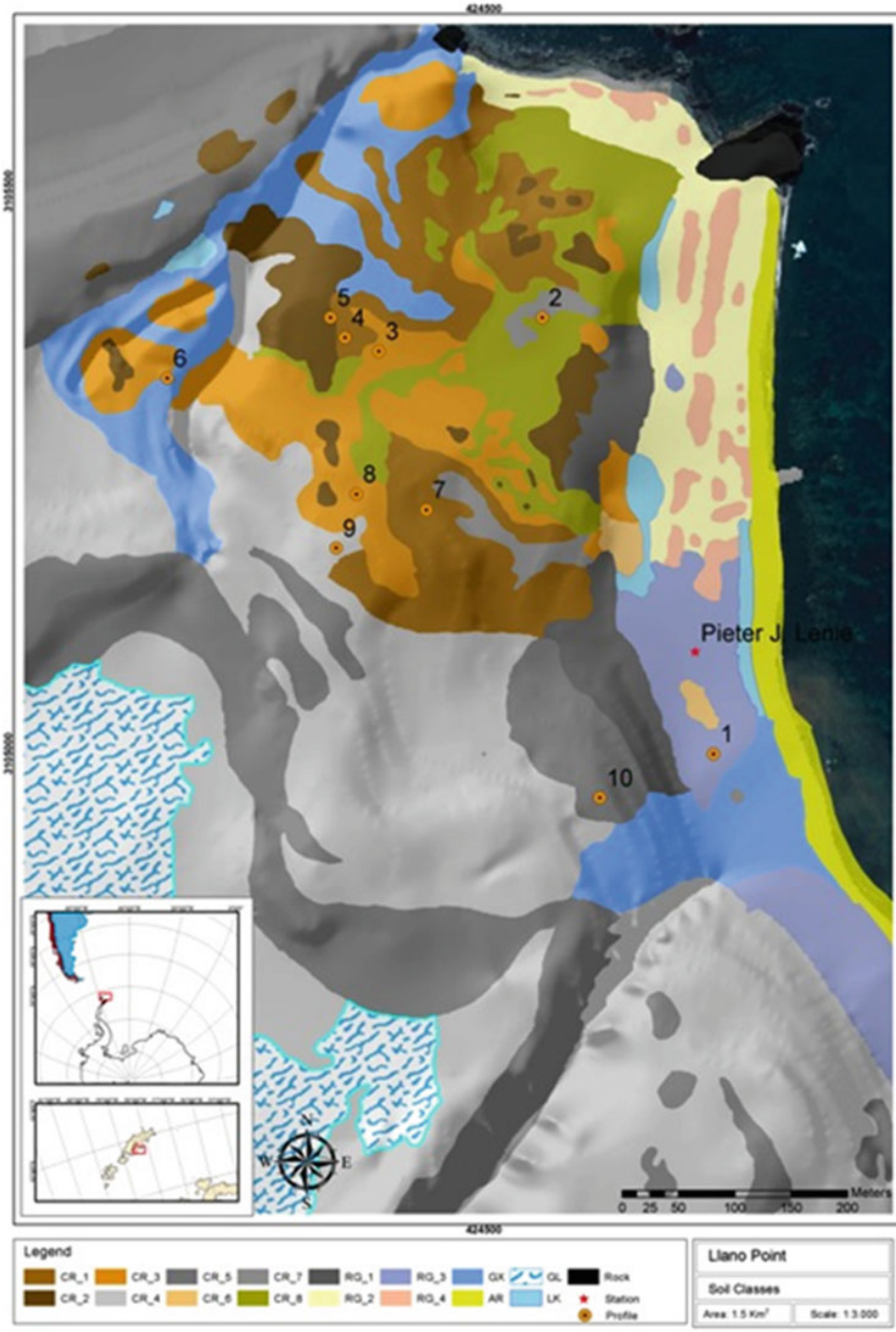

Fig. 13.7 Soil map of Llano Point, on the surroundings of the U.S.S. Peter J. Lenie refuge (see Table 13.3 for key to legend)

from Lions Rump is predominantly weak, medium-sized blocks, and moderate medium granular features, with clear to gradual, wavy transition between horizons.

Mean pH of acid ornithogenic soils, neutral ornithogenic soils, and nonornithogenic soils is 4.3 ± 0.33, 7.0 ± 1.2, and 7.4 ± 1.1, respectively. Neutral ornithogenic soils have high cation exchange capacity (CEC) and base saturation (BS) with eutrophic character; in contrast, acid ornithogenic soils are dystrophic and have a low CEC. Soils formed under direct penguin influence (acid and neutral ornithogenic soils) have a mean extractable P level of 1075 (±1210) mg dm^{-3}. Mean extractable P in acid ornithogenic soil is more than ten times higher than in nonornithogenic soils, and exchangeable Ca^{2+} is more than nine times lower (Table 13.6).

The soils from penguin rookeries have clear horizon differentiation, with relatively deep, dark, and yellowish

Table 13.3 Soil units mapped in Llano point, western coast of Admiralty Bay, KGI

Soil class	Area (ha)	(%)	Mapping unit
Typic Psamments	4.1	3.3	AR
Ornithogenic Haploturbel	4.1	3.3	CR_1
Ornithogenic. Lithic Haploturbel	1.8	1.5	CR_2
Lithic Fibristel	3.9	3.1	CR_3
Glacic Haploturbels + Lithic Haploturbel	42.9	34.6	CR_4
Skeletal. Lithic Haploturbel	33.2	26.7	CR_5
Ornithogenic. Lithic Haploturbel	0.2	0.2	CR_6
Ornithogenic Aquiturbel	0.2	0.2	CR_7
Ornithogenic Haploturbel	3.3	2.7	CR_8
Typic Gelaquent	17.6	14.2	GX
Lake	0.7	0.5	LK
Lithic Gelorthent (Gelic)	1.6	1.3	RG_1
Hyperskeletal. Typic Gelorthent	2.8	2.2	RG_2
Ornithogenic Gelaquent	6.2	5.0	RG_3
Ornithogenic Gelorthent (Ornithic. Gelic)	1.1	0.9	RG_4
Rock Outcrop	0.4	0.3	RK
Total	124.2	100	

brown, organic matter-rich A horizon overlying a phosphatic B horizon. Nonornithogenic soils at Lions Rump have high pH, Ca^{2+}, and Mg^{2+} levels, and salinity (Table 13.6). The mean extractable P level for nonornithogenic soils was 1023 ± 48 mg dm^3. In Lions Rump promontory, highly evolved, deep ornithogenic soils were described in abandoned rookeries, with atypical strongly oxidized colors and dense vegetation, suggesting a very old occupation site. Acid sulfate soils occur at one unique site on Lions Rump This soil has a much lower pH (3.62), high contents of exchangeable Al^{3+} (20 $cmol_c$ dm^{-3}) and H+Al (28.1 $cmol_c$ dm^{-3}), and very low extractable P contents (6.9 mg dm^{-3}).

Typic Haplorthels, Lithic Haplorthels, Typic Haploturbels, and Lithic Haploturbels occur above 80 m a.s.l., and represent the most extensive soil cover in the study area. Typic Haploturbels and Lithic Haploturbels are present on the edge of White Eagle Glacier, where the cryoturbation process is more expressed. Turbic Haplogelepts and Typic Haplorthels occur between 40 and 80 m a.s.l., without bird nesting influence. Vitrandic Cryopsamments and Oxyaquic Cryopsamments dominate the first level of terraces and former beaches in coastal areas. Other soil subgroups occur in restricted areas: "Ornithogenic" Cryorthents are present on sea stacks rock outcrops (basaltic plugs) close to the beach, and "Ornithogenic" Gelifluvents occur on a small area on glacial alluvial fans.

"Ornithogenic" Dystrogelepts and "Ornithogenic" Gelorthents occur in areas colonized by penguins in maritime Antarctica. "Ornithogenic" Typic Dystrogelepts from Lions Rump represent the deepest, most structured, and reddish soils so far described in maritime Antarctica. "Ornithogenic" Haplogelepts represent the main soils on first and second moraine levels from the White Eagle Glacier.

Potter Peninsula

Poelking (2011) studied 18 soil profiles on Potter Peninsula and mapped soils and associated landforms. Soils are shallow (<1 m) and skeletal. The texture of the <2 mm soil fraction varies from sandy to sandy loam with clay contents varying from 40 to 270 g kg^{-1} (Table 13.7).

On the western part of Potter Peninsula, between Petrels Rock and Mirounga Point, soils with histic epipedons (P15 and P17) occur on cryoplaned surfaces covered with thick moss turfs of *Polytricales sp.* and carpets of *Sanionia uncinata* with occasional occurrence of *D. antarctica* (P15). These soils with thick organic surface horizons (>50 cm) have a mean SOC of 180 g kg^{-1}, ice-cemented permafrost at a depth of 40–50 cm (P15 and P17) at approximately 40 m a.s.l., and key out as Histels. The pH values vary from 4.3 to 5.0, and extractable P levels are relatively low in P15 (62–161 mg dm^{-3}) but much higher in P17, decreasing gradually from 689 mg dm^{-3} at the surface to 351 mg dm^{-3} at a depth of 70 cm, suggesting current guano deposition.

Soils P3, P4, P8, P13, P16, and P18 are the mineral soils with the highest levels of extractable P; mean values range from 430 to 709 mg dm^{-3}, reflecting the influence of flying birds. All profiles are dystrophic with soil pH varying from 4.5 to 5.3 and SOC contents from 13 to 112 g kg^{-1}. These soils are keyed out as Umbriturbels and Humigelepts with an

Table 13.4 Chemical attributes of soils from the Warszawa Peninsula, western coast of Admiralty Bay, King George Island

Soil	Depth (cm)	Color	pH	P	K	Na	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	CEC	SOC	PSS
		dry		($cmol_c/dm^3$)								(g/kg)	(%)
Uchatka point													
Ornithogenic Gelorthent 4 m a.s.l. 62° 13′ 04″ S; 58° 26′ 22″ W	0–10	10YR 5/3	5.2	245.2	0.03	1.34	9.68	10.2	2.9	13	34.71	93.4	5.45
	20–40	10YR 6/2	5.1	729.7	0.02	1.05	9.21	7.57	14.51	45.6	63.9	10.2	3.21
Ornithogenic Gelorthent 23 m a.s.l. 62° 13′ 10″ S; 58° 26′ 27″ W	0–10	7.5YR 3/4	4.8	307.1	0.02	1.52	6.37	6.25	3.79	13.8	28.32	72.9	8.28
	20–40	10.5YR 5/3	5.0	270.1	0.01	1.2	6.75	5.28	1.82	18.2	31.81	66.5	7.79
Ornithogenic Gelorthent 17 m a.s.l. 62° 13′ 15″ S; 58° 26′ 34″ W	20–40	10YR 5/2	4.9	1837.1	0.01	1.37	3.81	3.45	1.92	22.9	32.57	24.3	11.8
Telefon point													
Ornthogenic Gelorthent 6 m a.s.l. 62° 14′ 03″ S; 58° 28′16″ W	0–10	10YR 5/2	4.9	4056.1	0.01	4.29	6.47	2.19	0.44	17.4	30.89	60.1	30.77
	20–40	10YR 4/3	4.5	644.5	0	1.69	3.75	1.12	1.43	25.8	33.46	21.8	18.58
Ornithogenic Gelorthent 5 m a.s.l. 62° 14′ 06″ S 58° 28′ 11″ W	0–10	7.5YR 6/1	5.9	7153.4	0.07	13.76	11.99	25.42	0.1	8.1	39.93	431.1	n.d.
	10–20	7.5YR 4/1	7.1	8370.3	0.05	6.15	2.36	18.72	0	5.5	33.73	218	n.d
	20–30	7.5YR 6/2	7.9	8408.8	0.03	5.57	0.67	11.74	0	4.4	23.23	295.7	n.d
Ornithogenic Sapristel 4 m a.s.l. 62° 14′ 05′ ′ S 58° 28′ 10″ W	0–10	10YR 4/3	5.8	3935.9	0.01	5.88	3.36	4.29	0.2	7.1	21.2	411.2	n.d
	10–20	10YR 6/2	5.6	1341.6	0.01	6.74	3.87	4.04	0.64	10.4	25.89	417.8	n.d.
Agat point													
Typic Gelorthent 3 m a.s.l.	0–10	2.5YR 7/2	6.1	222.1	0.04	4.09	27.17	13.68	0	4.7	49.96	30.7	9.04
	10–40	2.5YR 7/2	7.9	208.5	0.03	3.46	44.06	11.21	0	0.5	59.42	2.6	5.88

Fig. 13.8 Utchakta Point (*top*) with leveled terraces and rocky promontories with ornithogenic soils covered with mosses and *Deschampsia antarctica* forming thick organic horizons in sites where water saturation is more frequent. Ornithogenic Gelorthent (*bottom*) at Telefon Point on rocky promontory affected by penguins and seals. Soil covered with *D. antarctica* and showing strong phosphatization (Table 13.4)

"Ornithogenic"character. P1, P5, P6, P7, P9, P10, and P11 are mineral soils with least ornithogenic influence and have pH varying from 5.4 to 6.8 (mean 6.1) and extractable P levels ranging from 45 to 167 mg dm^{-3} (mean of 122 mg dm^{-3}) with SOC normally lower than 20 g kg^{-1} but reaching 44 g kg^{-1} in P7 and 72 g kg^{-1} in P10 (Table 13.7). They occur on diverse landforms such as raised beaches and marine terraces (P6 and P11), outwash cones (P9), and rock fields and key out as Haploturbels, Cryopsamments, and Fluvents usually with lithic or paralithic contact within 70 cm depth.

Barton Peninsula

The few existing soil studies in Barton Peninsula focus on acid sulfate weathering, which is a widespread process in this ice-free area (Armstrong 1995; Jeong and Yoon 2001). We studied 31 soil profiles representing the major geomorphological units on the Barton Peninsula. The soils occur on several stable geomorphological surfaces and show variable characteristics varying from hyperskelectic to loamy materials according to the parent material and have a higher content of fines than acid sulfate soils. As in other areas of King George Island, cryoturbation is a widespread phenomenon resulting in intense cryoclastic weathering and patterned ground, sorted circles (Fig. 13.10), stripes, and gelifluction lobes. The active layer varies from 80 to 200 cm in depth, depending on substrate composition, vegetation cover, and topographic factors.

Soils from andesitic materials have relatively high pH values (6.4–8.1), high exchangeable bases, a eutric character, and extractable P varying from 67 to 233 mg dm^{-3}. At the highest elevations, stable moraines are densely colonized with the lichen *Usnea sp.* Total organic C levels are relatively high for maritime Antarctica, with values ranging from 20 to 200 g kg^{-1}. The increase in SOC results in slight soil acidification (Table 13.8).

The greater part of the Barton Peninsula is covered with acid sulfate soils, similar to those described on Keller Peninsula, with typical yellowish colors (Fig. 13.11). Soil pH values range from extremely acidic to acidic (2.8–6.0), and soils are strongly depleted in bases, exhibiting a dystrophic character with base saturation varying from 9 to 48 % (Table 13.8). In areas not having been influenced by birds, extractable P is much lower than on soils from andesitic materials, with values from 14 to 25 mg dm^{-3}. As reported by Simas et al. (2006) for soils from Keller Peninsula, clay mineralogy in these soils present jarosite and amorphous iron phases which account for a large P retention capacity.

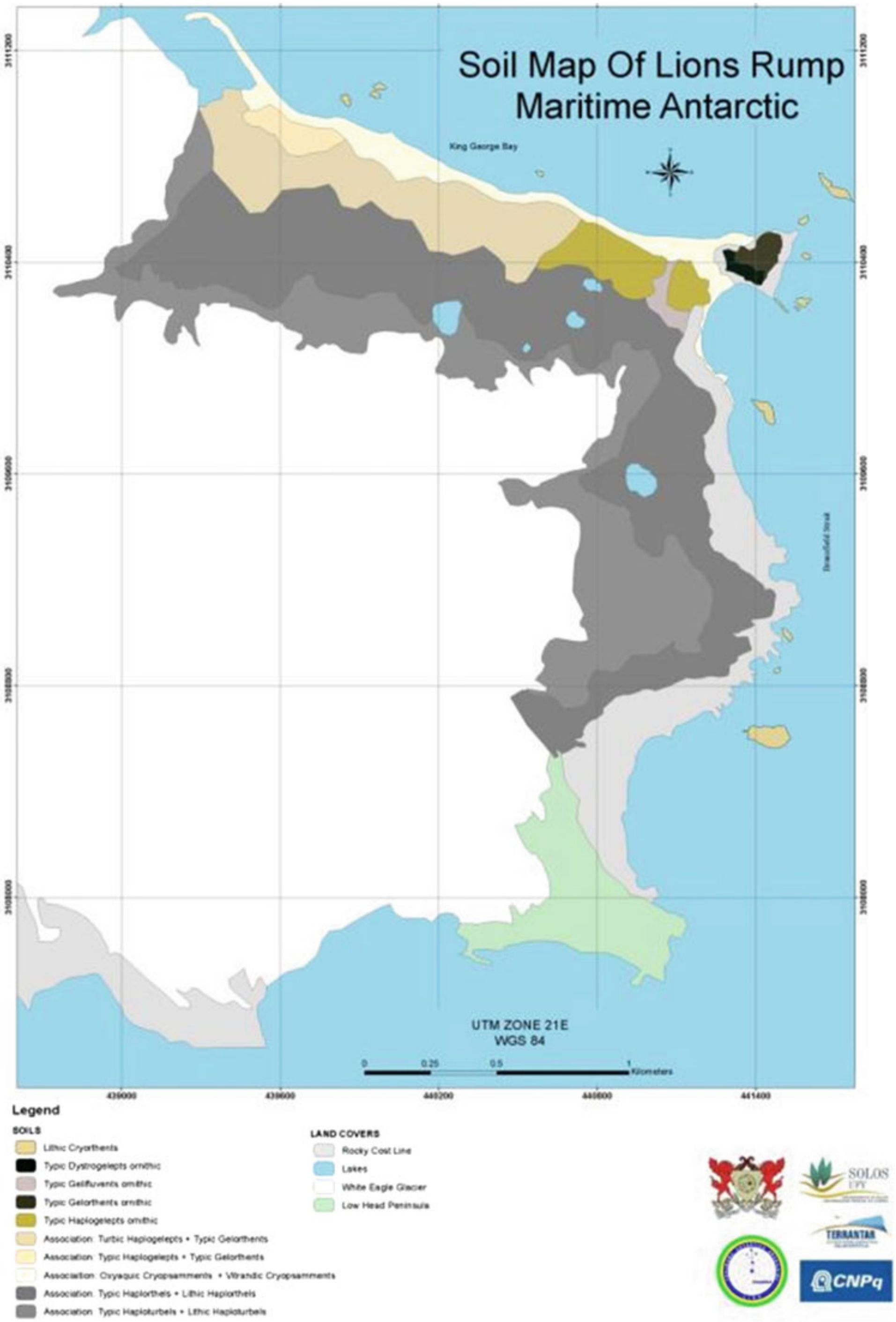

Fig. 13.9 Soil map of Lions Rump, King George Island

Soils under current ornithogenic influence by penguins have the distinguishing characteristic of extremely high contents of fibric organic materials with SOC levels ranging from 34 to 554 g kg^{-1} (Table 13.8). Many of the soils have thick histic epipedons composed of fibric materials, with frozen ground at a depth of approximately 70 cm and key out in the Histels suborder (Fig. 13.12).

Densely vegetated areas occur along uplifted marine terraces up to 45 m a.s.l. Extractable P levels reach 1895 mg dm^{-3} and suggest colonization by large numbers of birds, possibly before the glacioisostatic uplifting of these surfaces. SOC levels are also high by WAP standards, ranging from 13 to 262 g kg^{-1} (Table 13.8), but the organic material is more humified than that at the previously

Table 13.5 Soil units mapped at Lions Rump, King George Island

Soil mapping units	Hectares	(%)
Lithic Gelorthents	2.55	1.1
Ornithogenic Dystrogelepts	0.93	0.4
Ornithogenic Gelifluvents	1.75	0.8
Ornithogenic Gelorthents	1.69	0.7
Ornithogenic Haplogelepts	9.45	4.1
Turbic Haplogelepts + Typic Gelorthents	30.91	13.4
Oxyaquic Gelipsamments + Vitrandic Gelipsamments	15.45	6.7
Typic Haplogelepts + Typic Gelorthents	3.44	1.5
Typic Haplorthels + Lithic Haplorthels	98.87	43.0
Typic Haploturbels + Lithic Haploturbels	64.99	28.3
Sum	**230.03**	**100.00**

discussed site. Uplifted marine terraces are very pronounced on the Barton Peninsula, including near Seong Jong Station (Fig. 13.13). Photographs of structural, uplifted terrace landforms and soils on the east coast of the Barton Peninsula are given in Fig. 13.14.

A notable aspect of soils from the Barton Peninsula is the well-developed structure of the soils in relation to those observed in most ice-free areas in WAP; platy, blocky, and vesicular structures are common. Soils have been mapped for parts of the Barton Peninsula (1:10,000-scale) (Schaefer et al. unpublished).

Fildes Peninsula

Fildes Peninsula is the second largest ice-free area of the SSI and the largest on King George Island. Soils on the Fildes Peninsula have been studied by Chen and Blume (2000) and Chen et al. (2000) who characterized the soils and studied their soil moisture regimes. Mendonça et al. (2013) studied the clay mineralogy of soils from the Fildes Peninsula, and Michel et al. (2012) monitored active layer temperatures over a 2 year period. Recently, Michel et al. (2014) surveyed the soils over the entire Fildes Peninsula area and described additional 31 soil profiles. Entisols and Gelisols are the most important soil orders and Inceptisols also occur, all with gelic properties, and with varying degree of faunal influence. Most of the Gelisols on the Fildes Peninsula are cryoturbated and key out as Turbels.

Average values of selected physical and chemical properties of soils from the Fildes Peninsula are provided in Table 13.9. High contents of gravel are present in most soils and large areas have soils with leptic and skeletic characters. From 19 pedons, the active layer depth ranged from 10 to 120 cm and averaged 55 cm. Moderate granular soil structure is common along with subangular blocks. Textures ranged from clay loam to sand with abundant coarse fragments (>2 mm). Soils with coarser textures have single-grain structure while soils with higher clay + silt content (silt loam and clay loam textures) have a weak to moderate, small to medium granular, and moderate subangular blocky structure. The soils have a mixed mineralogy (Soil Survey Staff 2010) with hydroxy-interlayered smectite, chlorite, plagioclase, and mafic minerals in the clay fraction (Michel et al. 2014).

Gelisols on the Fildes Penisula have a slightly acid to neutral pH (Table 13.9). The soils are eutric with highly variable levels of available nutrients such as K^+, Ca^{2+}, Mg^{2+}, and Na^+ (Table 13.9). Ornithogenic Gelisols are enriched in organic C, extractable P and total N. These soils have lower pH and exchangeable Ca^{2+} and Mg^{2+} than nonornithogenic Gelisols. High values of extractable Na are common in soils from King George Island (Michel et al. 2006; Simas et al. 2007b; Francelino et al. 2011), due to sea saline spray as well as weathering of primary minerals. All profiles are coarse textured (sand, sandy loam, or loamy sand).

Cryopsamments are soils with a loamy sand or coarser texture, less than 40 % coarse fragments, and lacking permafrost within 1 or 2 m. Seven profiles were classified accordingly; these soils were usually located at intermediate altitudes (maximum of 33 m a.s.l.), showed minimal cryoturbation, little horizon differentiation, and no diagnostic horizon other than an ochric. These soils are developed over basaltic and andesitic lavas or related transported fragments and are found on landforms such as raised beaches, gentle slopes, berms, and deposits as till and outwash plains. Average particle sizes are 626 g kg^{-1} (±142) CS, 125 g kg^{-1} (±56) FS, 154 g kg^{-1} (±73) silt, and 104 g kg^{-1} (±37) clay. Vegetation cover includes moss carpets, lichens and, when near penguin or mammal colonies, terrestrial algae (*Prasiola crispa*). The soils have a single-grain structure and, in some cases, a weak granular or moderate subangular blocky structure, when enriched with organic matter. The pH values are near neutrality and high contents of extractable K^+, Ca^{2+}, Mg^{2+}, and Na^+ are present in comparison to the other soils, despite their coarse texture.

Table 13.6 Physical and chemical properties of soils from Lions Rump, King George Island

Hor	Depth	Structure[1]	Transition	Color	>2 mm	CS	FS	Silt	Clay	pH	P	K	Na	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	CEC	SOC	PSS
	(cm)			(dry)	(%)	(g kg^{-1})				H_2O	(mg/dm^3)			(cmolc /dm^3)———					(g/kg)	(%)
Loamy-skeletal, mixed, active, subgelic, Turbic Haplogelept																				
A	0–5	w f m bl/md m gr	Gradual wavy	2.5Y 4/3	22	290	210	360	140	7.52	109.50	18.84	16.46	0.24	1.53	n.d.	1.90	37.07	3.8	4.12
AB	5–17/20	w m bl/md m gr	Gradual wavy	2.5Y 4/4	25	270	200	330	200	7.74	170.80	26.30	20.01	0.17	1.18	n.d.	1.10	47.66	2.6	2.47
Bi	20–47/52	w m bl/md m gr	Gradual wavy	2.5Y 5/3	51	330	210	270	190	7.98	167.20	26.31	14.19	0.14	0.92	n.d.	0.30	41.56	1.3	2.21
BC	47–52–70	w m bl	–	2.5Y 5/4	55	310	180	320	190	8.48	176.30	30.45	12.07	0.14	0.79	n.d.	n.d.	43.45	2.6	1.81
Loamy-skeletal, mixed, active, subgelic, Typic Psammorthel																				
A	0–5	w f bl/md m gr	Gradual wavy	2.5Y 5/2	35	460	160	280	100	8.20	147.90	20.96	6.98	0.19	1.35	n.d.	n.d.	29.48	2.6	4.59
AB	5–22/24	w f m bl/md m gr	Gradual wavy	2.5Y 5/3	45	360	220	390	30	8.61	123.00	21.40	5.79	0.17	1.05	n.d.	n.d.	28.41	1.3	3.69
Bi	24–45/47	md m l bl/w m gr	Gradual wavy	2.5Y 5/3	51	370	220	390	20	8.67	124.50	22.25	5.27	0.09	0.74	n.d.	n.d.	28.35	1.3	2.62
BC	45/47–75	w md l bl	–	2.5Y 5/3	33	370	220	400	10	8.62	112.80	24.54	5.72	0.17	0.70	n.d.	n.d.	31.13	1.3	2.25
Loamy-skeletal, mixed, active, subgelic, Typic Gelorthents																				
C1	0–23	w m bl/w m gr	Gradual wavy	2.5Y 4/3	36	280	140	560	20	8.63	61.40	39.25	4.46	0.09	1.48	n.d.	n.d.	45.28	3.8	3.28
C2	23–60	w m bl/w m gr	Gradual wavy	2.5Y 4/4	27	330	110	530	30	8.78	94.80	37.66	3.85	0.12	2.09	n.d.	n.d.	43.72	3.8	4.79
C3	60–90	w md l bl	–	2.5Y 5/4	32	340	110	530	20	8.77	73.40	39.97	3.64	0.12	2.40	n.d.	0.20	46.13	3.8	5.20
Loamy-skeletal, mixed, active, subgelic, Ornithogenic Dystrogelepts—62 m a.s.l.—UTM position1 0439687/3110784																				
O	0–5	fibric/st m gr	Clear flat	10YR 3/3	21	440	200	210	150	4.88	79.60	1.85	2.45	0.09	0.45	0.48	4.50	4.84	396.6	8.43
A	05/dez	w m l sb/st m gr	Clear flat	10YR 3/4	71	360	210	250	180	4.37	390.40	3.82	6.42	0.70	1.53	8.00	22.30	12.47	70.4	7.46
AB	dez/18	w m l sb/st m gr	Clear wavy	10YR 5/3	42	510	180	180	130	4.04	603.40	0.91	1.29	0.42	1.22	8.00	29.60	3.84	64	10.33
BA	18–32	md f bl/st m gr	Clear wavy	10YR 6/3	55	570	110	210	110	3.88	1199.30	0.29	0.35	0.93	0.92	6.46	8.40	2.49	20.5	10.26
B1	32–70	md f bl/st m gr	Gradual wavy	10YR 6/3	45	520	230	160	90	3.94	1065.80	0.95	0.58	1.26	0.79	6.84	41.80	3.58	20.5	7.56
B2	70–100	st m gr	Gradual wavy	10YR 6/4	42	400	330	200	70	3.98	1093.80	0.85	0.65	1.81	0.71	6.65	44.50	4.02	21.8	6.69
B3	100–120	st m gr	–	10YR 5/6	32	450	170	220	160	3.85	1468.50	0.41	0.38	1.08	0.71	6.17	50.60	2.58	20.5	8.16
Loamy-skeletal, mixed, active, subgelic, Ornithogenic Gelorthent—102 m a.s.l.—UTM position 0439762/3110565																				
A	0–8	st m gr	Gradual flat	10YR 5/3	49	430	230	210	130	4.26	5485.10	8.17	2.27	0.57	1.57	0.67	15.10	12.58	53.7	11.85
Cr	Ago/40	sg/ w m gr	–	10YR 7/3	67	300	80	390	230	3.96	1004.20	2.18	0.49	1.61	0.52	3.18	17.80	4.80	23	6.55
Lithic Haplorthel—257 m a.s.l.—UTM position/3108658																				
A	0–8/25	st m gr	Clear wavy	10YR 3/3	27	330	290	260	120	7.33	138.90	15.60	24.91	0.54	1.87	n.d.	1.30	42.92	14.2	4.36
C	8–25/30	md l sb/st m gr	–	10YR 4/3	34	400	300	210	90	7.41	117.70	20.86	25.01	0.54	1.83	n.d.	1.60	48.24	7.8	3.79

(continued)

Table 13.6 (continued)

Hor	Depth	Structure[1]	Transition	Color	>2 mm	CS	FS	Silt	Clay	pH	P	K	Na	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	CEC	SOC	PSS
	(cm)			(dry)	(%)	($g\ kg^{-1}$)				H_2O	(mg/dm^3)			($cmolc\ /dm^3$)———					(g/kg)	(%)
Loamy-skeletal, mixed, active, subgelic, Typic Haplorthels—222 m a.s.l.—UTM position 0440804/3108792																				
A	0–8	sg	Clear flat	2.5YR 4/3	54	420	250	250	80	7.62	124.50	22.01	24.98	0.32	1.92	n.d.	1.10	49.23	1.3	3.89
AC	Ago/15	w md l sb/w m gr	Clear wavy	10YR 4/3	40	380	140	320	160	6.09	101.10	20.58	22.06	0.24	1.48	0.87	3.20	44.36	1.3	3.27
C	15–65	w l sb/w m gr	–	10YR 5.5/8	51	610	170	130	90	3.62	6.90	4.03	9.18	0.05	0.43	19.5	28.10	13.69	1.3	1.31
Coarse-loamy, mixed, active, subgelic, Ornithogenic Haplogelept—41 m a.s.l.—UTM position 0441154/3110281																				
O1	0–3/4	Fibric	Clear wavy	10YR 3/3	11	360	250	230	160	5.28	1037.80	18.60	22.11	1.41	2.05	0.10	8.90	44.17	64.6	4.62
O2	¾–9/11	Fibric	Clear wavy	10YR 3/4	0	360	250	230	160	5.66	771.10	18.30	23.48	1.00	1.65	0.29	8.70	44.43	67.8	3.70
OA	11–16/17	Fibric/md m gr	Gradual wavy	10YR 5/3	24	320	220	280	180	5.99	1290.10	23.56	23.02	0.85	1.92	n.d.	7.50	49.35	29.7	3.88
Bi1	17–37/38	w md m l bl/md m gr	Gradual wavy	10YR 6/3	33	420	170	270	140	7.40	803.00	29.25	24.63	0.62	1.35	n.d.	1.40	55.85	3.9	2.41
Bi2	37/38–60	w m l bl/w m gr	Gradual irregular	10YR 6/3	27	430	170	250	150	7.61	837.40	30.65	19.33	0.67	1.44	n.d.	1.40	52.09	2.6	2.76
BC	60–80+	w m l bl	–	10YR 6/4	32	420	180	220	180	8.15	611.60	35.35	21.20	0.62	1.22	n.d.	1.40	58.39	1.3	2.09
Mixed, active, subgelic, Oxyaquic Gelipsamments—3 m a.s.l.—UTM position—0440081/3110799																				
A	0–4	w l bl/sg	Clear wavy	2.5Y 3/3	1	540	210	150	100	6.58	52.50	12.64	23.48	0.40	1.44	n.d.	3.80	37.96	2.58	3.78
AC	04/12/15	w l bl/sg	Gradual wavy	2.5Y 4/4	17	650	110	20	220	6.28	80.50	12.73	23.55	0.46	1.70	0.87	5.60	38.44	0.78	4.32
C1	15–30/35	sg	Gradual wavy	2.5Y 4/3	23	820	60	50	70	6.54	88.40	9.16	22.25	1.47	1.74	n.d.	4.80	34.62	0.26	4.88
C2	30/35–70	sg	–	2.5Y 4/3	22	810	70	50	70	6.91	85.10	7.30	30.89	1.98	2.22	n.d.	3.70	42.39	0.26	5.21
Coarse-loamy, mixed, active, subgelic, Typic Gelipsamment—67 m a.s.l. UTM position 0441211/3109813																				
O	0–3/4	w l bl/sg	Clear wavy	10YR 3/4	26	230	250	400	120	6.55	47.40	9.47	18.96	0.23	0.65	n.d.	1.60	29.31	16.15	2.22
A	¾–8/10	w l bl/sg	Gradual wavy	10YR 5/3	16	440	300	210	30	6.92	62.40	14.72	22.34	0.20	1.26	n.d.	1.70	38.52	0.39	3.27
AB	10–18/20	w m bl/st m gr	Gradual irregular	10YR 5/3	14	510	250	210	30	7.58	88.30	17.69	18.28	0.13	1.04	n.d.	0.60	37.14	0.13	2.81
Bi	20–45/50	md st l bl/md m gr	Gradual irregular	10YR 6/3	32	410	260	310	20	8.02	192.60	18.14	14.61	0.05	1.04	n.d.	0.60	33.84	0	3.08
BC	45/50–65	md m bl/sg	–	10YR 6/3	30	380	270	330	20	8.20	220.80	20.60	13.43	0.03	0.87	n.d.	0.60	34.93	0	2.49
Sandy-skeletal, mixed, active, subgelic, ornithogenic lithic Gelipsamment—4 m a.s.l.—UTM Position 0439889/3111016																				
A	0–16	w l bl/md m gr	Abrupt irregular	5Y 2.5/2	48	810	100	40	50	7.26	920.50	8.40	11.49	0.57	2.92	n.d.	1.30	23.38	4.2	12.48
Sandy-skeletal, mixed, active, subgelic, Ornithogenic Gelifluvents—17 m a.s.l.—UTM Position 0441054/3110247																				
A	0–8/10	w m l bl/w m gr	Clear wavy	10YR 4/2	25	540	190	220	50	5.89	3118.30	17.20	22.29	1.85	0.96	n.d.	5.70	42.30	1.16	2.26
Bi	10–22/24	w m l bl/md m gr	Clear wavy	10YR 5/2	25	420	270	270	40	5.81	403.80	28.77	15.95	0.82	1.44	0.19	3.70	46.98	0.13	3.04
C	24–28/30	w m bl/md m gr	Clear wavy	7.5YR 4/3	35	420	350	200	30	8.40	122.30	50.49	14.80	n.d.	1.57	n.d.	1.30	66.86	n.d	2.34
2A	30–34/36	sg	Clear wavy	7.5YR 4/2	59	650	230	110	10	8.53	120.20	40.99	10.92	n.d.	1.48	n.d.	0.60	53.39	n.d	2.77
2C	34/36–90	st l bl/md m gr	–	7.5YR 5/2	73	690	170	130	10	8.35	155.30	51.72	9.34	0.08	1.52	n.d.	0.60	62.66	n.d	2.43

