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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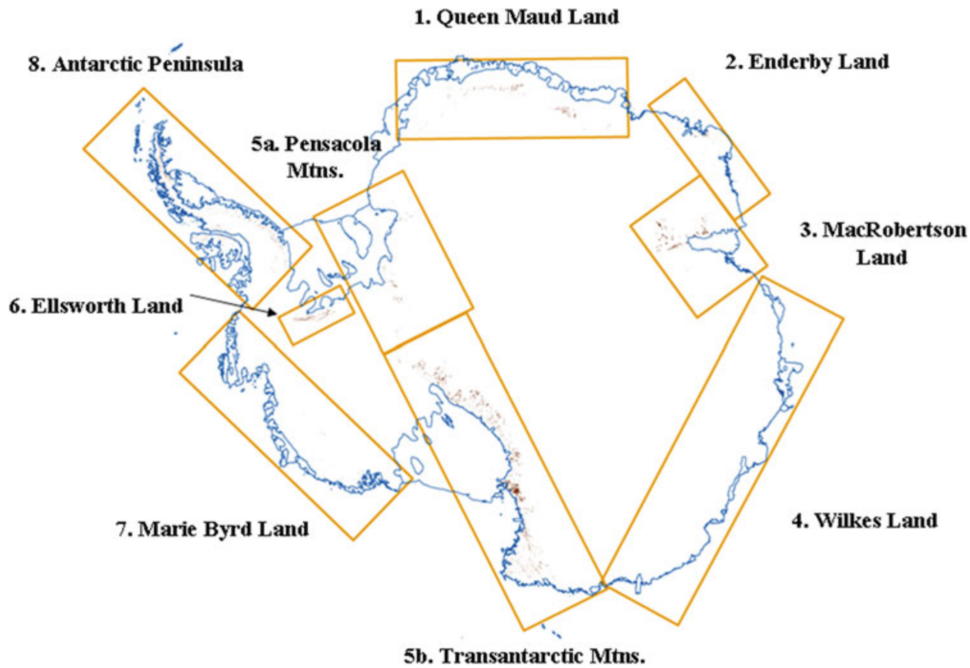

Fig. 2.1 Ice-free regions of Antarctica

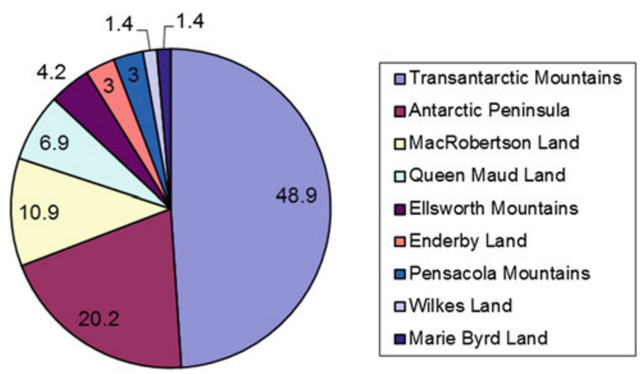

Fig. 2.2 Distribution (percent) of ice-free areas by region in Antarctica

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
	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**

(continued)

Table 2.1 (continued)

