J. C. F. Tedrow and C. C. Thompson

Rutgers *

CHEMICAL COMPOSITION OF POLAR SOILS

Abstract

For pedologic purposes the polar regions are divided as follows: (1) Arctic Brown soil zone, which occupies that terrain between the tree line and the high arctic, (2) Polar Desert soil zone, which is contiguous with the high arctic, and (3) Cold Desert soil zone of Antarctica. In going from the Arctic Brown soil zone to the colder, drier, polar deserts of the high arctic and finally to the cold deserts of Antarctica, one encounters certain pedogenic changes. Soils of the northern fringes of the forest zone tend to have weak podzolic affinities, but in progressing to cooler, drier conditions, the soils could be described as being a variety of cold steppe. Soils of the high arctic and of the antarctic continent have many features in common with those of the temperate deserts. Representative deep, well-drained (zonal) soils from each of the regions were analyzed for organic matter, pH values, Si, Al, Fe, Ca, Mg, Na, K, Cl, Cu, Co, B, Ga, Pb, Zr, Ni, Sn, Zn, Mo, Mn, V, Cr, Sr, and Ti. Zonal soil processes of the polar regions are briefly discussed.

In order to provide for a systematic understanding of the various soil conditions and process within the polar regions, we have used an Arctic Brown, Polar Desert, Cold Desert trichotomy [1]. Briefly, the Arctic Brown soil depicts the zonal processes of, and is penecontiguous with, the main arctic belt just north of the tree line. The Polar Desert [2] soil zone represents the zonal soil of the sectors recognized by naturalists as high arctic and the Cold Desert [2] soil zone is exemplified by the ahumic deserts of Antarctica. These three main varieties of soil can be arranged in the form of a hypothetical pedogenic gradient somewhat analogous to a Chernozem-Steppe—Desert gradient within the temperate regions. While there have been numerous descriptions of the polar soils

---

* Rutgers, the State University, U.S.A.

[1] Pedogenic gradients of the polar regions (Prepared manuscript) J. C. F. Tedrow.

[2] The term *Polar Desert soil* is used exclusively in the northern polar regions (Gorodkov, 1939), whereas the term *Cold Desert soil* is restricted to the Antarctic continent and offshore islands (Markov, 1956). This terminology, although not entirely satisfactory, is tentatively adopted.

during the past, there is a paucity of data as to the soil properties, particularly those related to chemical composition. This report therefore provides certain chemical data as to the total soil composition and from these data certain pedogenic processes are depicted for the major polar regions.

SOIL DESCRIPTIONS

In order to show the spectrum of quantitative and qualitative processes within various polar regions, this study centers on 5 main soil profiles. The Arctic Brown soil, from Northern Alaska, typifies the zonal process within the main arctic belt. Arctic Brown soil from Prince Patrick Island depicts the zonal process further north where climate is cooler and drier. Two Polar Desert soils are reported from Prince Patrick Island; one from sandy textured material and the other from loamy material. The fifth soil profile typifies the Cold Deserts of Antarctica. One may justifiably question regional interpretation from such a small number of sites but nevertheless the data are considered realistic guideposts.

Profile 1: Arctic Brown soil on glacial drift c. 68°29′ N, 156°15′ W, Northern Alaska. Vegetation consists of a closed cover of *Dryas, Cladonia,* dwarf heaths and herbs. Morphology follows:

Depth in.	*Horizon*	*Morphology*
0—10	I	Dark brown to brown (10 YR 4/3) loam, friable with crumb structure. Few rock fragments present.
10—14	II	Yellowish brown (10 YR 5/6) sandy loam with single grain to weak crumb structure. Few rock fragments present.
14—20	III	Olive brown (2.5 Y 4/4) loam, with firm, single grain structure. Till is composed of quartzite, gabbro, sandstone and siltstone.

Sand fractions of the soil are comprised of quartz and chert with about 1 percent fresh-appearing feldspar (Hill and Tedrow, 1961). Clay-size minerals consist of hydrous mica with small quantities of kaolinite and quartz with a little goethite in the uppermost horizon.