(continued)

Table 13.6 (continued)

Hor	Depth	Structure[1]	Transition	Color	>2 mm	CS	FS	Silt	Clay	pH	P	K	Na	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	CEC	SOC	PSS
	(cm)			(dry)	(%)	($g\ kg^{-1}$)				H_2O	(mg/dm^3)			($cmolc\ /dm^3$)———					(g/kg)	(%)
Sandy-skeletal, mixed, active, subgelic, Typic Gelipsamment—86 m a.s.l.—UTM Position																				
A	0–8	w l bl/sg	Clear wavy	10YR 4/3	48	510	280	180	30	6.64	67.50	12.13	22.99	0.23	1.17	n.d.	3.80	36.52	1.94	3.22
AB	Ago/20	w l bl/sg	Gradual wavy	10YR 4/4	50	490	290	180	40	6.78	77.80	12.16	22.78	0.23	1.13	n.d.	3.80	36.30	1.03	3.12
BA	20–33	w m bl/st m gr	Gradual irregular	10YR 5/4	60	470	290	210	30	7.12	92.50	14.88	23.72	0.23	1.35	n.d.	2.70	40.18	0.78	3.36
Bi	33–52	md st l bl/md m gr	Gradual irregular	10YR 5/3	48	520	250	210	20	7.37	186.60	16.37	21.90	0.18	0.83	n.d.	1.10	39.28	0.13	2.10

[1] w-weak; md-moderate; st-strong; s-small; m-medium; l-large; bl-blocky; sg-single grain; gr-ganular

Table 13.7 Physical and chemical properties of soils from Potter Peninsula, King George Island

	Depth	C.S.	F.S.	Silt	Clay	Color	pH	P	K	Na	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	CEC	N	SOC
Horizon	(cm)	(g/kg)					H_2O	(mg/dm^3)			($cmol_c/dm^3$)					(g/kg)	
Profile 2—sandy, subgelic, Humic Gelorthent																	
A1	0–8	490	130	200	180	5YR2/2	5.2	158	187	257	4.94	6.04	1.25	11.1	23.7	5.0	58.0
A/C	8–20	630	130	110	130	7.5YR2.5/3	5.2	428	122	208	2.56	3.28	5.3	8	15.1	2.3	23.8
C1	20–30	610	100	140	150	2.5YR3/2	5	476	134	156	1.79	1.7	8.87	19.9	24.4	4.0	21.5
C2	30–45	680	40	120	160	2.5YR3/2	4.9	359	118	137	1.58	1.31	9.54	22.6	26.4	1.8	14.9
C3	45–55	600	100	160	140	2.5YR3/2	4.7	310	103	128	1.69	1.02	8.67	21.3	24.8	1.5	12.0
C4	55–80	580	120	170	130	2.5YR3/2	4.8	306	102	128	1.77	1.19	7.71	21	24.8	1.2	13.3
CR	80–100	500	160	200	140	2.5YR2.5/2	5.2	237	100	145	2.78	1.99	5.2	17	22.7	1.3	11.5
Profile 3—sandy, ornithic, Lithic Umbriturbel																	
A1	0–8	600	70	120	210	10YR2/1	4.5	443	298	266	1.92	2.56	2.41	25	31.4	10.9	118.0
CR	8–40	590	80	130	200	10YR2/2	4.3	507	318	209	0.95	1.11	4.05	34.7	38.5	9.1	97.4
Profile 4—sandy, ornithic, Lithic Umbriturbel																	
A	0–8	560	200	90	150	10YR2/2	5	555	154	477	1.23	1.64	4.24	20.8	26.1	4.8	77.0
AB	0–15	420	140	210	230	7.5YR2.5/3	4.7	756	145	256	0.85	0.97	10.99	26.1	29.4	2.8	30.0
Bi/R	15–28	270	140	320	270	10YR4/4	4.6	769	193	209	0.65	0.82	14.84	29.4	32.3	4.0	17.0
Profile 5—sandy, subgelic, oxiaquic, Lithic Gelorthent																	
A	0–3	770	90	50	90	7.5YR2.5/1	6.1	151	111	376	11.2	8.55	0	1.1	22.8	0.4	4.2
CA	3–15	680	140	80	100	5YR2.5/1	6.8	140	107	400	13.21	10.15	0	0.8	26.2	0.1	2.1
C	15–25	790	50	60	100	5YR2.5/1	6.9	127	94	418	14.39	9.37	0	1	26.8	0.2	3.8
Profile 6—subgelic, turbic Humic Gelaquept																	
A	0–5	630	100	110	160	10YR2/1	4.3	419	125	159	1.1	0.85	3.9	19.1	22.1	7.2	60.1
AB	5–10	610	230	70	90	10YR2/1	5.9	60	122	226	14.42	6.03	0.1	3.2	24.9	0.5	6.4
Bi	10–25	580	220	100	100	10YR2/1	6.2	54	124	316	8.47	6.34	0.39	2.9	19.4	0.5	3.2
Bi2	25–30	640	140	120	100	10YR2/1	6.5	54	100	246	9.2	7.29	0.1	2.1	20.1	0.3	4.3
BC	30–42	460	170	200	170	5YR3/2	6.7	141	129	437	19.35	13.29	0.1	2.1	37	0.3	2.3
C1	42–50	480	160	190	170	5YR2.5/2	6.7	112	115	380	18.43	11.9	0.1	1.9	34.2	0.2	4.5
C2	50–90	750	200	100	40	10YR3/1	6.7	133	63	296	4.37	2.11	0.1	1.3	9.2	–	2.9
Profile 7—sandy, Lithic Umbriturbel																	
Afos	0–10	450	190	180	180	7.5YR2.5/2	5.7	69	117	256	2.55	3.11	0.87	10.2	17.3	4.2	76.7
Cfos	10–30	520	150	200	130	7.5YR2.5/2	6	81	102	218	2.66	3.08	0.39	7.5	14.5	2.8	29.6
CR	30–50	590	120	180	110	7.5YR2.5/2	6.2	90	107	209	3.68	3.83	0.1	5.6	14.3	2.2	24.3

(continued)

Table 13.7 (continued)

	Depth	C.S.	F.S.	Silt	Clay	Color	pH	P	K	Na	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	CEC	N	SOC
Horizon	(cm)	(g/kg)					H_2O	(mg/dm^3)			($cmol_c/dm^3$)					(g/kg)	
Profile 8—sandy, ornithic, Lithic Aquiturbel																	
A	0–8	550	180	150	120	5YR2.5/1	6	705	157	296	4.38	5.16	0.58	8.4	19.6	1.7	18.5
AC	8–25	490	200	210	100	5YR2.5/1	6.2	629	175	276	4.3	4.58	0.58	8	18.5	1.2	9.5
C1	25–30	410	240	210	140	5YR2.5/2	5.4	413	176	244	4.06	3.68	1.83	15.9	25.2	–	56.9
C2	30–50	440	170	210	180	5YR2.5/2	5.5	245	208	226	4.1	3.95	3.57	16.5	26.1	–	48.9
CR	phosphatic	390	210	220	180	5YR3/2	5.3	149	315	456	–	–	14.8	2.8	16	–	–
Profile 9—subgelic, Typic Cryopsamment																	
A	0–10	580	360	20	40	7.5YR2.5/1	5.3	227	696	1259	3.22	3.57	0	2.1	16.2	1.0	5.5
C1	10–60	720	160	40	80	10YR2.5/1	5.3	104	646	1490	3.52	5.25	0.1	3.7	20.6	–	14.1
C2	60–100	730	210	20	40	7.5YR3/1	5.7	128	591	1428	1.79	2.69	0.19	2.9	15.1	–	7.9
Profile 10—skeletal, Lithic Umbriturbel																	
A/R	0–40	280	300	240	180	10YR2/1	6.3	44	161	257	8.07	4.39	0	5.4	19.4	3.7	58.3
Profile 11—subgelic, Typic Gelaquept																	
A	0–10	690	120	90	100	7.5YR2.5/2	6.1	128	124	230	8.58	3.21	0	3.8	16.9	0.8	16.0
AC	10–20	730	90	100	80	5YR2.5/1	6.3	102	129	316	10.65	3.41	0	3	18.8	–	10.9
Cfos	20–50	720	70	16	50	5YR2.5/1	7	202	142	336	14.29	3.23	0	1.4	20.7	–	4.3
fos	50–fosf.	570	100	190	140	5YR3/3	7	233	150	314	12.74	2.57	0	1.9	19	–	4.6
Profile 12—sandy, ornithic, subgelic, Cryofluvent																	
A1	0–8	560	180	140	120	2.5YR2.5/1	5.1	219	232	1288	11.92	3.72	3.18	8	29.8	2.3	5.1
Bi	8–27	290	120	510	80	2.5YR2.5/1	7.8	543	193	189	60.71	7.58	0	1.4	71	1.3	2.7
C1	27–42	320	600	60	20	2.5YR2.5/1	7.6	240	581	2178	11.15	3.92	0	1	27	–	2.1
A2	42–60	160	680	90	70	2.5YR2.5/1	7.6	336	980	2716	10.49	7.56	0	1.4	33.8	–	3.0
C2	60–65	250	370	270	110	2.5YR2.5/2	9.2	540	1189	4355	11.44	7.78	0	0.6	41.8	–	3.2
A3	65–90	210	620	90	80	2.5YR3/2	8.2	367	1070	3835	10.15	7.87	0	0.6	38	–	2.6
A4	90–93	110	370	380	140	5YR2.5/1	4.4	277	1100	4235	15.42	12.52	2.7	8.3	57.5	–	31.3
C3	93–110	200	630	100	70	5YR2.5/2	7.7	437	1199	3696	10.39	12.19	0	0.6	42.3	–	2.3
A5	110–120	40	350	500	110	2.5YR2.5/1	7.1	453	1219	4355	17.84	15.85	0	1.4	57.1	–	2.8
Profile 13—ornithic, subgelic, Typic Humigelept																	
AC	0–10	630	100	130	140	10YR4/4	4.7	757	213	236	1.34	0.54	3.66	24.2	27.6	4.4	35.3
C1	10–25	580	130	160	130	5Y3/3	4.6	814	362	200	1.06	0.48	5.59	28.3	31.6	1.5	10.6
C2	25–40	590	110	150	150	7.5YR3/3	4.4	661	348	179	1.16	0.64	5.88	27.7	31.2	1.3	10.0

(continued)

Table 13.7 (continued)

	Depth	C.S.	F.S.	Silt	Clay	Color	pH	P	K	Na	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	CEC	N	SOC
Horizon	(cm)	(g/kg)					H_2O	(mg/dm^3)			($cmol_c/dm^3$)					(g/kg)	
C3	40–70	680	100	90	130	5YR3/3	4.6	655	228	113	1.09	0.38	4.63	25	27.5	1.8	12.8
Profile 14—sandy, ornithic, Lithic Umbriturbel																	
A	0–5	630	90	90	190	10YR4/4	4.4	829	193	204	2.58	0.89	1.93	20	24.9	5.6	68.8
CR	5–50	650	60	120	170	10YR4/4	4.3	41	224	236	2.43	0.69	1.45	20.4	25.1	6.5	57.4
Profile 15—skeletal Lithic Fibristel																	
A	0–10	500	180	110	210	10YR	5	62	103	218	2.29	2.17	2.02	18.9	24.6	12.9	188.3
Cr	10–50	450	190	150	210	5YR2.5/2	5.5	161	76	177	3.68	2.23	0.77	16.5	23.4	7.1	145.7
Profile 16—Loamy-skeletal. mixed. subgelic. “Ornithic” Lithic Gelorthents																	
A	0–5	590	90	120	200	10YR2/1	4.5	618	248	180	2.18	1.79	1.35	19.2	24.6	7.6	143.3
Cr	5–30	430	180	180	210	7.5YR2.5/2	4.3	461	110	128	0.6	0.56	9.06	31.5	33.5	5.0	100.1
Profile 17—ornithic, sandy, Terric Fibristel																	
H1	0–20	370	220	220	190	10YR2/1	4.4	549	43	96	0.75	0.32	3.08	22.3	23.9	12.8	182.8
H2	20–40	410	180	190	220	7.5YR 2.5/3	4.1	612	68	111	0.78	0.28	3.76	22.7	24.4	10.9	168.4
Bh	40–45	490	160	170	180	7.5YR2.5/2	4.9	326	86	157	3.46	1.38	2.31	18.4	24.1	7.8	170.5
Perm.	45–70	620	170	90	120	7.5YR2.5/2	5.4	351	92	200	3.28	1.87	1.35	16.1	22.4	3.9	154.0
Profile 18—Loamy-skeletal. mixed. subgelic. “Ornithic” Typic Gelorthents																	
A1	0–10	710	210	30	50	7.5YR2.5/3	5.2	119	82	326	0.7	0.5	1.83	8.6	11.4	1.0	39.8
A2	10–20	690	270	00	40	5YR2.5/1	5.6	96	109	529	0.62	0.87	1.25	5.1	9.2	0.5	9.7
AC	20–30	660	170	60	110	5YR2.5/2	4.4	431	104	529	0.65	0.97	2.6	16.7	20.9	3.5	82.4
C1	30–40	730	130	40	100	7.5YR2.5/2	5.5	428	64	18	1.19	1.07	2.41	17.5	20	2.7	71.9
C2	40–70	730	140	30	100	10YR2/2	5.4	647	59	176	1.18	0.94	2.51	17.7	20.7	2.4	77.0

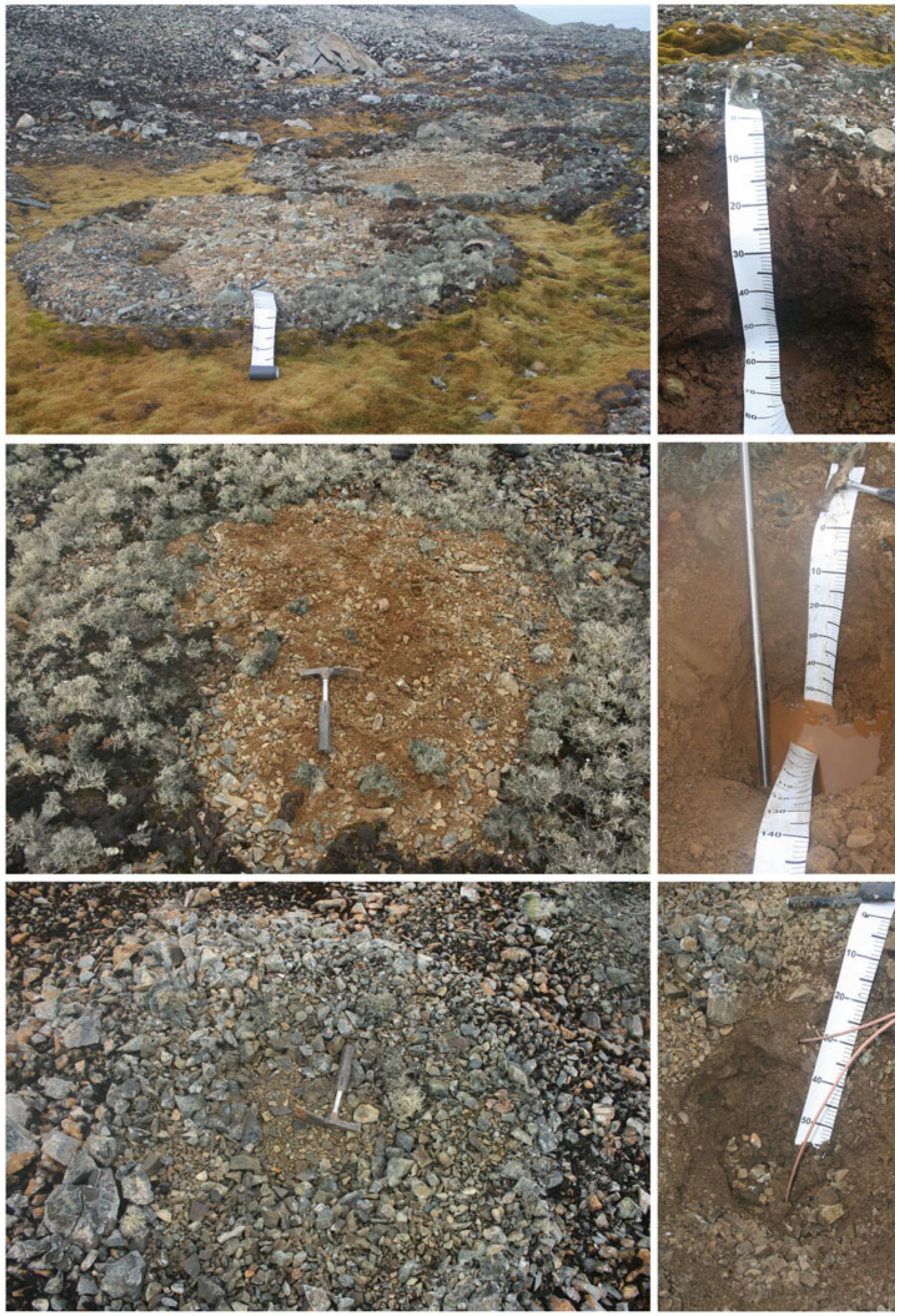

Fig. 13.10 Mudboils and sorted circles and associated soil profiles from Barton Peninsula, King George Island. From *top* to *bottom*, profiles correspond to Bt6, Bt24, and Bt25 in Table 13.8

Table 13.8 Physical and chemical properties of soils from the Barton Peninsula, King George Island

Hor	Depth	C.S.	F.S.	Silt	Clay	pH	P	K	Na	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	CEC	TOC	PSS
	(cm)	(g/kg)				H_2O	(mg/dm^3)			($cmol_c/dm^3$)					(g/kg)	(%)
Bt1—Lithic Psammoturbel—184 m a.s.l.—UTM1 0409595/3099212																
C1	0–3	760	90	40	110	6.7	172.1	103	209.2	4.61	7.46	2.24	5	18.24	4.0	5.88
CR	3–5	405	160	260	130	6.4	290.9	93	207.3	9.93	11.3	1.07	3.9	26.27	5.4	3.85
Bt2—Lithic Psammoturbel—152 m a.s.l. UTM 0409528/3098624																
A	0–3	360	150	330	160	7.5	232.9	73	130	6.39	1.73	n.d.	0.5	9.38	2.7	6.37
Cr	3–40	550	170	190	90	8.2	210.3	69	112.2	9.1	1.15	n.d.	0.3	11.22	5.4	4.47
Bt3—Lithic Psammoturbel—108 m a.s.l.—UTM 0410167/3098736																
A	0–3	55	170	190	90	7.9	67.4	125	270.6	6.93	1.88	n.d.	1.9	12.21	20.2	11.41
Bi	3–18	230	280	390	100	8.0	71.2	163	330	8.01	1.71	n.d.	1.4	12.97	12.1	12.4
CR	15–40+	360	190	320	130	8.0	105.1	124	197	11.06	1.16	n.d.	0.3	13.7	7.8	6.39
Bt4—Lithic Umbriturbel—121 m a.s.l.—UTM 0407771/3097352																
A1	0–10	290	260	360	90	6.0	170.1	92	246.8	1.51	1.93	0.49	10.6	15.35	97.4	20.48
A2	10–30	250	240	390	120	6.3	207.1	86	226.7	2.41	3.11	0.1	10.1	16.83	107.5	14.43
Bt 5—Typic Haploturbel—91 m a.s.l.—UTM 0407785/3098499																
A	0–5	420	180	260	140	6.1	20.4	67	122.1	0.87	1.77	0.49	5.5	8.84	20.2	13.86
Bi	5–40	220	160	340	280	6.4	14.9	77	118.2	1.87	4.78	n.d.	3.5	10.86	6.7	6.98
Bt6—Typic Umbriturbel—66 m a.s.l.—UTM 0407741/3098442																
A1	0–20	640	80	140	140	5.7	222.6	73	132	1.97	3.36	3.22	14	20.9	39.0	6.16
A2	20–40	470	150	220	160	5.6	199.2	38	94.4	0.78	0.42	1.85	15.6	17.31	151.1	11.53
Bi	20–40	490	150	250	110	5.4	553.9	52	109	1.54	2.2	5.37	18.4	22.74	34.9	4.88
Bi2	25–30	390	150	310	150	5.4	25.2	47	76.6	1.72	1.23	2.15	7.1	10.5	6.7	6
Bt7—Sulfuric Haploturbel—65 m a.s.l.—UTM 0407743/3098447																
A1	0–5	430	90	300	180	4.7	139.5	49	102.3	0.95	0.56	5.56	13.7	15.78	16.1	5.82
2 A2	5–8	380	270	240	110	4.4	157.2	59	110.2	1.44	0.33	2.34	14.8	17.2	60.5	10.11
2C	8–50	270	90	280	360	3.9	13.7	24	14.6	0.22	n.d.9	4.0	9.2	9.63	1.3	1.43
Bt8—Typic Umbriturbel—71 m a.s.l.—UTM 0407740/3098428																
A	0–3	540	200	150	110	5.2	327.1	119	191.4	0.77	0.65	1.66	15.9	18.45	120.9	19.77
BC	3–5	230	200	410	160	5.8	651.3	218	307	0.91	0.59	1.85	15.3	18.69	81.9	25.47
Bt9—Oxiaquic Gelorthent—33 m a.s.l.—UTM 0410252/3097830																
H	0–10	210	340	300	150	4.8	238.8	34	76.9	0.88	0.57	2.44	18.8	20.67	167.9	7.76
AC1	10–350	610	80	150	160	5.2	88.5	109	130	0.55	0.39	3.32	17.2	18.89	107.5	11.06

(continued)

Table 13.8 (continued)

Hor	Depth	C.S.	F.S.	Silt	Clay	pH	P	K	Na	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	CEC	TOC	PSS
	(cm)	(g/kg)				H_2O	(mg/dm^3)			($cmol_c/dm^3$)					(g/kg)	(%)
C3	35–60	450	90	300	160	5.2	94.4	209	175.6	0.6	0.24	4	21.1	23.23	30.9	12.45
Cr4	60–75⁺	760	60	70	110	5.1	204.7	127	116.2	1.19	0.59	3.51	25.8	28.41	22.8	8.26
BT10—Lithic Haploturbel—90 m a.s.l.—UTM 0410276/3098460																
A	0–3	530	150	200	120	6.4	91.4	89	231	2.65	2.93	n.d.	3.9	10.71	23.5	14.74
BC	3–10	330	210	330	130	7.1	86.6	107	25.1	4.73	3.48	n.d.	3.4	11.9	33.6	1.27
Bt11—"Ornitogenic Umbric Gelifluvent"—68 m a.s.l.—UTM 04102/3098149																
H1	0–5	490	90	190	230	5.0	226.2	36	76.9	3.49	1.49	0.88	11.8	17.2	564.2	5.32
C1	5–7	–	–	–	–	5.4	469.1	36	103	2.51	0.83	1.37	11.8	15.68	315.7	8.53
C2	10–20	500	210	160	130	5.1	627.7	66	227.6	2.1	0.63	1.85	13.2	17.09	60.5	17.17
2H2	20–35	–	–	–	–	5.2	487.3	20	30.7	0.64	0.13	0.98	6.4	7.35	584.4	6.92
3C3	35–45	130	330	490	50	5.6	2001.6	298	347.2	13.9	3.7	0.1	8.4	28.27	51.0	7.56
Bt12—Umbric Gelipsamment—11 m a.s.l.—UTM 0409744/30976941																
AC1	0–10	560	170	160	110	5.4	109.2	85	167.7	0.63	0.53	1.27	11.1	13.21	60.5	21.57
C1	10–30	290	270	340	100	6.0	266.8	167	207.3	0.43	0.25	1.17	12.6	14.61	29.6	28.34
2 A2	28–30	430	200	280	90	5.9	206.9	211	205.3	0.47	0.48	1.85	12.6	14.98	32.2	21.1
CR3	40–60⁺	230	70	440	260	5.6	68.3	216	187.5	0.43	0.5	3.32	12.7	15.0	21.5	14.51
Bt13—Ornithogenic Gelorthent—35 m a.s.l. UTM 0409814/3097763																
AC	0–12	420	180	240	160	5.1	448.4	78	117.1	0.64	0.48	2.34	17.7	19.53	262.0	12.21
C1	12–30	440	100	280	180	5.3	876.6	54	608.3	0.48	0.15	3.8	14.3	17.71	33.6	36.68
Bt14—Ornithogenic Gelorthent—42 m a.s.l.—UTM 0409922/3097809																
C1	0–25	530	60	260	150	5.5	1897.1	74	528	1.76	0.41	3.51	13.7	18.36	17.5	28.1
Cr2	25–60⁺	870	30	30	70	5.6	213.6	153	211.2	1.54	0.68	2.44	20.9	24.43	16.1	15.38
Bt15—Typic Umbriturbel—26 m a.s.l.—UTM 0409439/3097844																
A	0–5	420	200	210	170	5.3	154.1	67	139.9	1.47	1.24	1.66	13.7	17.19	127.6	11.81
C1	5–10	640	50	130	180	3.0	461.9	109	330	0.77	0.46	6.63	21.2	24.14	17.5	14.99
C2	10–70	720	30	100	150	4.5	424.1	119	161.7	0.24	0.16	5.07	20.9	22.3	14.8	10.87
Bt16—Ornithogenic Sulfuric Psamment—66 m a.s.l.—UTM: 0407911/3098406																
A	0–2	590	110	170	130	5.3	454.5	255	211.2	1.75	1.65	1.27	23.8	28.77	110.8	14.72
BC	2–7	500	140	230	130	4.2	483	185	173.6	0.79	0.46	4	31.7	34.17	57.1	11.67
CF	7–25	500	260	170	70	3.9	649.5	128	91	0.63	0.42	6.05	27	28.78	13.4	5.05
Bt 17—Ornithogenic Fibristel—86 m a.s.l.—UTM 0407911/3098406																

(continued)

Table 13.8 (continued)

Hor	Depth	C.S.	F.S.	Silt	Clay	pH	P	K	Na	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	CEC	TOC	PSS
	(cm)	(g/kg)				H_2O	(mg/dm^3)			($cmol_c/dm^3$)					(g/kg)	(%)
H2	10–40	670	140	140	50	5.2	60.4	6	36.1	1.81	0.49	1.46	14.6	17.08	561.9	3.98
H3	40–70	320	310	250	120	5.4	174.4	32	95	3.56	1.31	1.07	17.7	23.06	416.5	6.42
Bt18—Ornithogenic Fibristel 0 83 m a.s.l.—UTM 0407906/3098403																
H1	0–20	330	160	310	200	4.6	256.2	10	52.8	0.6	0.27	3.02	22.5	23.63	557.5	5.53
H2	20–30	290	250	320	140	5.4	647.7	32	76.9	2.49	0.85	0.49	14.2	17.95	403.0	7.89
Bt19—Typic Umbriturbel—81 m a.s.l.—UTM 0407906/3098403																
AC	0–30	430	150	270	150	5.8	257.4	110	117.3	2.93	2.07	1.46	18.5	24.55	129.0	10.26
CR	30–50$^+$	350	170	310	170	5.5	223.8	113	141.9	1.11	0.62	2.15	23.8	26.44	87.3	12.88
Bt20—Typic Umbriturbel—77 m a.s.l.—UTM 0410154/3097960																
A	0–10	640	8	13	15	4.8	260.9	74	129.1	0.77	0.83	3.51	22.9	25.25	164.6	9.58
Bt21—Ornithogenic Fluviturbel—29 m a.s.l.—UTM 0409460/3097897																
A	0–5	570	190	140	100	5.8	537.9	121	211.2	3.59	1.26	0.1	6.3	12.38	17.5	14.86
C1	3–15	740	70	100	90	5.6	554.3	147	179.5	4.11	0.93	0.39	9	15.2	8.1	11.84
2C2	15–20	600	190	120	90	5.5	1545.4	188	173.3	6.45	1.07	0.2	7.89	16.65	20.2	8.42
2C3	20–35	590	80	180	150	6.0	1298.7	216	159.7	8.64	1.47	0.1	9.7	21.05	34.9	6.06
2C4	35–50	330	220	280	170	6.0	1984.7	160	201.4	10.61	1.81	n.d.	6.3	2n.d.1	77.9	6.39
2C5	50–60	350	180	370	100	5.0	1912.4	200	209.5	21.87	2.28	0.1	7.4	32.97	45.7	3.55
2C6	60–100$^+$	330	250	300	120	4.9	1951.8	162	203.4	37.15	3.66	0.2	10.1	52.2	98.1	2.09
Bt22—Ornithogenic Fibristel—47 m a.s.l.—UTM 04007860/3098319																
H2	8–45	230	260	310	200	4.6	235.4	18	71.9	1.87	0.22	1.66	16.1	18.55	335.9	7.61
H3	45–50	210	210	320	260	4.5	221.9	18	67.9	1.95	0.25	1.27	13	15.55	426.3	7.73
Bt23—Ornithogenic Umbriturbel—41 m a.s.l.—UTM 0407827/3098266																
A1	0–5	500	90	220	190	4.1	278.7	236	165.7	2.54	0.69	2.15	27	31.55	81.9	10.75
A2	5–20	520	90	220	170	3.8	197	155	94.4	0.46	0.14	3.8	25.6	27.01	45.7	7.88
C	20–60	490	100	240	170	3.8	214.8	101	56.8	0.27	0.12	4.49	22.2	23.1	10.7	4.48
Bt24—Typic Haploturbel—108 m a.s.l.—UTM 0407776/3098876																
A	0–10	310	170	420	100	7.2	29.6	125	209.2	1n.d.7	10.96	n.d.	2.4	24.66	5.4	4.09
C2	20–30	360	200	320	120	7.2	32.4	101	155.8	10.9	9.8	n.d.	2.9	24.54	6.7	3.13
	60–75	350	170	370	110	5.3	26.1	82	131.1	9.18	8.87	7.22	10.5	29.33	1.3	2.19
Bt25—Typic Haploturbel—108 m a.s.l. UTM 0407775/3098877																
C1	25–30	180	240	490	90	7.9	39.4	191	310.2	11.69	6.98	n.d.	1.8	22.31	607	6.58

(continued)

Table 13.8 (continued)

Hor	Depth	C.S.	F.S.	Silt	Clay	pH	P	K	Na	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	CEC	TOC	PSS
	(cm)	(g/kg)				H_2O	(mg/dm^3)			($cmol_c/dm^3$)					(g/kg)	(%)
CR	70–75	270	160	440	130	7.8	38.3	196	290.4	13.79	8.4	n.d.	1.6	25.55	14.8	5.27
Bt26—Sulfuric Gelorthent—2 m a.s.l.—UTM 0409012/3100637																
C1	0–10	250	180	370	200	4.3	13.6	58	206.6	0.72	0.33	6.73	11.6	13.7	1.3	10.17
C2	10–20	830	80	50	40	3.9	19	20	46.8	0.35	0.14	3.51	9.8	10.54	n.d.	4.79
C3	142–160	410	260	220	110	3.1	367.5	10	46.8	0.2	n.d.9	3.8	22.9	23.42	1.3	4.71
C4	160–180	100	420	350	130	2.9	38.2	4	14.6	0.26	n.d.6	7.22	10.3	10.69	1.3	0.83
Bt27—Sulfic. Lithic Gelorthent—31 m a.s.l.—UTM 0408549/3100544																
C	0–20	350	140	300	210	5.1	30.8	64	161.3	1.41	1.44	3.02	6	9.71	4.0	10.42
Bt28—Lithic Gelorthent—11 m a.s.l.—UTM 0407960/3100018																
A	0–5	440	170	280	110	5.9	98.6	166	206.6	2.14	2.17	1.17	3.7	9.33	6.7	13.21
C1	5–20	320	200	350	130	6.1	156.4	166	209.5	2.75	3.3	0.68	3.1	10.48	1.3	11.3
Bt29—Typic Umbriturbel—180 m a.s.l.—UTM 0408496/3099264																
A	0–5	440	110	290	160	6.2	466.4	59	193.4	2.79	1.58	0.1	8.5	13.86	47.0	15.4
A2	5–10	400	140	320	140	7.0	552.7	73	199.3	4.88	2.39	n.d.	6	14.33	40.3	10.4
AC	10–30	440	120	300	140	6.6	496.8	55	167.7	3.21	1.65	0.1	7.7	13.43	40.3	12.51
Bt30—Typic Umbriturbel—180 m a.s.l.—UTM 0408496/3099264																
A1	0–5	330	200	350	120	6.1	404.3	78	181.3	1.62	1.28	0.39	10.1	13.99	59.1	18.42
A2	0–5	390	150	290	170	5.4	232.9	47	130	1.62	2.23	3.71	11.3	15.84	13.4	6.85
Bt31—Typic Haploturbel—51 m a.s.l.—UTM 0407432/3099459																
A	0–15	470	240	220	70	5.5	104.7	106	189.4	1.48	1.19	0.49	4.5	8.26	13.4	19.38
C	15–40+	380	210	340	70	6.2	99.3	128	193.4	3.28	3.17	0.1	2.3	9.92	n.d.	10.89

