SOILS OF THE POLAR LANDSCAPES

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CHAPTER 9

The Tundra Zone and Its Soils

Tundra is used in a pedologic sense as a zonal concept, a broad and generalized term to depict all soils north of the forested land, and, in a more specific sense, as the name of a gleyed soil in the same region. Individual investigators have combined it with geobotanical terms to take account of variant conditions in soils on the northern fringes of forested land; the names Forest tundra and Wooded tundra are examples. Also, in treeless mountain sectors well to the south of the main tundra zone, soils have been designated as Mountain tundra, Alpine tundra, and so forth. When Tundra is defined in general soil textbooks, it is usually described as a soil north of the forested land, underlain by permafrost, characteristically gleyed, acid, and silty, and displaying a prominent organic mat. With more information being added to the polar pedologic literature each year, however, we now have at least a general picture of soil properties in the tundra zone on a circumpolar basis. Probably all will agree that a great variety of other soils are present in the tundra zone.

Thawing and Freezing of Soils of the Tundra

The snow cover in the tundra zone usually disappears during the month of June, generally coinciding with the initial thaw in Tundra soil (Table 9-1). Thawing takes place rather rapidly during the first 3 to 4 weeks of the season, during which time some 75 percent of the total depth of seasonal thaw penetration is reached (Brown, Dingman & Lewellen, 1968). In contrast, the well-drained sites, for example, those with Arctic brown soils, are usually in elevated positions and lose their snow cover early, partly by wind action. This early loss of snow cover and the fact that only a small quantity of ground ice is present in the Arctic brown soil offer favorable conditions for an early and rapid thaw.

Fig. 9-1 compares the rate and depth of thawing in Tundra and Arctic brown soils in northern Alaska. Summer season soil temperatures in these soils are shown in Fig. 9-2.

TABLE 9-1 Climatic and hydrologic summary, Barrow, Alaska. (Brown, Dingman & Lewellen, 1968.)

	1963	1964	1965	1966
Thaw season began*	4 June	6 June	24 June	11 June
Snow runoff began	8 June	7 June	24 June	13 June
Thaw season ended	4 Sept.	9 Sept.	27 Aug.	28 Aug.
Length of thaw season (days)	93	96	65	79
Thaw season precipitation (mm)†	115	22	42	73
Thaw season mean temperature (°C)	2.3	1.8	4.1	2.8
Runoff records began	23 July	23 June	3 July, 12 Aug.	11 July
Runoff records ended	19 Aug.	11 Aug.	7 July, 6 Sept.	3 Sept.
% thaw season covered by records	30	52	31	62
% thaw season precipitation during period of record	44	77	34	78
Avg. maximum thaw (cm)‡	32	24	31	31
75% thaw penetration	8 July	4 July	17 July	6 July
100% thaw penetration	16 Aug.	5 Aug.	21 Aug.	4 Aug.

*Accumulation of positive degree-days.
†Recorded at United States Weather Bureau Station.
‡Thaw from corresponding soils adjacent to watershed (plots 30 and 25) (Brown & Johnson, 1965).

Little thawing takes place in Tundra soil during the latter part of the summer; the greatest seasonal thaw penetration is generally recorded during the first half of August. The seasonal thaw naturally begins somewhat later in the mountains and where snow cover persists late.

During freeze-up, which usually begins in late August or early September, the well-drained sites, which have a lower heat capacity, begin to freeze at the onset of prolonged negative ambient temperatures. The freezing of the Tundra soil begins some days later, or, in certain conditions, several weeks later (Fig. 9-1).

Tundra Soil

Fig. 9-3, an idealized profile of Tundra soil as it occurs in the main tundra zone, approximates the central concept of Tundra soil. To imply that there is uniformity among all soils designated as Tundra would, of course, be unrealistic; conditions vary regionally as well as locally. Plate IB shows an example of Tundra soil from Umiat, Alaska, and Fig. 9-4 shows a core of Tundra soil taken near Point Barrow, Alaska.

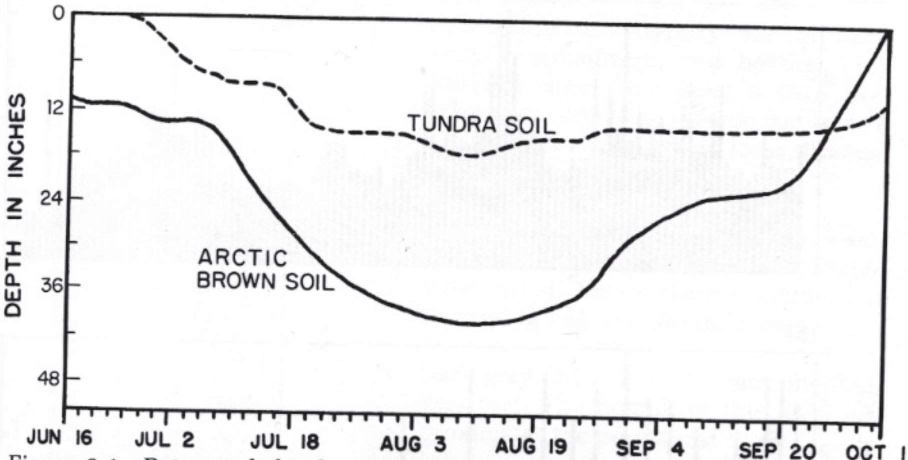


Figure 9-1 Rates and depths of thawing in polar soils near Point Barrow, Alaska. Data were collected during 1956. (Drew *et al.*, 1958.)

The Organic Components

The organic mat on the surface of the Tundra soil usually is fibrous and is humified only to a small degree. Table 9-2 gives the composition of the organic matter in selected Tundra soils of Siberia. Fulvic acid types are the dominant forms of organic acids in most Tundra soils, and the humic substances are quite mobile (Kononova, 1966). Since the humic acids are not so complex as in other soil regions, they are able to pass into solution and migrate to the lower horizons, where they accumulate (Karavaeva & Targulian, 1960).

Whereas there is a tendency for fulvic acids to predominate in the East European tundras, this is not necessarily the case in the Yakutian tundra. There is considerable potentially mobile organic matter in the

TABLE 9-2 Composition of organic matter in Tundra soils of the northern U.S.S.R.

Depth (inches)	Organic C (%)	N (%)	C:N	Organic Carbon of Humus Formation (expressed as % of organic carbon) Humic Acid	Fulvic Acid
		Northern Yakutia (Karavaeva & Targulian, 1960)			
2–4	12.17	0.95	12.8	24.98	36.16
14–16	4.74	0.35	13.5	25.31	23.65
		Vaigach Island (Ignatenko, 1967)			
0–2	17.83	—	—	20.6	29.0
2–6	7.23	—	—	32.0	43.5
6–9	6.52	—	—	31.0	40.0
9–14	0.15	—	—	21.7	33.0
14–17	0.56	—	—	18.0	27.0

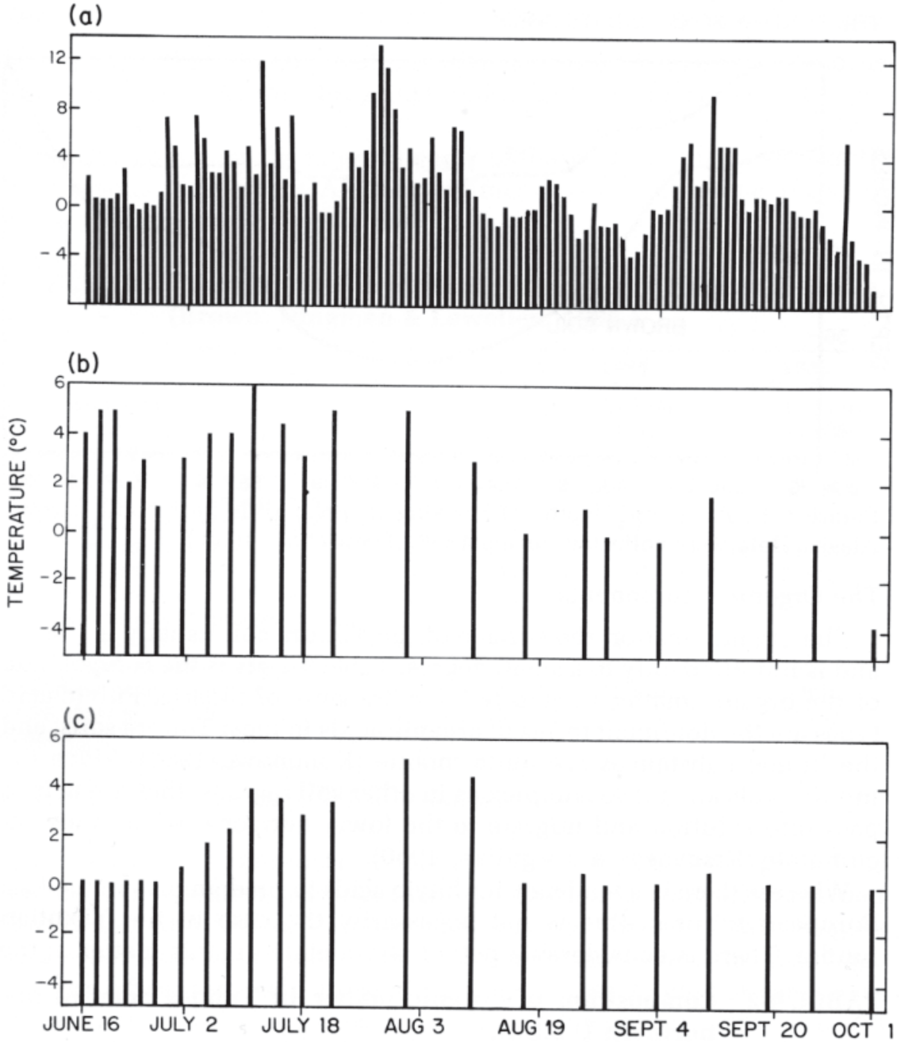
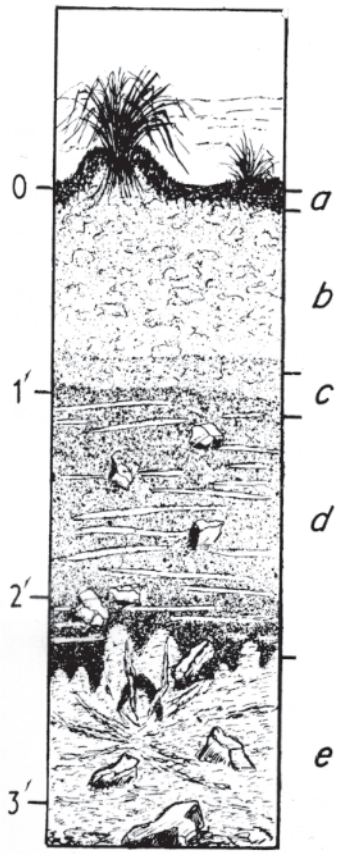