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

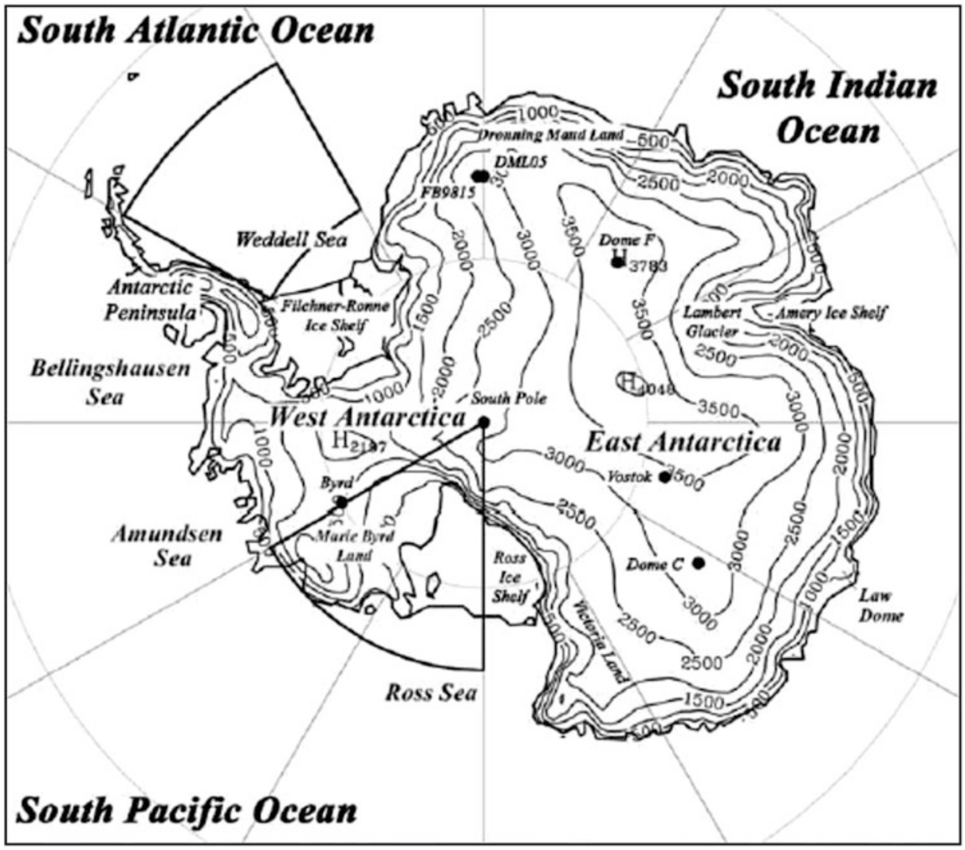

Fig. 2.3 Elevation map of Antarctica (500 m contour interval) (Bromwich et al. 2004)

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

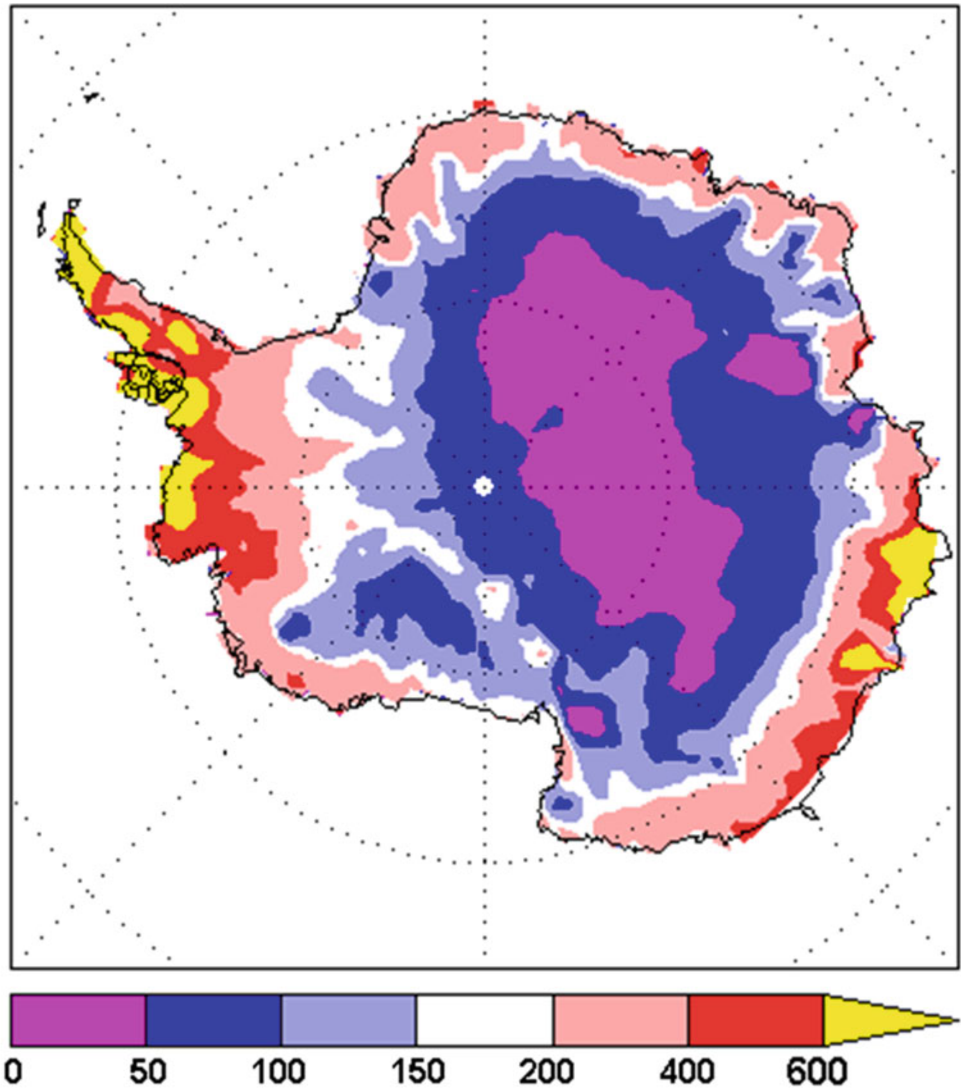

Fig. 2.4 Distribution of mean-annual precipitation (mm/year, water equivalent) in Antarctica (Connolley unpublished)