Profile: 2: Arctic Brown soil on sandstone, Prince Patrick Island. Complete cover of *Dryas*. Morphology follows:

Depth in.	*Horizon*	*Morphology*
1—0	I	Organic mat of *Dryas* roots.
0—3	II	Dark gray (10 YR 4/1) gravelly sandy loam with speckled appearance. Loose and friable with carbonates on rocks.
3—9	III	Dark brown (10 YR 3/3) sandy loam, loose consistence. Carbonates present on rocks.
9—13	IV	Light olive gray (5 Y 6/2) gravelly sandy loam. Frozen at 10 inches (July 7, 1964).

Clay minerals consist of mainly an illite-vermiculite-montmorillonite mixed layer mineral, vermiculite, illite, kaolinite and clay-size quartz.

Profile 3: Polar Desert soil on carbonate-bearing sandstone, Prince Patrick Island. Virtually no vascular plants are present. Morphology follows:

Depth in.	*Horizon*	*Morphology*
0— 5	I	Poorly developed desert pavement of subangular rock fragments underlain by loose gray brown (2.5 Y 5/2) gravelly fine sandy loam. Pedogenic carbonates throughout profile.
5—13	II	Yellowish red (5 YR 4/6) sandy clay loam, firm.
13—15	III	Light gray (5 Y 7/1) loamy material (frozen July 6, 1964).

Clay-size minerals consist of an illite-vermiculite-montmorillonite mixed layer mineral, vermiculite, illite, kaolinite and quartz. The 13—15 inch depth represents a geologic unconformity containing mostly montmorillonite.

Profile 4: Polar Desert soil (Storkerson series[3]) on a gla-

[3] See Tedrow and Douglas (1964) and Tedrow (1966) for more details.

cio-fluvial deposit (Beaufort formation) from Prince Patrick Island. A scattering of lichens is present. Morphology follows:

Depth in.	*Horizon*	*Morphology*
0—0.5	I	Desert pavement of closely knit gravel resting on a 0.5-inch layer of light gray sand.
0.5—2	II	Yellowish brown (10 YR 5/6) gravelly sand with speckled appearance. Loose and dry with non-coherent single grain structure.
2—22	III	Brownish yellow (10 YR 6/8) gravelly sand with speckled appearance. Loose consistence with a single grain structure.
22—24	IV	Light olive brown (2.5 Y 5/4) gravelly sand, firm and partially frozen (July 9, 1964).

Profile 5: Ahumic soil of the Cold Desert, Taylor Valley, Antarctica. Barren glacial drift from granite, marble, gneiss and related rocks. No visible plant life. Morphology follows:

Depth in.	*Horizon*	*Morphology*
0—2	I	White (5 Y 8/2) gravelly sand with poorly developed desert pavement. Very dry and loose with slight carbonate cementation.
2—6	II	Light olive gray (5 Y 6/2) loamy sand. Very dry and loose with slight carbonate cementation as above.
6—8	III	White (5 Y 9/2) loamy sand, hard with high concentration of pedogenic carbonates. Very dry.
8—15	IV	Light olive-gray (5 Y 6/2) loose loamy sand. Carbonates present but in much lower concentration than horizon III. Dry frost present (Nov. 25, 1961).

METHODS

Soil samples were collected by genetic horizon and analyzed by conventional methods in the laboratories at Rutgers University. The pH values were estimated by a potentiometer equipped with

Pl. 1. Pedogenic carbonate coatings on glacial cobbles. Rock specimens are from the 1 foot depth of an Arctic Brown soil on Prince Patrick Island, N.W.T., Canada

Pl. 2. Dry saline basin, Wright Valley. Antarctica. The light colored salt is up to 0.5 inch thick

a glass electrode, and organic matter by chromic acid oxidation. After fusing, SiO_2 and R_2O_3 were determined gravimetrically. Fe was estimated, using a Perkin Elmer atomic absorption unit, and Al reported by difference. Ca, Mg, K and Na were also estimated using atomic absorption techniques. Trace element composition was estimated by arcing a soil-graphite mixture in Jarrel--Ash 3.4 meter grating spectrograph using Ge and Pd as internal standards.