Figure 9-2 Summer soil and air temperature measurements near Point Barrow, Alaska (1956): (*a*) daily mean air temperatures. (*b*) temperatures of Arctic brown soil at the 3-inch depth. (*c*) daily temperatures of Tundra soil at the 3-inch depth. (Data of Drew *et al.*, 1958.)

upper horizon of the soils of the lower Lena River area, and Soviet investigators report that conditions in the Yakutian tundras are more favorable for downward movement of organic matter because the thixotropic properties of the soil are less pronounced than in the East European tundras. Organic matter may be concentrated deep in the profile of both the active and the permafrost layers. The term retinization or cryogenic retinization has been used to describe the process by which



a Dark brown to black organic matter, consisting of partially decomposed sedges, sphagnum, and heaths. This horizon may vary from a thin discontinuous one to an organic mat some 6 inches thick. Usually very loose, fibrous, wet, and strongly acid.

b Light olive-brown (2.5Y 5/4) silt loam. Usually very wet but loose and friable when dried. Nearly always mottled but in varying degrees. Strongly acid.

c Dark gray (2.5Y 4/0) silt loam, mottled, very wet. The bottom of this layer approximates the permafrost table.

d Very dark gray (2.5Y 3/0) silt loam, permanently frozen. Considerable organic staining in the ice; shreds of organic matter intermixed throughout the horizon. The bottom of the layer is very uneven and is much darker in color than the central portion of the horizon. The upper part of the horizon is also darker than the central portion. The horizon varies from frozen mineral soil to ground ice. Pieces of peaty material are commonly present.

e Frozen gray mineral matter interspersed with ground ice. No evidence of organic staining. In many instances the material is nearly clear ice. Weakly acid to calcareous, depending upon parent material.

Figure 9-3 Idealized profile of a Tundra soil. Soil colors are based on field conditions. (Tedrow *et al.*, 1958.)

organic matter is translocated and rearranged in the lower part of the active layer (Karavaeva & Targulian, 1960; Karavaeva, 1964). Retinization is not generally considered a part of the illuvial mechanism.

The C:N ratios of Tundra soil generally approximate 15:1 (Douglas & Tedrow, 1959), but the ratios tend to be wider with very turfy material. The organic surface in certain places is 4 to 6 inches thick but is generally only 2 to 3 inches; and particularly where cotton grass communities grow on sloping land, a mosaic of mineral soil is often exposed at the surface.

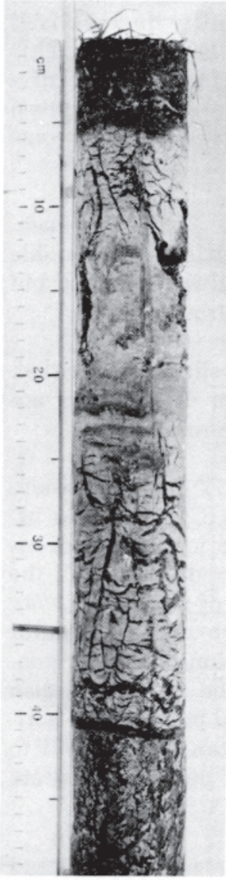


Figure 9-4 A core of Tundra soil from the Arctic Coastal Plain of Alaska. The permafrost table occurs at a depth of 14 inches. Note the ice-segregated zones in the central portion of the core. (Photo J. Brown.)

Soil Structure

During the early summer months, when the soils are in a supersaturated semiviscous state, they have few, if any, clearly defined structural units. As a general rule, the soils become drier as the summer progresses; and after the disappearance of large quantities of free water, poorly defined blocky or subangular structural units may be detected. Where the mineral soil contains an appreciable amount of humic substances, a poorly defined granular structure may be seen. At depth, usually just above the frost table, a platelike structure may be observed; apparently it is the result of freezing and subsequent thawing of the horizontal ice lenses (Taber, 1943; Filatov, 1945).

Particle Size

Particle-size distribution in Tundra soil does not appear to follow any pedogenic rule, as is the case with Podzol and Laterite. Geologic materials, rather than pedogenesis, are responsible for the predominantly silty texture of the soils (Table 9-3). A majority of Tundra soils are formed on Quaternary deposits, and the enormous variation in texture from one location to another is invariably attributable to geologic events. The Gubik formation of northern Alaska is predominantly sand, whereas the Cretaceous deposits of the Arctic Foothills are silty or, in localized situations, clayey in character. On the other hand, the drift of the crystalline rocks in eastern Canada has a high sand component. Where slightly better drainage conditions develop in Tundra soils, especially where there are positive relief elements and sandier textures, some downward translocation of the finest material is evident, but information on this subject is incomplete.

An ice wedge in permanently frozen silts along the Aldan River near Yakutsk, Siberia. The frozen upturned beds result from growth of the ice wedge. The scalloped face of the ice wedge is produced by overhead drip. Covering the frozen strata is a 5-foot-thick active layer of well-drained silts and fine sands. The site is colonized by Dahurian larch (*Larix dahurica*).

Plate IA

Plate IB

Upland tundra soil, Umiat Lakes, Alaska. Cotton grass (*Eriophorum*) tussocks form an irregular surface. Permafrost can be seen at the bottom of the photograph. A buried organic layer is situated between the permafrost and the brown mineral material. The age of the buried organic horizon approximates 9,200 years.

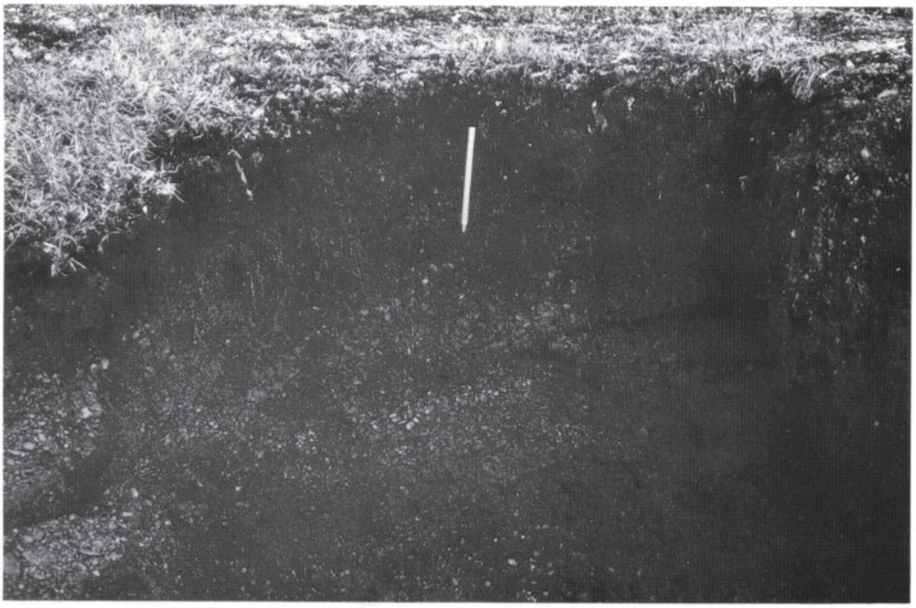


Plate IC

Arctic brown soil on the Gubik formation near Barrow, Alaska. The site, a beach ridge of Quaternary age, is composed mostly of sands and fine gravel. The dark reddish-brown solum is about 24 to 27 inches thick. A dry frost is present at a depth of 30+ inches.