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)

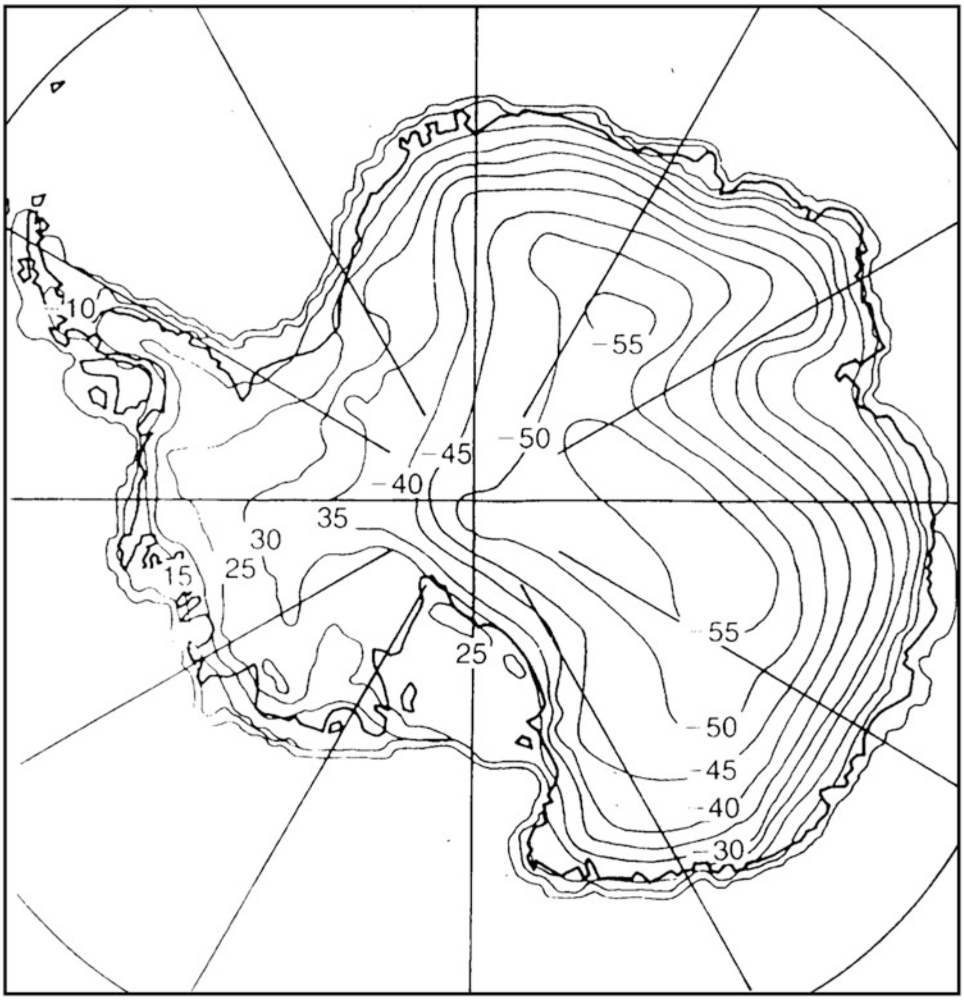

Fig. 2.5 Mean annual air temperature of the surface of Antarctica (Connolley and Cattle 1994)

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.