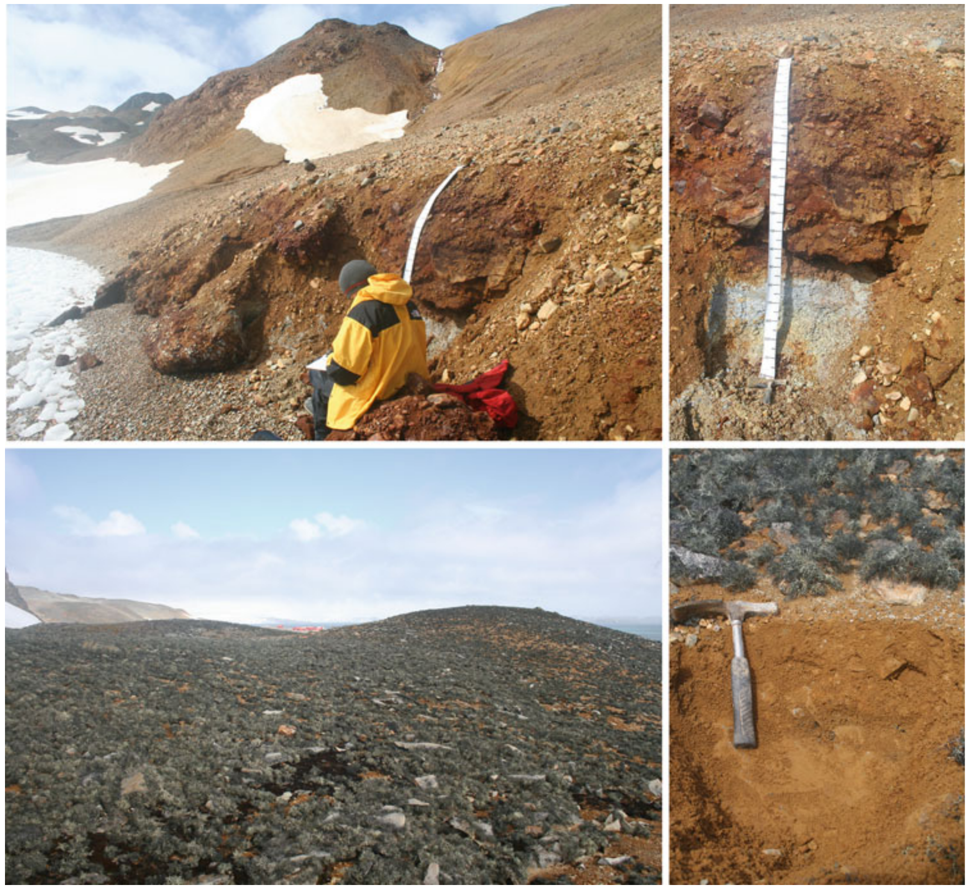

Fig. 13.11 Landforms with acid sulfate soils in Barton Peninsula. Soils Bt26 (*top*) and Bt28 (*bottom*) in Table 13.8

Fig. 13.12 Histoturbel landform and soil on the Barton Peninsula (soil Bt17 in Table 13.8)

Fig. 13.13 Uplifted marine terrace and associated soil with circular patterned ground covered by lichens and mosses close to the King Seong Jong Station (soil Bt31 in Table 13.8)

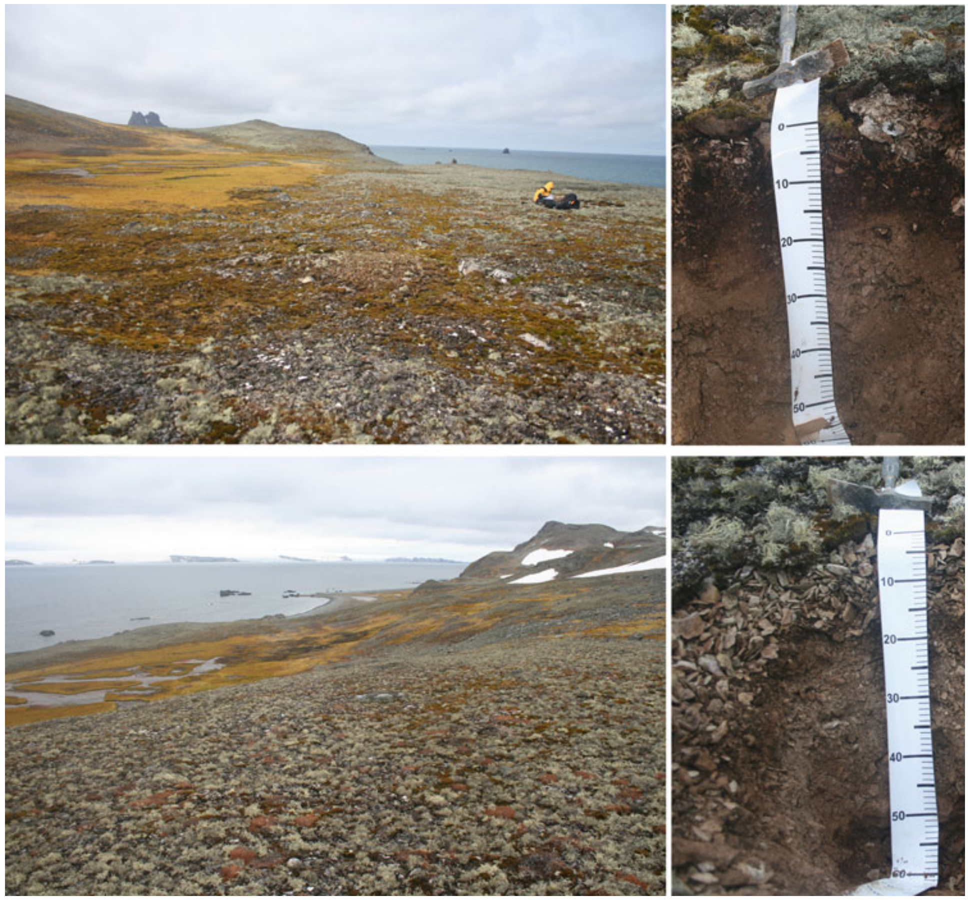

Fig. 13.14 Melanized soils on uplifted marine terraces forming escalated structural platforms on the Barton Peninsula, King George Island (soils Bt13 and Bt14 in Table 13.8)

Loamy-skeletal, mixed, subgelic, Typic Gelaquents occur near melting water channels and have a loamy sand texture (440 g kg^{-1} CS, 190 g kg^{-1} FS, 230 g kg^{-1} silt, and 140 g kg^{-1} clay) and weak medium subangular blocky structure; these soils are colonized by a sparse moss cover. The pH is near neutrality, and the level of bases is high while extractable P is low. Inceptisols are represented by profiles P9, formed from basaltic lavas influenced by Skua nesting, supporting a mix cover of lichens and mosses; and P-8, formed on lapilli and tuffs devoid of vegetation. Both have loam texture, moderate/strong medium subangular blocks structure, and incipient horizon differentiation. P-8 has an alkaline reaction, moderate contents of K^+ and Mg^{2+}; high contents of Ca^{2+}. P-9 has acid pH, moderate contents of K^+, lower levels of Ca^{2+}, Mg^{2+}, and higher extractable P (Table 13.9).

Ardley Island

Ardley Island is a small (1.2 km^2) southeast of KGI. The island (62° S, 59° W) is an important bird sanctuary and is preserved as ASPA 150. With a maximum elevation of 65 m, the island has well-developed vegetation comprised of 25 lichen species, 130 moss species, and the Antarctic grass (*Deschampsia Antarctica*). Michel et al. (2014) examined the soils of this area and a soil map is in progress. Average values of selected physical and chemical attributes of soil profiles from Ardley Island are presented in Table 13.9. It is notable the widespread occurrence of ornithogenic soils (16 out of 17 soils profiles, Fig. 13.15), with high extractable P and SOC values and acidic pH.

13.4.2.2 Livingston Island

Livingston Island is the largest in the South Shetland group. About 13 % of Livingston Island is ice-free, including the Byers Peninsula (largest in SSI) with 60 km^2 and the Hurd Peninsula (20 km^2). The island contains several ice-caps. Everett (1971) delineated three glacial events on Livingston Island. The oldest event entailed coalescing of ice caps on islands in the Bransfield Strait. The intermediate-aged event included an inland ice cap and cirque glaciers. The youngest event left push moraines in the False Bay area. Deglaciation on Livingston Island began after 6.4 ka, and subsequent glacial advances were recorded in 720–350 year BP and after 300 year BP (Pallas et al. 1995). Glaciers on Livingston Island are retreating (Molina et al. 2000). López-Martínez et al. (1992) identified moraines of several ages, including recent ice-cored moraines, three groups of moraines of Holocene age, and an "ancient" moraine of unknown age. Each of the two earlier glacial events of

Table 13.9 Mean physical and chemical attributes for soil profiles from Fildes Peninsula and Ardley Island, King George Island

ID	Soil taxa	Color	CS^1	FS^2	$Silt^3$	$Clay^4$	>2 mm	PD	pH	P	K	Na	Ca^{2+}	Mg^{2+}	Al^{3+}	SOC
		dry	(g/kg)				(%)	(g/cm^3)	H_2O	(mg/kg)			($cmol_c/kg$)			(g/kg)
Soil profiles from Fildes Peninsula																
1	Sandy. mixed. subgelic. typic Gelorthents.	10YR 4/3	540	130	210	120	31.4	2.21	6.98	14.7	66	186.7	8.44	4.97	n.d.	5.6
2	Sandy. mixed. subgelic. typic Gelorthents	10YR 5/2	760	50	120	70	41.4	2.23	6.92	31.0	140	274.6	4.56	5.32	0.16	3.1
3	Sandy. mixed. subgelic. Typic Gelorthents	10Y 4/2	690	90	130	90	20.7	2.58	7.02	23.3	67	101.6	4.76	1.40	n.d.	22.5
4	Sandy. mixed. subgelic. Oxyaquic Cryopsamments (2)	10YR 3/1	570	210	160	60	36.1	2.63	7.32	27.0	67	14n.d.	12.50	4.98	n.d.	1.3
5	Sandy. mixed. subgelic. “Ornithic” Typic Cryopsamment	7.5YR 7/2	860	80	20	40	43.1	2.21	7.42	22.4	58	317.2	6.54	1.97	n.d.	4.8
6	Sandy. mixed. subgelic. Oxyaquic Cryopsamments	2.5Y 3/3	450	190	250	110	20.2	2.51	6.26	75.2	76	99.2	5.80	2.19	1.39	30.8
7	Sandy. mixed. subgelic. Typic Gelorthents	7.5YR 7/2	480	150	220	150	31.6	2.31	7.35	5.1	96	191.1	8.12	8.99	n.d.	5.0
8	Coarse-loamy. mixed. subgelic. Lithic Eutrogelepts	5Y 7/6	260	110	430	200	37.4	2.24	8.52	2.1	40	58.0	3.15	1.67	n.d.	3.1
9	Coarse-loamy. mixed. subgelic. Ornithic” Lithic Eutrogelepts	10YR 4/2	280	210	340	170	27.4	2.21	4.93	190.7	51	67.1	0.37	n.d.7	2.85	103.8
10	Loamy-skeletal. mixed. subgelic. Fluvaquentic Aquorthels	10YR 5/2	440	190	230	140	39.2	2.20	7.29	25.5	93	133.0	8.75	4.94	n.d.	12.0
11	Loamy-skeletal. mixed. subgelic. Oxyaquic Gelorthents	7.5YR 5/2	640	80	180	100	44.7	2.76	7.08	26.8	80	129.8	4.88	2.26	n.d.	6.7
12	Coarse-loamy. mixed. subgelic. Typic Haploturbels	2.5Y 5/2	240	160	400	200	35.0	2.15	7.71	92.0	62	173.3	9.62	5.09	n.d.	5.4
13	Coarse-loamy. mixed. subgelic. “Patterned”. Typic Haploturbels	5Y 6/6	290	120	470	120	30.3	2.56	8.5	4.7	17	34.3	4.16	3.18	n.d.	2.9
14	Coarse-loamy. mixed. subgelic. “Patterned”. Typic Haploturbels	2.5Y 7/6	200	290	420	90	15.9	2.42	8.53	2.3	14	24.5	4.40	4.64	n.d.	3.8
15	Coarse-loamy. mixed. subgelic. “Patterned”. Typic Haploturbels	2.5Y 7/6	510	200	180	110	14.3	2.51	8.51	1.6	17	22.9	6.34	1.34	n.d.	2.6
16	Coarse-loamy. mixed. subgelic. “Patterned”. Typic Haploturbels	7.5YR 5/4	330	160	330	180	21.5	2.53	8.76	45.0	53	190.4	12.19	3.25	n.d.	3.0
17	Coarse-loamy. mixed. subgelic. Psammentic Aquorthels	10YR 5/4	460	200	200	140	48.2	2.18	6.8	11.6	32	107.1	5.19	2.77	n.d.	52.0
18	Coarse-loamy. mixed. subgelic. Lithic Haplorthels	2.5Y 4/2	320	150	390	140	29.6	2.14	7.12	87.5	119	237.1	4.24	6.32	n.d.	5.2
19	Loamy-skeletal. mixed. subgelic. “Patterned”. Lithic Haploturbels	7.5YR 5/2	400	190	270	140	42.9	2.23	6.42	10.9	90	123.9	3.91	5.29	n.d.	23.1

(continued)

Table 13.9 (continued)

ID	Soil taxa	Color	CS[1]	FS[2]	Silt[3]	Clay[4]	>2 mm	PD	pH	P	K	Na	Ca^{2+}	Mg^{2+}	Al^{3+}	SOC
		dry	(g/kg)				(%)	(g/cm^3)	H_2O	(mg/kg)			($cmol_c$/kg)			(g/kg)
20	Loamy-skeletal. mixed. subgelic. Typic Haploturbels	7.5YR 6/3	380	190	300	130	55.1	2.11	8.48	80.7	77	155.3	8.40	5.84	n.d.	1.7
21	Loamy-skeletal. mixed. subgelic. "Patterned". Typic Haploturbels	10YR 6/2	580	170	140	110	48.7	2.45	7.02	6.7	58	218.2	6.12	4.33	n.d.	8.9
22	Coarse-loamy. mixed. subgelic. Lithic Haploturbels	10YR 4/4	350	90	370	190	37.7	2.56	7.27	7.3	57	145.5	9.37	7.07	n.d.	5.5
23	Loamy-skeletal. mixed. subgelic. "Patterned". Typic Haploturbels	7.5YR 7/2	300	150	430	120	34.5	2.19	7.57	56.4	81	129.1	7.89	8.57	n.d.	4.8
24	Coarse-loamy. mixed. subgelic. "Patterned". Typic Psammoturbels	10YR 5/4	510	160	170	160	32.8	2.48	7.11	8.5	61	151.3	9.33	7.45	n.d.	8.8
25	Coarse-loamy. mixed. subgelic. "Patterned". Typic Haploturbels	7.5YR 6/3	330	200	350	130	39.1	2.56	7.57	16.5	75	178.7	7.25	4.48	n.d.	6.4
26	Loamy-skeletal. mixed. subgelic. Lithic Haploturbels	10YR 5/2	350	250	250	150	41.7	2.72	6.6	14.5	73	116.1	2.37	1.46	n.d.	25.4
27	Loamy-skeletal. mixed. subgelic. "Patterned". Aquic Haploturbels	2.5Y 5/3	510	110	250	130	39.7	2.63	6.86	11.9	86	114.1	2.95	2.85	n.d.	5.4
28	Coarse loamy-skeletal. mixed. subgelic. "Patterned". Aquic Haploturbels	10YR 6/3	240	220	390	150	38.6	2.56	7	35.2	97	135.0	6.31	3.34	n.d.	16.3
29	Loamy-skeletal. mixed. subgelic. "Ornithic" Lithic Haploturbels	7.5YR 4/3	390	240	260	110	19.8	2.63	6.28	35.7	72	108.8	4.16	0.93	0.95	31.3
30	Sandy. mixed. subgelic. "Ornithic" Typic Psammorthels	2.5Y 5/4	460	210	220	110	9.1	2.59	5.05	116.4	92	46.4	4.10	0.79	4.29	10.1
31	Sandy. mixed. subgelic. Lithic Cryopsamments	2.5Y 3/2	630	140	140	90	18.2	2.70	7.32	25.7	187	404.9	6.75	4.40	n.d.	0.53
Soil profiles from Ardley Island																
32	Loamy-skeletal. mixed. subgelic. "Ornithic" Typic Gelorthents	7.5YR 4/2	660	100	120	120	39.2	2.48	5.91	551.0	56	83.8	2.78	1.34	n.d.	21.7
33	Sandy. mixed. subgelic. "Ornithic" Lithic Psammoturbels	5Y 2.5/1	210	360	330	100	32.8	2.38	5.25	1043.7	87	236.6	1.75	0.96	0.51	199.0
34	Coarse-loamy. mixed. subgelic. "Ornithic" Lithic Haplorthels	10YR 4/3	160	300	310	230	33.0	1.98	5.12	192.5	67	109.5	1.47	1.37	1.04	156.7
35	Coarse-loamy. mixed. subgelic "Ornithic" Typic Aquorthels	10YR 4/4	90	420	390	100	28.5	1.12	5.64	30.3	17	49.8	1.49	1.22	0.17	193.2
36	Loamy-skeletal. mixed. subgelic. "Ornithic" Typic Molliturbels	10YR 6/3	320	200	340	160	405	2.31	5.96	126.1	60	83.1	0.49	0.56	0.54	96.8
37	Coarse-loamy. mixed. subgelic. "Ornithic" Aquic Haploturbels	7.5YR 2.5/2	410	230	230	130	285	2.35	5.95	202.1	40	75.1	0.80	0.60	0.31	49.3

(continued)

Table 13.9 (continued)

ID	Soil taxa	Color	CS[1]	FS[2]	Silt[3]	Clay[4]	>2 mm	PD	pH	P	K	Na	Ca^{2+}	Mg^{2+}	Al^{3+}	SOC
		dry	(g/kg)				(%)	(g/cm^3)	H_2O	(mg/kg)			($cmol_c/kg$)			(g/kg)
38	Loamy-skeletal. mixed. subgelic. "Ornithic" Typic Haploturbels	2.5Y 6/2	250	310	280	160	37.1	2.20	5.6	222.3	62	107.4	0.83	0.61	1.16	152.5
39	Loamy-skeletal. mixed. subgelic. Typic Haploturbels	2.5Y 7/4	320	120	360	200	37.9	2.95	7.69	0.1	8	15.2	2.22	1.16	n.d.	2.4
40	Coarse-loamy. mixed. subgelic. "Ornithic" Fluvaquentic Aquorthels	5Y 4/1	70	440	400	90	26.9	2.56	5.45	847.1	48	113.9	2.16	1.04	n.d.	58.5
41	Coarse -loamy. mixed. subgelic. "Ornithic" Typic Haploturbels	2.5Y 5/3	330	200	320	150	35.0	2.38	4.52	223.9	34	41.5	0.16	0.14	1.28	94.6
42	Fine-loamy. mixed. subgelic. "Ornithic" Aquic Haploturbels	2.5Y 7/2	220	110	420	250	33.9	2.55	5.97	886.6	80	121.9	2.49	1.53	0.17	59.3
43	Loamy-skeletal. mixed. subgelic. "Ornithic" Typic Haploturbels	10YR 4/2	240	380	220	160	41.8	1.96	5.03	33.6	22	51.4	0.42	0.44	1.33	267.4
44	Loamy-skeletal. mixed. subgelic. "Ornithic" Typic Haploturbels	10YR 5/4	490	200	180	130	37.4	2.54	5.92	88.4	63	93.6	1.98	3.92	1.24	29.9
45	Loamy-skeletal. mixed. subgelic. "Ornithic" Typic Gelorthents	2.5Y 7/4	450	150	160	240	36.5	2.55	5.82	119.7	24	48.8	1.22	1.79	0.13	4.6
46	Loamy-skeletal. mixed. subgelic. "Ornithic" Typic Gelorthents	10YR 5/2	420	90	190	300	46.2	2.52	5.65	2655.0	581	423.9	0.92	1.42	0.29	85
47	Sandy-skeletal. mixed. subgelic. "Ornithic" Typic Gelorthents	2.5Y 3/3	470	190	150	190	38.9	2.68	6.02	40.1	26	49.2	1.76	1.14	n.d.	17.8
48	Loamy-skeletal. mixed. subgelic. "Ornithic" Oxyaquic Gelorthents	2.5Y 7/3	300	210	260	230	35.5	2.46	5.72	356.6	73	147.4	2.32	1.67	0.41	76.7

n.d. not detected
[1]Coarse sand (0.2–2 mm)
[2]Fine sand (0.05–0.2 mm)
[3]Slit 0.002–0.05 mm
[4]Clay <0.002 mm

Fig. 13.15 Ornithogenic soils and associated landscapes in Ardley Island, SSI

Everett (1971) was accompanied by the construction of raised beaches. Additionally, wave-cut rock benches occur at elevations of 180–190 m a.s.l.

Byers Peninsula

Although this is the largest ice-free area of the SSI, there have been few soil studies on the Byers Peninsula. Schaefer et al. (unpublished) surveyed the soils of the entire southern part of Byers Peninsula. Navas et al. (2008) reported data on soils from Byers Peninsula, and Moura et al. (2012) characterized and mapped soils form the northern part of the peninsula. On the northern part, only two (P#1 and P#2) of 23 soil profiles described during the peak of the summer (February of 2009) had clear evidence of permafrost within the upper 100 cm; frozen ground was encountered at 53 cm for profile P#1 and 35 cm for profile P#2.

Soils derived from volcanic tuffs and basaltic lava have dry colors with a yellowish hue that range from brown (7.5YR 4/2) to dark grayish brown (10YR 4/2). Soil pH is high, increasing from 7.7 at surface to 8.1 at 50 cm depth. Ca^{2+} and Mg^{2+} are also high, with mean values of 8.1 and 15 $cmol_c$. dm^{-3}, respectively (Moura et al. 2012).

Soils from claystones, siltstones, and conglomerates are grayish brown (2.5Y 5/2) to olive gray (5Y 5/2) with silt contents up to 390 g kg^{-1} and clay up to 410 g kg^{-1} (profile P#13). Soils formed from these marine sediments had the highest mean extractable P and exchangeable Ca^{2+} when compared to the other soil groups. Total organic carbon was also higher than for the nonornithogenic soils. On the other hand, mean extractable Na^+ value is almost twice that of other soil groups.

Ornithogenic soils are found in coastal sites of abandoned or active bird nesting areas, especially penguins. These soils have high extractable P, total organic carbon and Al^{3+} contents, low pH, and low Ca^{2+} and Mg^{2+} contents. We found extremely high values of extractable P, reaching 2,800 mg dm^{-3} in soil P#5 (Moura et al. 2012). Mean pH for the ornithogenic soils was 4.7. Mean extractable P is almost nine times higher than that observed for the nonornithogenic soils while exchangeable Ca^{2+} is almost seven times lower.

According to *Soil Taxonomy*, soils from Byers Peninsula key out in the Gelisols, Inceptisols, and Entisols. The soil prepared by Moura et al. (2012) uses the WRB system and is composed of 13 soil map units, Haplic Leptosol (ornithic, skeletic); Histic Cryosol (ornithic, oxiaquic), and Turbic Cryosol with well-defined circular patterned ground. The other ten soil units are associations or complexes of Gelisols and Entisols and terrain types, which were not separable at the given scale

Hurd Peninsula

Navas et al. (2008) studied four soils on raised beaches and wave-cut platforms on the Hurd Peninsula. Haus and Bockheim (in progress) described, sampled, and analyzed 20 pedons on seven geomorphic surfaces on Hurd Peninsula, Livingston Island (62° 39′ S, 60° 21′ W), with the goal of understanding pedogenesis in relation to geomorphic surface. The surfaces included nivation hollows, moraines, raised beaches, modern beaches, rock glaciers, stone-banked lobes, and nonsorted stone circles. The elevations of ice-free areas on the Hurd Peninsula range from 0 to 400 m a.s.l.

The mean annual air temperature along the Hurd Peninsula is −2.7 °C at sea level. February is the warmest month at 1.3 °C and August is the coldest at −7 °C. For 2010 at St. Kliment Ohridski base, the mean annual, February monthly, and August monthly temperatures were −1.9, 1.7, and −4.2 °C, respectively (Vieira, unpublished). The adiabatic lapse rate is −0.80 °C/100 m (Ramos and Vieira 2003; Vieira et al. 2008). Hurd Peninsula receives about 500 mm yr^{-1} of precipitation and has an average relative humidity between 80 and 90 %. There is continuous snow cover from April to December, and the snow thickness is recorded in decimeters in areas unaffected by wind (Vieira and Ramos 2003).

The dominant rock type on Hurd Peninsula is the Miers Bluff Formation, which is comprised of metamorphic turbidites (greywacke, sandstone, shale, conglomerate, and breccias), dolerite dykes, and quartz veins (Arche et al. 1992). Vieira and Ramos (2003) identified eight geomorphic surfaces on the Hurd Peninsula, including frost-shattered debris, talus, stone-banked lobes, rockglaciers, patterned ground (nonsorted circles), beaches, raised beaches, and moraines. Five geomorphic surfaces were delineated on a 1:10,000 scale map by López-Martínez et al. (1992), including glaciofluvial fans, debris cones, raised beaches, supraglacial debris, and moraines. Ice-cored moraines and two rockglaciers occur on Hurd Peninsula down to sea level (Serrano and López-Martínez 2000; Vieira et al. 2007). Patterned ground is found on Livingston Island at elevations exceeding 200 m.

Eight raised beaches occur at Spanish Cove at elevations ranging from 1.5 to 18.6 m a.s.l. (López-Martínez et al. 1992). Pallas et al. (2001) correlated three groups of tephra layers on Livingston Island with those on Deception Island. According to Pallas et al. (2001), the tephra groups originated from the 1829 and 1967–1970 eruptions. These interpretations suggest that many of the soils on Livingston Island are less than 200 year in age.

Permafrost is absent below 35 m a.s.l. (López-Martínez et al. 1992) and is present above 150 m a.s.l. (Ramos and Vieira 2009). Permafrost is >25 m thick on Reina Sofia (275 m). The active layer depth ranges from 4 m at elevations between 35 and 150 m and 0.9 m at 275 m on Reina Sofia.

Vegetation occurs only sporadically on the Hurd Peninsula and includes numerous species of mosses and lichens. Antarctic hairgrass, *Deschampsia antarctica*, and Antarctic pearlwort, *Colobanthus quitensis*, the only two flowering

Table 13.10 Mean physical and chemical properties of soil taxa on Hurd Peninsula, Livingston Island

Horizon	Depth (cm)	SOC (g/kg)	Tot. N (g/kg)	Tot. P (%)	Mehl P (mg/L)	pH (H_2O)	EC, 1:2 (µS/cm)	Al_d (mg/kg)	Fe_d (mg/kg)	>2 mm (%)	Clay (g/kg)	Silt (g/kg)	Sand (g/kg)
	L01; ashy, mixed, subgelic Lithic Gelorthents												
C1	1–8	1.8	0.53	0.03	3.4	6.51	20.9	NA	NA	60	30	50	920
2C2	8–38	1.6	0.53	0.03	1.5	6.74	16.6	NA	NA	65	50	110	840
2Cfm	38–43	1.8	0.55	0.03	2.0	7.03	17.0	NA	NA	80	60	120	820
	L03; ashy-skeletal, mixed, subgelic Typic Gelorthents												
A	1–9	0.9	0.64	0.02	11.3	6.76	18.3	NA	NA	46	70	100	830
Bw	9–20	1.0	0.62	0.02	2.8	7.26	12.6	NA	NA	56	30	70	900
BC	20–50	0.4	0.38	NA	NA	7.46	12.1	NA	NA	66	20	30	950
C	50–60	0.3	0.39	0.05	6.1	7.72	10.4	NA	NA	64	40	80	890
	L10; sandy-skeletal, mixed, subgelic Typic Gelorthents												
A	0–7	3.1	0.69	0.22	>38.5	5.48	52.9	2063	4683	20	30	60	910
2C	7–18	11.1	1.96	1.62	21.2	6.56	19.0	7441	14145	5	170	260	570
3Ab	18–24	NA	NA	1.04	30.7	6.75	14.8	4891	9569	20	40	100	860
3C1	24–51	3.5	0.87	0.96	>45.1	6.21	40.5	4781	8504	2	60	440	500
4C2	51–62	NA	NA	1.00	>40.4	4.87	65.1	3731	9489	15	70	330	600
	L11; sandy-skeletal, mixed, subgelic Typic Gelorthents												
Cu1	0–11	NA	NA	0.03	6.4	6.93	23.3	NA	NA	0	30	100	870
Cu2	11–63	NA	NA	0.04	7.5	6.86	19.7	NA	NA	0	30	70	900
	L18; ashy, mixed, subgelic Typic Gelorthents												
A	0–8	4.6	0.87	0.06	3.9	6.49	16.6	2436	5671	10	80	150	770
A/B	8–20	10.3	1.25	0.07	1.8	6.78	15.6	2651	6702	8	80	190	730
B/A	20–31	10.1	1.31	0.09	0.6	7.07	13.5	4922	10707	5	70	140	790
Bw	31–40	26.1	2.67	0.11	0.1	6.95	19.2	7276	15264	10	80	340	580
2BC	40–52	9.5	1.32	0.10	1.3	7.05	16.9	7206	14301	20	90	170	740
2C	52–70	6.5	1.04	0.09	2.9	7.15	17.1	5535	10636	45	80	140	790

plants in Antarctica, are common on Hurd Peninsula (Lindsay 1971). Slopes range from level on beaches, raised beaches, and nonsorted circles to moderately sloping on solifluction lobes and frost-shattered debris, to steep on talus, rock glaciers, and glaciofluvial cones (Vieira and Ramos 2003).

From the provisional work of Haus and Bockheim (in progress), no diagnostic horizons were observed in soils on Hurd Peninsula other than umbric and campic horizon on the uppermost raised beaches at Spanish Bay. Two-thirds of the soils have a sandy texture, with most of the remaining soils being loamy sands (Table 13.10). Bw horizons on soils of the upper raised beaches were sandy loams. Coarse fragments averaged 54 %.

Four suborders of soils were observed on the Hurd Peninsula, Orthents (12 pedons), Gelepts (3 pedons), Turbels (3 pedons), and Orthels (2 pedons). We classified soils into five great groups: Gelorthents (12 pedons), Humigelepts (3 pedons), Haploturbels (2 pedons), Haplorthels (1 pedon), and Aquiturbels (1 pedon).

13.4.2.3 Deception Island

Deception Island (63° S, 60° W) offers a singular setting for the study of soil genesis in Antarctica. Due to the recent volcanic activity in 1960, pyroclastic materials cover the whole island and offer a baseline for understanding weathering of such materials under a polar climate. The mean annual air temperature is −2.9 °C (Igarzabal 1974). The mean temperature of the warmest (January) and coldest (August) months are 1.1 °C and −10 °C, respectively. The mean annual precipitation is 510 mm, of which 100 mm falls as rain during the summer. Cloud cover averages 50 %, and the relative humidity commonly ranges between 80 and 90 %. Prevailing winds originate from the northwest and west.

Deception Island is a basaltic shield volcano with a flooded caldera. The oldest rocks (pre-caldera) are of the Port Foster Group, <750 ka in age and include hydrovolcanic tephra, lavas and Strombolian scoria (Smellie 2002). Subsequent lithostratigraphic units include the Mount Pond Group, which is comprised of tuff cone and maars and tephra deposits. Historical eruptions were recorded in 1842, 1967, 1969, and 1970 (Pallas et al. 2001). Vegetation occurs only sporadically on Deception Island, primarily in penguin and other bird rookeries. The vegetation is limited to 18 species of mosses and lichens. However, exotic grasses (*Poa* spp.) that have since been eradicated were reported at Whaler's Bay (Longton 1966). Slopes range from level on beaches and lag surfaces to gently sloping on fans and lahars, to steep on debris flows, talus, and glaciofluvial cones.

There is no patterned ground, rock glaciers, or cryoplanation terraces on Deception Island. Ice-cemented permafrost exists from near sea level to the highest summits but is absent on beaches and in areas of geothermal activity such as faults and fumaroles. The permafrost is 2 m thick (Vieira et al. 2008). The active layer depth ranges from 30 to 90 cm (Vieira et al. 2008).

Haus and Bockheim (in progress) described, sampled, and analyzed 28 pedons on 13 geomorphic surfaces on Deception Island. Resck (2011) reported data from five soils along and altitudinal sequence from 45 to 105 m a.s.l. (Table 13.11). The soils are shallow and frequently present lithic, paralithic, or permafrost in the first 100 cm (Fig. 13.16). All soils have high gravel contents (30–90 %) and a sandy-skelectic texture. Clay contents in the <2 mm fraction are very low (30–50 g kg^{-1}) and soils have very little horizon differentiation. Soils have grayish colors with yellowish hue (5Y) and very low chroma (1 and 2) indicating a low degree of oxidation.

All soils studied by Resck (2011) are eutric. D1, D2, and D5, with no ornithogenic influence, have pH varying from 6.1 to 7.6 with very low SOC values. Levels of exchangeable Ca^{2+} (2.4–4.8 $cmol_c$ dm^{-3}) and Mg^{2+} (2.1–2.9 $cmol_c$ dm^{-3}) are lower than those obtained for soils without ornithogenic influence from basaltic and andesitic areas of the SSI (Table 13.11). This is also true for extractable P (57–133 mg dm^{-3}). Soil D3 was sample close to a current penguin rookerie and show slight increase in extractable P (205 mg dm^{-3}) and extractable Ca^{2+} (7.4 $cmol_c$ dm^{-3}) and Mg^{2+} (4.9 $cmol_c$ dm^{-3}) in surface, decreasing with depth. The values of pH are high in the whole profile (6.9–7.92). Similar results were obtained for soil D5, developed in site covered with the terrestrial alga *Prasiola crispa* that is an indicator of initial guano transformation and occur in sites recently abandoned by penguins.

There is a predominance of poorly crystalline Fe phases in the soils studied by Resck (2011) as indicated by high oxalate-extractable/dithionite-extractable ratios but poorly crystalline Al–Si phases (allophane-like minerals) are not sufficiently abundant to qualify as Andic properties.

Based on the studies of Resck (2011) and unpublished data of Haus and Bockheim (in progress), soils from Deception Island have little cryoturbation and key out in the Orthel suborder, although Typic Haploturbels occur to a limited extent. Ornithogenic soils with an umbric epipedon are classified as "Ornithic" Umbrorthels. Entisols (Typic Gelifluvents and Typic Gelorthents) complete the soil taxa identified in Deception Island. Soil mapping is in progress.