Plate ID

Podzol soil on glacial drift, Anaktuvuk Pass, Alaska. Soils such as these are present on many of the younger, acid deposits in the valleys of the Brooks Range. (Photo by J. Brown.)

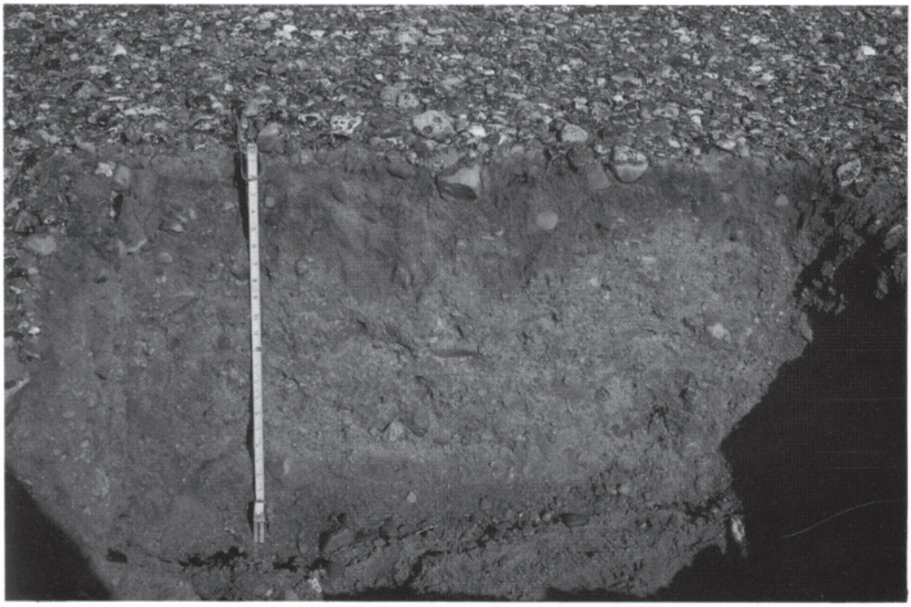


Plate IIA

Polar desert soil on the Beaufort formation, Prince Patrick Island, Queen Elizabeth Islands, Canada. Desert pavement is continuous. The comparatively dark topsoil contains 1 to 2 percent organic matter. The well-drained active layer may be as much as 3 feet thick.

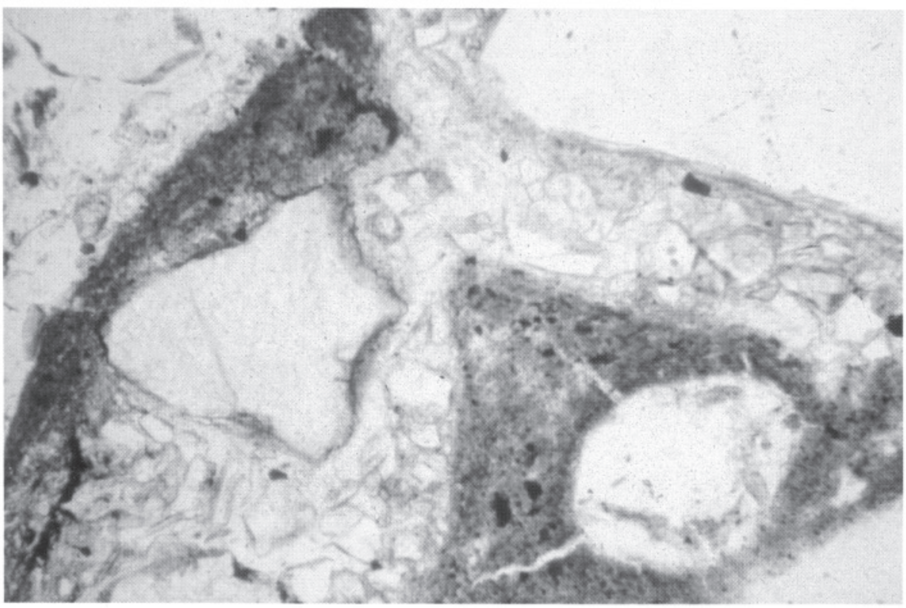


Plate IIB

Iron-stained granules formed in Polar desert soil, Inglefield Land, Greenland. Thin section preparation by W. L. Kubiëna (35×).

Plate IIC

Ahumic soil of the cold desert, Taylor Valley, Victoria Land, Antarctica.

Plate IID

Ahumic soil of the cold desert with an iron-enriched horizon, Wright Valley, Victoria Land, Antarctica. There is a 1- to 2-inch gray layer directly below the desert pavement, and this is underlain by an iron-enriched horizon.

TABLE 9-3 Mechanical composition of Tundra soils from northern Alaska (in percentages). (Douglas & Tedrow, 1960.)

Depth (inches)	Very Coarse Sand (2–1mm)	Coarse Sand (1–0.5 mm)	Medium Sand (0.5–0.25 mm)	Fine Sand (0.25–0.1 mm)	Very Fine Sand (0.10–0.05 mm)	Coarse Silt (0.05–0.02 mm)	Fine Silt (0.02–0.002 mm)	Clay (<0.002 mm)
				Gubik Formation				
3–8	12.0	4.6	5.4	19.9	15.2	10.7	9.3	22.8
12–18	16.1	6.1	5.7	16.4	10.9	7.5	8.9	28.4
23–24	3.7	1.6	2.1	23.7	20.2	17.2	12.1	19.4
26–30	7.6	7.8	7.5	19.1	16.7	10.9	12.0	18.4
				Sagavanirktok Formation with Aeolian (?) Mantle				
0–1	0	0.1	0.8	3.9	15.8	30.2	25.6	23.6
4–6	0	0.0	0.5	3.2	17.3	30.7	26.4	21.9
10–12	0	0.0	0.5	3.3	16.6	31.5	25.6	22.5
15–18	0	0.0	0.5	3.4	17.3	34.0	23.9	20.9
18–19	0	0.0	0.6	4.9	26.5	35.8	19.7	12.5
19–21	0	0.0	0.4	3.5	18.5	27.8	30.6	19.2
23–25	0	0.0	0.4	4.6	26.4	36.7	19.9	12.0
				Seabee Formation with Aeolian (?) Mantle				
1–4	0.1	0.05	0.05	0.1	4.5	42.6	29.8	22.8
6–12	0	0.05	0.05	0.1	6.0	44.7	27.1	22.0
20–30	0.1	0.1	0.1	0.7	4.1	41.4	30.1	23.4
40–45	0	0.05	0.05	0.2	4.0	39.5	32.3	23.9

Bulk Density

Bulk density values have considerable practical application in soil science because they can be used as indices to characterize properties such as soil compaction, moisture transmission, rooting suitability, and so on. By definition, bulk density is the mass of dry soil per unit of bulk volume. Since the definition of bulk density excludes ice as a part of the mass, much smaller bulk density values will be produced as the ice content of a soil increases. In situations where ice laminae, ice stems, or ice wedges are present, bulk density values will be extremely small and for practical purposes lose much of their significance. By strict interpretation of the definition, clear ice within the soil would have a bulk density of near zero. In the case of the active layer of well-drained sites, the bulk densities during summer months will approximate those found in warmer climates. Poorly drained mineral and organic sites will, however, have low values. These low values result from segregated ice formation within the soil matrix.

From bulk densities determination of blocks of soil (tesseras) in the Point Barrow area of Alaska, it was found that values were extremely low (Gersper, 1972). Such values represent ice content and distribution rather than particle arrangement. In a wet mineral soil (classified by Gersper as Histic pergellic cryaquept, which approximates Upland tundra soil of this author), the surface organic horizon had a bulk density of only 0.13 g/cm^3 and values for the mineral horizon ranged between 0.36 and 0.82 g/cm^3.

Chemical Composition

Data on the total chemical composition of Tundra soils are fragmental. Kreida (1958) reported on the composition of soils of the East European tundras, and her data on soils of the northern and southern tundra subzones of the Bolshezemelskaya Tundra are summarized in Table 9-4. There is a distinct depletion of Fe_2O_3 in the upper horizons, but there appears to be no clearly expressed removal, translocation, or accumulation of other elements within the soil. No particular trend ascribable to soil formation has been found for calcium, magnesium, aluminum, sodium, or potassium.

The range in pH values of Tundra soil is considerable, depending upon materials as well as local soil processes. Values may be as low as pH 4.0 but may exceed 8.0; in the majority of cases, they range from 4.5 to 6.5 (Kreida, 1958; Targulian, 1959; Douglas & Tedrow, 1960; Brown, 1962). Since there is a low-order leaching in Tundra soil, the surface may be as much as two pH units lower than the C horizon. Table 9-5 gives some pH values from various Tundra soils; nearly all are more acid at the surface.