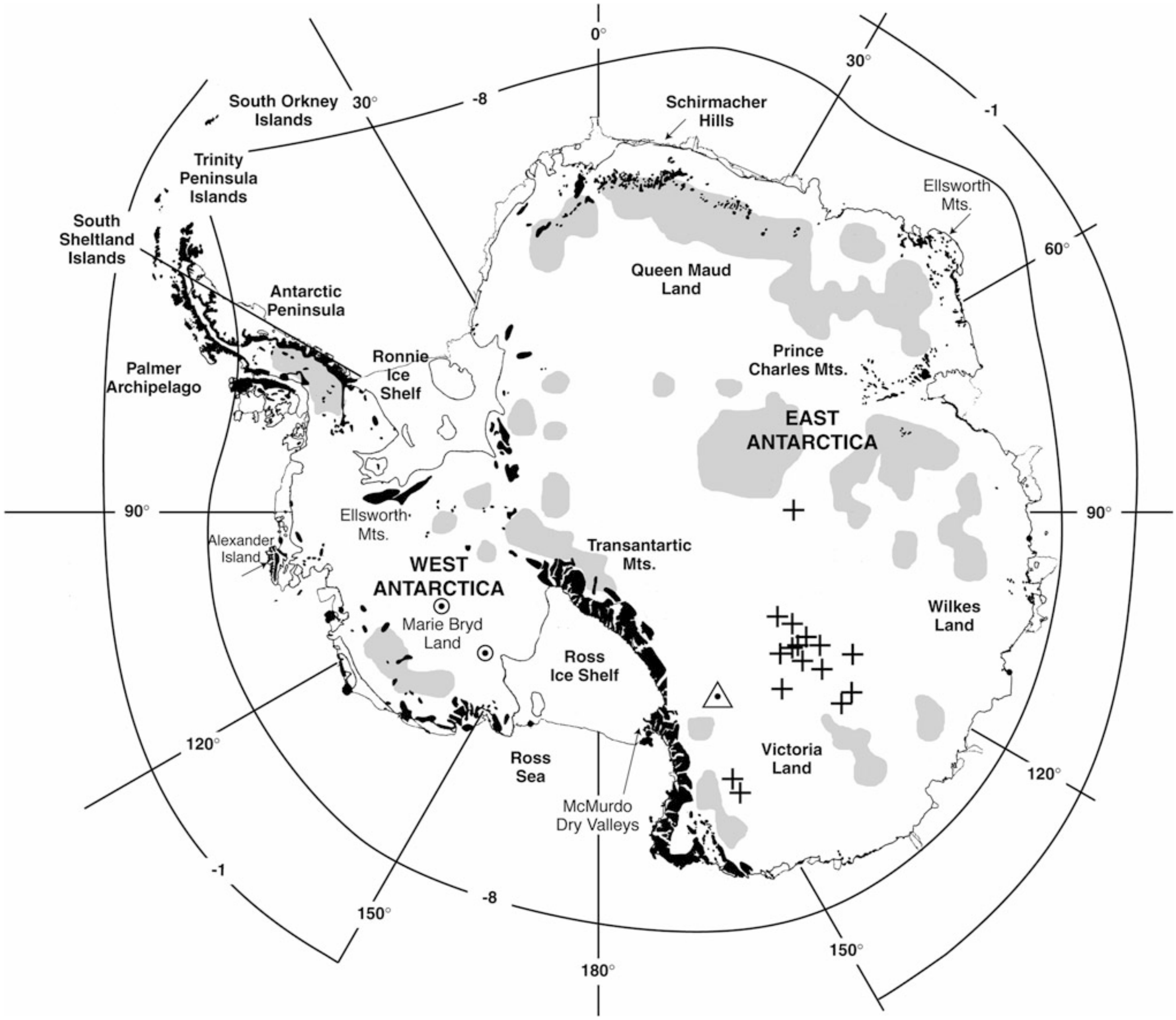

Fig. 2.6 Permafrost distribution in Antarctica (Bockheim 1995)