Table I

Some physical and chemical properties of Polar soils

Depth in.	Textural composition	pH	Organic matter %	CO_3
Profile 1 — Arctic Brown Soil, Alaska (Glacial drift)				
0—10	l.	3.5	16.9	—
10—14	sa. l.	3.6	3.9	—
14—20	l.	4.7	1.7	—
Profile 2 — Arctic Brown Soil, Prince Patrick Island (Sandstone)				
0— 3	gr. sa. l.	7.2	4.9	—
3— 9	sa. l.	6.9	6.6	—
9—13	gr. sa. l.	7.4	0.4	—
Profile 3 — Polar Desert Soil, Prince Patrick Island (Sandstone)				
0—5	gr. f. sa. l.	7.4	6.0	—
5—13	sa. cl. l.	7.5	1.1	+
13—15	l.	7.7	0.4	+
Profile 4 — Polar Desert Soil, Prince Patrick Island (Beaufort Gravel)				
0.5— 2	gr. sa.	4.4*	1.7	—
2 —22	gr. sa.	4.4*	0.2	—
22 —24	gr. sa.	5.4*	<0.1	—
Profile 5 — Ahumic Soil of the Cold Desert, Taylor Valley, Antarctica (Glacial drift)				
0— 2	l. gr. sa.	8.9	<0.1	—
2— 6	l. sa.	8.4	<0.1	+
6— 8	l. sa.	8.8	<0.1	+
8—15	l. sa.	8.4	<0.1	+

— — absent, + — present; * — low pH values are a reflection of the coarse grained, base deficient rocks (see Tab. II).

RESULTS AND DISCUSSION

ORGANIC MATTER

Table I shows that organic matter of the Arctic Brown soil is quite high. Progressing northward to the transition zone between the Arctic Brown and Polar Desert soil zones, the organic matter content of the former soil decreases somewhat. Organic matter of the Polar Desert soil is usually at a lower level than in the case of Arctic Brown soil, especially with coarse-textured substrate. In medium-textured material of the Polar Desert soil, organic matter commonly persists at relatively high levels. Gorodkov (1943) ascribed the main source of the organic component in Polar Desert soils to algae. One of the surprising characteristics of Polar Desert soils is that while they possess a strict mineral appearance, organic matter at the 4 to 6 percent levels may be present (Tedrow, 1966).

Cold desert soils of Antarctica are virtually void of the humic component (Tedrow and Ugolini, 1966; Boyd, Staley and Boyd, 1966). Even rare situations in which the surface of the mineral substrate is colonized by some lower form of plant life, the underlying mineral material is strikingly humus-free.

pH VALUES

Well-drained Arctic Brown soils are usually moderately acid, but on base-rich deposits or wind-exposed positions they may be alkaline even at the surface. In the high arctic both Polar Desert and Arctic Brown soils reflect the low degree of leaching, and pH values accordingly tend to be quite high (Tedrow and Douglas, 1964). Plate 1 shows carbonate accumulation on the lower sides of rocks taken from the solum of an Arctic Brown soil on Northern Banks Island. With base-deficient coarse-textured materials, however, pH values tend to be quite low in Polar Desert soil (Tabl. I, Profile 4) as well as in Arctic Brown soil. Ahumic soils of the Cold Deserts of Antarctica are almost universally alkaline and/or saline. High pH values, which occur throughout the ice-free areas, reflect the aridity of the landscape. Saline conditions are present in many depressions of the Antarctic continent (Pl. 2).