TABLE 9-4 Summary of chemical analysis of Tundra soils of the Bolshezemelskaya Tundra of the U.S.S.R. (Kreida, 1958.)

Depth (inches)	Horizon	SiO_2 (%)	TiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MnO_2 (%)	CaO (%)	MgO (%)	K_2O (%)	Na_2O (%)
Northern Tundra Soil										
1–2	A_l	88.5	0.37	6.49	0.16	0.02	0.91	0.23	1.58	0.95
8–12	B_h	88.9	0.28	5.79	0.83	0.02	0.80	0.36	1.43	0.80
28–32	C	88.7	0.25	5.91	1.02	0.01	0.73	0.17	1.63	0.66
Southern Tundra Soil										
1–4	A_l	76.94	0.73	13.05	2.20	0.03	1.39	1.05	2.26	1.67
4–8	g	77.47	0.85	12.27	2.49	0.06	1.51	1.15	2.20	2.04
24–28	B_h	71.15	0.87	14.94	6.08	0.06	1.39	2.02	2.55	1.32

TABLE 9-5 pH values of selected Tundra soils in the main tundra zone of Alaska and the Bolshezemelskaya Tundra of the U.S.S.R.

Alaska								Bolshezemelskaya Tundra§			
Ogotoruk R.*		Umiat†		Sagavanirktok R.†		Jago R.‡		Southern		Northern	
(depth, inches)	pH	(depth, inches)	pH	(depth, inches)	pH	(depth, inches)	pH	(depth, inches)	pH	(depth, inches)	pH
1–0	4.7	1–4	4.6	0–1	7.2	0–2	4.7	1–4	4.6	1–3	4.4
0–3	4.2	6–12	4.6	4–6	7.6	2–7	5.7	4–8	5.2	4–8	5.4
3–7	4.7	20–30	5.2	10–12	7.5	9–12	5.9	24–28	5.6	24–31	6.6
7–12	4.9	40–45	6.4	15–18	7.4	15–20	5.8				
12–22	5.5			18–19	7.5						
22–30	7.1			19–21	7.0						
				23–25	7.7						

*Holowaychuk *et al.* (1966).
†Douglas & Tedrow (1960). Sagavanirktok profile on carbonate rock.
‡Brown (1962).
§Kreida (1958).

Where carbonate-bearing sediments are present, however, the pH values may be much higher throughout the soil. For example, the Sagavanirktok River area of Alaska's Arctic Coastal Plain and the Arctic Foothills have some Tundra soils that are alkaline throughout. J. V. Drew (1957) traced the origin of carbonate-bearing sediments along the floodplains and terraces. The headwaters of the Sagavanirktok River flow through limestone deposits of the Brooks Range and become charged with limestone detritus, some of which eventually finds its way into the fluvial deposits along the river. Subsequently, the material blows inland from the floodplains, furnishing a continuous source of fine carbonate sediment for the landscape. Thus, as long as the limestone material continues to blow inland from the floodplains, the high pH values will prevail in the soil.

Cation exchange data on Tundra soils show that with an acid substrate the surface horizons are primarily hydrogen-saturated, but that there is a definite tendency for base saturation to increase with depth. Holowaychuk *et al.* (1966) reported that base saturation values in the surface horizons of Tundra soil in western Alaska were less than 20 to 30 percent, but increase to some 75 percent or more at depth. Other reports (Brown & Tedrow, 1958; Kreida, 1958; Douglas & Tedrow, 1960; and Brown, 1962) indicate a pronounced leaching process in the upper horizon but comparatively little leaching at depth. Ratios of saturating cations follow a normal pattern, with perhaps a tendency for magnesium to be at a higher level in the upper soil horizons. The Ca:Mg ratio tends to be narrow in Tundra soils, as compared to soils of temperate regions.

It is pertinent to point out some potential fallacies in the interpretation of cation exchange data in soils of the polar regions. First, the soil exists in nature in a somewhat diluted chemical state during the period of vital activity because standing water frequently covers the flat areas and depressions. Further, the chemical reactions and physiological processes take place in nature only a few degrees above the freezing point. When soil samples are transferred to a laboratory, they are air-dried, the concentration of cations and anions in the soil solution increases, and the exchangeable cations are extracted at room temperature. This increase in temperature has a potential effect on the solubility of the soil constituents. How closely the laboratory values typify field conditions is uncertain.

The vegetative mat has a high regulatory influence on chemical processes in Tundra soils. During the summer months only minor chemical change takes place during the rain-rainless cycles in the turf-covered soil, but this is not the case with bare areas, such as the exposed earthy material on frost boils. After a few days without rain,

TABLE 9-6 Chemical data on some Tundra soil samples from northern Alaska. (Data are from saturated paste extracts.) (Douglas & Tedrow, 1960.)

	Tundra Soil	Adjacent Frost Boil
	Barrow	
Electrical Conductivity (mmhos)	0.9	2.9
Na (meq/liter)	1.6	4.8
pH	8.1	8.4
	Umiat	
Electrical Conductivity (mmhos)	0.9	2.9
Na (meq/liter)	1.5	4.8
pH	8.1	8.4
	Sagavanirktok River Area	
Electrical Conductivity (mmhos)	1.6	3.4
Na (meq/liter)	1.0	5.2
pH	6.6	7.4

vegetation-free spots in the tundra acquire a grayish to white crust. Evaporation from the mineral surface results in the formation of a salt crust. The efflorescence is primarily thenardite, a Na_2SO_4 salt which crystallizes in orthorhombic form. The salt is usually finely divided but can be easily identified by X-ray techniques. During rainfall, the mineral solubilizes and the whitish crust disappears. These efflorescences have been frequently referred to as "salt fading crusts," especially by investigators working in the East European and Siberian tundras. Table 9-6 gives some comparative values of Tundra soil surfaces and the adjacent frost boils. The vegetative-free areas have much higher conductivity values and more water-soluble sodium than the adjacent vegetated areas.

As to the nature of leaching in Tundra soil, there is good evidence of a process of lateral leaching. This is indicated in the field, but can also be shown by the low base saturation in the uppermost horizons. There are no field data to support the concept that drainage waters move down to the permafrost table. If some lateral movement does take place in the uppermost soil horizons, chemical analysis of drainage waters should yield information on mineral losses through pedogenic processes. Table 9-7, giving selected data on streams in northern Alaska, clearly shows that the composition of the drainage waters varies according to the substrate through which they flow (Brown *et al.*, 1962). For example, drainage waters from calcium-rich rock were much higher in calcium and magnesium than waters flowing through acid, crystalline rocks.

Brown, Dingman & Lewellen (1968) made a comprehensive study of the hydrology and geochemistry of a small watershed at Point Barrow.

TABLE 9-7 Chemical composition of some arctic drainage waters in northern Alaska. (Brown et al., 1962.)

Drainage Water	Ca (ppm)	Mg (ppm)	Na (ppm)	K (ppm)	Fe (ppb)	Al (ppb)	Mn (ppb)	Co (ppb)	Zn (ppb)	Sr (ppb)
Stream from granite (102)*	5.9	1.1	6.3	3.5	130	94	13	0.1	4	9
Stream from granite (209)*	6.9	6.8	0.2	0.1	<25	31	<6	2	15	42
Stream from limestone (101)*	40	11	2	1.5	215	155	41	1		24
Stream from calcium rock area (107)*	58	6	2	0.4	60	19	<6	Tr		41

*Reference number in original publication.

TABLE 9-8 Cation composition of runoff water from the Barrow watershed, Alaska. (Brown, Dingman & Lewellen, 1968.)

Sample Date	Na^+ (meq/liter)	K^+ (meq/liter)	Ca^{++} (meq/liter)	Mg^{++} (meq/liter)	Sum of Cations (meq/liter)	Conductivity of Runoff Water (μmhos)
18 June 64	2.1	0.03	0.11		2.96	357
14 July 64	2.7	0.01	0.33		4.14	480
3 Aug. 64	3.3	0.01	0.43		5.14	570
7 Aug. 64	3.3	0.01	0.37		5.08	565
14 Aug. 64	3.3	0.01	0.41		4.63	630
27 June 65	0.77	0.08	0.06		1.10	135
2 July 65	1.1	0.05	0.12		1.61	198
14 July 65	1.7	0.01	0.17		2.56	315
27 Aug. 65	2.9	0.01	0.28		4.19	500
2 Sept. 65	2.1	<0.01	0.21		3.08	362

A 1.6 km^2 drainage basin on the flat coastal area was monitored for runoff and composition of the drainage waters over a 4-year period. Table 9-8 gives the chemical composition of the surface runoff at selected times during the course of their study. Conductivity values ranged from less than 250 micromhos during high runoff periods to more than 500 micromhos during low flows.

Nutrient cycling in the tundra is of considerable interest not only to the pedologist but also to biologists who recognize the importance of following nutrients throughout the ecosystem. In the Tundra Biome Program, Bilgin & Douglas (1972) analyzed drainage waters from the Arctic Coastal Plain of Alaska (Table 9-9) and concluded that their nutrient content reflected the dominant soil type as well as the degree of surface runoff in relation to the area it drained. NH_4-N and particulate iron concentrations were higher in the Bog and Half-bog soil areas.