13.4.2.4 Penguin Island

Penguin Island is a small (1.8 km^2) island that is comprised dominantly of volcanic materials. According to Birkenmajer (1979), the volcanic forms in Penguin Island suggest volcanic activity no older than 173 years B.P. Pyroclasts have basaltic and andesitic composition, similar to the materials found on Deception Island, but with a longer time of exposure. The island is rich in bird life and mammals such as elephant seals. The grasses *Deschampsia antarctica* and *Colobanthus quitensis* are common on the island, as well as mosses and lichens, including *Usnea Antarctica.*

Resck (2011) studied three soil profiles on Penguin Island along an altitudinal sequence from 25 to 55 m a.s.l (Fig. 13.17). The soils are skeletic and have slightly higher clay contents (30–110 g kg^{-1}) than those on Deception Island. The soils have a redder hue (2.5 YR) and higher chroma (2–4) indicating a higher degree of oxidation than on Deception Island.

Soils P1 (45 m a.s.l.) and P2 (55 m a.s.l.) have pH values varying from 6.8 to 7.5. Exchangeable Ca^{2+} and Mg^{2+} are lower in the surface horizons than at depth (Table 13.12). The soils are eutric, but the percentage of bases on the exchange complex is lower than in soils on Deception Island (54–92 %). Extractable P levels range from 26 to 55 mg.$dm^{-3.}$ All chemical properties described above increase with depth indicating depletion of bases in surface. Soil P3 (25 m a.s.l.) is covered by mosses and *Deschampsia Antarctica* with current influence of Giant Petrels. These soils have an acidic reaction, with pH varying from 5.1 to 5.7. Extractable P is very high when compared to the other soils on Penguin Island, reaching 500 mg dm^{-3} at a depth of 30 cm with sharp reduction to 84 mg dm^{-3} at 50 cm and reaching 42 mg dm^{-3} at the depth of 80 cm. This soil is dystric throughout the whole profile with lower values of Ca^{2+} and Mg^{2+} than for P1 and P2. SOC levels are much higher in P3, ranging from 83 g kg^{-1} in the first 15 cm to 26 g kg^{-1} at 30 cm. Such characteristics indicate incipient phosphatization, although no crystalline phosphates were identified through XRD analysis (Resck 2011).

As with soils on Deception Island, poorly crystalline Fe phases prevail in Penguin soils; however, Andic properties are present as indicated by high pH in NaF values (>10.0) and high 0.5Feo + Al_o/Si_o values (>2 %) (Resck 2011).

Table 13.11 Physical and chemical properties of soils from Deception Island

	Depth	Coarse sand	Fine sand	Silt	Clay	Color	pH	P	K	Na	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	CEC	N	SOC
Horizon	(cm)	(g/kg)					H_2O	(mg/dm^3)			($cmolc/dm^3$)					(g/kg)	
Dec 1—sandy-skeletal, subgelic Lithic Gelorthents																	
A	0–5	450	330	170	50	5Y3/2	6.07	57.4	190	954.3	2.46	2.07	0.21	1.7	10.87	–	6.4
C2	5–15	450	290	210	50	5Y4/2	7.46	62.7	189	482.2	2.9	2.04	0	1	8.52	–	6.4
C3	15–30	470	240	240	50	5Y4/2	7.56	84.5	202	487.3	3.45	2.4	0	0.7	9.19	–	6.4
Dec 2—sandy-skeletal, subgelic Lithic Gelorthents																	
	0–30	440	190	320	50	5Y4/1	7.58	133.4	183	467	4.85	2.86	0	0.3	10.51	–	6.4
Dec 3—ornithic, Typic Psammoturbel																	
C1	0–5	340	330	290	40	5Y3/1	7.92	205.3	268	720.8	7.45	4.89	0	0.2	16.36	–	6.4
C2	5–20	430	310	210	50	5Y5/1	7.27	58	124	340.1	1.44	1.25	0	1	5.49	–	6.4
C3	20–35	440	240	280	40	5Y6/1	6.88	65.6	160	522.8	3.03	1.88	0	0.7	8.29	–	6.4
Dec 4—ornithic, Typic Psammoturbel																	
A	0–5	470	320	170	40	5Y3/1	6.4	43.1	328	517.8	3.02	1.78	0	1.4	9.29	–	6.4
C1	5–35	410	400	170	20	5Y3/1	7.23	39.1	258	416.2	2.2	1.78	0	0.5	6.95	–	3.2
C2	35–75	420	280	280	20	5Y3/2	7.52	63.9	253	665	3.32	2.08	0	0.2	9.14	–	6.4
Dec 5—ornithic, Lithic Gelorthent																	
C1	5–35	290	90	590	30	5Y4/2	6.84	139.5	288	786.8	4.23	2.92	0	0.2	11.51	–	3.2

Fig. 13.16 Soil profiles and landscapes from Deception Island, corresponding (from *top* to *bottom*) to soils D1, D2, D3, D4, and D5 in Table 13.11

Fig. 13.17 Soil profiles and associated landscapes from Penguin Island, corresponding (from *top* to *bottom*) to soils P1, P2 and P3 in Table 13.12

13.4.2.5 Elephant Island

Elephant Island (61° S, 55° W) is an ice-covered mountainous island in the northeastern most part of the South Shetland Islands. It has an area of 558 km^2 and the highest elevation is 853 m a.s.l. About 5 % of the island is ice-free (~275 km^2). The island is covered by till, has abundant polygonal patterned ground features, and a continuous moss cover on raised beaches. Penguin colonies are abundant on the island. The island features continuous permafrost with an active layer depth in 1970–1971 of >90 cm (O'Brien et al. 1979). There are minimal climate data for Elephant Island; however, records from the early 1970s suggest a mean annual temperature of about 4.5 °C and mean temperatures for the coldest month (July) of −10 °C and the warmest month (January) of 1 °C. Mean annual precipitation may be 1,500 mm. The three soils examined by O'Brien et al. (1979) were derived from quartzose mica schist or phyllites.

O'Brien et al. (1979) studied three pedons from Elephant Island (Table 13.13). The soils featured abundant coarse fragments (average = 63 %); the fine-earth fraction was dominated by silt in two the pedons (55 %); and the soils were enriched in SOC (0.22–2.8 %). The total soluble salt concentrations were low, but one of the pedons (P1) had abundant $CaCO_3$ (1.5–3.5 %). Pedon P2 had high levels of exchangeable phosphate. Base cations were high in P1, but P2 had mainly exchangeable H ion. The three profiles had a mixed mineralogy. Leucophosphite was found in the penguin-affected P2 soil. Wilson and Bain (1976) also reported the occurrence of leucophosphite in an ornithogenic soil

Table 13.12 Physical and chemical properties of soils from Penguin Island

	Depth	C.S.	F.S.	Silt	Clay	Color	pH	P	K	Na	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	CEC	N	TOC
		(g/kg)					H_2O	(mg/dm^3)			($cmolc/dm^3$)					(g/kg)	
Profile 1—sandy-skeletal, subgelic Typic Gelorthent																	
C1	0–5	610	270	70	50	2.5YR4/3	6.75	26	136	203	0.74	0.39	0	1.2	3.56	–	2.6
C2	5–18	610	280	60	50	2.5YR4/2	7.13	19.6	136	238.6	1.17	0.77	0	1.4	4.73	–	2.6
C3	18–37	590	280	80	50	2.5YR4/2	7.18	17.8	218	190.9	1.75	1.21	0	1.4	5.75	–	3.8
C4	37–70	550	220	180	50	5YR4/1	7.46	55.2	104	284.3	5.03	5.4	0	1	12.94	–	2.6
Profile 2—sandy-skeletal, subgelic Typic Gelorthent																	
A	0–8	620	230	70	80	2.5YR6/3	6.75	39.1	128	136	1.24	2.03	0	3.6	7.79	–	10.2
AC	8–22	650	160	110	80	2.5YR6/4	6.96	33.1	127	176.6	2.47	3.08	0	3	9.64	–	9.0
C1	22–45	670	120	130	80	5Y5/2	7.34	63.9	228	340.1	4.84	6.39	0	2.2	15.49	–	7.7
C2	45–65	800	80	90	30	5Y3/1	7.55	49.5	141	173.6	1.24	1.32	0	0.5	4.17	–	6.4
Profile 3—Tipic Umbrorthel																	
A	0–15	670	150	70	110	2.5YR6/4	5.47	500.9	93	138.1	0.63	0.54	0.92	11.5	13.51	–	26.9
C1	15–30	610	190	110	90	2.5YR6/4	5.31	84.5	82	133	1.05	1.24	0.51	6.1	9.18	–	6.4
C2	30–50	560	190	180	70	2.5YR6/2	5.67	42.1	123	202	2.34	2.53	0.82	5.1	11.16	–	2.6

Table 13.13 Properties of three soils on Elephant Island (O'Brien et al. 1979)

Depth (cm)	SOC (g/kg)	Tot. N (g/kg)	P(%)	$CaCO_3$ (%)	pH (H_2O)	Sol. Salts (%)	Exch. Bases ($cmmol_c/kg$)	Exch. H ($cmmol_c/kg$)	>2 mm (%)	Clay (g/kg)	Silt (g/kg)	Sand (g/kg)
P1												
0–5	3.3	0.4	0.022	1.5	8.2	0.019	6.1	<0.1	79	100	560	340
15–25	5.0	0.3	0.135	2.5	8.4	0.023	23.3	<0.1	77	10	580	410
45–55	6.1	0.5	0.195	3	8.5	0.023	41.1	<0.1	76	10	610	380
65–75	5.5	0.5	0.194	3.5	8.6	0.024	40.6	<0.1	76	10	630	160
P2												
0–5	28.0	4.2	5.08	Nil	nd	0.049	7.0	15	16	nd	nd	nd
15–25	11.4	4.2	8.35	Nil	4.3	0.018	3.2	15.2	58	160	500	340
35–45	15.2	3.4	3.96	Nil	4.2	0.017	1.6	16.2	54	180	520	300
55–65	12.5	4.4	8.48	Nil	4.2	0.018	2.5	15.4	42	160	470	370
P3												
0–5	2.2	0.2	0.089	Nil	5.4	0.007	0.2	1.0	100	10	10	980
5–15	3.4	0.6	1.24	Nil	5.7	0.013	2.7	1.7	69	30	40	930
40–50	16.8	3.0	1.70	Nil	5.0	0.030	3.6	4.8	48	80	250	670

from Elephant Island. From the descriptions and analytical data provided by O'Brien et al. (1979), we classify P1 as an Aquiturbels, P2 as an "Ornithogenic" Haplorthels or Gelaquents, and P3 as an Aquiturbels.

13.5 Discussion

13.5.1 Soil-Forming Processes

Specific soil-forming processes in the SOI and SSI include cryoclastic weathering, cryoturbation, phosphatization (Michel et al. 2006; Simas et al. 2006, 2007; Schaefer et al. 2008), brunification, podzolization (Blume et al. 1997), sulfurization (Simas et al. 2006; Schaefer et al. 2008), and andosolization (Resck 2011).

Physical disaggregation of mineral substrates is a major process in SOI and SSI due to the frequent daily freeze-thaw cycles as temperatures oscillate around 0 °C, especially during the summer. At higher landscape positions eutrophic, alkaline soils prevail that are normally devoid of vegetation and with low SOC. Clay formation results mainly from physical particle-size reduction of parent materials. Incipient chemical transformation of easily weatherable primary minerals with formation of poorly crystalline Al–Si phases has been reported in King George Island (Simas et al. 2006). Oxidized stains and rock varnish also indicate that chemical alterations are occurring. Unlike soils from the drier continental Antarctica, soils form the SOI and SSI do not show accumulation of salt crusts. Snow melt and a shallow active layer enable oscillations in the redox potential throughout the soils many sites; this process also favors chemical weathering of primary minerals. High levels of base cations and Si, with reduced leaching favor the stability of double-layered clay minerals with predominance of chlorite, smectite, and hydroxy-interlayered smectites.

High precipitation as rainfall and snow and melting of ice within the active layer provide high water availability that favor downslope movement by gelifluction. Mudflows and other forms of mass movement result in addition of materials eroded from upslope to lower surfaces. Uplifted beaches and terraces often have extensive waterlogged areas in which gleization is favored.

Biological processes are particularly important for soil formation in the SOI and SSI. The islands have a variable plant cover and feature organisms such as bacterially dominated microbial communities, nematodes, and collemboles (Bölter 2011). Most importantly, the vegetation that occurs in suitable spots can create stable conditions on the soil surface that would otherwise be subject to intense periglacial erosion and cryoturbation. The cryptogamic vegetation markedly changes the thermal and hydric regimes, enable insulation of the permafrost (Guglielmin et al. 2008), and result in enhanced weathering and clay formation. Vegetated sites are usually less prone to wind erosion, and display greater surface rugosity. Such landscape anisotrophy is thought to create a long-term soil stability that favors organic matter accumulation and greater microbial activity under lichens or mosses.

Soils with abundant organic carbon on vegetated sites are normally acidified. The soils are usually eutrophic but have low base contents. The acidity causes instability of clay minerals releasing elements that may be leached, taken up by plants, or react to form organometallic complexes or poorly crystalline Si–Al phases.

The abundant precipitation and sea spray in maritime Antarctica also contribute nutrients to vegetation growth. Nesting and migrating birds contribute substantial sources of external nutrients and organic materials. This favors vegetation development and soils have considerably higher organic matter contents than in soils unaffected by avians. At sites with long-term colonization by birds, soils are melanized and have a more developed structure and horizon differentiation than in soils not affected by birds.

Where penguin rookeries are established, the amount of sea–land transfer of matter and energy is especially high (Tatur and Barzuk 1983). Phosphatization is the main soil-forming process in areas under past or current influence by penguin rookeries (Simas et al. 2007b). Initially, deposition of bird guano results in eutric, alkaline soils with high exchangeable Ca^{2+} and Mg^{2+} and high extractable P levels and relatively low organic carbon. Soils are devoid of vegetation due to trampling by animals and harsh chemical environment due to the microbiological oxidation of penguin droppings. As guano mineralization progresses, sulfuric and nitric acids are produced, soils become acidic, and vegetation can become established. P–Ca crystalline phases of ornithogenic origin (i.e., bone apatite, struvite) are unstable in the soils. XRD data show drastic changes in the structure of clay minerals, which eventually become undetectable in samples from well-developed phosphatic horizons. In these horizons, crystalline clay-sized Al–P and Fe–P minerals occur in equilibrium with high levels of poorly crystalline Al–Si–P phases (Simas et al. 2007b). Soils become progressively depleted in bases, dystrophic, and with high SOC, maintaining high levels of extractable P along with high levels of Al^{3+} as in some soils amorphous and crystalline P minerals account for approximately 70 % of the clay fraction (Simas et al. 2006).

Ornithogenic soils are the largest pool of stored organic carbon in Antarctica and enable formation of umbric and histic epipedons (Michel et al. 2006; Simas et al. 2007a). After site abandonment by penguins, exuberant vegetation colonizes the areas with a predominance of mosses at wetter sites, lichens at very dry sites and a community of higher plants (*Deschampsia antarctica* and *Colobanthus quitensis)*, mosses and lichens at well-drained sites. Waterlogged areas that receive enriched solutions from ornithogenic sites allow the formation of fibric horizons. Histic epipedons have a thermal insulating effect, resulting in the occurrence of permafrost within the upper 70 cm even at low altitudes. At well-drained sites, organic matter is in great part humified with participation in soil aggregation and formation of umbric epipedons.

Frequently, ornithogenic soils with abundant organic matter content have low clay and high sand contents. Because of the high water availability, organometallic complexes and poorly crystalline Al–Si phases migrate downward and tend to accumulate in the transient layer above the permafrost table resulting in podzolized soils, as reported by Blume et al. (1997); however, typical E horizons are not present.

Some of the volcanic areas of the SSI have quartzpyrite intrusions. Acidity generation due to sulfide oxidation (sulfurization) enhances chemical weathering and formation of sulfuric horizons with highly reactive, poorly crystalline Fe phases (Simas et al. 2006; Schaefer et al. 2008). These soils undergo natural acid drainage with solubilization and mobilization of Al, Fe, and other metals. Poorly crystalline iron phases (ferrihydrite) and crystalline iron sulfates (jarosite) are common in the clay fraction of soils formed in these environments (Simas et al. 2006). In general, acid sulfate soils have a higher proportion of fine particles (silt and clay) and lower gravel and sand content in relation to the other soils from the SOI and SSI and soils have a typical morphology with yellowish horizons with high chroma.

Incipient and osolization occurs on pyroclastic materials in Deception Island and Penguin Island. Apparently, the older age of the eruptions that covered Penguin Island (ca., 170 years BP) accounts for a higher degree of chemical transformation resulting in andic properties. The soils studied on Deception Island derived from more recently exposed materials (c.a. 54 years B.P.) apparently have not had enough time to undergo significant chemical alteration apart from the formation of poorly crystalline Fe minerals.

13.5.2 Pedodiversity

Pedodiversity is unusually rich in the SOI and SSI because of differences in climate due to latitude, longitude, elevation differences, plant community distribution, landforms, and parent material. Most of the soils are less than 10 ka in age and, therefore, are closely related to the nature of the parent material. Soil variability is high, in terms of morphological, physical, and chemical properties, due to varying lithic contributions and mixing of different rocks in these active periglacial environments, as well as to different degrees of faunal influence. At least 37 taxa in *Soil Taxonomy* (Soil Survey Staff 2010) have been delineated in an ice-free area of less than 400 km^2 (Michel et al. 2014) indicating high spatial variability in soil properties used for separation of soil classes (mineralogy, texture, SOC, gravel content, base saturation, permafrost, seasonal ice, etc.). Figure 13.18 illustrates the high pedodiversity within a small ice-free area for the SSI.

13.5.3 Soil Classification

One of the key attributes for classifying soils from the SOI and SSI is the occurrence of permafrost. As most soils are

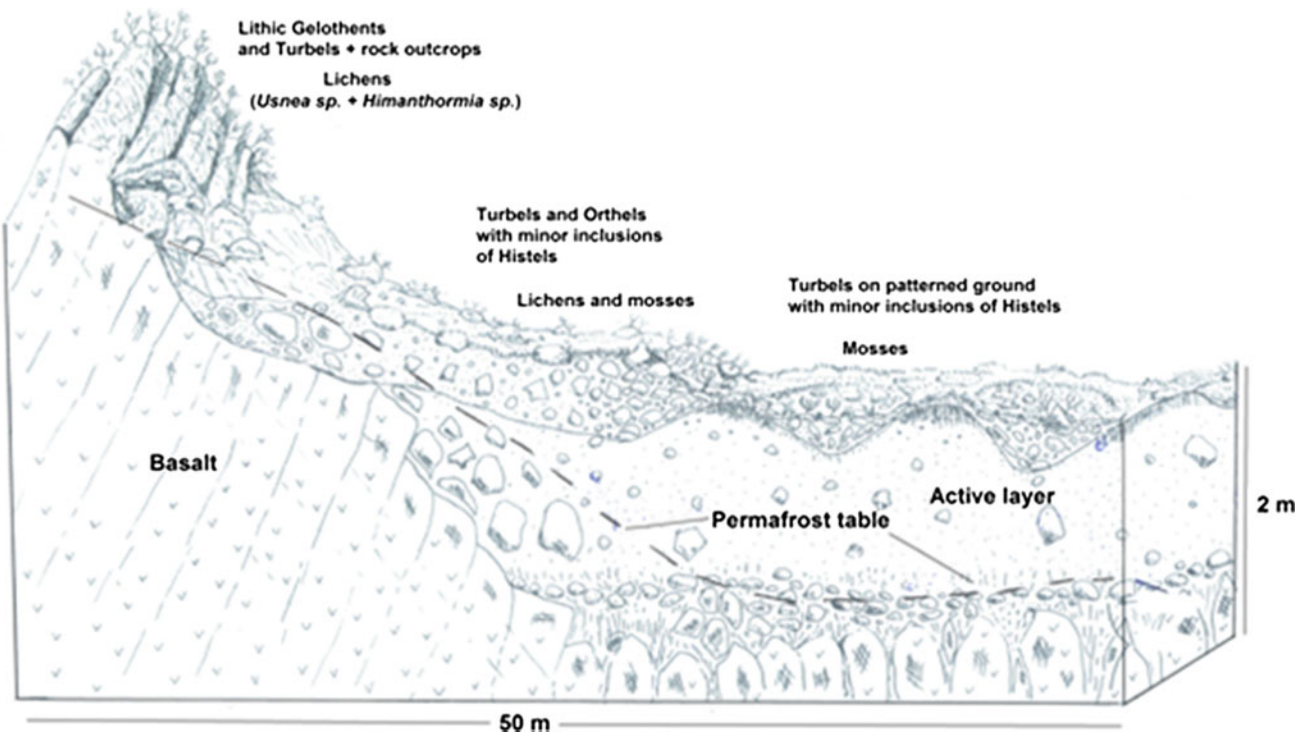

Fig. 13.18 Central Byers Peninsula—Illustration of a local sequence of typical SSI soils ranging from the Chester Cone (columnar jointed basalt) to the upper platform with polygonal soils on volcanic tuffs with strong cryoturbation and patterned ground formation. It highlights the difficulties in separating soils at a mesoscale, in a zone of space and time discontinuous, depth-variable permafrost, all with highly varied stoniness and organic matter content at a meter-scale

cryoturbated, the keying out of Gelisols depends on the presence of permafrost in the first 200 cm of soil. Data from two sites in King George Island (Michel et al. 2012) suggest that soils at altitudes higher than 80 m a.s.l. become perennially frozen at approximately 1 m from the surface. This is in agreement with the most accepted model for permafrost distribution in the SSI (López-Martínez et al. 2012). At lower altitudes, permafrost is regarded as discontinuous, which has important implications for production of soil maps. From 20 to 80 m a.s.l., Turbels usually occur in association with Entisols and, in some areas, with Inceptisols. Below 20–30 m a.s.l. permafrost is regarded as absent and normally soils key out as Entisols (Cryopsamments, Cryofluvents, Aquents).

Simas et al. (2007b) proposed the inclusion of the "Ornithogenic" qualifier in the *Soil Taxonomy* to allow a better classification of soils formed through phosphatization due to bird terrestrial activity. Extractable P, soil mineralogy, morphological characteristics are some parameters that need to be specified to allow the inclusion of Onithogenic soils *in Soil Taxonomy*, similarly to what is used in the WRB to define the "Ornithic" character (IUSS, WRB 2006).

The occurrence of well-drained soils with sulfuric horizons, cryoturbation, and permafrost in the first 200 cm has been commonly reported. However, there is no sulfuric qualifier to separate these soils with unique characteristics and associated genetic processes. We suggest the inclusion of the sulfuric qualifier to separate subgroups of all the Turbel suborders. At the moment it is only included as a subgroup of the Aquiturbel group.

Table 13.14 summarizes soil taxa that have been delineated in ice-free areas of the South Orkney and South Shetland Islands. The list is not all-inclusive. Six soil orders have been reported in the SOI and SSI, including Gelisols, Entisols, Inceptisols, Histosols, Mollisols, and Spodosols, which represent half of the orders in ST. Gelisols are predominant at elevations above 30–100 m where discontinuous permafrost exists. Gel-suborders and great groups are present below this elevation, e.g., Gelorthents, Gelepts, Gelods, and Gellols. One of the deficiencies of ST is that Histosols with permafrost below 1 m are classified in Cry-great groups; these soils should be classified in Geli great groups, e.g., Gelifibrists, Gelihemists, and Gelisaprists.

The most abundant great group is the Haploturbels, illustrating the important of cryoturbation in the SOI and SSI. Aquiturbels are also abundant, reflecting the effect of ice-cemented permafrost on drainage and the gleization process. Haplorthels are common on stable upland surfaces.

Figure 13.19 is a schematic of soil formation in maritime Antarctica. The descriptive model recognizes seven soil-

Table 13.14 Soils classified in different ice-free areas in the South Orkney and South Shetland Islands

Location	Ice-free area (km^2)	Latitude (°S)	Longitude (°W)	MAAT (°C)	MAP (mm)	Active layer depth (cm)	Soil taxa[a]	References
			Western Antarctic Peninsula					
South Orkney Islands (Coronation,		60° 43′	45° 38′	–3.5	400	40–220	Psammoturbels, Haplorthels, Haploturbels,	Holdgate (1970); Guglielmin et al. (2008)
(Laurie, Signy)	10+						Psammorthels, Histoturbels, Historthels,	
							Fibristels (7/7)	
South Shetland Islands								
Elephant, Clarence Islands	195+	61° 14′	55° 30′		>415	>75	Aquiturbels (3/3)	O'Brien et al. (1979)
King George Island	100	62° 14′	58° 40′	−2.0	635	50–180	Lithic Umbriturbels, Glacic Haploturbels, Lithic Fibristels, Psammentic Aquiturbels, "Sulfic" Haploturbels, Typic Haploturbels, "Ornithogenic" Haploturbels, Lithic Haploturbels, Typic Psammoturbels, Andic Umbriturbels, Terric Fibristels, Andic Cryofluvents (11/12)	Chen and Rlume (2000); Lee et al. (2004); Michel et al. 2006; Simas et al. (2006, 2007b, 2008); Schaefer et al. (2008); Bölter (1995, 2011)
Nelson, Robert, Greenwich Is.		62° 28′	59° 40′	−1.7		>100	Hydric "Gelifibrists", Lithic Gelorthents, Oxyaquic Humicryods, Lithic Haplogelolls, Lithic Eutrogelepts, Histic Gelaquepts (0/6)	ASPA,____
Livingston, Smith Is.	198+	62° 39′	60° 21′	−2.0	800	90–500+	Typic Haplorthels, Lithic Gelorthents, Typic Cryorthents, Typic Haploturbels, Typic Aquiturbels, Typic Humigelepts, Aquic Haploturbels (5/19)	Navas et al. (2005, 2008)
Deception Island	49	63° 00′	60° 30′	−2.0	500	25–90	Typic Haplorthels, Typic Umbrorthels, "Ornithogenic" Bockheim, unpubl. Umbrorthels, Typic Gelifluvents, Fluventic Haplorthels, Typic Gelorthents, Typic Haploturbels (24/28)	Bockheim, unpublished

[a]Soil Taxonomy (Soil Survey Staff 2010)

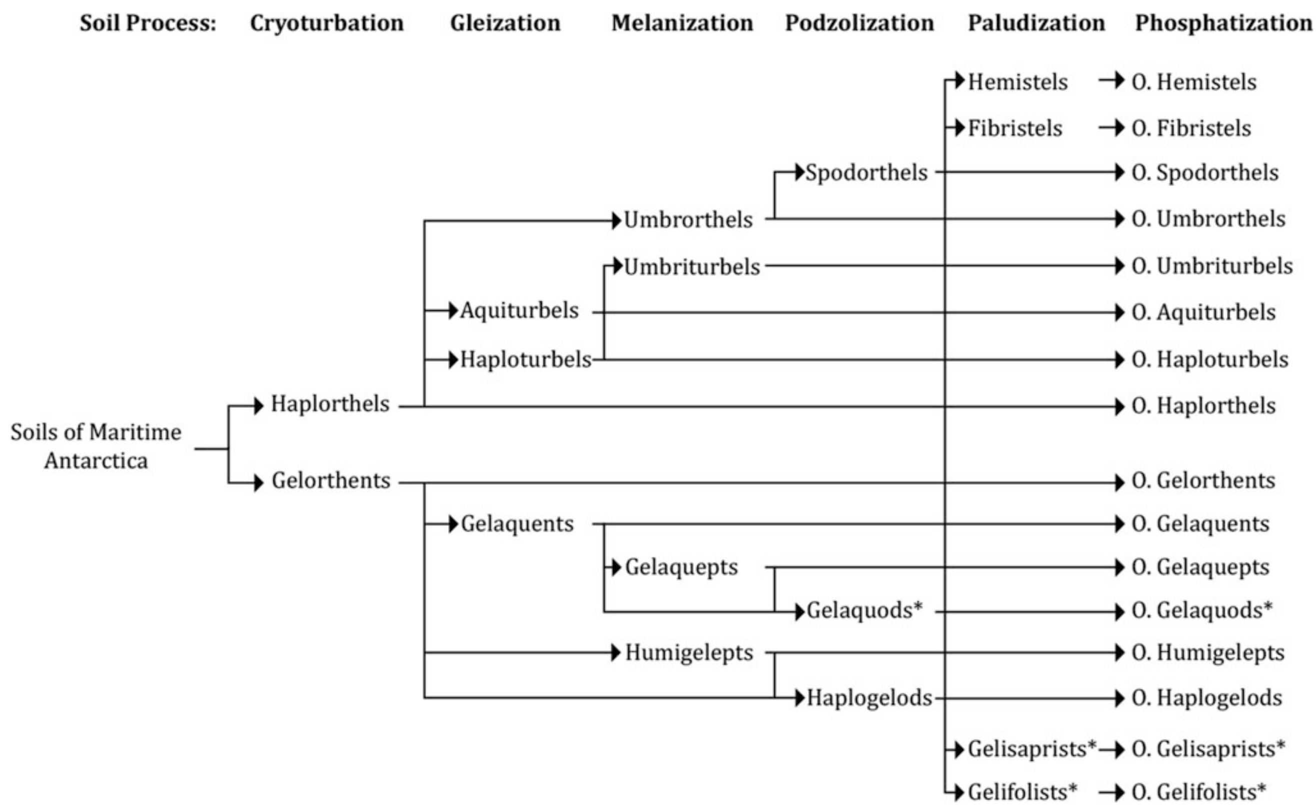

Fig. 13.19 Schematic of soil formation in Maritime Antarctica using Soil Taxonomy (Soil Survey Staff 2010). *Asterisk* indicates where the prefix "Gel" has replaced the prefix the "Cry"; Soil Taxonomy currently does not accommodate these soils. Spodorthels are proposed by Beyer et al. (2000) to identify Gelisols with spodic materials. O. abbreviates ornithogenic as proposed by Simas et al. (2007b)

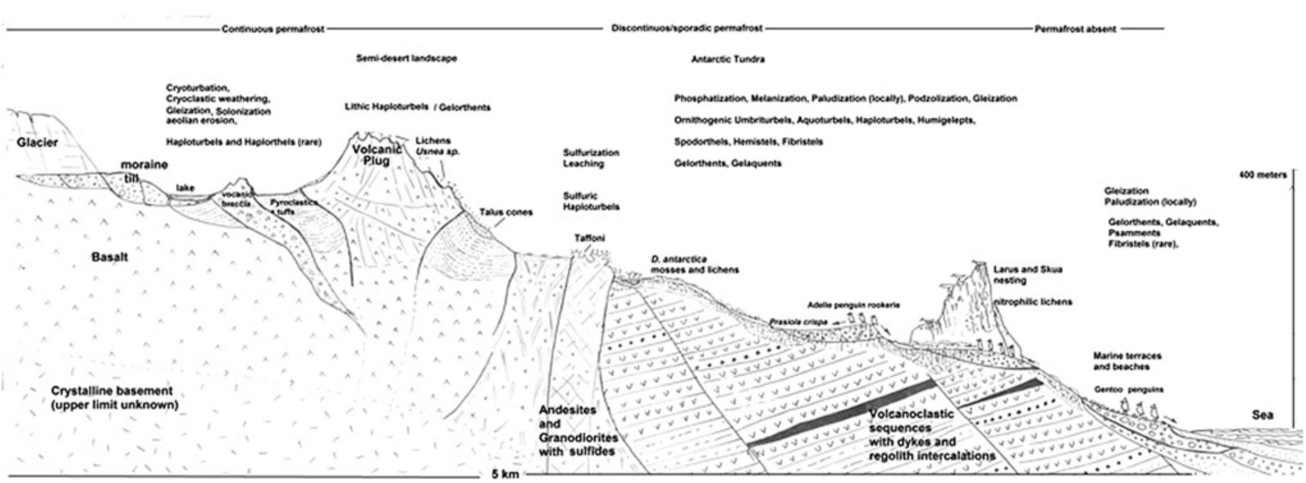

Fig. 13.20 Integrated diagram showing the distribution of soil-forming processes and soil taxa along a typical altitudinal sequence in the South Shetland Islands

forming processes, including cryoturbation, gleization, melanization, podzolization, paludization, and phosphatization and shows the dominant soil great group resulting from each process. Figure 13.20 shows the distribution of soil-forming processes and taxa along a typical altitudinal sequence in the SSI.

13.5.4 Future Prospects

A review of the recent literature suggests that more than 80 % of the pedologic studies in this region have been conducted on King George Island (KGI), where 11 stations representing 10 countries are located. In addition, we suggest the following topics of future research.

1. We need a more integrated view on SSI and SOI soils in relation to the thermal regime, since permafrost is either sporadic or discontinuous in most parts of these islands and does not follow a latitudinal gradient.
2. The relationship between soil-forming process and micromorphology deserved further attention, since it is one of the least used approaches to studying pedogenesis. This can further help to distinguish the chemical effects of weathering in contrast with mechanical processes.
3. The origin of organic matter in these soils should receive a strong emphasis in future studies, since it provides a unique set where lignin is in very low quantities, if present at all.
4. The influence of varying stoniness and shallowness of SSI soils is prominent and deserves attention for developing more appropriate methods for estimating SOM accumulation and chemical features in a complex of soils.

13.6 Summary

- Chemical weathering has a distinct role in soil formation in the SSI and SOI, notably in soils under bird guano influence and in sulfide-bearing rocks, where sulfate soils form.
- The presence of permafrost, intense cryoclastic weathering, and cryoturbation under a periglacial regime leads to a predominance of turbic soils (Turbels). However, clay formation, phosphatization, and organic matter accumulation also occur in stable areas where vegetation exists, allowing long-term stability, illuviation (podzolization), and soil horizonation.
- Cryptogamic vegetation, despite its low biomass and the dominance of saxicolous lichens and mosses, strongly acidifies the topsoil, generating organic acids that enhance chemical weathering; the volcaniclastic nature of the regional bedrock further facilitates chemical dissolution and clay formation.
- Soils of the SOI and SSI have a combination of unstable primary minerals and secondary minerals in the clay fraction, attributed to intense physical weathering.
- The amount of stones, gravels, and cobbles are normally high in this part of Antarctica and is directly related to the sedimentary/lithological nature of the bedrock. Tuffs, ashes, closely jointed volcanics, volcanic breccia, and sandstones are usually shattered into small fragments, whereas igneous rocks of plutonic origin are more resistant. Sulfide-bearing rocks are those which promote a greater clay formation and are dominated by poorly crystalline minerals (jarosite, ferrihydrite)
- The suite of soil-forming processes in the SOI and SSI are varied: acidification, podzolization, gleying, cryotubation, sulfurization, phosphatization, brownification—all suggesting a variety of soils according to the landscape position and the composition/nature of parent material.