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

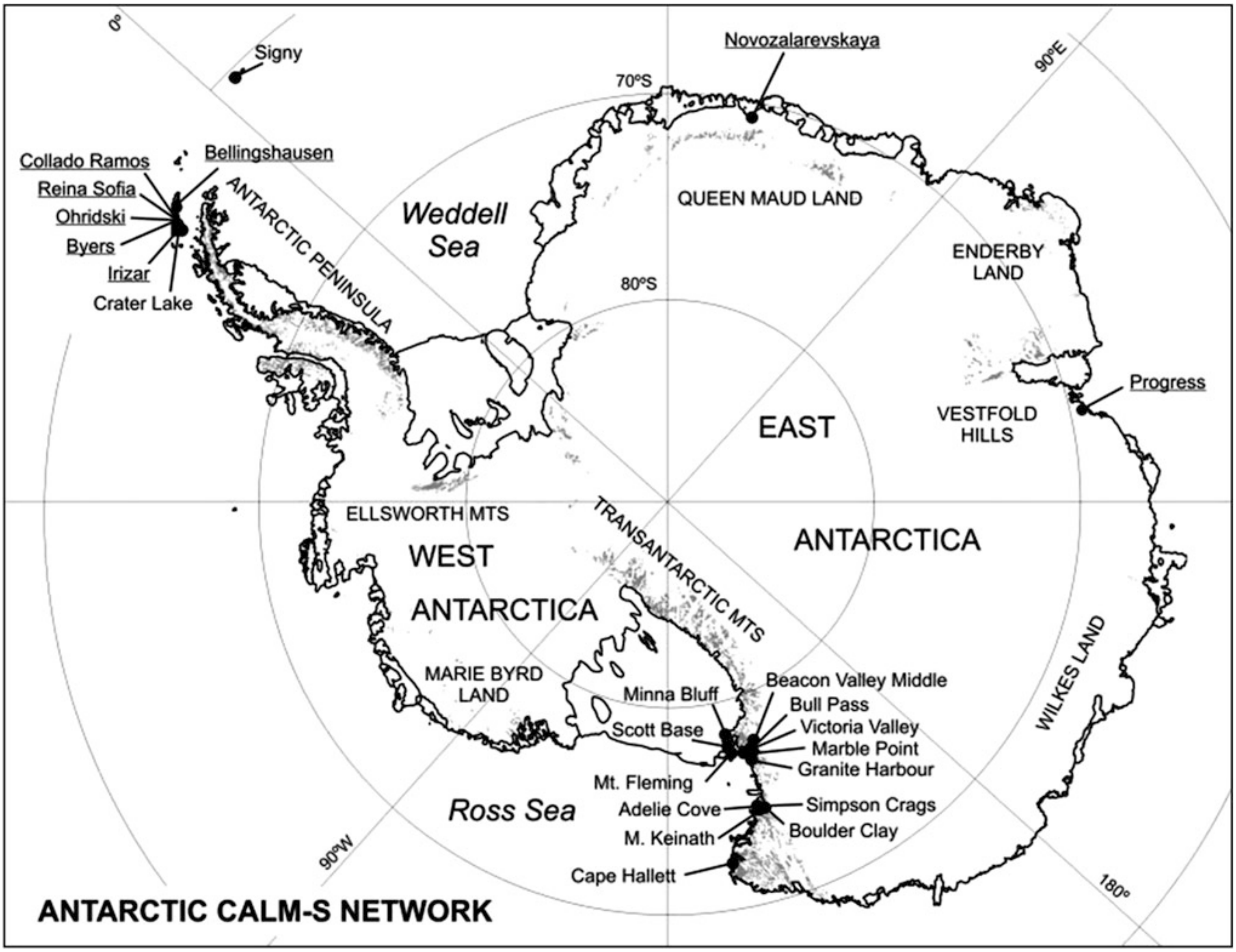

Fig. 2.7 Distribution of circumpolar active-layer monitoring-south sites (Vieira et al. 2010)