Solutions of the Tundra soils of the western Taimyr Peninsula were analyzed after extracting the solutions with a hydraulic press (Ivanov, 1972). The solutions contained bicarbonate, calcium, and magnesium, with mineralization on the order of 0.1 to 0.4 g/liter. The concentration of HCO_3 ions was higher in the autumn than in the summer months. The potassium and sodium concentrations ranged from 10 to 40 mg/liter. A sharp increase in water-soluble compounds was observed in the organic horizons after heavy rainfall.

Buried Organic Matter

The genesis of organic matter buried in Tundra soil is of special interest. Aleksandrova (1937) reported inclusions of peat and fossil *Larix* in the C horizon of Tundra soil near the Popigai River on the Central Siberian Plateau. Svatkov (1958) reported similar conditions on Wrangel Island, as did Tedrow *et al.* (1958) in Alaska. Subsequently, there have been a number of reports on the genesis of this buried organic matter (Douglas & Tedrow, 1960; Brown, 1965b, 1969c; Tedrow, 1965b). Whereas the presence of buried organic matter in some places results from solifluction processes, such processes alone can by no means account for the near-universal presence of buried organic matter in Tundra soils. Investigations in the tundra from the Bering Sea eastward through Alaska, Canada, and Greenland show that the Tundra soil nearly always has a buried organic layer, except on such sites as recent stream deposits and recent glacial deposits. This buried organic layer may be 48 or more inches below the surface (Douglas & Tedrow, 1960), but more often it is found at a depth of 20 to 24 inches; in the high arctic it frequently lies less than 1 foot below the surface.

There are many places in which the genesis of the buried material cannot be linked to contemporary processes, such as wind, water, ice,

TABLE 9-9 Average nutrient concentrations (ppm) in surface waters at different sites in northern Alaska. (Bilgin & Douglas, 1972.)

Site	Fe		NH_4-N	NO_3-N	PO_4	CO_3	HCO_3	Cl	Ca	Mg	K
	Filt.	Non-filt.									
71–01	.03	.03	.26	.007	.016	1.0	215	2.4	28.9	2.3	.53
72–01	.24	.57	.42	.007	.023	nil	309	31.6	44.5	5.7	.53
72–03	.36	.48	.47	nil	.029	nil	307	26.2	43.0	5.3	1.28
72–04	.20	.27	.50	.016	.030	nil	461	29.2	63.5	7.4	1.24
73–01	.05	.07	.27	.010	.019	1.3	188	19.9	29.8	2.6	.53
74–01	.04	.05	.36	.005	.024	2.3	325	7.2	49.4	3.4	.64
75–01	.07	.10	.26	.011	.030	.5	232	28.7	37.6	3.5	.70
76–01	.60	1.33	1.33	.011	.058	nil	784	51.0	107.1	9.5	.63
76–02	.20	.30	.64	.003	.022	nil	496	16.4	66.8	4.6	.68
76–03	.18	.24	.36	.001	.022	nil	246	17.9	35.3	3.6	.50
76–04	.22	.27	.39	.016	.009	nil	244	17.8	43.3	3.8	.50
76–05	.09	.11	.33	.004	.023	1.0	236	16.6	33.6	3.5	.55
76–06	.10	.13	.44	nil	.013	nil	277	20.5	37.7	4.1	.67
77–01	.06	.10	.35	.038	.022	4.7	258	0.2	33.9	5.0	.23
78–01	.96	1.28	.96	.006	.026	nil	525	21.6	68.0	7.1	1.81
78–02	.17	.26	.58	nil	.034	2.7	353	24.6	49.0	4.6	1.03

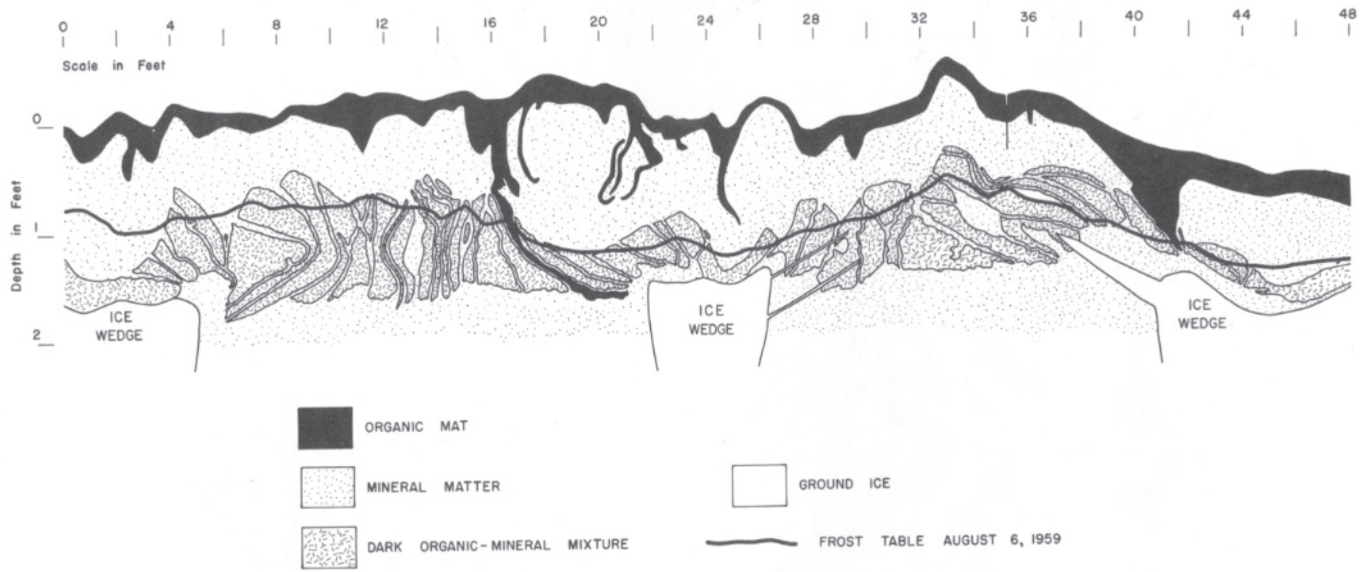


Figure 9-5 Cross section of Tundra soil in the Arctic Coastal Plain of Alaska. (Douglas & Tedrow, 1960.)

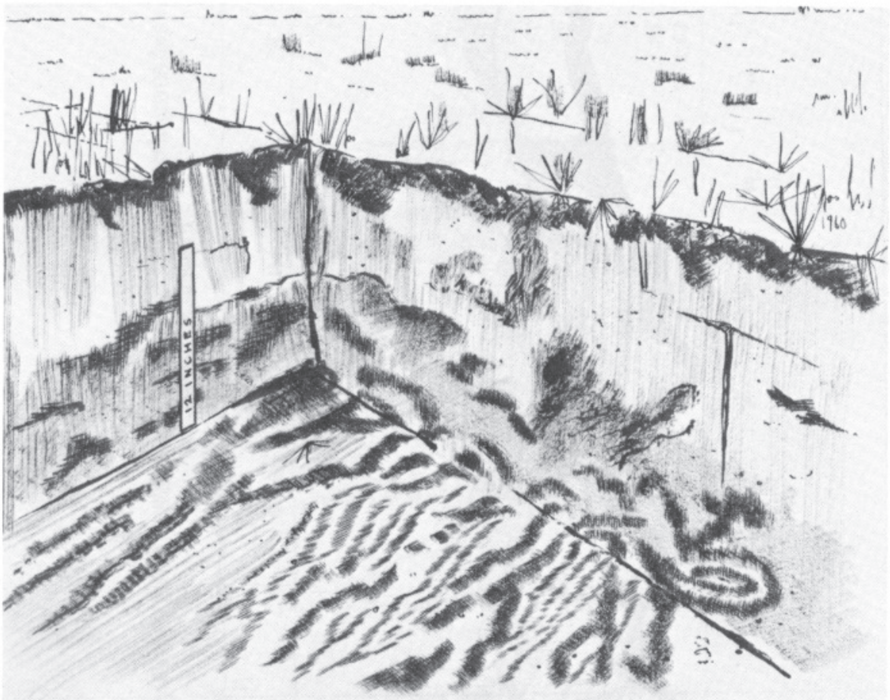


Figure 9-6 Tundra soil near Barrow, Alaska, showing organic matter erratically distributed throughout the profile.

or gravity; and there is little doubt that nearly all of it has been buried by physical agents relating to frost dynamics. MacKay (1958) believes that buried organic matter did not form as a part of Tundra soil development in the pedologic sense, but is composed of organic tongues that extended downward in the depressions between hummocks and were progressively buried. The buried organic layer is usually within the permafrost; but inasmuch as it is now below the depth of seasonal thaw, it must have reached its present position during a warmer episode. Fig. 9-5, drawn from a series of ground photographs, shows the nature of the buried material with reference to surface configuration, ice-wedge position, and topography.