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14 Soils of the Weddell Sea Sector, Antarctica

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14.1 Introduction

The Antarctic Peninsula (AP) marks the climatic transition between maritime and dry subpolar Antarctica. The western side of the AP has a mean annual air temperature (MAAT) between –2.7° and –3.4 °C, with up to two months with temperatures above freezing, and a mean annual precipitation (MAP) ranging from 400 to 800 mm, with some of the precipitation falling as rain. In contrast the eastern side of the AP has a MAAT between –5.5 and –9.4 °C, with no monthly temperature above freezing, and a MAP of 200–250 mm, all of which falls as snow (Table 2.2). These climate differences are due to the fact that the AP, which projects out into the Pacific Ocean, acts as a barrier to oceanic and atmospheric thermal exchange generated by the westerly Antarctic Circumpolar Current (Turner et al. 2009).

Terrestrial ecosystems on the western side of the AP have 100–1000 m^2 patches of continuous vegetation that include not only mosses, lichens, and algae, but also two grasses (*Deschampsia Antarctica and Colobanthus quitensis*), the only vascular plants reported in Antarctica. In contrast, land surfaces on the Weddell Sea islands are nearly completely devoid of plants (Fretwell et al. 2011).

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14.2 Regional Setting

There are 16 islands in the Weddell Sea sector, four in the Joinville Island Group and the rest in the James Ross Archipelago (Fig. 14.1). Collectively, these islands occupy around 6500 km^2, of which only 4 % is ice free (260 km^2). The largest ice-free areas are James Ross Island (isolated areas totalling 90 km^2), Seymour Island (77 km^2), and Vega Island (80 km^2). The maximum elevations of the islands vary considerably, ranging from 200 m a.s.l. on Seymour Island to 1640 m on James Ross Island, which has a local ice cap (Fukui et al. 2008).

14.3 Soil-Forming Factors

The mean annual temperature varies with elevation and ranges between –5.5 °C at Marambio Base on Seymour Island (5 m a.s.l.) to –9.4 °C on James Ross Island (200 m a.s.l.). At Marambio Station December is the warmest month (–1.5 °C) and June is the coldest (–15 °C). The mean annual, water equivalent precipitation is 200–250 mm, all of which falls as snow (Ermolin et al. 2004).

Permafrost is continuous throughout the Weddell Sea islands (Ermolin et al. 2002), with thicknesses ranging from 6 m at the lower elevations to 200 m at higher elevations (Fukada et al. 1992; Borzotta and Trombotto 2004). The thickness of the active layer ranges between 0.35 and 1.45 m and averages 0.60–0.70 m (Koizumi and Fukuda 1989; Fukuda et al. 1992; Borzotta and Trombotto 2004; Fukui et al. 2008).

The Joinville Island Group is a geological continuation of northeast Graham Land, and the islands are comprised of Carboniferous sandstones, shales, graywackes, siltstone, and conglomerates of lower to middle Jurassic age and volcanic rocks of upper Jurassic age (Elliot 1967). The rocks have been intruded by gabbros from the Cretaceous through the Tertiary.

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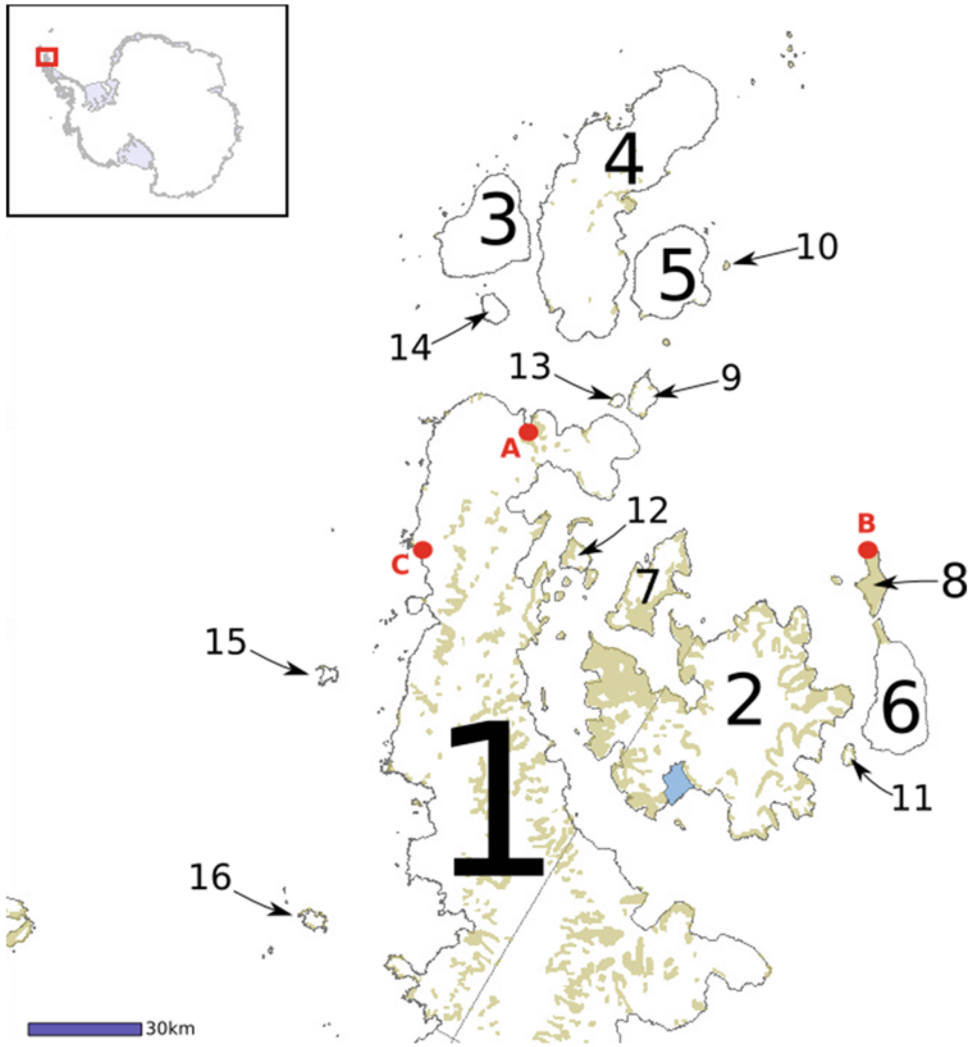

Fig. 14.1 Antarctic Peninsula (*1*) and the eastern offshore islands, including James Ross (*2*), D'Urville (*3*), Joinville (*4*), Dundee (*5*), Snow Hill (*6*), Vega (*7*), Seymour (*8*), Andersson (*9*), Paulet (*10*), Lochyer (*11*), Eagle (*12*), Jonassen (*13*), and Bransfield (*14*) (*Source* Wikipedia)

The more southerly James Ross Island Group is comprised of Jurassic and upper Cretaceous rocks dominated by sandstones that are overlain by sedimentary rocks of Tertiary age that are cut by basaltic dikes (Zinsmeister 1982). On Seymour Island some of the early to middle Tertiary (Paleocene) rocks include the fossiliferous and carbonate concretion-bearing La Meseta formation, the Cross Valley formation deltaic complex, the laminated siltstones and glauconite-rich sandstone of the Sobral formation, and sulfide–and bitumen-rich siltstones of the Lopez Bertodano formation (Macellari 1988).

From geomorphological data and a numerical ice sheet model, Bentley et al. (2010) demonstrated the West Antarctic Ice Sheet thinned by 230–480 m in the Weddell Sea embayment since ca. 15 ka. In addition to Last Glacial Maximum (LGM) glacial deposits, alpine glaciers on James Ross Island have fluctuated at least three times during the Holocene (Hjort et al. 1997). Most of the ice-free areas in the Weddell Sea islands emerged 9.4–7.6 ka so that the soils likely are of early to middle Holocene age.

Several of the islands contain distinct marine terraces; James Ross Island has seven terraces ranging from 0.75–1 to 100 m, and Seymour Island has five terraces ranging between 1–2 and 200 m a.s.l. (Borzotta and Trombotto 2004; Fukui et al. 2008). Patterned ground in the form of ice wedge polygons is ubiquitous in the islands (Koizumi and Fukuda 1989; Fukuda et al. 1992), and rock glaciers have been reported on James Ross Island (Fukui et al. 2008) and Vega Island (Ermolin et al. 2002).

14.4 Soils of the Weddell Sea Islands

Soil studies in the Weddell Sea islands are very recent (Souza 2012; Spinola 2012; Gjorup 2013; Souza et al 2014). Together, they described and sampled 44 pedons. Only six of the 44 pedons (14 %) had ice-cemented permafrost within 100 cm of the surface, and seven of the soils (16 %) were cryoturbated. Soil depth ranged from 20–120 cm and averaged 84 cm. Some of the soils contained salt flecks

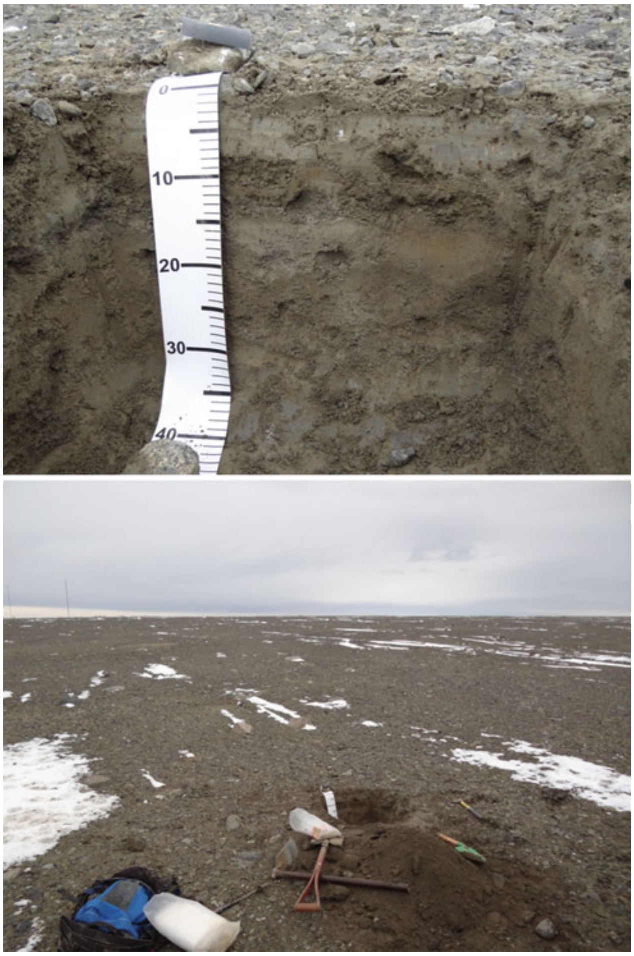

Fig. 14.2 Pedon MP 20 and associated semidesert landscape on uplands of the La Meseta, Formation, Seymour Island

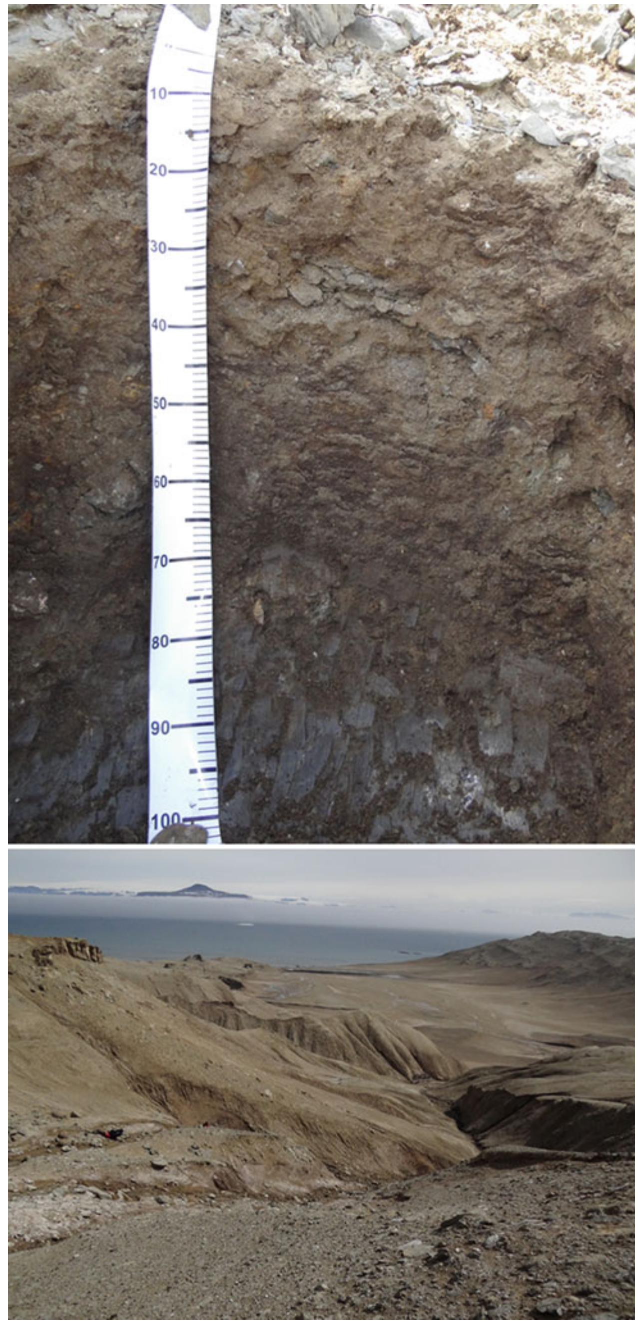

Fig. 14.3 Pedon MP 08 and associated semidesert landscape on scree slope on the La Meseta Formation, Seymour Island

indicating salt enrichment (Fig. 14.2); some were influenced by penguins (Fig. 14.3); and others have redoximorphic features and contain abundant sulfides (Fig. 14.4).

Based on morphological chemical and physical characteristics, they were able to identify three main soil groups on Seymour Island: (i) alkaline soils on sandstones and siltstones, (ii) ornithogenic soils, and (iii) acid sulfate soils. The first group of soils were slightly alkaline to very strongly alkaline (pH 7.5–9.1), were slightly to strongly saline (EC = 3.6–48 dS m^{-1}), and often were sodic (Na saturation = 12–60 %) (Table 14.1). In addition, the alkaline soils were 100 % base saturated and contained minimal exchangeable Al. The soils had low levels of Mehlich-1 extractable P (10–100 mg dm^{-3}) and low amounts of organic C in the surface horizon (0.26–0.98 dg kg^{-1}). The soils had primarily loam and sandy loam textures.

The acid sulfate soils were slightly acid to strongly alkaline (pH 6.0–9.0) in the upper horizons but were extremely acid (pH 3.3 to 4.5) in the sulfide-bearing subsoil (Table 14.1). These soils are very slightly saline (EC = 1.0–4.5 dS m^{-1}) and often sodic (Na saturation = 4–50 %). Acid sulfate soils were strongly base saturated (78–100 %) in the upper horizons, but decreased to low base saturation in the lower horizons (37–92 %). The soils had low levels of Mehlich-1 extractable P (13–170 mg dm^{-3}) and low amounts of organic C in the surface horizon (0.33–0.91 dg kg^{-1}), increasing in the lower horizons (0.91–1.4 dg kg^{-1}). The soils had primarily loam and sandy loam textures.

The third group of soils, the ornithogenic soils, were moderately acid to neutral (pH 5.6–6.8), very slightly to

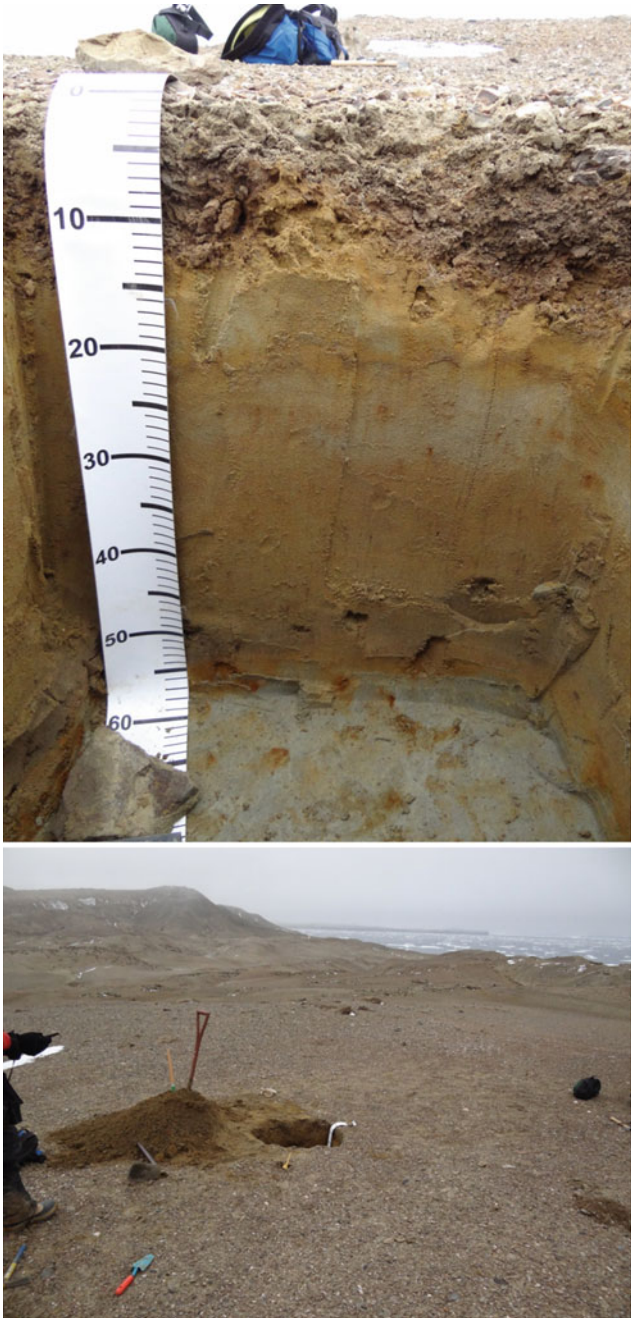

Fig. 14.4 Pedon MP 20 and the associated semidesert landscape on a gentle mid-slope on the La Meseta Formation, Seymour Island. The soil features sulfide accumulation

moderately saline (EC = 2.5–9.0 dS m^{-1}), and often sodic (Na saturation = 1.4–41 %). These soils were completely saturated with bases and had very high levels of extractable P, especially in surface horizons (1000–2000 mg dm^{-3}). In addition, organic C concentrations were high in surface horizons (1.7–9.8 dg kg^{-1}). The soils had sandy loam textures.

Table 14.1 Properties of 21 soils from Seymour Island (adapted from Souza et al. in 2014)

Property	Alkaline	Acid sulfate	Ornithogenic
Pedons	P1-P3, P6, P9, P13-P16, P20	P4, P5, P7, P17- P19, P21	P8, P10-P12
Mean depth (cm)	87	87	98
Mean pH	7.5–9.1	6.0–9.0/3.3–4.5	5.6–6.8
Mean extr. P, surface (mg dm^{-3})	10–100	13-170	1,000–2,000
Mean Al sat. %)	0	0/23–51	0
Mean base sat. (%)	100	78-100/37–92	100
Mean na sat. (%)	12–60	4–50	1.4–41
Elect. conduct. (dS m^{-1})	3.6–48	1.0–4.5	2.5–9.0
Organic C, surface (dag kg^{-1})	0.26–0.98	0.33-0.91/ 0.91–1.04	1.7–9.8
Textural class	L, SL	L, SL	SL

These data suggest that the dominant soil-forming processes in soils of the Weddell Sea islands are desert pavement formation, salinization, alkalization, phosphatization, and acidification from sulfurization (Fig. 2.12).

In view of the youthful stage of these soils, it is unlikely that they contain dry-frozen permafrost. Moreover, the mild climate, relatively abundant moisture, and common gleying of the soil do not suggest anhydrous conditions. Therefore, alkaline soils on sandstones and siltstones are Typic (Salic) Haplorthels where there is permafrost in the upper 1 m, and Gelorthents where permafrost is below this depth (Table 14.2). The acid sulfate soils are Typic (Sulfuric) Aquorthels or Gelaquents, depending on permafrost depth. The ornithogenic soils are Typic (Ornithogenic) Haplorthels or Gelorthents. Cryoturbated soils would be Typic (Sulfuric) Aquiturbels or Gelaquents, depending on permafrost depth.

We suggest that sulfuric ornithogenic subgroups should be recognized in ST to address soils markedly influenced by sulfurization and phosphatization.

Table 14.2 Proposed classification of soils on Seymour Island

	Depth to permafrost table	
Group	>1 m	<1 m
Alkaline	Typic (Salic) Gelorthents	Typic (Salic) Haplorthels
Acid sulfate	Typic (Sulfuric) Gelaquents	Typic (Sulfuric) Aquorthels
Ornithogenic	Typic (Ornithogenic) Gelorthents	Typic (Ornithogenic) Haplorthels
Cryoturbated		Typic Aquiturbels

14.5 Conclusions

Soils of the Weddell Sea islands comprise only a small portion of the ice-free area of Antarctica. However, they are important soils because they link the wet maritime soils of the western AP with the cold and semiarid soils along the East Antarctic coast. Three general soil groups were identified on Seymour Island, which constitutes the single largest ice-free area in the region (77 km^2): alkaline soils on sandstones and siltstones, ornithogenic soils, and acid sulfate soils. Depending on depth to permafrost, the soils would be classified as Gelorthents or Haplorthels Gelaquents or Aquorthels, and Gelorthents or Haplorthels, respectively. Cryoturbated soils would be classified as Aquiturbels.

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15 Human Impacts on Soils

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15.1 Introduction

Antarctic soils are vulnerable to disturbance due to their physical properties and naturally slow recovery rates that are suppressed by low temperatures and low availability of liquid moisture (Campbell et al. 1998a; O'Neill et al. 2013a). As most human activities are concentrated in relatively small ice-free areas, particularly in the Ross Sea region and Antarctic Peninsula, the potential for adverse human impacts on the soil landscape is great. Ice-free areas are home to the majority of the historic huts, research stations, and biologically rich sites, and thereby attract a short influx of visitors each summer. Consequently, as human visitation is on the increase, concerns about cumulative effects and about the ability of the most frequented sites to recover after human disturbance are also increasing.

Antarctic soils generally lack structural development and coherence, and the loose material is covered by a thin protective layer of gravel and coarse sand known as desert pavement. Desert pavements play an important role in the desert system, acting as protective armour to stabilise both the slope and the soil (McFadden et al. 1987; Bockheim 2010). Once the desert pavement is disturbed, underlying finer, loose material is susceptible to wind erosion. The subsurface material beneath the desert pavement includes the active layer and permafrost. The active layer is the layer of soil material (above the permafrost) that is subject to annual or diurnal cycles of freezing and thawing (Campbell et al. 1994). Permafrost is the material beneath the soil active layer that remains perennially frozen for at least two consecutive years (Grosse et al. 2011). The presence of permafrost is an important soil property with implications for landscape stability if disturbance leads to melting.

The prevailing low temperatures, low humidity, freeze-thaw cycles, and salinity of Antarctic soils combine to create a harsh environment for plant and animal life. Although few animals and plants have managed to colonise and survive in the soil, bacteria are distributed throughout.

15.2 History of Human Activity

15.2.1 Early Explorers

Impacts of human activities on the Antarctic environment date back to the arrival of the first explorers. The early explorers, and onset of whaling, brought the construction of the first permanent structures, and sustained human presence on the continent. The Heroic Era (1895–1917) comprised at least eight expeditions in the Ross Sea region, and many others elsewhere in Antarctica. As a consequence, the Heroic Era teams, with leaders such as Borchgrevink, Scott, Shackleton, Mawson, and Amundsen, left relics, including huts (Fig. 15.1), relating to human discovery of the continent. They carried out geographic and scientific exploration, collecting plant, animal and rock specimens, mapping previously undiscovered areas. Also, with them, came the first legacies of environmental impacts.

15.2.2 National Programmes and Scientific Visitors

The upsurge in scientific activity of the early 1900s was reignited in the International Geophysical Year (IGY), of 1957/58, and the intensity and diversity of human activities in Antarctica have increased, along with the risk of disturbance to Antarctic flora, fauna and landscapes. Three

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Fig. 15.1 Shackleton's Nimrod Hut at Cape Royds (*Photo* Taken January 2010 by Megan Balks)

year-round scientific bases were established as a result of IGY, McMurdo Station (U.S.A) and Scott Base (New Zealand), and they are examples of two of the larger permanent stations, with combined summer populations of approximately 1,700 individuals (Waterhouse 2001). Many other national research stations have been established since the 1950s, scattered around the continental margins, but concentrated on the Antarctic Peninsula with increasing personnel involved. It is estimated that from 1957 until 2001, approximately 70,000 people have been involved in scientific research and logistic support in the Ross Sea region (Waterhouse 2001); an estimate likely to be approaching 90,000 in 2013. Many scientists visit the Antarctic Peninsula; however, tourists make up a larger proportion of the visitors in the relatively accessible Antarctic Peninsula region.

Land-based research activities are diverse and have included solid earth geophysics, biological sciences, drilling projects, climatology and environmental sciences. Terrestrial scientific research continues to occur and can involve soil pit digging, rock and soil sampling and equipment installation. Legacies of the last 60 years of scientific investigation and human occupation are scattered at isolated sites across Antarctica, particularly in areas close to the major research stations and semi-permanent field camps (Campbell et al. 1993; Tin et al. 2009; Kennicutt et al. 2010).

15.2.3 Tourist Visitors

Tourism on the Antarctic continent dates back to 1891, when the first tourists were passengers on resupply ships to the sub-Antarctic islands. Antarctic tourism, as it is practised today—expeditions in large vessels that enable many small groups to land using small boats, such as "zodiacs"—was initiated in 1966 when passengers were ferried around the Antarctic Peninsula. Tourist activities in Antarctica are based largely around visiting historic huts, research stations, and seal and penguin breeding sites. Some sites, such as Whalers Bay on Deception Island (Fig. 15.2), experience up to 14,000 visitors over a short summer tourist season (International Association of Antarctic Tour Operators 2013). Antarctic-wide visitor numbers peaked in the 2007/2008 season with 46,265 tourists (and approximately 32,000 landings), and have since dropped to 25,284 tourists for the 2012/2013 season (International Association of Antarctic Tour Operators 2013).

The first Ross Sea region tourist ship carried 24 passengers to Scott Base and McMurdo Station in January 1968. The nature of tourism in the Ross Sea region—long journeys on board icebreaker vessels, high expense, inaccessibility of some sites due to sea ice, and lesser abundance of wildlife compared with the Antarctic Peninsula—keep Ross Sea region tourist numbers to an average of 400 landing passengers per season (International Association of Antarctic Tour Operators 2013). Ross Sea region tourism accounts for approximately 2 % of annual Antarctic tourism.

15.3 Types of Human Impacts

There are many human impacts visible in the Antarctic terrestrial environment. Such impacts have included landscape modification as a result of construction activities, geotechnical studies, and roading (Campbell et al. 1993, 1994; Harris 1998; Kiernan and McConnell 2001; Kennicutt et al. 2010); disturbance to soil communities (Naveen 1996; Harris 1998; Tejedo et al. 2005, 2009; Tin et al. 2009 and

Fig. 15.2 Historic structures at Whaler's Bay on Deception Island (*Photo* Taken January 2013 by Tanya O'Neill)

references therein); local pollution from hydrocarbon spills (Aislabie et al. 2004 and references therein; Kim et al. 2006; Klein et al. 2012); waste disposal (Claridge et al. 1995; Sheppard et al. 2000; Snape et al. 2001; Santos et al. 2005); and the introduction of alien species (Frenot et al. 2005; Cowan et al. 2011; Chown et al. 2012).

All activities in Antarctica are regulated through the national administrative and legal structures of the countries active in the region, underpinned by the international legal obligations resulting from the Antarctic Treaty System.

15.4 The Antarctic Treaty System

15.4.1 Overview

The Antarctic Treaty was signed in Washington DC on 1 December 1959 by the 12 nations active in Antarctica during the International Geophysical Year (1957/58). The Treaty established the guiding principles for all activity in Antarctica. In response to increasing concern over rapidly rising tourism in the late 1980s and early 1990s, and the need to harmonise and adopt a more comprehensive Antarctic-wide environmental protection framework, the Protocol on Environmental Protection to the Antarctic Treaty (hereafter referred to as the Madrid Protocol) was formulated and adopted for signature in Madrid in October 1991. The Madrid Protocol designates Antarctica as "a natural reserve devoted to peace and science".

The Madrid Protocol brings together existing environmental recommendations adopted through the Antarctic Treaty system through a series of technical annexes which outline specific rules for the protection of the Antarctic environment. Annex I of the Madrid Protocol requires that before any activity is conducted the possible environmental impacts need to be assessed. The other four annexes deal with conservation of flora and fauna, waste disposal, prevention of marine pollution and protected areas. The Madrid Protocol also mandates the protection of the wilderness and aesthetic values of Antarctica.

By ratifying the Madrid Protocol, countries signalled their commitment to ensuring Antarctic activities comply with its standards. Independent environmental audits of national programme activities are undertaken to assess the level of compliance with the Protocol and identify areas which could be improved.

15.4.2 Environmental Impact Assessment

Environmental Impact Assessment (EIA) was introduced in Article 8 of the Madrid Protocol and requires persons responsible for an activity in Antarctica to predict its significance and likely environmental impacts (Committee for Environmental Protection 2005). The EIA process is undertaken at one of three levels, depending on the nature and scale of the activity (from Antarctica New Zealand undated):

(1) **Preliminary Environmental Evaluations (PEE)** are processed at the national level and required where impacts are likely to be less than minor or transitory;
(2) **Initial Environmental Evaluations (IEE)** are notified to the Antarctic Treaty Parties and required where impacts are likely to be minor or transitory; and
(3) **Comprehensive Environmental Evaluations (CEE)** are considered by the Antarctic Treaty Parties and required where impacts are likely to be more than minor or transitory.

Project leaders must assemble and analyse information on the potential environmental effects the proposed activity may have and how the potential impacts can be best prevented or mitigated. For activities where a CEE is necessary, such as the multinational Cape Roberts Drilling Project (1997–1999) in the Ross Sea region of Antarctica, the draft CEE was made publically available and considered by the Committee for Environmental Protection (established to advise parties on implementation of the Protocol). A key aspect of the Madrid Protocol, and mandatory for any activity requiring a CEE, is the requirement to regularly monitor impacts caused during a project (Hughes 2010; Kennicutt et al. 2010). Ideally, monitoring should include ongoing assessment of the levels of physical disturbance to terrestrial environments, record levels of pollutants (noise, dust, chemical spills, etc.) and the impacts of pollutants to local ecosystems. Biodiversity studies should also be undertaken so introduced non-native species can be identified and eradicated (Hughes and Convey 2010).

The International Association of Antarctic Tourism Operators was founded to "advocate, promote, and practise safe and environmentally responsible private-sector travel to the Antarctic", and over the course of the last few decades has worked alongside specialists to establish extensive guidelines for tourism including: site inventories in the Antarctic Peninsula (Naveen 1996); regulations and restrictions on the number of tourists ashore; safe staff-to-passenger ratios; and contingency and emergency evacuation plans (International Association of Antarctic Tour Operators 2012).

15.4.3 Wilderness and Aesthetic Values

The Madrid Protocol mandates the protection of wilderness and aesthetic values. Wilderness values are conventionally thought of as relating to large natural areas undisturbed by human activity. Aesthetic values relate to a person's perception of scenic beauty (Summerson and Bishop 2012). The wilderness and aesthetic values of a landscape are clearly influenced by human activity and in particular whether the activity is permanent, such as a station, or minor transitory activity, such as small field camps. Article 3 of the Madrid Protocol, Environmental Principles, states the following:

> 1. The protection of the Antarctic environment and dependant and associated ecosystems…including wilderness and aesthetic values,… shall be fundamental considerations in the planning and conduct of all activities in the Antarctic Treaty area.
> 2. To this end:
> (a) activities in the Antarctic Treaty area shall be planned and conducted so as to limit adverse impacts on the Antarctic environment and dependant and associated ecosystems;
> (b)… so as to avoid: … (iv) degradation of, or substantial risk to, areas of biological, scientific, historic, aesthetic or wilderness significance (Secretariat of the Antarctic Treaty 1991).

Despite the inclusion of wilderness and aesthetic values under the protocol, there is no formal definition in the Antarctic Treaty System of how these values should be defined in the context of Antarctica (Summerson and Bishop 2011).

15.5 Landscape Modification

15.5.1 Sources of Disturbance

Disturbance to Antarctic desert pavement surfaces has historically occurred from a number of sources. Vehicles and bulldozers (Broadbent 1994; Campbell et al. 1994) undertake earthmoving, the overturning of large cobbles, and indentation and compression of sub-pavement soils (Fig. 15.3). Disturbances also result from activities such as telecommunications antennae and pipeline installation; active layer removal for road or fill material (Balks et al. 1995, 2002); scientific investigation (Campbell et al. 1993; Kiernan and McConnell 2001); and lower level disturbance

Fig. 15.3 Earth moving equipment preparing a building site adjacent to Scott Base is an example of the most intense scale of disturbance that occurs near permanent bases (*Photo* Taken January 2004 by Megan Balks)

from camping and pedestrian traffic (Campbell et al. 1993, 1998a; Tejedo et al. 2005, 2009). Antarctic desert pavement surfaces are easily disturbed and disturbance can have long-lasting visible impacts on the Antarctic landscape (Campbell and Claridge 1987; Campbell et al. 1993, 1998a, b; Kiernan and McConnell 2001).

15.5.2 Impacts on Soil Physical and Chemical Properties

At Marble Point, in the Ross Sea region of Antarctica, earthworks were conducted in the late 1950s and early 1960s, after which the site was abandoned. Removal of the seasonally thawed (active) layer resulted in retreat of the permafrost table and consequent thawing of the ice contained in the upper part of the permafrost (as a new equilibrium was established forming a new active layer). Lowering of the ground surface, slumping and release of salts that were contained within the permafrost were observed (Campbell and Claridge 1987; Campbell et al. 1994; Balks et al. 1995). Forty years after disturbance, patterned ground cracks were seen to extend through cut or scraped materials, such as bulldozer cut tracks, whereas most fill material showed little sign of new patterned ground formation. The lack of patterned ground cracks in fill material was attributed to lower ice content in the fill material, which became the upper, newly formed, permafrost layer (Campbell et al. 1994, 1998b). In the Ross Sea Region at many “cut” sites, where permafrost melting occurs, salt accumulated on the new ground surface (Fig. 15.4).