Table II

Chemical composition of Polar soils *

Depth in.	Horizon	SiO_2 %	Al_2O_3 %	Fe_2O_3 %	CaO %	MgO %	Na_2O %	K_2O %	Cl %
Profile 1 Arctic brown soil, Alaska (Glacial drift)									
0—10	I	70.68	13.12	7.39	0.25	0.38	1.38	0.86	—
10—14	II	78.63	8.09	5.22	0.48	0.30	1.14	1.12	—
14—20	III	74.73	8.03	10.71	0.10	4.18	1.29	0.72	—
Profile 2 — Arctic brown soil, Prince Patrick Island (Sandstone)									
0— 3	I	82.38	5.69	3.86	0.26	0.15	0.12	0.53	—
3— 9	II	87.13	6.10	3.32	0.25	0.16	0.80	0.47	—
9—13	III	88.14	8.29	1.89	0.02	0.25	1.15	1.15	—
Profile 3 — Polar desert soil, Prince Patrick Island (Sandstone)									
0— 5	I	78.62	8.35	4.54	0.07	1.48	0.32	0.77	—
5—13	II	61.56	7.49	20.33	4.02***	0.53	2.12	1.08	—
13—15	III	74.79	9.15	2.36	1.52***	0.62	0.44	0.14	—
Profile 4 — Polar desert soil (Storkerson gravelly sand) Prince Patrick Island (Beaufort Gravel)									
0.5— 2	II	98.31	0.45	1.36	0.02	0.08	0.44	0.29	—
2 —22	III	94.98	0.84	0.94	0.30	0.05	0.11	0.12	—
22 —24	IV	95.96	1.90	1.22	0.29	0.06	0.16	0.23	—
Profile 5 — Ahumic soil of the cold desert, Taylor Valley Antarctica (Glacial drift)									
0— 2	I	63.87	17.50	3.72	0.98***	1.03	4.92	2.42	—
2— 6	II	63.24	21.07	5.66	2.26***	1.48	3.66	0.15	0.41
6— 8	III	62.05	16.66	5 21	6.20***	1.92	3.10	1.77	—
8—15	IV	63.38	12.04	7.92	2.33***	2.03	4.50	1.67	—
Glacial drift near Canada Glacier, Antarctica ****									
0—4		61.79	13.50	3.80	2.33	1.77	3.99	1.37	—
Glacial drift, polygon near Suess glacier, Antarctica									
0—4		51.95	20.86	8.49	0.80	0.26	3.72	2.64	3.15
Glacial drift, polygon near Canada glacier, Antarctica									
0—4		61.90	13.61	4.39	1.46	1.25	4.57	2.03	1.20

* — air-dry samples, expressed on an organic matter-free basis

** — water soluble

*** — carbonates present

**** — SO_4 present in trace quantity. Phosphorus not determined in any samples

Table III

Trace element composition of Polar soils

Depth in.	Cu	Co	B	Ca	Pb	Zr	Ni	Sn	Zn	Mo	Mn	V	Cr	Sr	Ti
	ppm														
Profile 1 — Arctic brown soil, Alaska (Glacial drift)															
0—10	11	4	17	309	7	19	151	2	800	3	176	92	86	33	1000
10—14	6	1	8	218	6	15	12	1	285	3	59	37	78	45	1000
11—20	10	1	9	122	6	15	30	1	362	3	75	48	77	56	1000
Profile 2 — Arctic brown soil, Prince Patrick Island (Sandstone)															
0— 3	2	1	24	54	4	15	8	1	173	1	31	19	39	29	346
3— 9	2	1	24	75	5	9	10	1	188	2	37	20	51	30	327
9—12	2	1	72	12	4	14	5	1	198	1	3	23	36	29	351
Profile 3 — Polar desert soil, Prince Patrick Island (Sandstone)															
0— 5	4	1	55	84	7	20	56	1	378	2	45	57	65	43	423
5—13	3	7	46	323	5	17	234	3	255	13	63	42	201	144	710
13—15	3	6	52	30	26	12	4	1	132	1	19	168	53	274	504

Profile 4 — Polar desert soil (Storkerson gravelly sand) Prince Patrick Island
(Beaufort Gravel)

0.5 – 2	2	1	7	4	5	3	4	1	54	1	84	8	31	24	136
2—22	2	1	11	3	4	6	2	1	35	1	47	6	30	21	63
22—24	3	1	10	5	6	17	7	1	151	1	130	10	44	31	235

Profile 5 — Ahumic soil of the cold desert, Taylor Valley, Antarctica
(Glacial drift)