In order to test a theory that a veneer of aeolian silts may have buried a preexisting land surface, a site 2 miles north of Umiat, Alaska, was selected for study. The site was on a flat watershed divide, presumably nonglaciated and also free of solifluction processes. Douglas (1961) made heavy mineral analyses and found qualitative uniformity of the heavy mineral suites with depth. Heavy minerals consisted of rutile, antigorite, chlorite, and apatite, plus opaques. Antigorite increased somewhat with depth, but rutile decreased. Chlorite, apatite, and the opaques remained rather constant.

Fig. 9-6 shows examples of the buried organic matter *in situ*. The nature of the organic matter varied in character from place to place. In some places, the organic matter was dispersed through the ground ice as an amber to black stain. In others, it was only partially humified or consisted primarily of sections of well-matted turf 6 to 8 inches across. The latter condition virtually rules out the possibility that the buried organic mat reached its present position through thixotropic processes.*

Although the Chita Oblast of eastern Transbaikalia is well south of the tundra zone, it has permafrost. A considerable amount of organic matter is concentrated throughout the profile, including the upper boundary of the permafrost. Dimo (1965) designated such soils as Meadow forest permafrost soils. Discounting the idea that the organic matter above the permafrost table results from solifluction processes,

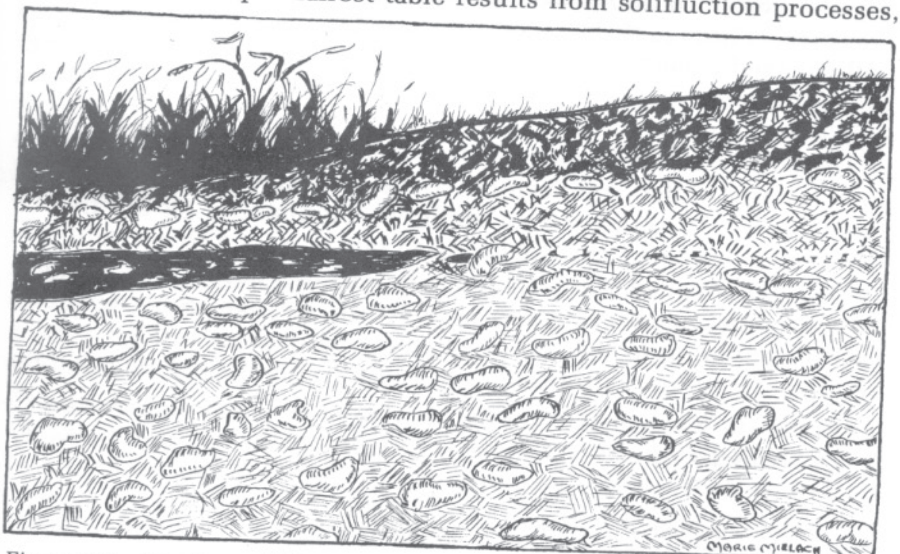


Figure 9-7 Tundra and Arctic brown soils existing side by side in northern Alaska. Note that the buried organic matter in the Tundra soil, on the left, "feathers out" in wedge-shaped fashion near the center of the drawing and that a buried organic horizon is not present in the Arctic brown soil. Drawing from a series of photographs. (Tedrow, 1965b.)

*Thixotropy is a term used to describe colloidal systems in which a gel is converted to a sol by agitation, and the sol resets to a gel when left undisturbed (*thixis* = touch; *trepein* = to turn or change, Gk.). Soviet investigators commonly refer to a thixotropic process in arctic soils in which the organic material "churns" or migrates downward while the soil is in a viscous state.

Dimo ascribes the unusual organic matter distribution to (1) cryogenic weathering at the phase boundary; (2) mass and energy exchange of the weathering products; (3) gravitational illuviation of organic and mineral colloids in the period of summer rains; (4) movement of the colloids to the cold front of the permafrost; and (5) accumulation and retinization of organic and mineral colloids in the layer above the permafrost. This explanation appears valid for the area described, but it probably cannot apply to all situations in the tundra zone because of the turfy nature of the buried organic matter. The humified materials can move downward by natural processes, but the turfy material cannot.

A fresh landslide in northern Alaska offered an unusual opportunity to study the origin and nature of buried organic material (Tedrow, 1965b). The entire exposure was glacial drift of uniform character in which Tundra and Arctic brown soils existed side by side, as shown in Fig. 9-7, compiled from a set of photographs. The buried organic matter was present only in the Tundra soil, terminating at the point where the soil changed from Tundra to Arctic brown. This, plus other field evidence, leaves little doubt that the buried material is confined to Tundra soil.

The buried material was further studied from the standpoint of absolute age and pollen composition. Table 9-10 gives pertinent data on various organic samples from arctic North America. Of the five C^{14} dates, four occur in the 8,000- to 11,000-years B.P. bracket. Brown (1965a, b) published four C^{14} dates from Barrow, Alaska, three of which were included in the 8,000- to 11,000-years B.P. age group, while the fourth sample, from the top of an active ice wedge, yielded a much younger date (Fig. 9-8). Douglas & Tedrow (1960) suggested that the

TABLE 9-10 Carbon 14 dates of buried organic matter in Tundra soils of northern Alaska. (Douglas & Tedrow, 1960; Tedrow, 1965a, b.)

Sample Location	Depth (inches)	C^{14} Date (yr B.P.)	Pollen
Barrow Pleistocene sands (L-400B)	23–24	10,600 ± 260	—
Umiat Cretaceous sediments (L-400C)	46–48	8,150 ± 150	—
Umiat Aeolian deposits (I-354)	16–22	9,325 ± 250	*Betula*, Ericales, Cyperaceae
Umiat Aeolian deposits (I-356)	16–22	9,130 ± 240	*Betula*, Ericales, Cyperaceae
Killik River Glacial till (I-1005)	12–18	2,310 ± 110	*Betula*, Ericaceae, *Salix*, *Alnus*

buried organic matter may have been incorporated in the permafrost during a warmer episode, in which case the active layer would have been much thicker; subsequently some of the buried material may have been squeezed upward during the rapid cooling of the landscape, and vegetation became established on the newly exuded earthy material. Late Pleistocene amelioration of climate in the northern areas is probable (Detterman, 1970). Hopkins (1959) presented good evidence that a sharp warming trend in world temperatures began some 9,000 to 11,000 years ago, which falls within the Hypsithermal Interval (Deevy & Flint, 1957). Colinvaux (1964, 1967a, b), basing his work on pollen spectra in buried organic samples from northern Alaska, believes that there has been a warming trend in Alaska for 14,000 years B.P.*

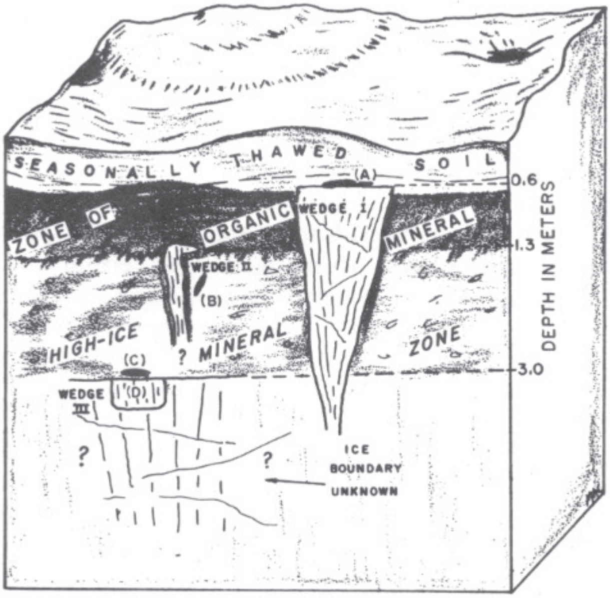
J. Brown (1965a) has provided a graphic view of the complexity of organic matter and ground ice distribution in Tundra soil (Fig. 9-8). The ice accumulates more or less continually over long periods of time, filling annual contraction cracks with hoar frost and meltwater; and with the growth of the ground ice, high-order changes occur in the morphology of the soil. Brown believes that the site shown in Fig. 9-8 was perennially frozen until about 10,000 years B.P., with active ice wedges being formed. This was followed by a period of deeper thawing and subsequent refreezing, which caused some of the substrate to be extruded to the surface.

Clay Mineralogy

Fragmental data strongly indicate that the clay in Tundra soil is mainly of an allogenic nature. The 2:1 layer silicate minerals generally predominate, and there are usually appreciable quantities of kaolinite, in addition to some clay-sized quartz (Brown & Tedrow, 1958). Most Tundra soils change very little in composition with depth. Montmorillonite, the genesis of which is somewhat uncertain, is present in some Tundra soils. Volcanic deposits are common in the bedrock, as well as in surficial sediments in northwestern North America and eastern Siberia, particularly in the vicinity of Kamchatka, and also in Iceland, which is considered to be in the subarctic zone. Volcanic deposits form an admixture in many of the soils in the vicinity of the Bering Strait. Rieger (1966) described deposits of volcanic ash of different ages in the tundra region of southwestern Alaska in which the clay consists almost entirely of allophane.