Physical disturbance in the landscape from lower impact activities, such as walking, is greatest where there is a pebble surface pavement and the soils have a low proportion of coarse materials (Campbell et al. 1993, 1998a). During a treading trial undertaken on two contrasting parent materials in the Wright Valley of the McMurdo Dry Valleys, Campbell et al. (1998a) observed no disturbance where the surface was bedrock. On the softer till material, after as few as 20 passes, a clear walking track formed. The 1993 treading trial tracks were revisited in 2011 by O’Neill et al. (2013a) and the walking track on the softer till material was still obvious 17 years after it was formed. The colour difference associated with disturbance had disappeared (likely to be a result of wind removing the finer material exposed at the surface); however, displacement of coarser particles to the margins of the track and the recontouring with raised edges and lower centre of the track remained visible (Fig. 15.5).

Fig. 15.4 Surface slumping and salt accumulation is evident on a track formed by a bulldozer that removed the active layer leading to melting and subsequent evaporation of salt-rich permafrost ice; the white material that is visible is salt, not snow (*Photo* Taken January 2009 by Megan Balks)

Disturbances on active surfaces, such as gravel beach deposits, aeolian sand dunes, and areas where meltwater flows occur, recover (visually) relatively quickly (Roura 2004; McLeod 2012; O'Neill et al. 2012a, b, 2013a). Roura (2004) reported the relatively quick recovery of the active sandy beach gravels at the former Greenpeace World Park Base site at Cape Evans. On revisiting the site, O'Neill et al. (2013a) reported natural-looking beach gravel deposit over the entire site with no obvious visible evidence of the previous habitation. The beach-worked loose gravel at the site had been readily resorted by surface wind, water, freeze-thaw and snowmelt and run-off processes.

Campbell and Claridge (1975, 1987) recognised that older, more weathered, desert pavements and associated underlying soils, were the most vulnerable to physical human disturbance. McLeod (2012) produced a 1:50,000-scale soil vulnerability map for ice-free areas in the Wright Valley of the McMurdo Dry Valleys, based on a rapid method to assess the impact of foot trampling. McLeod based his assessment on the impact score (occurrence of boot prints) from 10 footsteps, and identified areas of high, medium, and low, classes of soil vulnerability within the Wright Valley. Strongly weathered soils, as well as material with a high silt content in the layer below the desert pavement, were deemed highly vulnerable, whereas aeolian sand dunes, while readily disturbed (Fig. 15.6), quickly recover and were thus considered of low vulnerability (McLeod 2012).

15.5.3 Factors Influencing Desert Pavement Recovery

Wind action, through the processes of deflation (wind gusts and air turbulence detaching and lifting loose particles from the soil surface), transportation (surface creep, saltation or suspension), and finally deposition (Hillel 1998), is likely to be the primary driver of desert pavement recovery

Fig. 15.5 An experimental treading trial on a fan near Lake Vanda in the Wright Valley illustrates the longevity of a walking track formed on gravelly sand fan materials. *Top* Site immediately after 200 walking passes in 1993. *Bottom* Same site revisited 17 years later in 2011. The pale coloured material visible on the track in photo b is fine sediment deposited by a recent fan-building event (*Photos* Megan Balks)

(Campbell and Claridge 1987; Campbell et al. 1998a, b). The midday heating of a dry soil surface and the microtopography are known to influence wind strength (Hillel 1998) and therefore the inputs of energy available to regenerate disturbed surfaces. The intermittent supply of water, and freeze-thaw action also contribute to surface sorting and, therefore, recovery following disturbance (McFadden et al. 1987; Campbell and Claridge 1987; Haff and Werner 1996). The rate and extent of desert pavement recovery can be attributed to the active surface processes in combination with factors including the intensity of the initial disturbance, properties of the soil material, and also the restoration and remediation efforts undertaken at the site.

At most sites wind is likely to be the instigator in the first stages of formation of an incipient desert pavement and thus the rehabilitation of disturbed desert pavement. In instances of low level disturbance, such as impacts from tent sites, wind action is likely to result in natural infilling of footprints and sorting of surface materials to recreate the surface armouring of coarser material, and thus recovery of randomly trampled areas. Wind action, however, was not sufficient to redistribute larger clasts that lined the margins of foot tracks, formed by repeatedly walking the same route, or vehicle tracks in the Dry Valleys dating back to the 1970s (Fig. 15.7) (O'Neill et al. 2013a).

The intermittent supply of moisture from snowmelt may assist desert pavement recovery at sites in moist coastal climatic zones. Repetitive freeze-thaw action may also aid recovery, and, over time, jostle surface clasts into a more embedded position in the desert pavement surface and infill impressions of removed clasts (O'Neill et al. 2013a). In drier zones, such as in the McMurdo Dry Valleys, further from the coast, moisture available for soil surface processes is less, and visible surface recovery is generally not as advanced as equivalent intensity disturbances in moister areas (Campbell et al. 1998a; O'Neill et al. 2013a).

Campbell et al. (1993) developed a means of rapidly assessing sites that had been impacted by human activity which was called a *visual site assessment* (VSA). A VSA rates the extent of surface disturbance against 11 impact assessment criteria, such as extent of disturbed surface stones, evidence of boot imprints, and evidence of foreign objects, as a means of comparing disturbance severity across different sites. The cumulative impact of a disturbed site is also rated and is described as the "total visual cumulative impact from the various individual impact assessment criteria" (Campbell et al. 1993). Campbell et al. (1998a) showed that the unconsolidated nature of many Antarctic surface materials means visible tracks form quickly, but increased usage of the formed tracks does not add greatly to impacts, and most visible impacts occur quickly and at low

Fig. 15.6 Foot prints on a sand dune will be quickly obliterated as wind moves sand across the ground surface (January 2010) (*Photo* Taken January 2010 by Jeronimo López-Martínez)

levels of use (O'Neill 2013; O'Neill et al. 2013a). Thus, where repeated use is likely over a long period, from this study it is expected that the overall impact will be less if a track is allowed to form and then used repeatedly. However, without rehabilitation, any track formed will remain visible for many decades.

15.6 Disturbance to Fauna and Flora

Soil ecosystems in the Antarctic terrestrial environment are characterised by low and fluctuating temperatures, high aridity, low precipitation, low moisture availability, desiccating winds, high exposure to UV radiation, and often low levels of organic matter (Campbell and Claridge 1987; Wynn-Williams 1990). Mean annual soil temperatures can range from –15 to –40 °C; however, during the continuous daylight of the summer months, surface soils are subject to large daily temperature fluctuations and near-surface soil temperatures can reach 20 °C (Balks et al. 2002). The lack of plant roots and limited available water in some areas mean that carbon and nutrients are not translocated easily down the soil profile and, as a result, the dominant food web, including bacteria, is limited to the near-surface environment (Wall and Virginia 1999). Despite the hostile environment, Antarctic mineral soils can harbour bacterial numbers of up to 10^9 cells g^{-1} dry soil (Aislabie et al. 2008; Cannone et al. 2008; Ganzert et al. 2011).

In polar climates high spatial variability in soil abiotic factors can exist, and the structure of bacterial communities has been observed to be controlled predominantly by soil pH (Yergeau et al. 2007; Aislabie et al. 2008, 2011; Chong et al. 2012), soil salinity (Aislabie et al. 2006; O'Neill et al. 2013b), soil moisture (Aislabie et al. 2006; Barrett et al. 2006; Cary et al. 2010; Ganzert et al. 2011), and nutrient availability (Barrett et al. 2006; Hopkins et al. 2006; Sparrow et al. 2011). Microbes are sensitive to the concentration of soluble salts in soils and past studies have shown that high

Fig. 15.7 Vehicle wheel marks are still evident in the Wright Valley (*left* at ground level and *right* from the air) over 40 years after the last vehicle travelled in the area (*Photos* Taken December 2009 by Megan Balks)

salinity reduces microbial biomass (Wichern et al. 2006), amino acid uptake and protein synthesis (Norbek and Blomberg 1998), and reduces soil respiration (Gennari et al. 2007). Ross Sea region soils contain high levels of soluble salts, and small pulses of water from a snowfall event (Ball et al. 2011; Ball and Virginia 2012), or an influx resulting from human disturbance to underlying permafrost (such as the removal of the permafrost-insulating soil active layer and consequent thawing of the salt-rich ice contained in the upper part of the permafrost), can create unfavourable habitats for soil biota, releasing salts into the soil profile or accumulating salts at the ground surface (Campbell et al. 1993, 1998a; Balks et al. 1995).

In all soil communities, disturbances or environmental changes that indirectly affect soil physical and chemical properties can have a detrimental impact on the soil biota (Wall and Virginia 1999). The impacts of human activities can adversely affect different levels of biological organisation, from larger scale localised habitats to community structure, to the individual species themselves through physiological stress. Few scientific reports (apart from those describing impacts of hydrocarbon spills—see Sect. 15.7.3.3) have described the effects of human disturbance on biota, particularly microbial communities, in Antarctica.

Tejedo et al. (2005, 2009) conducted a series of trampling experiments on vegetation-free soils in the South Shetland Islands in the Antarctic Peninsula and documented increases in soil compaction and decreases in the abundance of soil arthropods under different trampling regimes.

One of the most widespread terrestrial fauna in the Ross Sea region are nematodes, with specimens found in 56 % of soil sampled in the McMurdo Dry Valleys and Ross Island (Freckman and Virginia 1997). The influence of soil salinity on population dominance was recognised in soil nematode studies in the McMurdo Dry Valleys (Wall and Virginia 1999). Nematode *Scottnema lindsayae* exhibited the greatest salinity tolerance of three species found in the Dry Valleys, with drier, more saline, and disturbed sites, being dominated by or solely occupied by *S. lindsayae* (Wall and Virginia 1999). Ayres et al. (2008) compared nematode populations (abundance, ratio of living to dead individuals and dominant species) in tracks used continuously for 10 years during summer months with those used for 2 years. Ayres et al. (2008) showed increased nematode mortality, lower abundances and a greater level of physical disturbance to the surface of tracks, which were used at higher intensities and at longer durations, compared with newer tracks and control areas.

Few reports have described the effects of human activity on Antarctic flora; however, it is evident that where high concentrations of scientific bases and infrastructure occur, such as the Fildes Peninsula on King George Island, there are many areas of damaged vegetation (Antarctic and Southern Ocean Coalition 2004). Evidence from sub-Antarctic islands has shown that trampling has impacted on plant species and soils. Impacts include track widening, vegetation degradation, species replacement and soil compaction (Scott and Kirkpatrick 1994; Gremmen et al. 2003; Hughes 2006).

No investigation into the effect of human activity on lichen or moss distribution has been reported in the Ross Sea region; however, it is assumed that past and present day activities around major stations, such as Scott Base, including use of bulldozers and vehicles will have influenced the spatial distribution of local populations.

Algae and cyanobacteria are probably the major primary producers in many parts of Antarctica and occur in any wet area on, under and beside stones, and in endolithic communities. The 'lithic' environment (in, around, under stones) can provide some protection for microbial communities, particularly from wind scouring (Wynn-Williams 1990), UV exposure (Cockell et al. 2008), thermal extremes (Wynn-Williams 1990) and desiccation (Broady 1981; Chan et al. 2013). Human activity, such as vehicle and bulldozer use, resulting in the overturning of large cobbles, can inevitably disturb lithic habitats and adversely affect the communities within. Campbell et al. (1998a) noted impacts from vehicle use to cyanobacterial mats and microbial cryptobiotic soil crusts in the McMurdo Dry Valleys and Marble Point areas. Surface salt accumulations, often associated with surface disturbances, are unlikely to be readily colonised by organisms (Campbell et al. 1998a). However, in areas where available water is plentiful, for instance wetland areas at Marble Point, bulldozed during the late 1950s, algae and mosses have become re-established (Campbell et al. 1994; O'Neill 2013).

Little is known about the impact of human activities on microbes. Surface trampling could dislodge surface particles that protect the soil interface thus exposing underlying soil to changes in soil temperature, moisture and freeze-thaw patterns, which would effectively modify the habitat for microbes (Wall 2007). Moderate-scale disturbances, such as vehicle movement, have the potential to impact on soil physical properties such as bulk density, and thus on soil macro- and microporosity. Through the loss of aggregate stability and the reduction of pore space, compaction has been shown to affect soil microbial communities in temperate localities by impacting on soil water-holding capacity and aeration (Schimel and Parton 1986; Zabinski and Gannon 1997). Changes to soil respiration, decomposition rates and the availability of nutrients may result, thereby affecting functioning of the entire soil ecosystem.

Drivers of Antarctic soil bacterial community structure are predominantly soil EC, soil pH, soil moisture and nutrient availability (Barrett et al. 2006; Yergeau et al. 2007; Aislabie et al. 2008, 2011; Arenz et al. 2011; Ganzert et al. 2011; Chong et al. 2012), which, if disturbed, may cause a shift in bacterial community structure. Soil disturbance that would affect ecosystem functioning near the soil surface (for example Ayres et al. (2008) reported declines in nematode abundance with increased surface compaction from human trampling) could also have an indirect effect on ecosystem functioning at greater depths. Declines in nematode abundance could be due to shifts in bacterial diversity and abundance. O'Neill et al. (2013b) investigated the short-term effects of human disturbance on soil bacterial community structure at an experimental site near Scott Base. They found that the simulated disturbance (removal of the top 2 cm of soil) did not cause any major shifts in the structure of the bacterial communities over the 35 day sampling period. The distinct bacterial communities across the study site reflected differences in spatial variability in soil EC, soil pH and soil moisture content. However, the authors noted that they would expect a disturbance of sufficient intensity to affect the properties mentioned above, could cause a shift in bacterial community structure, over and above the time frame measured in their experiment. There are many unanswered questions relating to the impacts of human disturbances on soil biota, and investigations incorporating DNA–RNA-based analyses and CO_2 efflux studies may lead to greater understanding.

15.7 Chemical Contamination

15.7.1 Sources of Chemical Contaminants

Chemical contamination of Antarctic soils from abandoned waste disposal sites and past fuels spills is a legacy from when environmental management was less stringent before the ratification of the Madrid Protocol in 1991 (Bargagli 2008). The Madrid Protocol provides guidelines for comprehensive environmental management and protection and established the obligation to remediate abandoned sites. Subsequently, many countries that maintain research stations in Antarctica have improved management practices and developed strategies to reduce environmental disturbances, including mitigating past impacts. There is no detailed inventory of contamination in Antarctica; however, the amount of contaminated soil and waste has been estimated at 1–10 million m^3 (Snape et al. 2001). Contaminants most often reported in Antarctic soils are heavy metals and hydrocarbons (Tin et al. 2009). Fuel spills are the most common incidents and have the potential to cause the greatest environmental harm in and around the continent (Aislabie et al. 2004). The presence of persistent organochlorine pollutants in Antarctica has been attributed to long-range atmospheric transport from lower latitudes (Bargagli 2008).

15.7.2 Heavy Metals

Human activities can contaminate soils with heavy metals, but as heavy metals also occur naturally, it can be difficult to distinguish between natural and anthropogenic sources. Elevated levels of metal concentrations have been reported at sites of current or former scientific research stations, especially those areas used for waste disposal or affected by scattered rubbish (Fig. 15.8) or emissions from incinerators or fuel spills (Claridge et al. 1995; Sheppard et al. 2000; Webster et al. 2003; Santos et al. 2005; Stark et al. 2008; Guerra et al. 2011). The highest reported concentrations of metals were detected in soils collected near the site of the former British Base (Trinity House) at Hope Bay on the Antarctic Peninsula (Guerra et al. 2011). For the most impacted site, concentrations of copper (Cu) reached 2,082 mg kg^{-1}, lead (Pb) reached 19,381 mg kg^{-1} and zinc (Zn) was up to 5,225 mg kg^{-1}. Similarly, high levels were reported for waste soil from the Thala Valley landfill at Casey Station, East Antarctica (Stark et al. 2008). At the Thala Valley site, concentrations of total and leachable metals in excavated soil were used to classify the waste for treatment and disposal before transportation to Australia. At other sites, reported levels of heavy metal contamination are considerably lower. For example, Claridge et al. (1995) detected elevated levels of Pb (28.5 mg kg^{-1}) in soil near a crushed battery and Cu (10.6 mg kg^{-1}) in soil sampled from beneath copper wire, at Marble Point, the site of a former USA research station. A detailed investigation of soils at New Zealand's Scott Base has revealed areas contaminated with silver (Ag), cadmium (Cd), Pb, Zn and arsenic (As) (Sheppard et al. 2000). Silver contamination was attributed to disposal of photographic chemicals, whereas As contamination, particularly in surface soils, was attributed to emissions from the incinerator that was operational at Scott Base and has since been decommissioned. Pb in soil could also derive from emissions from the incinerator and spillage of leaded fuel. Elevated levels of methyl lead have been detected in soil from a former fuel storage site at Scott Base (Aislabie et al. 2004 and reference therein).

Fig. 15.8 Metallic rubbish (since removed) from a 1960s era camp at Marble Point, Antarctica was a source of contamination of underlying soil materials (*Photo* Taken January 1990 by Megan Balks)

Once deposited on soil, heavy metals may be mobilised by snowmelt. Claridge et al. (1999) investigated the capacity for soluble contaminants to move through Antarctic soils. Lithium chloride was irrigated into plots of contrasting climate and parent material and soils were subsequently sampled over several years at varying depths to detect movement of the contaminant through the soil. Claridge et al. (1999) showed meltwater facilitated the movement of soluble contaminants down-profile and laterally across the permafrost surface. Webster et al. (2003) investigated the behaviour of heavy metal contaminants at the site of former Vanda Station on the shores of Lake Vanda in the McMurdo Dry Valleys. Some contaminants were susceptible to leaching (e.g. Zn, Cu, Cd and Ni). However, as the area of contamination was small and the concentration of contaminants was low the authors considered the risk to water quality in the lake to be negligible.

15.7.3 Hydrocarbon Spills

15.7.3.1 Occurrence and Characterisation of Hydrocarbon Spills

Hydrocarbon spills on Antarctic soils occur mainly near the scientific research stations where fuel is transported and stored in large quantities and where aircraft and vehicles are refuelled (Aislabie et al. 2004 and references therein; Klein et al. 2012).

Characterisation of the hydrocarbon contaminants in Antarctic soil has revealed that *n*-alkanes predominate with lesser concentrations of the more toxic aromatic and polyaromatic compounds. Naphthalene and methylnaphthalenes are the dominant aromatic compounds detected (Aislabie et al. 2004; Kim et al. 2006) reflecting the chemistry of the fuels, such as JP-8 and JP-5, used and hence spilled in Antarctica (Klein et al. 2012). JP-8 has about 80 % *n*-alkanes in the range of C_6–C_{18}, with a maximum at C_{12}, and 18 % aromatics with <0.5 % PAHs having three or more rings (Ritchie 2003).

At some spill sites, residual hydrocarbons are detected predominantly as an unresolved complex mixture (UCM) (Aislabie et al. 2004 and references therein; Klein et al. 2012). UCM can derive from a number of sources including lubricating oils, motor oils or from severely biodegraded or weathered oils (Frysinger et al. 2003). When spilled on Antarctic soils, hydrocarbons can undergo a number of fates including dispersion, evaporation and biodegradation (Aislabie et al. 2004). The observed persistence of hydrocarbons over decades, however, indicates that biodegradation rates must be low under in situ conditions.

15.7.3.2 Impacts of Hydrocarbon Spills on Soil Properties

Hydrocarbon spills impact on soil chemical, physical and biological properties. Antarctic mineral soils are generally low in carbon and nutrients and therefore, hydrocarbon spills can increase soil carbon concentrations but can further deplete nitrogen and phosphorus when they are assimilated during biodegradation. Hence, soil C:N ratios of >70 have been measured in contaminated sites, whereas those in control sites were <17 (Aislabie et al. 2012).

Monitoring of soil temperature in hydrocarbon-contaminated and control sites at Scott Base and Marble Point in the Ross Sea region indicate that during summer fine weather, when the soils are snow free, the daily maximum surface temperature of the hydrocarbon-contaminated sites may be up to 10 °C warmer than adjacent control sites (Balks et al. 2002). The higher temperatures were attributed to decreased soil albedo from surface darkening by hydrocarbon contamination (Fig. 15.9). There is also evidence that fuel spills impact on soil moisture regimes through increased hydrophobicity (Balks et al. 2002).

15.7.3.3 Impact of Hydrocarbons on the Soil Microbial Community

Introduction

Most investigations of the impacts of hydrocarbon spills on soil biological properties have focused on bacteria. There has been little consideration of the impacts of hydrocarbons on fungi, archaea, photosynthetic microbes, and invertebrates in Antarctic soils. Filamentous fungi and to a lesser

Fig. 15.9 Measurement of albedo on a surface darkened as a result of an oil spill about 40 years prior to the photo being taken (*Photo* Taken January 2001 by Megan Balks)

extent yeasts from the Ascomycota phylum are commonly associated with petroleum contamination in Antarctic soils (Hughes et al. 2007). However, there is limited understanding of those Antarctic species that are not just tolerant to, but are capable of degrading, hydrocarbons.

Soil Bacterial Community Structure

Hydrocarbon spills on Antarctic soils can enrich hydrocarbon-degrading bacteria within the indigenous microbial community (Delille 2000; Aislabie et al. 2004). Cultured hydrocarbon degraders can reach $>10^5$ colony forming units (CFUs) g^{-1} contaminated soils; in contrast, numbers of hydrocarbon degraders are often low or below detection limits in pristine soils. The detection of hydrocarbon mineralisation activity in Antarctic soil, albeit in the laboratory, indicates that the hydrocarbon degraders can be active in situ, conditions permitting (Aislabie et al. 2012; Okere et al. 2012).

Both culture-dependent and -independent methods have been employed to determine the impacts of hydrocarbon contamination on the diversity of bacterial communities in Antarctic soils. Total community DNA extracted from control and hydrocarbon-contaminated mineral soil from near Scott Base on Ross Island (Saul et al. 2005) and ornithogenic soil from Cape Hallett (Aislabie et al. 2009) have been used to prepare 16S rRNA gene clone libraries. In the mineral soil, members of the phyla Acidobacteria, Bacteroidetes, Deinococcus/Thermus, Firmicutes and Candidate TM7 dominated control soils, whereas the contaminated soils were dominated by Proteobacteria only. Similarly, Proteobacteria were dominant in hydrocarbon-contaminated soil from King George Island (Foong et al. 2010). In contrast, both control (abandoned) and contaminated ornithogenic soil was dominated by Proteobacteria (Aislabie et al. 2009). Hydrocarbon spills on mineral soil can lead to a decrease in overall soil bacterial diversity (Saul et al. 2005; Chong et al. 2009; Foong et al. 2010), whereas, for ornithogenic soil, an increase in bacterial diversity was detected in the surface organic soil layer but a decrease in the subsurface mineral layer (Aislabie et al. 2009). Proteobacteria prevalent in hydrocarbon-contaminated mineral soils were assigned to Alpha-, Beta- and Gammaproteobacteria, specifically members of the genera *Sphingomonas*, *Sphingobium* (formerly included in *Sphingomonas*), *Pseudomonas* or *Variovorax* (Saul et al. 2005). Members of the Actinobacteria were found in both hydrocarbon-contaminated and control soils. However, whereas *Rubrobacter* were most prevalent in the control soil from Scott Base, *Rhodococcus* spp. were prevalent in the hydrocarbon-contaminated soil (Saul et al. 2005). In ornithogenic soil, Gammaproteobacteria dominated the control (abandoned) and contaminated soil (Aislabie et al. 2009), with those dominating the control soil most closely related to *Rhodanobacter* or *Dokdonella*, and those in the contaminated soils related to *Alkanindiges* and *Psychrobacter*.

Culturing hydrocarbon degraders from Antarctic soils has resulted in the isolation of members of the phyla Proteobacteria (e.g. *Acinetobacter*, *Sphingomonas*, *Sphingobium, Alkanindiges* and *Pseudomonas*) and Actinobacteria (e.g. *Rhodococcus* and *Gordonia*). Alkane degraders assigned to *Rhodococcus* are frequently isolated from Antarctic soil (Aislabie et al. 2006). *Rhodococcus* spp. strains 7/1, 5/1 and 5/14 grew on a range of alkanes from hexane (C_6) to eicosane (C_{20}) and the methylated compound pristane (2,6,10,14-tetramethyl-pentadecane) (Bej et al. 2000). In contrast, *Sphingobium* sp. Ant 17, degraded numerous compounds in the aromatic fraction of crude oil, jet fuel and diesel fuel (Baraniecki et al. 2002), and utilised many aromatic compounds for growth, including *m*-xylene, naphthalene and its methyl derivatives, and the PAHs fluorene and phenanthrene.

Hydrocarbon-degrading bacteria isolated from Antarctic soils are commonly cold tolerant rather than psychrophilic. They grow at low temperatures (<10 °C) but have an optimum growth temperature > 15 °C. Some of the isolates (e.g. *Rhodococcus* spp.) produce biosurfactants to enhance hydrocarbon degradation (Aislabie et al. 2006 and references therein).

Investigations of Hydrocarbon-Degradative Genes in Bacteria

Functional genes encoding enzymes for hydrocarbon degradation from bacterial isolates have been used to design probes for the presence of microbes with genetic potential to degrade hydrocarbon contaminants in Antarctic soils (Whyte et al. 2002; Luz et al. 2004; Flocco et al. 2009; Jurelevicus et al. 2012a, b). Total DNA extracted from soils near the Brazilian Station Comandante Ferraz on King George Island and cultured bacteria were screened for alkane degradation potential using primers or probes for four alkane monooxygenase genotypes from *Pseudomonas putida* (Pp *alkB*), *Rhodococcus* spp. (Rh *alkB1* and Rh *alkB2*) and *Acinetobacter calcoaceticus* (Ac *alkM*). These analyses revealed that Rh *alkB1* and Rh *alkB2* homologues are common in both contaminated and control soils, and Rh *alkB1* was more prevalent in culturable psychrotolerant bacteria. Pp *alkB* homologues were commonly detected in contaminated soil but Ac *alkM* homologues were rare (Whyte et al. 2002). Based on their results, Whyte et al. (2002) proposed that *Rhodococcus* is the predominant alkane degrader in both control and contaminated Antarctic soils, while *Pseudomonas* may become enriched by the presence of contaminant hydrocarbons, and *Acinetobacter* is rare.

With respect to the genes for aromatic degradation, Ma et al. (2006) found that catabolic genes from several aromatic-degrading psychrotolerant *Pseudomonas* isolates from contaminated Antarctic soils were close matches to those described in mesophilic bacteria. The aromatic degradation genes were either plasmid or chromosomally located. Various PAH degrading isolates carried the *ndo* gene encoding naphthalene dioxygenase on a large self-transmissible plasmid that could be transferred to mesophilic strains (Ma et al. 2006). This indicates that horizontal gene transfer might play a role in transfer of hydrocarbon degradation genes from outside Antarctica to indigenous species. Probing soil DNA extracts have revealed the presence of the archetypal catabolic genotypes *ndoB* and/or *xylE* (encoding 2,3-catechol dioxygenase) in various contaminated soils (Luz et al. 2004; Flocco et al. 2009). Examination of the diversity of the *ndoA* genes in the soil indicated they were most closely related to those from *Pseudomonas* (Flocco et al. 2009). Recently, the alpha-subunit of the PAH ring hydroxylating diooxygenases from Gram-positive and Gram-negative bacteria were characterised in control and oil-contaminated soils from King George Island (Jurelevicus et al. 2012b). The PAH diooxygenases detected in the soil were diverse and included those most closely related to diooxygenases described in *Proteobacteria* (e.g. *Sphingomonas*, *Burkholderia*, *Pseudomonas*) *Actinobacteria* (e.g. *Mycobacterium*, *Nocardioides*, *Rhodococcus*) and *Firmicutes* (e.g. *Bacillus*). Clearly, based on what we know from culturing bacteria from Antarctic soils, there is still much to learn about the catabolic potential of hydrocarbon-degrading bacteria in the Antarctic environment.

15.8 Introduction of Foreign Organisms

15.8.1 Introduction

The geographic, oceanic and atmospheric isolation of the Antarctica terrestrial environment, combined with harsh environmental conditions, provides a barrier to colonisation by terrestrial biota. However, this barrier can be overcome through both scientific and tourist activities in the Antarctic, as well as through the actions of vectors such as wind or migrating birds. With warming potentially leading to changes in habitat in some areas, and increased visitor numbers, the Antarctic is increasingly recognised as being vulnerable to the establishment of alien species.

The likelihood of invasions depends on the numbers of propagules of non-indigenous alien species entering the region, their probability of establishment, and the extent to which they able to spread and alter local ecosystems (Chown et al. 2012).

15.8.2 Plants and Invertebrates

There is evidence that alien plants and other taxa can successfully colonise Antarctic soil ecosystems and once established can spread (Frenot et al. 2005). The alien species, annual bluegrass *Poa annua* was initially recorded in 1985/1986 in the vicinity of the Polish Antarctic station Arctowski on King George Island. *Poa annua* has recently colonised moraines of the retreating Ecology Glacier (Olech and Chwedorzewska 2011), and has since also been reported at three different locations near scientific research stations on the Antarctic Peninsula (Molina-Montenegro et al. 2012). A laboratory experiment was conducted to investigate the effect of *P. annua* on the native pearlwort and hairgrass. It was revealed that the presence of *P. annua* reduced both the biomass and photosynthetic performance of the native species (Molina-Montenegro et al. 2012). In contrast to *P. annua*, *Poa pratensis* introduced to Cierva Point, Antarctic Peninsula, during 1954/1955 has increased in size, but has not yet spread (Pertierra et al. 2013).

Two flowering plants *Nassauvia magellanica* and *Gamochaeta nivalis* have been discovered near a ruined whaling station on Deception Island (Smith and Richardson 2011). As the plants were found near areas of high visitor frequency, and are both wind-dispersed and cold temperature species, it is difficult to determine if the colonisation was natural or a direct result of human activity. Six non-indigenous species of springtails have been recorded at Deception Island and only one elsewhere in maritime or continental Antarctica (Greenslade and Convey 2012). Greenslade and Convey (2012) suggested that high numbers of visitors combined with relatively benign terrestrial habitats, associated with areas of geothermal activity, promote invasion of alien species on Deception Island.

A flightless midge (*Eretmoptera murphyi*) and an enchytraeid worm (*Christensensenidrilus blocki*) were accidentally introduced to Signy Island with plant and soil material from South Georgia in the 1960s (Frenot et al. 2005). Although the midge has only spread slowly, following growth rate and microhabitat climatic modelling, Hughes et al. (2013) report that it could be dispersed to other locations in Antarctica by human activity.

Chown et al. (2012) carried out an Antarctic-wide evaluation of the risks of invasion by vascular plants. They sampled, identified and mapped vascular plant propagules carried by visitors to Antarctica during the field season 2007/2008 and assessed the risk of their establishment based on the identity and origin of the propagules and spatial variation in the Antarctic climate. Visitors carrying seeds averaged about 9.5 seeds per person, with scientists carrying a greater load than tourists. Their analyses revealed that the alien species establishment is currently most likely for the Western Antarctic peninsula. Should marked warming occur, the risk will increase in the Antarctic Peninsula, Ross Sea and East Antarctic coastal regions.

15.8.3 Microbes

The significance of microbial introduction and establishment in Antarctic soils is of increasing concern but there are few data available (Cowan et al. 2011 and references therein). Furthermore, although the application of molecular tools is revealing the extent of microbial diversity in Antarctic soils, it currently remains difficult to differentiate between microbes that might have been introduced to the soils with human activities from those that are naturally occurring.

The potential for introduction of non-indigenous microbes into Antarctic terrestrial ecosystems is high. Microbes are continually dispersed into and around Antarctica by wind and birdlife (Hughes and Convey 2010). Humans visiting Antarctica also release microbes by shedding skin, sneezing, coughing and hair loss. Similarly, the food and equipment used to support human activities on the continent also serve as a source of microbial contamination. Once released into the environment it is usually assumed that microbes of human origin, being mesophiles with a temperature optimum of ca 37 °C, are unlikely to survive, let alone become established, under in situ conditions. DNA, however, can survive in polar soils (Ah Low and Cowan 2005) and may be transferred to indigenous organisms by lateral gene transfer as suggested by Ma et al. (2006).

Of particular concern is the risk of introducing pathogens to wildlife, such as penguins, which can then spread (Kerry and Riddle 2009). It is difficult, however, to prove human activities as the source of infection when birds or mammals may travel between continents and pick up infections as they go (Frenot et al. 2005).

Blanchette, Farrell and colleagues have investigated the role of non-indigenous fungi in the biodeterioration of historic huts, and described the fungi that colonised the huts, artefacts and surrounding areas (Arenz et al. 2006; Duncan et al. 2008; Blanchette et al. 2010; Farrell et al. 2011). The material brought to Antarctic to support construction of the huts and activities of the early explorers was undoubtedly contaminated with fungi. Investigations of the fungi involved in biodeterioration has revealed that while some of the fungi may have established themselves in the soils (Arenz et al. 2006) others are likely to be indigenous, such as *Cadophora* spp. (Blanchette et al. 2004, 2010).

More recently concerns have been raised about the possibility of transferring microbes within the continent (Tin et al. 2009). Such transfers have the potential to contaminate unique ecosystems and pose a serious threat to the validity of molecular ecology studies (Cowan et al. 2011).

15.9 Cumulative Impacts

Cumulative impacts refer to individual and often minor impacts that may be significant when repeated over time (Harris 1998). With expansion of scientific expeditions and their supporting logistics, as well as the increase in tourism and non-governmental activities, there is concern about the cumulative impacts of smaller scale human activities. At vulnerable sites even short duration visits by small numbers of people can cause negative environmental impacts. When individually assessed, each activity may have little impact; however, together such impacts may amount to a substantial cumulative impact. Cumulative environmental impacts are difficult to address under the current environmental management systems in Antarctica, as single-event-based methods of EIA do not address activities that have happened previously in the same area.

Experimental treading trials (Campbell et al. 1998a) have shown that once a track has formed (within 20 or so passes) the cumulative impacts of larger numbers of people following the same track (20 passes, vs. 200 passes, vs. 2000 passes) are minimal. The width of the formed track, number of surface boulders and cobbles, and % area of pale colour exposed, were all impacted most in the first 20 passes of the track (Campbell et al. 1998a). Cumulative impacts on biota are unknown but are likely to affect biodiversity and ecosystem functioning (Wall 2007).

Researchers from the largest scientific station in Antarctica, McMurdo Station (Fig. 15.10), have documented the evolution of the aerial extent of the area impacted by the station, since base construction, through aerial photographs and satellite imagery (Kennicutt et al. 2010). The cumulative impacts of station activities expand rapidly in spatial extent over the first decade of occupancy, after which the station continued to expand at a slower rate (Kennicutt et al. 2010). The spatial extent of physical disturbance at McMurdo Station has been stable for more than 30 years. A similar evolution of environmental footprint is evident at the nearby Scott Base.