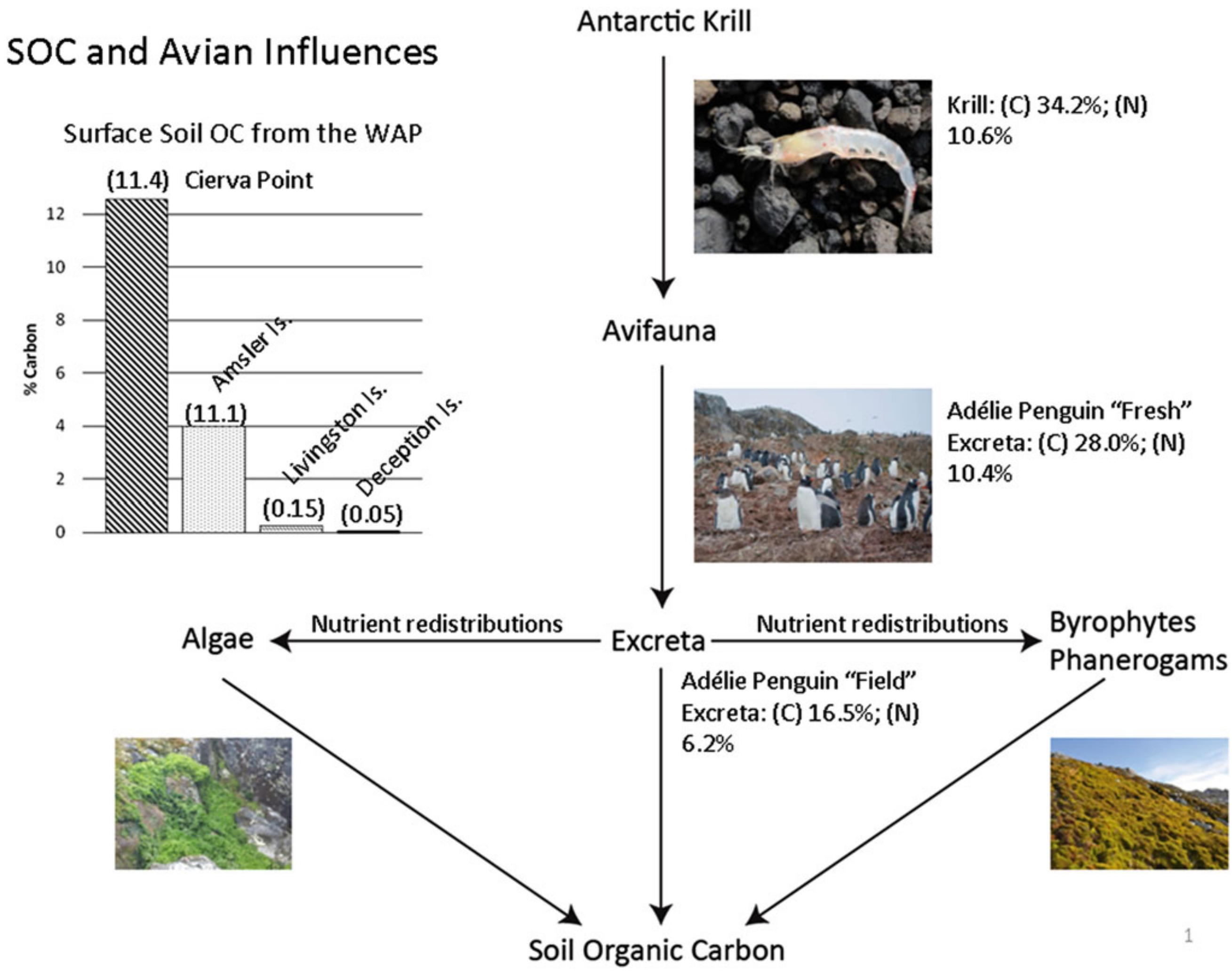

Fig. 2.8 Avian influences on nutrients and soil organic carbon (SOC) in maritime Antarctica (Bockheim and Haus 2014)

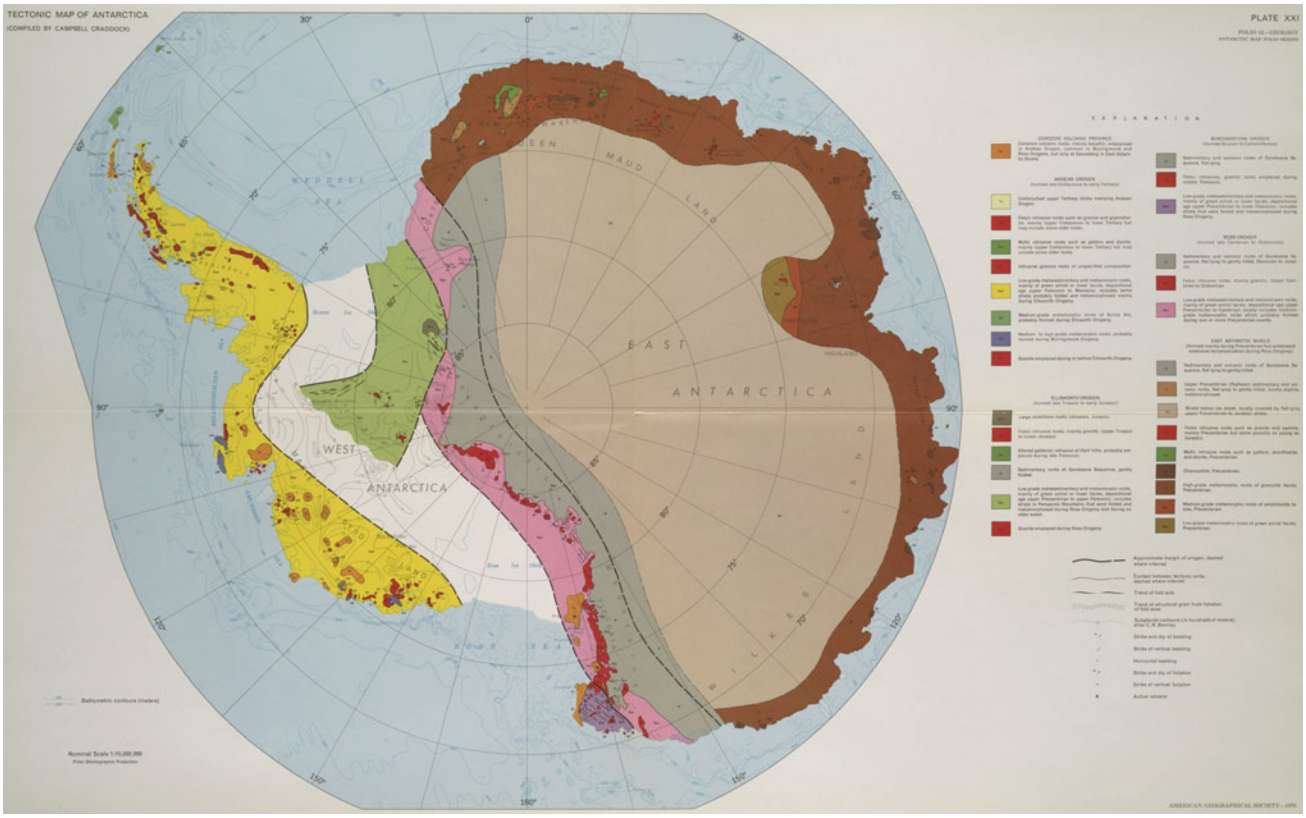

Fig. 2.9 Bedrock geology of Antarctica (Craddock et al. 1969). The major rock units from left to right (low-grade metasedimentary and metavolcanic rocks mainly of green schist of upper Paleozoic to Mesozoic age (*yellow*); low-grade metasedimentary and metavolcanic rocks mainly of green schist of upper 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