Douglas (1961) determined clay composition in Tundra soils from three locations in northern Alaska and found illite to be the dominant

*The changes in arctic climates during the past 10,000 years have been treated in depth by various investigators (Vasari, Hyvärinen & Hicks, 1972).



BURIED PEAT – RADIOCARBON DATED
Radiocarbon dates are:
(A) 1775 ± 120 (I-699)
(B) 9550 ± 240 (I-700)
(C) 10,525 ± 280 (I-701)
(D) 8200 ± 300 (I-992)

Figure 9-8 Morphology of a section of Tundra soil near Barrow, Alaska. (J. Brown, 1965a.)

clay, along with some kaolinite and small quantities of montmorillonite, clay-sized quartz, and an unidentified clay mineral with a 5.9 to 6.1Å diffraction spacing, possibly whewellite. The fine clay ($<0.2\mu$) is quartz-free, but has significant amounts of chloritized montmorillonite. Allan's (1969) investigations in northern Alaska accorded with those of Douglas in that the crystalline clays of Meadow tundra soil consisted mainly of micas, kaolinite, vermiculite, chlorite, and a little montmorillonite. Liverovskaya-Kosheleva (1964) reported beidellite with hydrous mica and amorphous substances in the Tundra soils of the Ob region of Siberia.

The Tundra Soil Process

The formation of Tundra soil involves four qualitative processes: organic matter production, gleyzation, podzolization, and frost action, the last representing a negative element of soil formation. The basic

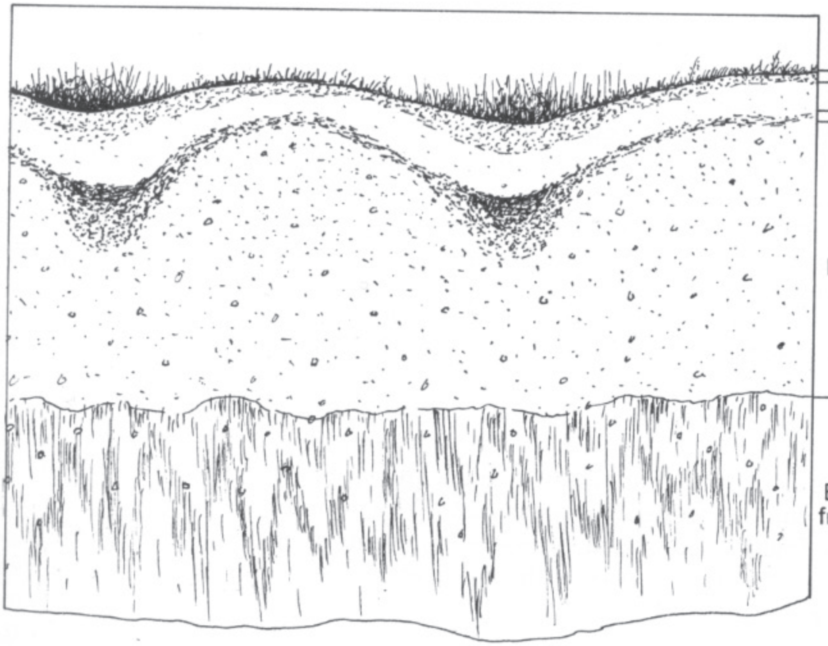


Figure 9-9 Profile of Arctic Coastal Plain sands of Alaska showing incipient Podzol formation at the surface with a frozen gley condition at depth. Drawing from field conditions from the uplands near the Kogosukruk River, about fifteen miles northeast of Umiat. The drawing shows the soil to a depth of about 20 inches.

features of Tundra soil formation, according to Karavaeva (1964), encompass slow weathering of parent material, slow removal of soil-formation products, with little total chemical composition change at depth, a gley process within the soil profile, slow decomposition and synthesis of organic matter, and strong cryogenic processes.

Targulian (1971) has considered dividing Tundra soils into two varieties, depending upon degree of development: Homogeneous gleyic soils, which are subject to intense frost action and lack a developed horizonation; and Differentiated gleyic soils, which have developed a sequence of horizons. Karavaeva (1964) reported that the gley process in the northern tundra zone decreases in intensity, and that the thickness of the organic matter on the surface of the soil also decreases.

In the main tundra zone, comparatively well-drained sites (those with positive relief elements) have soils with upper mineral horizons that may show only minor effects of gleyzation but clear evidence of leaching and even podzolization (Fig. 9-9). On very sandy materials, the soil may acquire a Nanopodzol morphology in the uppermost horizons but contain distinctive gley at depth.

Gorodkov (1939) believed that the predominance of the gley process over the podzolic in the tundra has caused some ambiguity in understanding the main soil processes of the polar landscape. Liverovskij stated that "it is clear that the soil formation process of the tundra cannot but be different from that in the podzolic zone" (Gorodkov, 1939). Except for the work of Liverovskaya-Kosheleva (1964), there has never been convincing evidence showing how or why processes of the tundra zone differ from those of the northern forest zone.

Liverovskaya-Kosheleva, in studying thixotropic properties of Tundra soils, recognized four horizons above the permafrost table: humus, gley, thixotropic gley, and subthixotropic gley. The thixotropic gley is characterized by an increase in "dust" (0.05 to 0.01 mm mineral particles), which is supposedly derived from the freeze-thaw cycles in which the freezing water loosens the upper layers and the mineral particles subsequently disintegrate. The mineral analysis of the <0.001 mm fraction consisted of beidellite, some hydrous micas, and amorphous material. It was further indicated that beidellite and beidellized mica, because of their physicochemical properties (swelling capacity and fineness), are ideal constituents for the thixotropic process. Liverovskaya-Kosheleva further found that iron hydroxide gels were prevalent in the thixotropic horizon. The fact that the colloids migrate ahead of the advancing top and bottom freezing fronts is believed to be responsible for the concentration of the fine material in the thixotropic zone.

Other arguments for a special tundra process continue to the present day. Gorodkov (1939), however, stated that "the soil climate of the permafrost areas, independently of the landscape zones, is similar to that of the forests because biochemical conditions of tundra soil formation are similar to conditions of the forest (podzolic) zone of eastern Siberia."

Basins, flats, and related low Tundra soil positions, which tend to be waterlogged most of the summer months, generally have a grayish subsoil. Near root channels, structural joints, and cleavage planes, where the air-moisture-organic matter regimes change, grays, yellows, rusts, and browns form a mosaic pattern.

The organic materials play an integral part in the soil system. Usually the organic mat is extremely irregular and is distributed erratically; but on flat terrain, for example, on sites colonized by lowland cotton grass, the organic mat may be quite uniform in thickness. As the soil organic matter slowly becomes humified, some of it moves through the mineral soil and into the drainageways; it can be seen in the tundra as amber-colored water draining from near-stagnant positions.

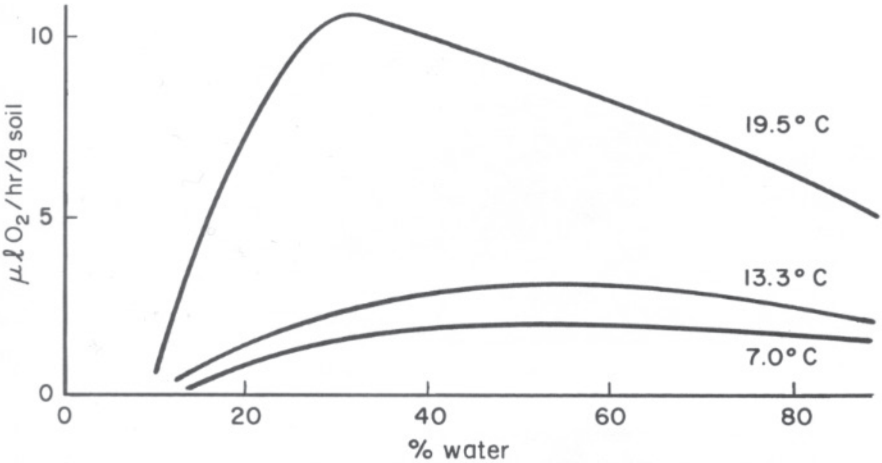


Figure 9-10 Effect of soil temperature and moisture content on rates of organic matter decomposition in Upland tundra soil in northern Alaska. (Douglas & Tedrow, 1959.)

In studies to determine the rate of organic matter decomposition in Tundra soil, Douglas & Tedrow (1959) showed that about 850 pounds of organic matter per acre were decomposing annually in Tundra soil in northern Alaska. Temperature and moisture content were regulatory in the rate of organic matter breakdown (Fig. 9-10). Laboratory studies indicated that at 19.5°C, the rate of organic matter decomposition was about seven times as great as at 7°C. How closely decomposition and production of organic matter are balanced in the arctic is understood only in general terms.