15.10 Management of Impacts

15.10.1 Introduction

The ice-free areas visited by humans are small, relative to the Antarctic continent as a whole, and impacts occur as isolated pockets among largely pristine Antarctic wilderness. The most intense and long-lasting visible impacts occur around the current and former research bases, and are remnants of

Fig. 15.10 The footprint of McMurdo Station, the largest Antarctic Base, while relatively large, has not increased markedly since the 1980s. The footprint extends beyond the buildings with hillsides repeatedly scraped and the active layer removed to provide fill material for base building activities (*Photo* Taken January 2010 by Megan Balks)

late 1950s through to the 1970s activity (Campbell and Claridge 1987; Webster et al. 2003; Kennicutt et al. 2010; O'Neill 2013). Since the 1980s when environmental accountability, enhanced environmental management, and environmental awareness increased the environmental footprint of stations such as Scott Base and McMurdo Station on Ross Island, these impacts have remained static or decreased (Kennicutt et al. 2010). Since the ratification of the Madrid Protocol in 1991, environmental awareness has increased and the standard of prevention of human impacts undertaken by many Antarctic programmes is high.

Contemporary occurrences of chemical contamination from waste disposal and fuel spills are few and far between due to the stringent management practices national programmes and tourist operators now have in place to prevent harm to the environment. Antarctic Treaty parties have introduced additional guidelines to avoid and minimise human impacts. As a consequence, visitors take responsibility for their footprint on the environment, and there is a high level of consistency between predicted impacts and actual impacts on the ground (O'Neill et al. 2012a).

Jabour (2009) states that it is often misleading to compare the relative environmental pressure exerted by the Antarctic national programmes and tourist sectors as a function of simple statistics (number of visitors in each sector). In the 2007/2008 season, over 73,000 people visited Antarctica as part of a tourism operation (tourists, staff and ship crew), whereas about 4,000 people visited as part of national programmes. However, the numbers do not represent the relative environmental pressure of the two sectors, as the number of person days ashore for the national programme personnel equates to approximately 675,000 days, while tourists in the 2007/2008 season accounted for about 32,000 person days ashore (Jabour 2009). The majority of Antarctic tourism is ship-based, with no permanent infrastructure. Short shore day trips are facilitated using small boats. In contrast, most people visiting as part of national programmes live in a permanent onshore structure, can spend several months ashore, some camping in remote, previously unvisited places. It is not just the scale of the presence or number of people involved that influence the risk of impacts to the terrestrial environment, but also the types of activities and where they occur. For example operations that involve many flights between low latitudes and Antarctica can create opportunities for the introduction of non-native species (Jabour 2009).

15.10.2 Managing Impacts from Landscape Modification

The longer lasting "worst case scenarios" of past physical disturbances are what we see left in the landscape today and are the subject of recent studies. There are many instances where the intensity of disturbance was low, such as widespread trampling around a tent site, and natural recovery has been such that there is no remaining visible evidence of previous impacts (O'Neill et al. 2013a).

O'Neill et al. (2012a) undertook five case studies of past EIA reporting in the Ross Sea region of Antarctica, ranging from former research stations to field campsites, to compare the impacts predicted in the EIA with observed impacts after the event. In all cases there was a high level of consistency between predicted and observed impacts. It was apparent that the environmental impact assessment process raised the environmental awareness of visitors, motivating them to avoid, remedy or mitigate, their environmental impacts.

Recent research (e.g. Campbell et al. 1993; McLeod 2012; O'Neill et al. 2013a) into the ability of different parent materials, and varying degrees of active surface processes, to recover from impacts has contributed to better informed decisions on site selection, and impact mitigation. For example opting to concentrate activity on active and readily recoverable surfaces or on resilient bedrock is likely to lead to less long-term visible impacts. In some instances, such as one-off campsites, medium-term visual impacts may be minimised by avoiding formation of walking tracks by walking in a random widespread fashion (O'Neill et al. 2013a). In other areas, where slopes are steep and repetitive use over long periods will occur, or where extensive moss and lichen communities are present, use of pre-existing tracks, or concentration of activity to form just one track, will cause less cumulative impact (O'Neill et al. 2013a; Pertierra et al. 2013).

Site remediation (raking and smoothing of disturbed surfaces to free up compacted soil, and redistribute out of place stones) can be effective and led to accelerated *visual* recovery of desert pavement surfaces (O'Neill et al. 2013a). By redistributing larger stones and raking the margins of walking tracks that result from field camps the visual aesthetic of a site is restored by eliminating unnatural surface irregularities. Larger stones, such as those used to pin down tents should be replaced in original orientations with salt-coated surfaces down and polished or weathered surfaces up, preferably in the indentations from which they were removed. Site rehabilitation needs to be undertaken with an understanding of the rock material's natural position in the environment. While the natural stratigraphy of a site cannot be restored, it is possible to mimic the natural geomorphology, and thus reduce visual impacts and longer term changes to geomorphic processes (Kiernan and McConnell 2001).

Although raking will enhance the visual aesthetics of a site there is a question of whether by the activity of raking we are further damaging the remaining microbial communities living in the surface material. The impacts of remedial measures on residing biota have yet to be investigated, so caution must be used as we also have an obligation under Annex II [Article 1(d) and 1(h)] of the Madrid Protocol to protect soil biota. Value judgments must be considered, particularly whether potential adverse impacts to biota outweigh the longer term positive visual effects of site restoration. Where moderate to high-intensity disturbances have changed the contour of the land and the disturbance is likely to change drainage patterns and other geomorphic processes in the longer term, raking the disturbed area may be the best option to ensure ecosystems down-slope of the disturbance are not adversely affected.

The Antarctic Site Inventory (ASI) commenced in 1994 to collect baseline information necessary to detect possible changes in the physical and biological variables. Regular monitoring of selected variables is undertaken to determine how best to minimise or avoid possible environmental impacts of tourism and non-governmental activities in the Antarctic Peninsula area (Naveen 1996). Over the first 17 seasons the ASI made 1,156 site visits and collected census and descriptive data at 142 Antarctic Peninsula locations, including repeated visits to the most heavily visited sites in the Antarctic Peninsula.

Information collected by ASI includes descriptions of key physical and topographical characteristics of the site, distribution of flora, and discrete groups of breeding penguins and flying birds. Variable site information includes weather and other environmental conditions biological variables (number of occupied nests, number of chicks per occupied nest, ages of chicks), and the nature and extent of any observed visitor impacts (footprints or paths, cigarette butts, film canisters, and litter). Photo documentation is carried out and used to compare between visits.

Currently there are no ASI sites in the Ross Sea region of Antarctica; however, Antarctica New Zealand administers a visitor site assessment scheme (VISTA), which aims to support the EIA process and address the shortfall of information on the cumulative impacts of visitor activity through a site monitoring programme. Assessors use a series of booklets, maps, and photographs to help orientate themselves at a site, and GPS waypoints to locate photo and ground disturbance monitoring sites. Annual replication of fixed photo points allows changes such as site recovery, or cumulative disturbance, over time to be monitored. Ground disturbance or "terrestrial impact visual assessments" are also carried out at all landings on ice-free areas using the visual site assessment method of Campbell et al. (1993). Where possible the assessment is carried out before the visitors land and repeated after their visit has been completed. Information on wildlife, vegetation, evidence of previous ground tracking, and other observations are also collected to give an overview of the environmental sensitivities of the site. Currently, 20 sites in the Ross Sea region are part of the VISTA monitoring programme (Antarctica New Zealand 2009), including the frequently visited sites at Cape Evans, Cape Royds, and the Taylor Valley Visitor Zone in the McMurdo Dry Valleys.

The Fildes Peninsula region, on the south-western part of King George Island, South Shetland Islands, on the Antarctic Peninsula, has six permanent Antarctic stations. It is a special case in Antarctica where different interests, from scientific research, station operations, transport logistics, and tourism, regularly overlap in space and time (Braun et al. 2012). Conflicts of interest between multiple users sometimes occur, as well as breaches in the environmental obligations outlined in the Madrid Protocol. There have been recent cases where the level of EIA undertaken by some national programmes has not always been appropriate for the likely level of impact, and in one instance an IEE indicating "minor and transitory" impacts was prepared for the expansion of a station, but the work resulted in destruction of beach ridges (Braun et al. 2012).

Tourists visit the Fildes Peninsula on flights operated by a Chilean air company. However, the tourists strictly follow the ASI site guidelines, and the local environmental impact of tourism was considered to be lower than the impact of national programme personnel (Braun et al. 2012). A potential solution for increasing coordinated environmental management and reducing the conflict of interests between national programmes is the designation of the Fildes Peninsula region as an Antarctic Specially Managed Area (ASMA). An ASMA, much like the McMurdo Dry Valleys ASMA (No. 2) (Antarctic Treaty Consultative Meeting 2011), is the best way to minimise the negative effects of human activities in the area, and provide stakeholders with effective management tools, such as an integrated management plan, codes of conduct for each facility zone and scientific research, and a management group to coordinate activities in the ASMA.

15.10.3 Managing Impacts to Flora and Fauna

Annex II of the Madrid Protocol on conservation of flora and fauna controls interference with native animals or plants and prohibits the introduction of any non-native species to Antarctica.

Article 1(h) of Annex II prohibits any "harmful interference" to flora and fauna, which refers to:

(i) flying or landing helicopters or other aircraft in a manner that disturbs concentrations of birds and seals;
(ii) using vehicles or vessels, including hovercraft and small boats, in a manner that disturbs concentrations of birds and seals;
(iii) using explosives or firearms in a manner that disturbs concentrations of birds and seals;
(iv) wilfully disturbing breeding or moulting birds or concentrations of birds and seals by persons on foot;
(v) significantly damaging concentrations of native terrestrial plants by landing aircraft, driving vehicles, or walking on them, or by other means; and
(vi) any activity that results in the significant adverse modification of habitats of any species or population of native mammal, bird, plant or invertebrate.

IAATO (International Association of Antarctic Tour Operators) members have adopted sets of guidelines to comply with Annex II of the Protocol and provide visitors with codes of conduct to help reduce potential disturbance to terrestrial and marine environments. To minimise disturbance to vegetation and wildlife IAATO also utilises the Antarctic Site Inventory site guidelines when taking visitors to specific locations on the Antarctic Peninsula.

15.10.4 Managing Impacts from Fuel Spills

International guidelines relating to fuel oil handling at research stations, spill prevention, containment of fuel spills, and contingency planning, were put in place at an Antarctic Treaty Consultative Meeting in 1998. Since then considerable improvements in fuel management have been seen across national programmes, as well as upgrades to fuel transport, transfer, and storage systems. Although fuel spills still occur, one might expect their frequency and size to decrease with infrastructure and procedural improvements (Aislabie et al. 2004).

It has been common practice to remove as much fuel-contaminated soil as possible, including contaminated ice and snow, and ship it back to the home country for disposal (Roura 2004; Aislabie et al. 2004). Depending on the situation, this "dig it up and ship it out" approach could potentially cause adverse impacts to the local environment, including permafrost melt out, which in turn could lead to environmental impacts such as altered stream flows, surface slumping, salinization, and mobilisation of contaminants (Campbell et al. 1994; Snape et al. 2001). In some cases, such as where a small fuel spill has occurred in an environment conducive to evaporative processes (such as the McMurdo Dry Valleys), or where the environmental impacts of a large clean-up operation are greater than the effects of the spill, "doing nothing" may be the most effective option. Alternative remediation technologies include use of permeable reactive barriers to intercept and facilitate removal of mobile contaminants (Snape et al. 2001) and bioremediation (Aislabie et al. 2006).

Bioremediation is increasingly viewed as an appropriate remediation technology for hydrocarbon contamination of Antarctic soils, whereby microorganisms are used to remediate oil spills (Aislabie et al. 2006 and references therein). There is an optimum temperate, nutrient level, and moisture level at which degradation occurs most effectively, and a number of options have been studied to increase rates of bioremediation. Strategies include hydration (addition of liquid water to facilitate increased microbial metabolic activity), biostimulation (addition of fertilisers to increase the assimilation and mineralisation of oil-derived organic carbon by microorganisms), and bioaugmentation (addition of specifically isolated hydrocarbon-degrading bacteria). Bioremediation technologies can either be carried out in situ (on site without soil removal) or ex situ (removal and transportation of contaminated material to a different location to be treated biologically) (Aislabie et al. 2006). The Antarctic Treaty precludes importation of foreign organisms into Antarctica, so indigenous microbes are required for in situ bioremediation.

15.10.5 Managing Impacts from Introduction of Alien Species

Understanding the initial phases of dispersal and establishment is important for managing the risks posed by invasive alien species. Mitigation measures that reduce the risk of introductions to Antarctica must focus on reducing propagule loads on humans, their food and cargo and transportation (Frenot et al. 2005).

Hughes et al. (2011) report that soil, mould, and invertebrates can all enter Antarctica with fresh fruit and vegetables. A number of measures are proposed for reducing the risk of non-native species introduction. They include limiting importation of fresh foods, likely to have high propagule loads, to those areas where non-native species are more likely to establish, and ensuring food waste and packaging is disposed of in a way that prevents release of associated alien species.

Once established, alien species such as plants or invertebrates can be removed before they spread. Removal is more difficult, if not impossible, for management of microbial contaminants. Hence Cowan et al. (2011) advocate the establishment of "a new tier of Antarctic Specially Protected Areas, essentially no-go, no-fly zones where access would be permitted only under the strictest of conditions of biological protection, designed to provide rigorous protection of the environment from human dissemination of non-indigenous organisms".

15.11 Summary

Antarctic soils are vulnerable to disturbance due to their physical properties and naturally slow recovery rates due to low temperatures and, in some regions, low moisture contents. The most intense human activities in Antarctica, such as establishment of bases or research stations, are concentrated in ice-free areas.

The first recorded human interactions with Antarctica were sightings from three ships in 1820. Human activity in Antarctica became sustained during the nineteenth century when whaling stations were established and in the "heroic era" (1895–1917) with exploratory expeditions such as those of Scott and Amundsen. The early visitors left structures and other equipment behind, thus establishing the first legacies of environmental impacts. Since the International Geophysical Year of 1957/58 there has been a sustained increase in human activity. In recent years there has been increased ship-based Antarctic tourism, with 46,000 tourists reported in the 2007/08 summer and 25,000 in the 2012/13 season.

The Protocol on Environmental Protection to the Antarctic Treaty (the Madrid Protocol) was signed in 1991 and designates Antarctica as "a natural reserve devoted to peace and science". The Madrid Protocol mandates the protection of Antarctic wilderness and aesthetic values and requires that before any activity is undertaken the possible environmental impacts are assessed.

Human impacts on the Antarctic terrestrial environment include physical disturbance, spillage of foreign substances, and introduction of foreign organisms. Physical disturbances range from land disturbance during construction activities for roads and bases, through to formation of foot tracks and individual footprints in areas where humans have never previously walked. Accidental spills of hydrocarbon fuels and wastewaters have occurred and human waste was sometimes disposed of by discharge onto land. There is now evidence that alien vascular plants and other taxa can successfully colonise Antarctic soil ecosystems and there is increasing concern about the potential for human activities to impact on soil microbial populations.

Where physical disturbance includes removal of the protective "active layer", the underlying permafrost will melt with resulting land surface subsidence and, in drier regions, the accumulation of salt at the soil surface. The concentration of ice that occurs near the top of the permafrost had not re-established 30 years after disturbance near the Ross Sea region coast. Larger scale surface recontouring, such as bulldozing of tracks or formation of vehicle or foot tracks in loose materials, may remain visible in the landscape for well over 50 years. Where surfaces such as sand dunes are active or where liquid water is available seasonally, smaller scale impacts are obliterated within a few seasons. Visible recovery from footprints, scattered across the environment, was often greater than if the same amount of foot traffic was concentrated to form a foot-track.

Hydrocarbon spills have been shown to persist in the environment, with fuel perching on top of ice-cemented permafrost, for decades. Hydrocarbon-degrading microbes are present in the Antarctic environment but, within the Ross Sea region, their effectiveness is limited by moisture and nutrient (N and P) availability.

Little is known about the response of Antarctic soil microbial communities to human disturbance or on what timescale responses can be detected. Studies of the long-term effects of trampling on soil fauna have shown increased mortality, lower abundances, and shifts in the dominant species of collembola with increasing trampling intensity and soil compaction. Current knowledge of the drivers of bacterial ecology suggests that a disturbance of sufficient intensity to affect soil EC, pH, or moisture content is likely to cause a shift in bacterial community structure. More rigorous investigations incorporating DNA–RNA-based analyses and CO_2 efflux studies could lead to a greater understanding of the effects of soil disturbance on biota.

Many of the most intense impacts on the Antarctic soil environment are legacies of past practice, and are concentrated in areas near bases. Visible disturbance collectively impacts only a small proportion of Antarctic terrestrial environment. With increasing environmental awareness, innovations such as ASMA and ASPA (Antarctic Specially Protected Areas) have been implemented. Thus, the standard of prevention of human impacts undertaken by many of the Antarctic programmes, such as those operating in the McMurdo Dry Valleys, is now more stringent than environmental management standards in most, if not all, other regions of the planet.

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16 Antarctic Soils and Climate Change

James G. Bockheim

16.1 Introduction

Along the Western Antarctic Peninsula (WAP), the mean annual air temperature has increased as much as 3.4 °C and the mid-winter temperature has increased 6.0 °C over the past 50 years, making the region one of the world's climate warming "hotspots" (Vaughan et al. 2003; Turner et al. 2005; Turner and Overland 2009). The causes of these changes in climate are not entirely understood, but they appear to be related to (i) changes in the solar cycle that impact the number of ice-free days in the polar regions (Clark et al. 2013) and (ii) shifts of the Antarctic Circumpolar Current to the south that impact sea-ice and ice-shelf coverage in the Southern Ocean (Böning et al. 2008; Vaughan et al. 2011).

Climate warming in Antarctica is manifested by a 0.17 °C warming of the Southern Ocean (Purkey and Johnson 2010), an increase in level of the Southern Ocean by 3 mm year^{-1} (Leuliette and Willis 2011), a 40 % decrease in sea-ice coverage in the Bellingshausen Sea (Stammerjohn et al. 2008), disintegration of ice shelves along both the eastern and western Antarctic Peninsula (Cook and Vaughan, 2010), warming of permafrost in NVL by 0.1° year^{-1} (Guglielmin and Cannone 2012), increases in vascular plant cover (Hill et al. 2011), and reductions in Adélie penguin populations (Lima and Estay 2013), all over the past two to five decades.

Soils are a sensitive and reliable indicator of climate change (Brevik 2013); however, few studies have investigated the impacts of recent climate change on soils in Antarctica. The purpose of this chapter is to compile the limited information available on climate change effects in Antarctica in response to the historical increase in MAAT, to report the author's observations on landscape and soil changes over his 44 years of research in Antarctica, and to predict the potential effects of continued climate warming on soils of the region.

16.2 Analysis of Published Literature and the Author's Observations

Soil regions that have experienced the most recognized warming include region 8 (Antarctic Peninsula) and region 5b (McMurdo Dry Valleys). However, it is likely that changes also have occurred in coastal East Antarctica (regions 1, 2, 3 and 4). Doran et al. (2002) argued that the entire Antarctic continent had cooled rather than warmed between 1966 and 2000. The study was criticized by Turner et al. (2002) on the basis of an "inappropriate extrapolation of station data across large, data-sparse areas of the Antarctic" (p. 291). Nielsen et al. (2012) attributed the unusual warming and flooding of streams and lakes in the MDV, particularly in 2001–2002, to "extreme" or "pulse" events that were considered important for understanding the present distribution and functioning of soil ecosystems.

In the McMurdo Dry Valleys, the evidence for warming includes a disintegration and retreat of alpine glaciers and ice in coastal areas (Fountain et al. 2004, 2008) that exposes new soil parent materials, a rise in the levels of inland lakes that decrease the soil cover (Webster et al. 1996), an increase in seasonal thaw depth (Guglielmin and Cannone 2012), an increase in the area of the hyporheic zone (Levy et al. 2011; Gooseff et al. 2013), a loss in semi-permanent snow patches that exposes nivation hollows, a flushing of salts from soils, and increased activity of ice- and sand-wedge polygons.

Fountain et al. (2004) attributed the recent glacier advance in Taylor Valley over the period 1972–1997 to an increase in MAAT that led to ice softening. Fountain and his group (2008) also observed an increase in cryoconite holes

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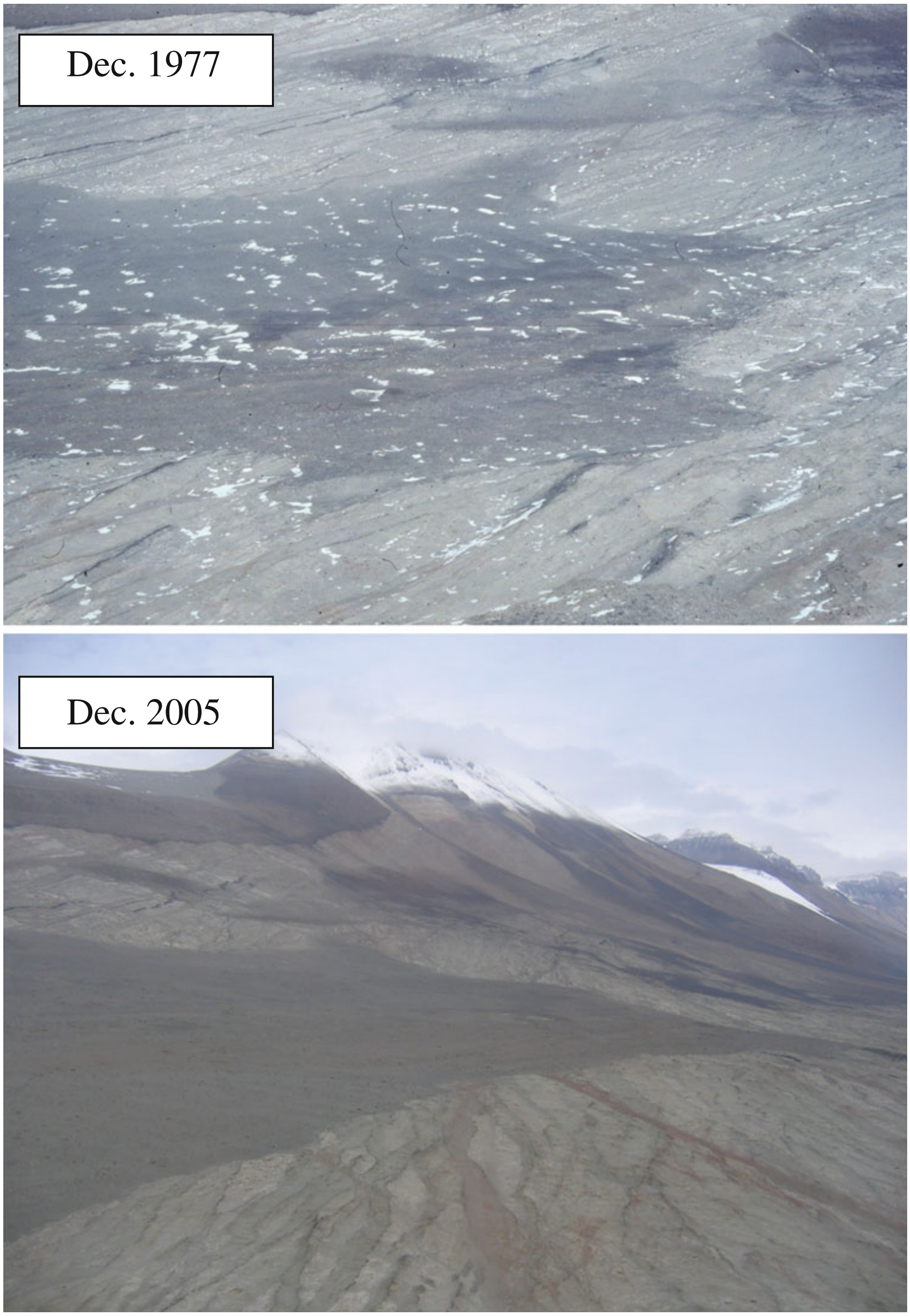

Fig. 16.1 Loss in semi-permanent snow patches in central Wright Valley over the period 1977–2005 (photos by J. Bockheim)

on Canada Glacier that was related to the ice softening. The level of Lake Vanda has risen over 10 m from the late 1960s (Chinn and McSaveney 1987; Webster et al. 1996), resulting in the dismantling of Vanda Station in 1995.

At the Mario Zucchelli research station in NVL, Guglielmin and Cannone (2012) observed a 0.31 °C per year warming of the ground surface during the summer over the decade beginning in 1997. In the same period, the active

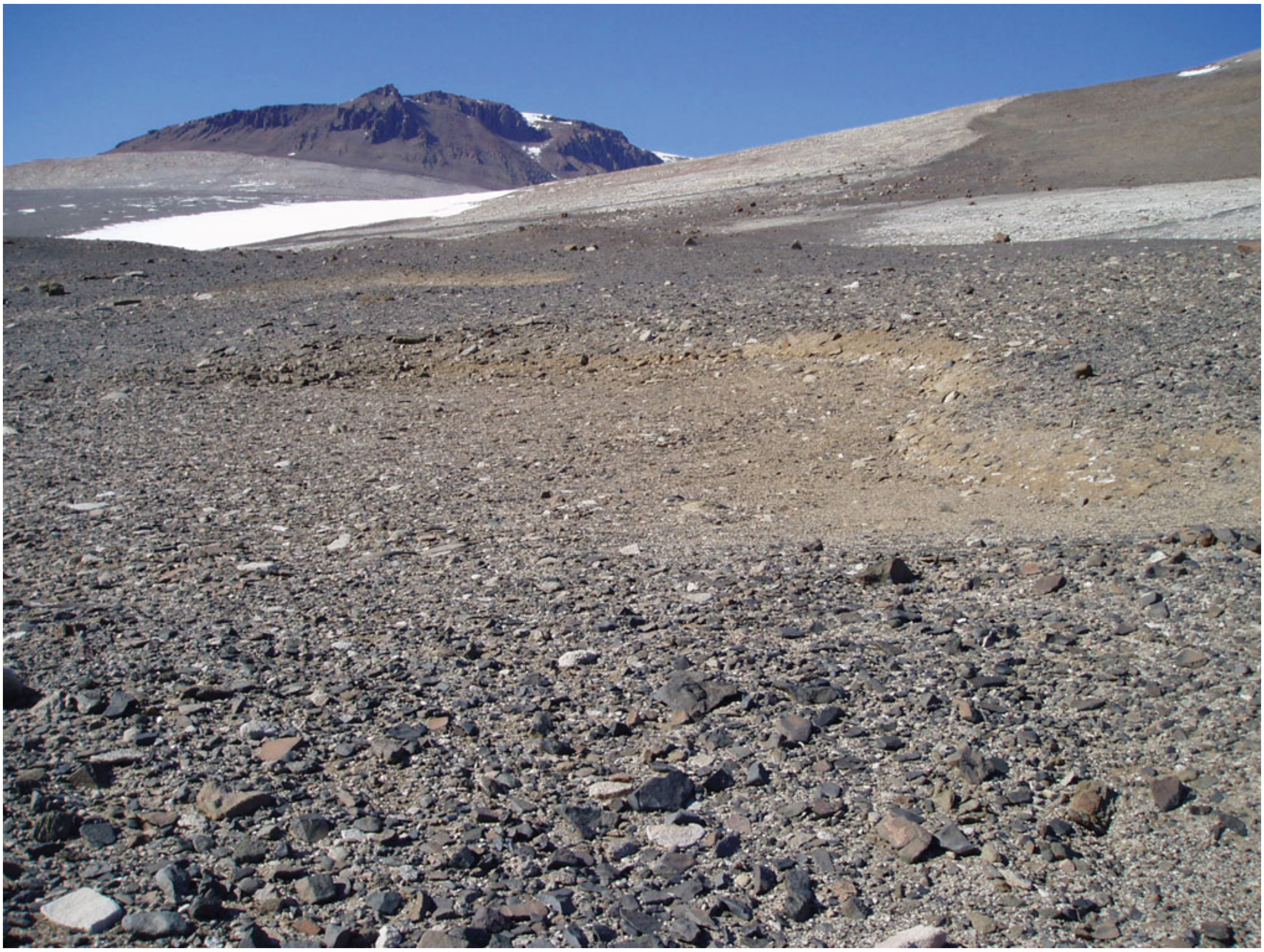

Fig. 16.2 Nivation hollow in Wright Valley from melting of semi-permanent snow patches (photo by J. Bockheim)

layer thickened by 1 cm year^{-1}, which was comparable to the thickening rates observed at several Arctic locations.

In the 1970s, prior to the availability of GPS units, we were able to locate our soil pit locations on aerial photographs by using semi-permanent snow patches as locators. After a 20 years hiatus from working in Antarctica, I was surprised to find these snow patches to no longer be present in areas such as central Wright Valley and Bull Pass in the mid-2010s to a loss in semi-permanent snow patches (Fig. 16.1). By the mid-2010s, the patches contained nivation hollows (Fig. 16.2) that had ice-cemented permafrost within 30 cm of the surface; permafrost was at a depth of 100 cm or more outside the hollows.

I also observed flushing of salts from soils along the lower valley walls in Wright Valley beginning in the mid-2010s (Fig. 16.3). These salts appear to be translocated along the surface of the ice-cemented permafrost from the upper valley walls. Levy et al. (2012) reported hypersaline "wet patches" in Taylor Valley that they attributed to localized flux of water vapor due to evaporation rather than reduced precipitation or groundwater sources.

One of the more startling observations beginning in the mid-2010s was a marked increase in the hyporheic zone. Whereas, the hyporheic zone was limited to stream and lake margins in the mid-1970s; by the mid-2010s, I observed moist streaks along the south valley wall of the South Fork

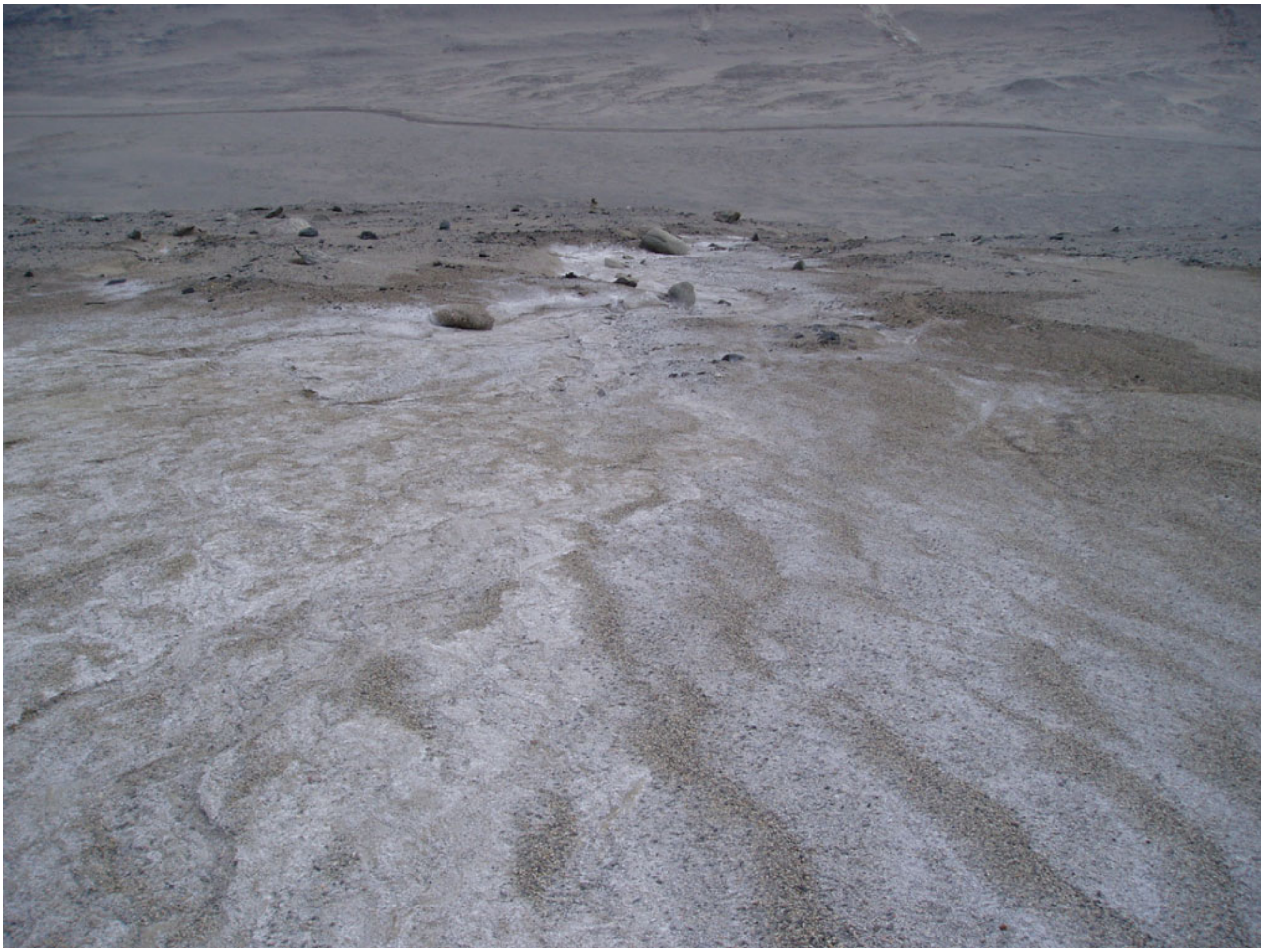

Fig. 16.3 Recent flushing of salts from the upper sidewalls of Wright Valley (photo by J. Bockheim)

of Wright Valley and melting of ice wedges throughout central Wright Valley (Fig. 16.4).

These observations are consistent with those of Levy et al. (2011) who reported for the first time the occurrence of water tracks in the MDV. Gooseff et al. (2013) identified shallow groundwater systems in the MDV that contributed to the wetted zones.

There appears to be an increased activity of ice- and sand-wedge polygons throughout the MDV. This is evidenced by exposed, highly weathered soil along the contraction fissures (Fig. 16.5). In lower Wright Valley, Malin (1994) reported an increase in the growth of contraction fissures of sand-wedge polygons at two of three sites over the period of 1969–1982 to 1982–1994.

Along the Antarctic Peninsula, the evidence for warming effects on soils is even more dramatic than in the MDV, including thermokarst from melting of ice-rich permafrost (Figs. 16.6, 16.7) (Vieira et al. 2008), debris flows and active-layer detachment slides (Fig. 16.8), thickening of the active layer (Cannone et al. 2006), loss of permafrost (Bockheim et al. 2013), increased decomposition of soil organic matter (Bokhurst et al. 2007), more efficient utili-

Fig. 16.4 These photographs illustrated an expanded hyporheic zone in Wright Valley from melting of snow high above the valley walls and subsurface flow over the top of the permafrost table, likely in response to increased solar activity (photos by J. Bockheim)

zation of N by vascular plants extending their geographic area (Hill et al. 2011), and shifts in populations of microorganisms (Yergeau et al. 2012).