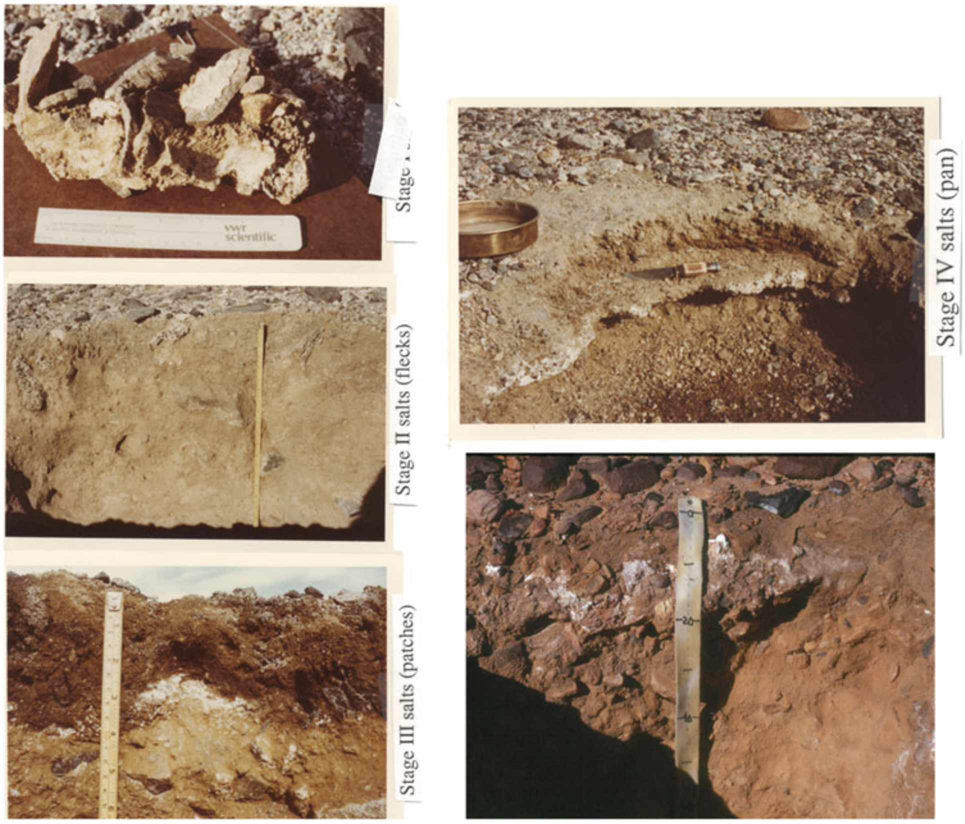

Fig. 2.10 Morphogenetic stages of salt development in Antarctic soils: *Stage I* coatings beneath stones (*upper*, *left*); *Stage II* salt flecks covering less than 20 % of soil area (*middle*, *left*); *Stage III* salt flecks covering more than 20 % of soil area (*lower*, *left*); *Stage IV* weakly 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

