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.