Fig. 16.5 Increased activity of this ice-wedge polygon is reflected in the exposed Bw horizon material along the contraction fissures (photo by J. Bockheim)

16.3 Potential Impacts of Continued Warming on Antarctic Soils

From data contained in the present study (Table 2.2), Antarctica can be divided into three broad climatic zones: (i) the West Antarctica Maritime Zone (WAMZ); (ii) the East Antarctica Maritime Zone (EAMZ); and (iii) the Inland Mountain Zone (IMZ). The WAMZ has a MAAT ranging from −1.7 to −3.4 °C, a mean summer (January and February) temperature of 0.9–2.0 °C, and a MAP between 400 and 800 mm/year. The EAMZ has a MAAT of −9 to −11 °C, a mean summer temperature of 0 to −0.5 °C, and a MAP

Fig. 16.6 Thermokarst from recent warming on Deception Island (photo by G. Vieira)

between 200 and 250 mm/year. The IMZ has a MAAT of −17 to −30 °C, a mean summer temperature of −1.0 to −3.6 °C, and a MAP between 5 and 100 mm/year.

If the temperatures in the WAMZ continue to rise 1.0 °C/decade (reference), the ice-free area in that region (region 8) could increase substantially from the current, 1,200 km^2 (Table 16.1). The same is true for the EAMZ, which has an area of 1,245 km^2. In the INZ, which contains 95 % of the ice-free area in Antarctica; it is unlikely that warming would increase the ice-free area, except possibly in subxerous soils of coastal areas. Warming in the WAMZ is already resulting in an increase in vascular plant cover (reference); the same is true for the EAMZ (reference). These changes would be accompanied by increases in net primary production of plant communities, ecosystem respiration, and possible SOC levels. Continued warming would increase the thickness of the active layer in the WAMZ and EAMZ but could also affect the IMZ. Soluble salts are of minimal concentrations in soils of the WAMZ, intermediate levels in the EAMZ, and high levels in older soils of the IMZ. Warming accompanied by increases in precipitation could result in desalinization of soils of coastal areas of the IMZ. Pervection, or frost sorting,

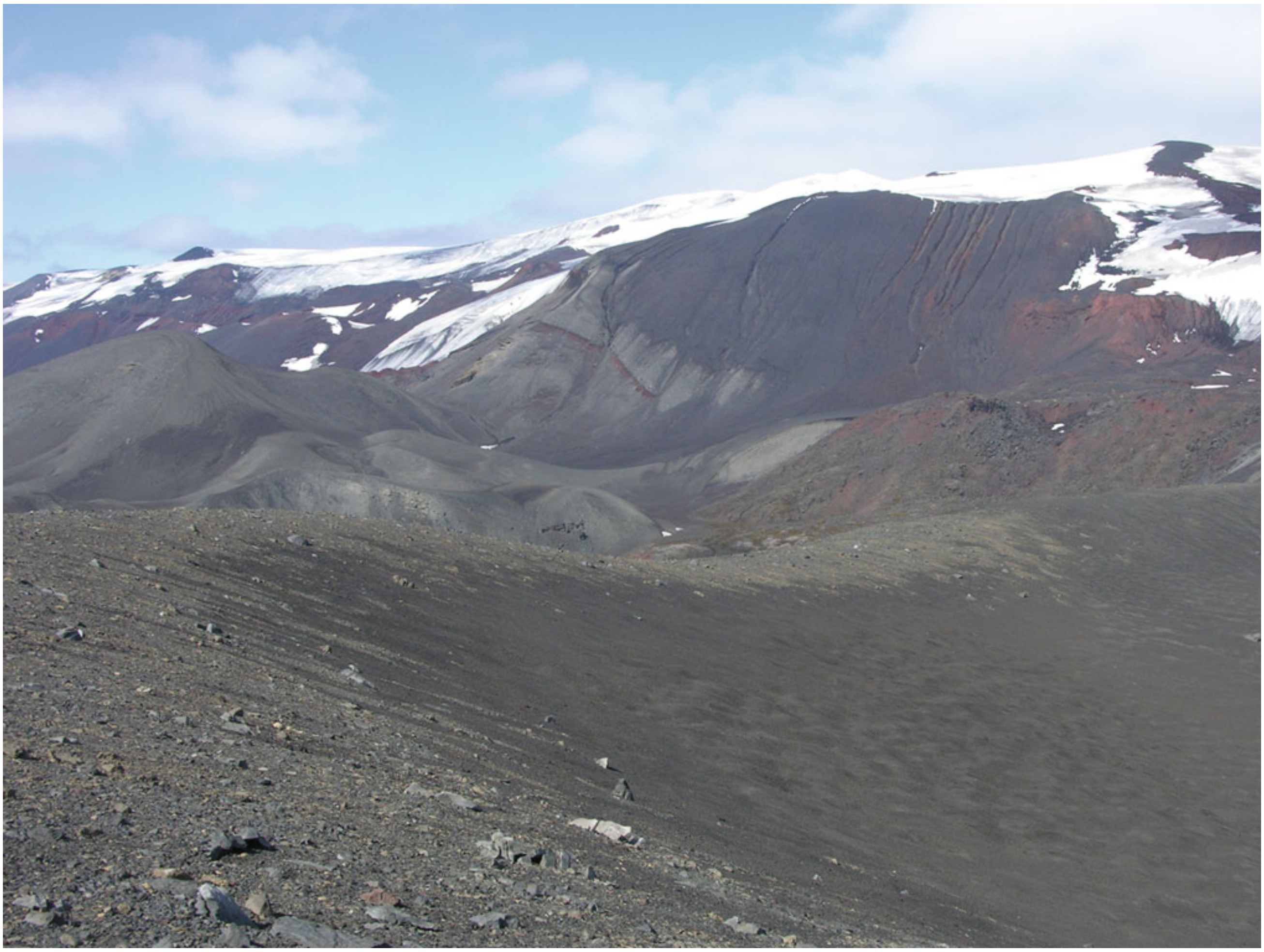

Fig. 16.7 Widespread thermokarst on Deception Island from recent warming (photo by G. Vieira)

would be impacted by increased temperatures in the WAMZ and EAMZ and to a less extent in the IMZ (Table 16.1).

Figure 16.9 shows the potential impacts of warming on soils of the McMurdo Dry Valleys. Warming would be expected to cause shifts from ultraxerous to xerous and especially from xerous to subxerous. These shifts would result in a slight increase in plant cover, an increase in the active-layer thickness, a decrease in soluble salts, and a change in microbial populations.

Swanger and Marchant (2007) modeled the sensitivity of ice-cemented Antarctic soils to greenhouse-induced thawing, reporting that most deposits in the MDV contain sufficient subsurface ice to induce sliding upon thawing. Silty soils on steep (>20°) would be most susceptible and could fail given an increase in mean summertime atmospheric temperature of 4–9 °C.

Fig. 16.8 Debris flows and active-layer detachment slides on Deception Island from recent warming (photo by G. Vieira)

Table 16.1 Potential impacts of global warming on soil properties and processes in the Southern Circumpolar Region (adapted from Bockheim 1993)

Bioclimatic zone	W. Antarctica maritime	E. Antarctica maritime	Interior mountains
Regions	So. Orkney I., So. Shetland I., Palmer Archipelago (8)	Schirmacher Oasis (1), Molodezhnaya (2), Ingrid Christensen coast (3), Windmill I. (4)	QML Mtns. (1), Scott-Tula Mtns. (2), Prince Chas., Grove Mtns. (3), Thiel- Pensacola Mtns. (5a), TAM (5b), Ellsworth Mtns. (6), MBL Mtns. (7), Palmer-Graham Mtns. (8)
Ice-free area (km^2)	1,200 (2.4 %)	1,245 (2.5 %)	47,055 (95.1 %)
Change in ice-free area	m+	m+	s+
Primary production	m+	m+	s+
Respiration	m+	m+	s+
Soil organic C (%)	m+	m+	s+
Depth to ice cement	m+	m+	s+
Salinization	o	s−	m−
Rubification	m+	m+	s+
Pervection	m+	m+	s+

m = moderate change; s = slight change; o = no change; + = increase; − = decrease

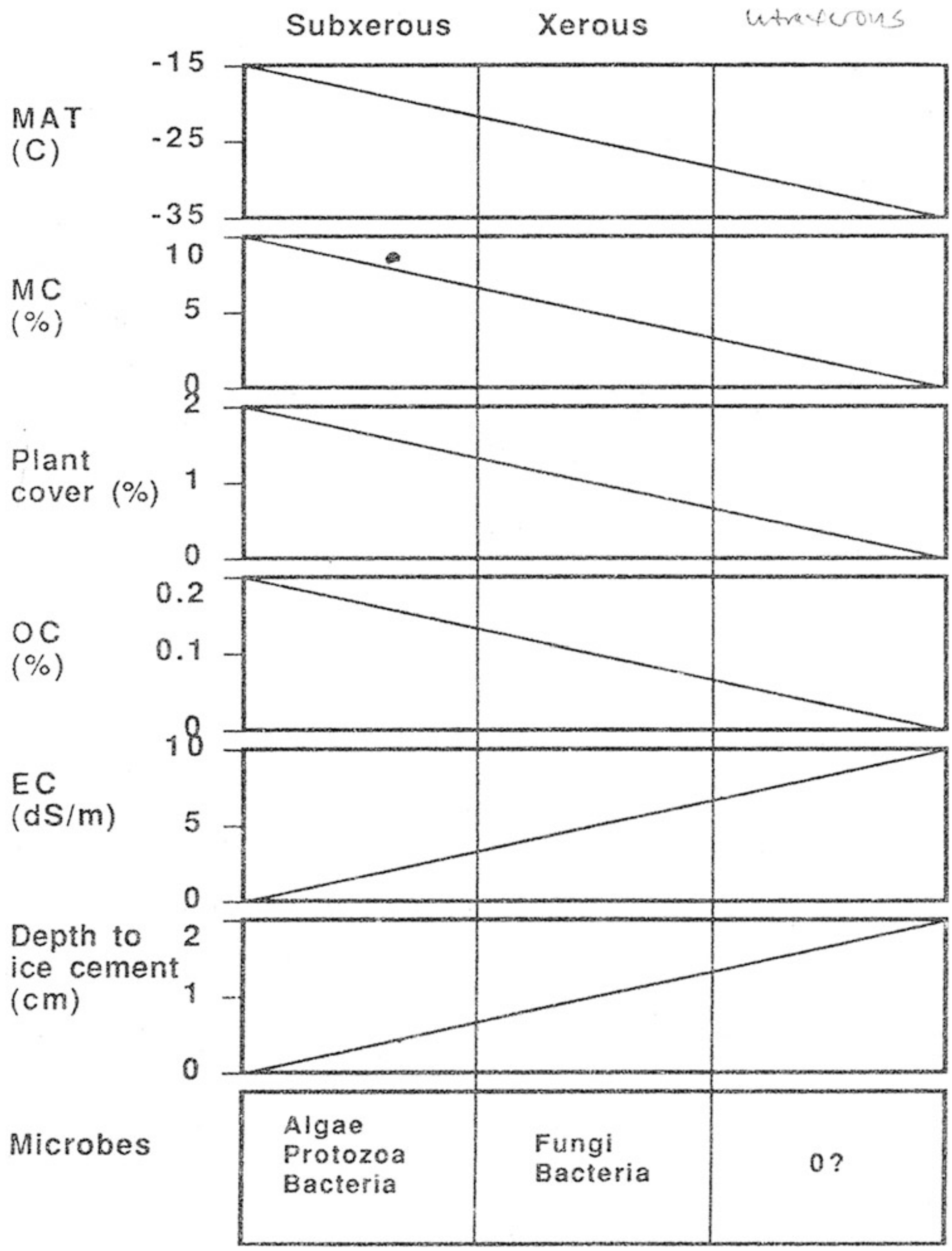

Fig. 16.9 Potential impacts of warming on soils of the McMurdo Sound region (Bockheim 1993)

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17 Summary

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Detailed soils investigations from all eight ice-free regions of Antarctica suggest that permafrost is continuous on the continent, but it is discontinuous in the South Orkney Islands (SOI) and South Shetland Islands (SSI), occurring primarily below an elevation of 30 m a.s.l. Based on data contained in Table 2.2, the temperature at the top of the permafrost (TTOP) ranges between 0 and −2.5 °C in the SOI, SSI, and on the western Antarctic Peninsula (WAP) mainland from the northern tip to at least 67° S. Permafrost temperatures range from −2.6 to −10 °C in areas on the southern WAP to Alexander Island, in the Weddell Sea islands, and in coastal East Antarctica (regions 1, 2, 3, 4, and 7). Permafrost temperatures range from −13 to −23 °C in the Thiel Mountains and Pensacola Mountains (region 5a), Transantarctic Mountains (TAM; region 5b), the Queen Maud Land mountains (region 1), and possibly in the southern Prince Charles Mountains and Grove Mountains (region 3). Dry permafrost occurs primarily in these mountains, especially those in central and southern Victoria Land.

The active-layer thickness is remarkably uniform in continental Antarctica, ranging from 0.3 to 1.1 m along the East Antarctic and Ross Sea coasts; however, the active-layer depth is only 0.1–0.3 m along the Ruppert Coast (75°, 137° W) of Marie Byrd Land (Table 2.2). The greatest variation in active-layer thickness is along the Antarctic Peninsula. On the WAP the active layer ranges from 1.0 to 6.0 m, but on the East Antarctic Peninsula (EAP), it averages 0.6 m.

Climate is an extremely important factor in soil development in Antarctica. There are basically three climates in the region: (i) a mild (MAAT −1.7 to −3.4 °C), wet (MAP 400–800 mm) climate along the WAP (including the SOI, SSI); (ii) a moderate (MAAT −9 to −11 °C), semiarid (MAP 200–250 mm) climate along the southern WAP, the EAP, and in coastal East Antarctica; and (iii) a hyper-cold (MAAT −17 to −35 °C), hyper-arid (MAP < 100 mm) climate in the mountains of Queen Maud Land, MacRobertson Land, and central and southern Victoria Land (Table 2.1). These climate zones were referred to as Subantarctic Tundra, Antarctic Polar Desert, and Antarctic Cold Desert, respectively, by Bockheim and Ugolini (Fig. 2.11). Goryachkin et al. (Chap. 5) refers to these zones as Polar Desert, Mid-Antarctic Desert, and Cold Desert, respectively.

Vegetation is an important soil-forming factor by virtue of its presence and absence. Higher plants (*Deschampsia Antarctica* and *Colobanthus quitensis* grasses) are found only along the WAP and the SOI and SSI. Small (10–1,000 m^2) patches of continuous vegetation cover, primarily mosses and lichens, may occur in coastal areas of regions 1, 2, 3, 4, 7, and 8. Algae influence soil development in these same areas. Endolithic lichens produce organic matter and initiate chemical and physical weathering throughout Antarctica. Microorganisms are present in nearly all soils of Antarctica, except possibly in old soils with pronounced salt accumulation. Birds, primarily penguins but also skua gulls and petrels, contribute organic matter, phosphates, and Na and are important in coastal areas of Antarctica (see especially Chaps. 2, 12, and 13).

Most of the soils in coastal regions of Antarctica are of Late Glacial Maximum age, or younger. However, strongly developed soils of early Pleistocene to Miocene age occur in the Sør Rondane Mountains (region 1), the southern Prince Charles Mountains and Grove Mountains (region 3), the Thiel Mountains and Pensacola Mountains (region 5a), and the Transantarctic Mountains (region 5b). Parent material results in unique soils in areas with sulfide rocks (sulfuric subgroups of soils), carbonates (calcification in coastal areas and north Victoria Land), and sandy (Psamments, Psammorthels, and Psammoturbels) materials. Relief is an important soil-forming process in coastal areas, particularly adjacent to melting snowbanks in coastal areas of East Antarctica (Table 17.1).

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Table 17.1 Relative importance of soil-forming processes in ice-free regions and subregions of Antarctica

Soil-forming process	Ice-free region (see Fig. 2.1)[a]													
	1C	1M	2C	3C	3M	4C	5aM	5bC	5bM	6M	7C	7M	8C	8M
Rubification	*	***	*	*	***	**	***	*	***	*	*		*	**
Salinization	*	***	*	*	***	*	***	*	***	*	*		*	*
Calcification	*	*	**	**	*	*	*	**	*	**	**		*	*
Soil organic matter accumulation	**	*	**	**	*	**	*	*	*	*	*		**	**
Pervection	**	*	**	**	*	**	*	*	*	*	*		**	**
Desert pavement formation	**	***	*	**	***	*	***	**	***	**	**		*	*
Permafrost development	**	***	**	**	***	**	***	**	***	***	***		*	**
Acidification	*	*	**	*	*	***	*	*	*	*	**		***	**
Hydromorphism	**	*	***	***	*	***	*	*	*	*	**		***	**
Phosphatization	*	*	**	**	*	**	*	*	*	*	*		***	***
Sulfurization	**	*	**	*	*	**	*	*	*	*	*		**	*
Paludification	*	*	**	**	*	**	*	*	*	*	*		***	**
Podzolization	*	*	*	*	*	**	*	*	*	*	*		**	**

Relative importance: *low or absent; **moderate; ***important
[a]*C* coastal; *M* inland mountains

These soil-forming factors lead to a variety of soil-forming processes in Antarctica. The relative importance of each of these processes is indicated by one asterisk (*) as being unimportant or absent, two asterisks (**) as being of moderate importance, and three asterisks (***) as being of major importance in Antarctica (Table 17.1). The table lists each of the ice-free regions and subdivides them, where appropriate, into coastal and inland (mountain) subregions. Processes such as rubification, salinization, desert pavement formation, and permafrost development operate to the greatest extent in the inland mountains of regions 3, 5a, and 5b. Calcification is not a dominant process but occurs primarily in coastal areas of regions 2, 3, 5, and 7. Soil organic matter accumulation, acidification, hydromorphism, phosphatization, paludification, and pervection occur in coastal areas of regions 1 through 4 and 8 but also in the mountains of the Antarctic Peninsula. In Antarctica, as in the Arctic, hydromorphism leads to reductive Eh values but no apparent redoximorphic features or gleying. Sulfurization is restricted to areas with sulfide-enriched parent materials, such as King George Island and Seymour Island. Podzolization is restricted to abandoned penguin rookeries in coastal areas of regions 4 and 8.

From the areas of each region and the distribution of soil taxa within each region, we were able to determine the distribution of soils in Antarctica (Table 17.2). Typic Anhyorthels are the dominant soil subgroup in Antarctica comprising nearly 15,000 km^2, or 30 % of the soils on the continent. These soils occur primarily in central and southern Victoria Land (region 5b), but also in the Prince Charles Mountains (region 3) and the mountains of Queen Maud Land (region 1). Typic Haploturbels and Typic Anhyturbels occupy 14 and 13 % of the soils of ice-free regions of Antarctica, respectively. Most abundant in central Victoria Land, they are common in most mountainous regions of Antarctica. Soils in lithic subgroups comprised only 15 % of the soils; however, in the mountains of Antarctica, especially regions 1, 3, 5a, 5b, 6, 7, and 8, we were unable to differentiate the Rockland land type from soils in lithic subgroups so that we have probably underestimated the areal distribution of these soils. Typic Gelorthents occupy about 8 % of the ice-free areas of Antarctica, mainly in Palmer and Graham Lands (region 8).

Forty-four percent of the soils of Antarctica are Orthels, Gelisols that show minimal evidence of cryoturbation; 36 % are Turbels showing cryoturbation (Table 17.3). Only 16 % of the soils of Antarctica lack permafrost in the control section and are classified as Entisols (Gelorthents), Inceptisols (Haplogelepts, Humigelepts, Dystrogelepts), or Histosols (Cryofibrists, Cryohemists, Cryosaprists, and Cryofolists). These soils occur almost exclusively along the western Antarctic Peninsula and at elevations below 50 m in the SSI and SOI; these organic soils may contain permafrost below 2 m. We estimate that ornithogenic soils occupy only 0.5 % of ice-free areas in Antarctica.

An understanding of the distribution of soil taxa is important for identifying sites of special scientific interest (SSSI) and ASPs (Areas of Special Protection) that should be protected (see also Chap. 15). Some of the most pedologically diverse areas in Antarctica include the SSI and

Table 17.2 Distribution (area and percentage of total area) of soil taxa by region in Antarctica

Region		Approx. area (km^2)		LHt	GHt	THt	AqHt	TAt	LAt	LAqt	LAo	TAo	THo	LHo	GHo	SAo	NAo
1	Queen Maud land	**3400**	%	0	5	24	0	15	2	0	4	45	0	0	0	0	0
			km^2	0	170	816	0	510	68	0	136	1530	0	0	0	0	0
2	Enderby Land	**1500**	%	25	4	30	0	0	0	3	0	3	0	30	0	0	0
			km^2	375	60	450	0	0	0	45	0	45	0	450	0	0	0
3	Macrobertson Land	**5400**	%	0	17	6	0	23	0	0	7	36	0	0	0	4	0
			km^2	0	918	324	0	1242	0	0	378	1944	0	0	0	216	0
4	Wilkes Land	**700**	%	0	0	7	0	0	0	7	0	0	0	58	0	0	0
			km^2	0	0	49	0	0	0	49	0	0	0	406	0	0	0
5a	Pensacola Mtns.	**1500**	%	0	7	9	0	17	0	0	4	47	0	0	3	0	3
			km^2	0	105	135	0	255	0	0	60	705	0	0	45	0	45
5b	Transantarctic Mtns.																
	NVL	2420	%	0	36	0	0	36	0	0	14	14	0	0	0	0	0
			km^2	0	871	0	0	871	0	0	339	339	0	0	0	0	0
	CVL	10890	%	0	2	36	0	14	2	0	1	43	0	0	0	0	0
			km^2	0	218	3920	0	1525	163	0	54	4683	0	0	0	0	0
	SVL	10890	%	0	7	9	0	17	0	0	4	47	0	0	3	0	3
			km^2	0	762	980	0	1851	0	0	436	5118	0	0	327	0	327
	Subtotal	**24200**	km^2	0	1851	4901	0	4247	163	0	829	10140	0	0	327	0	327
6	Ellsworth Mtns.	**2100**	%	0	0	0	0	0	0	0	36	27	14	18	5	0	0
			km^2	0	0	0	0	0	0	0	756	567	294	378	105	0	0
7	Marie Byrd Land	**700**	%	0	0	0	10	0	40	0	40	0	0	0	0	0	0
			km^2	0	0	0	70	0	280	0	280	0	0	0	0	0	0
8	Antarctic Peninsula																
	S. Orkney, S. Shetland Is.	645	%	4	0	4	2	0	0	0	0	0	41	0	0	0	0
			km^2	26	0	26	13	0	0	0	0	0	264	0	0	0	0
	Palmer, Graham Lands	9355	%	4	0	2	0	0	0	0	0	0	4	6	0	0	0
			km^2	374	0	187	0	0	0	0	0	0	374	561	0	0	0
	Subtotal	**10000**	km^2	400	0	213	13	0	0	0	0	0	638	561	0	0	0
	Grand total	**49500**	km^2	775	3104	6888	83	6254	511	94	2439	14931	932	1795	477	216	372
			%	2	6	14	0	13	1	0	5	30	2	4	1	0	1

Region		Approx. area (km^2)		PnAo	TSpo	Orn	LHs	LFs	TGe	THi	LHi	TGqe	LCsh	LCfoh	Other	Total
1	Queen Maud land	**3400**	%	0	0	0	0	0	0	0	0	0	0	0	5	
			km^2	0	0	0	0	0	0	0	0	0	0	0	170	3400
2	Enderby Land	**1500**	%	0	0	3	2	0	0	0	0	0	0	0	0	
			km^2	0	0	45	30	0	0	0	0	0	0	0	0	1500
3	Macrobertson Land	**5400**	%	0	0	2	0	0	0	0	0	0	0	0	5	
			km^2	0	0	108	0	0	0	0	0	0	0	0	270	5400
4	Wilkes Land	**700**	%	0	14	7	7	0	0	0	0	0	0	0	0	
			km^2	0	98	49	49	0	0	0	0	0	0	0	0	700
5a	Pensacola Mtns.	**1500**	%	3	0	0	0	0	0	0	0	0	0	0	7	
			km^2	45	0	0	0	0	0	0	0	0	0	0	105	1500

(continued)

Table 17.2 (continued)

Region		Approx. area (km^2)		PnAo	TSpo	Orn	LHs	LFs	TGe	THi	LHi	TGqe	LCsh	LCfoh	Other	Total
5b	Transantarctic Mtns.															
	NVL	2420	%	0	0	0	0	0	0	0	0	0	0	0	0	
			km^2	0	0	0	0	0	0	0	0	0	0	0	0	2420
	CVL	10890	%	0	0	0	0	0	0	0	0	0	0	0	3	100
			km^2	0	0	0	0	0	0	0	0	0	0	0	327	10890
	SVL	10890	%	3	0	0	0	0	0	0	0	0	0	0	7	
			km^2	327	0	0	0	0	0	0	0	0	0	0	762	10890
	Subtotal	**24200**	km^2	327	0	0	0	0	0	0	0	0	0	0	1089	24200
6	Ellsworth Mtns.	**2100**	%	0	0	0	0	0	0	0	0	0	0	0	0	
			km^2	0	0	0	0	0	0	0	0	0	0	0	0	2100
7	Marie Byrd Land	**700**	%	0	0	0	0	10	0	0	0	0	0	0	0	
			km^2	0	0	0	0	70	0	0	0	0	0	0	0	700
8	Antarctic Peninsula															
	S. Orkney, S. Shetland Is.	645	%	0	1	8	2	2	23	6	0	2	3	2	0	
			km^2	0	6	52	13	13	148	39	0	13	19	13	0	645
	Palmer, Graham Lands	9355	%	0	0	0	0	0	41	13	10	8	5	5	2	100
			km^2	0	0	0	0	0	3836	1216	936	748	468	468	187	9355
	Subtotal	**10000**	km^2	0	6	52	13	13	3984	1255	936	761	487	481	187	10000
	Grand total	**49500**	km^2	372	104	254	92	83	3984	1255	936	761	487	481	1821	49500
			%	1	0	1	0	0	8	3	2	2	1	1	4	100

LHt Lithic Haploturbels, *GHt* Glacic Haploturbels, *THt* Typic Haploturbels, *AqHt* Aquic Haploturbels, *TAt* Typic Anhyturbels, *LAt* Lithic Anhyturbels, *LAqt* Lithic Aquiturbels, *LAo* Lithic Anhyorthels, *TAo* Typic Anhyorthels, *THo* Typic Haplorthels, *LHo* Lithic Haplorthels, *GHo* Glacic Haporthels, *SAo* Salic Anhyorthels, *NAo* Nitic Anhyorthels, *PnAo* Petronitric Anyorthels, *TSpo* Typic Spodorthels, *Orn* Ornithogenic soils, *LHs* Lithic Hemistels, *LFs* Lithic Fibristels, *TGe* Typic Gelorthents, *THi* Typic Humigelepts, *LHi* Lithic Humigelepts, *TGqe* Typic Gelaquents, *LCsh* Lithic Gelisaprists, *Lcfoh* Lithic Gelifolists

Table 17.3 Influence of permafrost on distribution of soils in ice-free areas of Antarctica

Group	Area (km^2)	Area (%)
With permafrost in upper 1–2 m		
Orthels	21,639	43.7
Turbels	17,708	35.8
Histels	175	0.4
Non-Gelisols	7903	16.0
Ornithogenic soils	254	0.5
Other	1821	3.7
Total	49,500	100.0

SOI (region 8), coastal Enderby Land (region 2), and Arena Valley in the McMurdo Dry Valleys (region 5b). Areas of low pedodiversity include northern and southern Victoria Land (region 5b), and the Ellsworth Mountains (region 5).

Information contained in the 16 preceding chapters of this book provides key insights into the nature and properties, genesis, classification, and geography of soils of Antarctica. Chapter 1 (Bockheim) gives an overview of the history and challenges of studying soils in Antarctica. Chapter 2 (Bockheim) provides background information on the role of soil-forming factors in Antarctica.

Queen Maud Land (Chap. 3; Zazovskaya, Fedorov-Davydov, and Alekseeva.) is unique in several respects: (i) the low-lying, ice-free areas are 90 km or more from the coast so that birds have a minimal influence on soil development; (ii) micro-relief influences soil moisture levels, resulting in high small-scale variation in soils; and (iii) the soils are subject to a subpolar or Mid-Antarctic climate, but Ahumic soils (Anhyorthels and Anhyturbels) occur in dry areas as well as at higher elevations in the mountains.

Enderby Land (region 2; Chap. 4; Dolgikh, Mergelov, Abramov, Lupachev, and Goryachkin) has some of the same characteristics of QML, but there are abundant penguin rookeries and wind-sheltered sites lead to an unusual form of soils that are enriched in organic matter and weakly podzolized.

MacRobertson Land (region 3; Chap. 5; Mergelov, Konyushkov, Lupachev, and Goryachkin) features a dramatic elevational gradient in soils from the Lars and Ingrid Christensen coasts to over 3,000 m in the southern Prince Charles Mountains. The undulating, scoured, granitic bedrock topography (hills and inter-hills) yields a high diversity of soils that continues into Wilkes Land to the west. As with soils in several other coastal regions, melting snow patches produce a hydromorphic sequence of soils.

Podzol soils were first recognized in abandoned penguin rookeries of Wilkes Land (region 4; Chap. 6; Blume and Bölter). Soils in the Windmill Island are highly diverse; and "fertile islands" contain moss beds with cyanobacteria that fix atmospheric N.

Chapters 7 through 9 deal with soils in the northern, central, and southern Transantarctic Mountains, respectively (region 5b). The soils in north Victoria Land (Chap. 7; Bockheim) occur in small ice-free areas of actively glacierized mountains and are poorly developed. Central Victoria Land (Chap. 8; Bockheim and McLeod) contains the McMurdo Dry Valleys, the most extensive ice-free area in Antarctica (6,692 km^2). It is the most studied area in Antarctica in terms of soils. Southern Victoria Land (Chap. 9; Bockheim and McLeod) contains over 10,000 km^2 of ice-free area (similar to CVL). Soils of central and southern Victoria Land are unique in two ways: (ii) they may be of Miocene age (>11 Ma) and are among the oldest non-lithified soils in Antarctica; and (ii) they have been subject to a hyper-arid since the Pliocene. Soils of central and southern Victoria Land have played an important role in dating and correlation of glacial deposits and in differentiating the behavior of wet-based and cold-based glaciers.

Soils in Ellsworth Land (region 6; Chap. 10; Bockheim and Schaefer) have originated from a variety of rock types, including argillites, volcanic rocks, marbles, quartzites, conglomerates, and quartz phyllites. These soils occur in Antarctica's highest mountains, including the Vinson Massif (4,897 m a.s.l.).

Marie Byrd Land (region 7; Chap. 11; Lupachev, Abakumov, Abramov, Goryachkin, and Gilichinsky) is one of the most remote, difficult to access, the least studied area in Antarctica for soils. The climate at the old Russkaya station is unusual in that the MAAT is −12.4° (comparable to that along the East Antarctic coast) but has an unusually large mean annual precipitation (2,000 mm year^{-1}) which is entirely in the form of snow and is 4–10 times greater than in other coastal regions of Antarctica (except the western Antarctic Peninsula). Located at 74° S and 99° W, MBL has ornithogenic soils and Histels.

Graham and Palmer Lands, part of region 8 (Chap. 12; Haus, Schaefer, Bockheim, and Pereira) are unique in several respects: (i) they feature the greatest warming in the past several decades of any place on Earth; (ii) they contain the second largest ice-free area in Antarctica (8,800 km^2); (iii) the ice-free are predominantly nunataks and steep mountain ridges; (iv) it is the wettest region in Antarctica (400–800 mm year^{-1}) with a large portion of the precipitation in the form of rain; (v) warming is causing alpine and piedmont glaciers to retreat, yielding young soils and an increase in ice-free area; and (vi) they contain the largest proportion of non-Gelisols, i.e., Entisols, Inceptisols, and Histosols.

The South Orkney and SSI are also part of region 8 (Chap. 13; Simas, Schaefer, Michel, Francelino, Bockheim). These islands constitute the second most studied area in Antarctica. More than 80 % of these soils studies have been done on King George Island on which there are 12 scientific stations. Although the total ice-free area is only 645 km^2, the islands have an exceptionally high pedodiversity. Soils of the island are important also because (i) modern global soil taxonomic systems are insufficient to classify many of these soils; (ii) there have been very few published soil maps of the region or parts of the region and for this reason the geography of the soils has poorly understood; (iii) soil evolution is dominated by chemical weathering as well as cryogenic processes; (iv) the high pedodiversity is due to differences in parent materials, soil biological processes, and permafrost occurrence; (v) there is a poor understanding of soil organic C and N turnover despite large standing stocks of these elements; (vi) soil-forming processes include argilluviation, sulfurization, and podzolization which do not commonly occur in Antarctica; (vii) soil taxa are strongly related to geomorphic surfaces and permafrost distribution; and (viii) there is marked phosphatization and a dominance of amorphous material in the clay fraction of soils influenced by birds.

The islands to the east of the Antarctic Peninsula (Chap. 14; Schaefer, Souza, and Simas) comprise a small ice-free area (260 km^2) and have been poorly studied in terms of soils. Polar Desert soils of these islands have characteristics intermediate from those on the western Antarctic Peninsula and offshore island (SOI, SSI) and those in coastal East Antarctica. A detailed study on Seymour Island showed the presence of non-Gelisols as well as acid-sulfate soils containing jarosite and ferrihydrite minerals.

Humans have been affecting soils throughout Antarctica in small areas for the past 100 years. In Chap. 15, O'Neill, Aislabie, and Balks detail human impacts on soils from construction, geotechnical activities, road building, waste disposal, pollution by petroleum products and heavy metals, and introduction of alien species. They describe the

Antarctic Treaty (Madrid Protocol) and the importance of environmental impact statements.

The last chapter (Chap. 16) provides some of the editor's observations over the past 44 years on climate change effects in Antarctica, including the sublimation of semi-permanent snow patches yielding nivation hollows, flushing of salts from increased meltwater, expansion of the hyporheic zone, increased activity of ice-wedge and possibly sand-wedge polygons, thermokarst, and active-layer detachment slides. He predicts how further warming on the continent will impact soils and soil-forming processes.

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