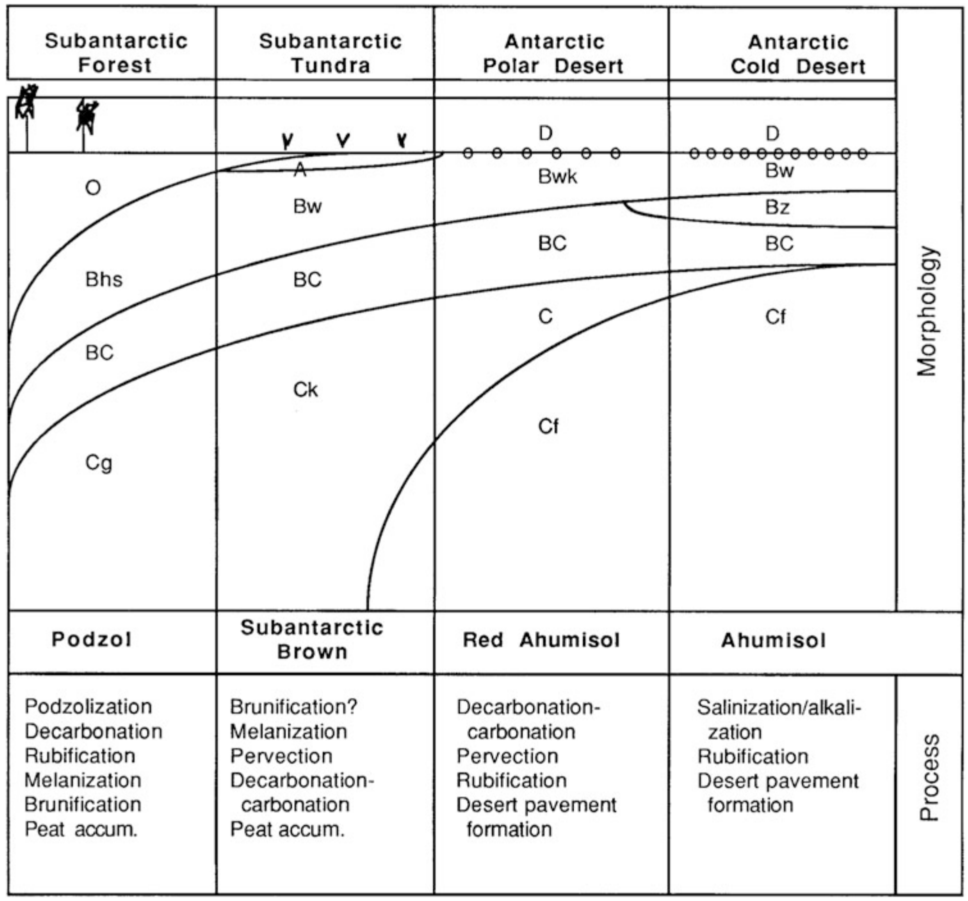

Fig. 2.11 Generalized soil horizonation and soil-forming processes in the Southern Circumpolar Region (Bockheim and Ugolini 1990)

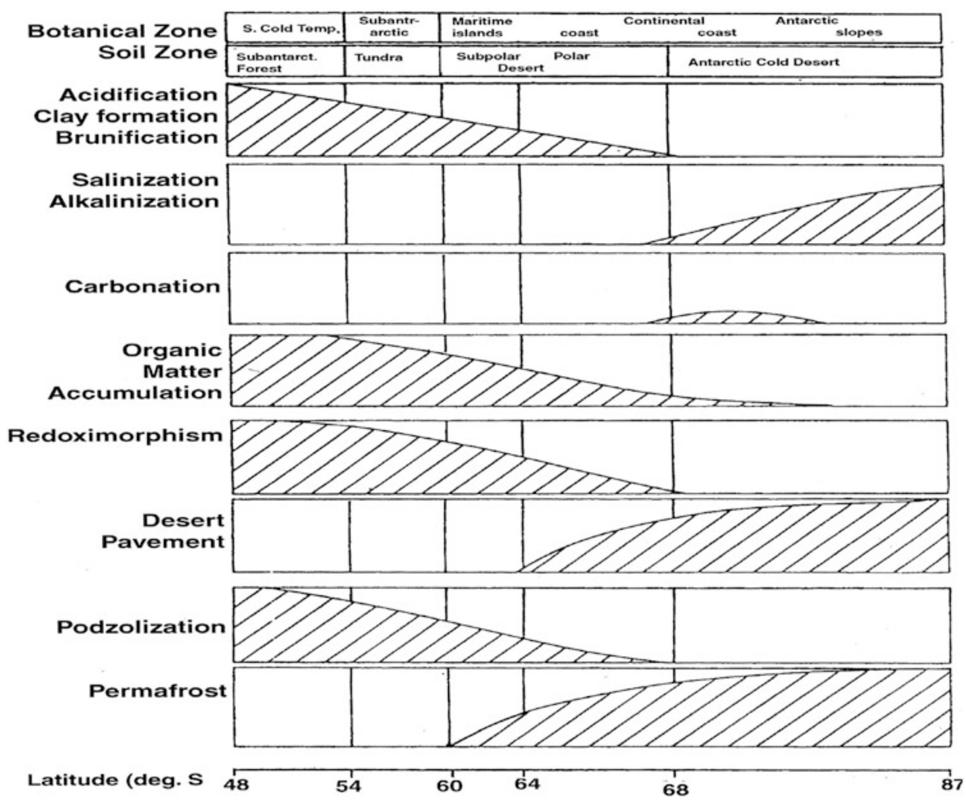

Fig. 2.12 Changes in pedogenic processes along a latitudinal transect in the Southern Circumpolar Region (Bockheim and Ugolini 1990; modified by Blume et al. 1997)

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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