0— 2	7	2	5	252	7	19	38	2	382	2	82	57	142	577	805
2— 6	5	3	4	117	8	15	151	2	682	3	209	42	131	687	438
6— 8	9	3	4	228	7	15	135	2	681	3	160	168	97	673	640
8—15	6	4	4	269	8	12	153	3	726	3	223	19	143	669	702

Salt crust (thenardite), Prince Patrick Island

Surface	2	1	12	14	1	14	4	1	186	1	6	22	3	38	793

Salt crust ($CaCl_2$), Wright Valley, Antarctica

Surface	6	1	8	116	3	3	3	1	57	3	21	8	40	767	201

CHEMICAL COMPOSITION

Table II gives the chemical composition of soils and certain geologic deposits from the three major polar pedogenic regions. Polar regions in general have a low leaching potential and there are few specific repetitive trends within the profile involving redistribution of clay, iron, or aluminum. With respect to major element distribution within the profile, table II shows that the cold deserts of Antarctica accumulate soluble soil constituents, a condition also reflected in conductivity determinations (Tedrow and Ugolini, 1966). Random tests for soluble Cl, SO_4, Na and K are usually positive throughout the ice-free areas of Antarctica. Polar deserts of the high arctic are similar in many respects to those of Antarctica (Tedrow, 1966), but the former do not display the extreme aridity and lack of humic substance as do the deserts of the antarctic continent.

Water-soluble Na and K in the soils and geologic deposits listed in Table II were determined. Arctic Brown soil showed about 0.1 ppm of water-soluble Na. Water-soluble Na approximated 0.5 ppm in the Polar Desert soils and as high as 34 ppm in the Cold Desert soils of Antarctica. Water-soluble K increased from about 0.5 ppm in the Arctic Brown soil to 1 to 2 ppm in Polar Desert soil and up to 4 ppm in the Cold Desert soils of Antarctica. The large number of saline and alkaline deposits in Antarctica reported by geologists, biologists, and pedologists that attest to the arid environment of the continent, are not considered in this report.

Table III shows total trace element content of selected soils by genetic horizon. The data show little specific trend with depth and there does not appear to be any specific trend among various profiles within the various polar regions. Strontium values are much higher, however, in the antarctic samples than is the case with those from the arctic. The high Sr values in samples from Antarctica were also reflected in the salt crust from Wright Valley (Tab. III). Boron values were lower in the antarctic samples than in those from the arctic regions.

The 5 to 13-inch depth of profile no. 3 (Tab. III) shows some concentration of Ga, Ni, Mo, Cr, and Ti. The concentrating of these five elements possibly may be more of a reflection of a trace-element-enriched stratum rather than pedogenic processes.

Trace elements in profile no. 4 (Tab. III) are much lower than is the case with the other profiles studied. Profile 4 is formed on extremely coarse-textured material that is silica-rich and very low in virtually all common bases and trace elements. The base-deficient nature of the profile is further brought out by the data in Table II.

Trace element distribution in the zonal soils of the polar regions apparently is somewhat like that of the temperate regions, in that the nature of the parent material appears to be the controlling factor in elemental distribution (Conner, Shimp and Tedrow, 1957).

References

Boyd, W. L., Staley, J. T. and Boyd, J. W., 1966 — Ecology of soil microorganisms of Antarctica. *Amer. Geophys. Union, Antarctic Research Series,* No. 8; p. 125—159.

Conner, J., Shimp, N. F., Tedrow, J. C. F., 1957 — A spectrographic study of the distribution of trace elements in some podzolic soils. *Soil Sci.*, vol. 83; p. 65—73.

Gorodkov, B. N., 1939 — Peculiarities of the arctic topsoil. *Izv. Gos. Geog. Obshchestva,* t. 71; p. 1516—1532.

Gorodkov, B. N., 1943 — Polar deserts of Wrangel Island. *Botanicheskij Zhurnal SSSR*, t. 28; p. 127—143.

Hill, D. E. and Tedrow, J. C. F., 1961 — Weathering and soil formation in the arctic environment. *Amer. Jour. Sci.*, vol. 259; p. 84—101.

Markov, K. K., 1956 — Some facts concerning periglacial phenomena in Antarctica (prelim. rept.). *Vestnik Mosk. Univ.*, ser. geog., 1; p. 139—148.

Tedrow, J. C. F. and Douglas, L. A., 1964 — Soil investigations on Banks Island. *Soil. Sci.*, vol. 98; p. 53—65.

Tedrow, J. C. F. and Ugolini, F. C., 1966 — Antarctic soils. *Amer. Geophys. Union, Antarctic Research Series,* No. 8; p. 161—177.

Tedrow, J. C. F., 1966 — Polar desert soils. *Soil Sci. Soc. Amer. Proc.,* 30; p. 381—387.

DISCUSSION

Professor Hoppe: Do you have any kind of absolute datings demonstrating at what rate the formation of Polar soils takes place?

Professor Tedrow: Within the main tundra belt the Arctic Brown soil will commonly have a thicker solum on the older terraces than is the case with the younger ones. At Umiat, Alaska, Arctic Brown soil has a solum thickness of 20 to 24 inches on the highest terrace whereas on the lowest terrace the thickness is only some 2 to 3 inches thick. Dr. J. Brown found out, however, that in the Brooks Range of Alaska, the lithology was about as important as age in determining the solum thickness — in fact in some situations it was more important. The Polar Desert soils of northern latitudes and the Cold Desert soils of Antarctica undergo a slow rate of development but the older glacial deposits have a more weathered and ironstained appearance than do the younger ones.

Perhaps it is important to mention some radio-carbon dating of the surface soils of the Arctic. At Point Barrow, Alaska, the organic matter of the surface horizon of the Arctic Brown soil yielded an age of about 2900 years. In Inglefield Land, Greenland, the Polar Desert soil yielded an age of about 3300 years.

Dr. Prusinkiewicz: What are the important differences in chemical composition between the Arctic Brown soil and the Brown Forest soil?

Professor Tedrow: If we adopt the term Brown Forest soil as used by Ramann and Tamm there is not very much difference between the two. I have long emphasized that pedologists have, perhaps, placed too much emphasis on the treeline. There is a great affinity between the two soils. Arctic Brown soil at southern fringes of the polar desert soil zone, however, is in a more arid environment and reflects a less leached condition. At the moment Arctic Brown includes a number of conditions which, in time, will probably be recognized individually.

Dr. Dumanowski: What is the origin of the pavement covering the soils of the polar deserts?

Professor Tedrow: Desert pavement is a widespread condition in both the high arctic and Antarctica. On the western fringes of Prince Patrick Island there is conclusive evidence that the stone pavement results from the removal of the sands and silts. In this sector I have observed and photographed the gravel fragments resting on pedestals of sand, the original surficial sands having moved by wind action. In the above sector there is also present-day dune formation. In other cases, however, there is little evidence of wind-polishing, wind transport, etc. Perhaps we should consider the possibility of several origins of desert pavement within the polar deserts.

Profesor Markov: Je félicite Professeur Tedrow pour sa communication. Les processus d'altération chimique sont autant caractéristiques pour les déserts arctiques que les processus de la désintégration mécanique. Ceux-là pourtant sont très longtemps restés insuffisamment connus. Les processus chimiques sont de première importance en Antarctique entre autres où la radiation solaire en été est égale à celle des régions équatoriales. C'est pour la première fois pourtant que nous avons l'occasion de prendre connaissance de la synthèse concernant les deux zones polaires au même temps.

Professor Tedrow: That there is rather pronounced chemical and physical weathering in both north and south polar regions is no longer a question. Of special interest is the important work of Professor Markov and his colleague, Prof. Glazovskaia, on the weathering in the antarctic deserts. I believe that our studies on weathering agree fundamentally with those published by Professor Markov and colleagues. In fact, Professor Markov's antarctic reports were a great help to us in our investigations in Antarctica during 1961—62, and still are. Our work on the polar deserts of the north, in the process of being published, will show that there is also considerable weathering in the high northern latitudes.