The horizons in Tundra soil are considerably modified by various frost-related processes. Where there is a minimum of displacement, soils may acquire some semblance of an orderly morphology (Fig. 9-3), but such sites are rare in some areas. The annual growth of ice wedges and other forces operate not only to disturb the soil physically but also to form new relief features; and these, in turn, form a mosaic of drainage conditions. Fig. 9-11 shows flat terrain that has become highly polygonized through the growth of ice wedges. The network of raised polygon edges creates shallow ponds that fill up with water. Other processes involve physical displacement at the local level, and still others lead to physical sorting.

The Influence of Time on Tundra Soil Development

The time factor is of great importance in soil formation, and this applies especially to the soils of the polar environment. Tundra soils on the young terraces, recently drained lake basins, and sand dunes, and

Figure 9-11 Low-center polygon on Tundra soil in northern Alaska. (Photo J. V. Drew.)

also some of the recently exposed ground adjacent to glaciers, exhibit morphologies different from those of the older landforms. The soils on young sites consist largely of a thin organic layer covering the gray mineral substrate, often without visible mottling (Fig. 9-12a). Soils on older sites have morphologies of the kind depicted in Fig. 9-12b; however, once Tundra soil has acquired certain properties, it reaches a static state and few developmental changes occur thereafter. The Arctic Foothills of Alaska offer an unusually favorable set of conditions for study of the time factor in soil development. Here Tundra soils in the old glaciated and the nonglaciated sectors display few, if any, changes in morphology ascribable to the time factor.

Ancient landscapes have always held a special interest for the pedologist, and many questions arise about the soil properties to be expected in Tundra soils on such landforms. From the standpoint of absolute chronology, there are very few sites in the polar region that can be considered ancient, because most of the northern landscapes were buried beneath glacial ice or were indirectly affected by it during the Pleistocene epoch. Although good examples of nonglaciated tundra terrain are found in parts of the Arctic Foothills and Arctic Coastal Plain of Alaska and in parts of Siberia, particularly at medium elevations of the East Siberian Highlands, there are uncertainties about whether they really exist as old landscapes, inasmuch as they have been modified by frost as well as aeolian processes.

Dahl (1956) mentioned the possibility that some alpine soils in the high mountains of Norway were "inherited" from other vegetation types of the past. The chief discernible difference between the soils of the glaciated and nonglaciated areas is the presence or absence of glacial erratics, which, of course, is a geologic and not a pedologic differentiation.

Shallow Tundra Soils

Gley soils characteristically are deep, with bedrock at a depth of 30 to 36 inches or more. There are isolated situations, however, in which Tundra soils may be rather shallow, especially where there is solifluction. Since hard sedimentary rock members are more resistant to weathering than softer rock, shallower Tundra soils can be expected over the hard rock (Fig. 9-13). Very often, however, these shallow soil areas are somewhat better drained, and the soil consists of a shallow Arctic brown–Lithosolic complex rather than Tundra soil. Excellent examples of such a complex are found in the De Long Mountains of northwestern Alaska.

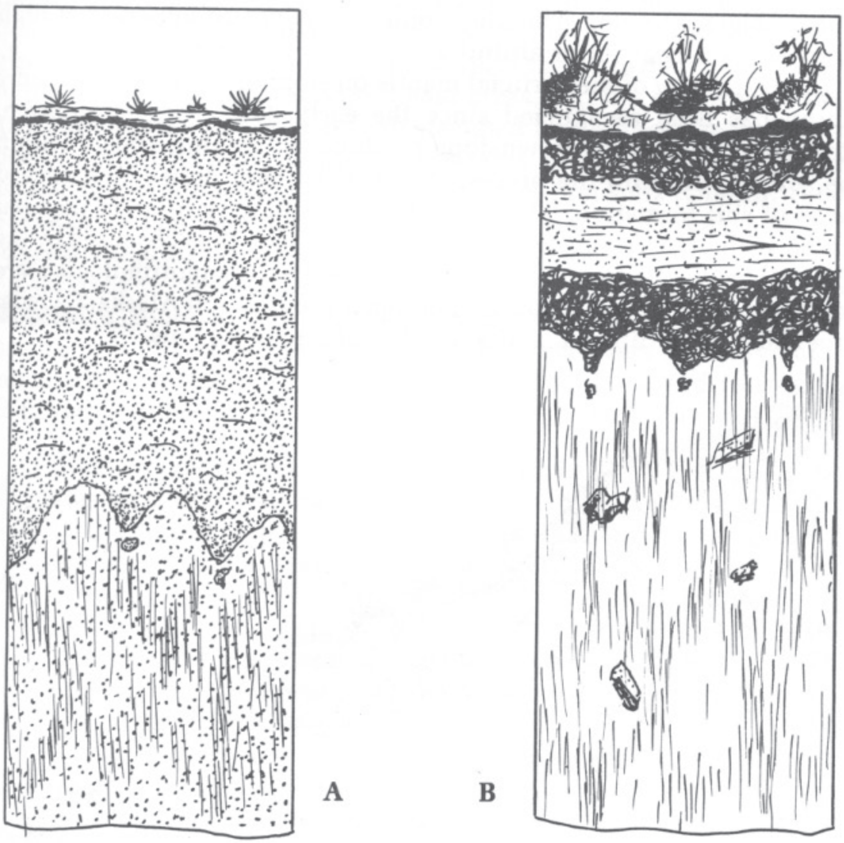


Figure 9-12 Influence of the time factor on the development of Tundra soil profiles. *A*. Youthful Tundra soil in a recently drained lake basin in northern Alaska in which the soil consists of gray, wet sands. *B*. Fully developed Tundra soil in the nearby older landscape.

Altitudinal Zonation of Tundra Soil

The major valleys in the Brooks Range are about 2,000 feet above sea level and are mantled extensively with Tundra soil. The valley slopes, however, are rather steep, and as the landscape becomes increasingly rocky with altitude drier conditions cause the Tundra soils to give way. Cantlon (1961) designated the land 4,000 to 5,000 feet above sea level as a tundra belt of the arctic alpine zone, but within this zone, Tundra soils are seldom present except in cols and basins; Tundra soils in these and similar positions have a rather constant supply of water from small drainageways and meltwater from late snowbanks. The soil consists of an acid organo-mineral mixture that is water-saturated and dark reddish to black in color. The gley condition is not so apparent at high altitudes as it is at lower altitudes.

The instability of the surficial mantle on sloping terrain of the tundra region has been recognized since the early days of polar research. Movement of material downslope produces a "mixing effect" within the soil mantle, and the processes of soil horizon destruction exceed those of soil formation. The result is a mass of gray mineral material mixed with organic substances. Soil processes are thus obscured by the physical movement of the material downslope. Geomorphologists are now quantifying these slope denudational processes in Alaska, Canada, Greenland, Scandinavia, and a number of alpine regions.

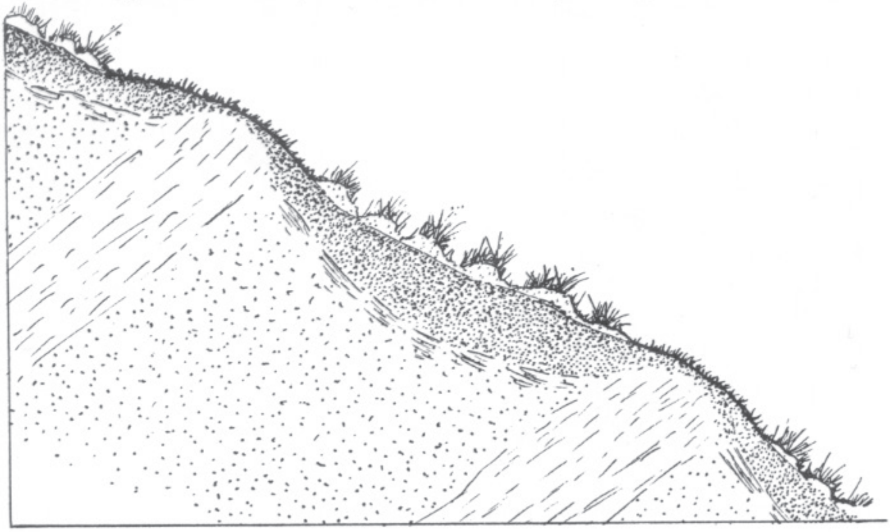


Figure 9-13 Cross section of a landscape in northern Alaska showing the hard rock members with shallow Tundra soil and the softer rocks with deeper Tundra soils. In many instances, however, such potential differences are obliterated by solifluction.

Organic Soils

Poorly drained soils with an organic layer at least 12 to 15 inches thick are generally designated as organic or Bog soils or simply as swamps, marshes, or muskegs. This is an incomplete definition but serves as a general base for discussion. The soils on shallow bogs, those with an organic layer approximating 6 to 12 inches, have been designated as Half-bog (Tedrow *et al.*, 1958); however, some polar investigators, particularly in Svalbard and Iceland, have designated 2- to 4-inch organic deposits as bogs. Organic soils form in almost all sectors of northern lands; the controlling factor is the wetness of the site (Brown & Williams, 1972). One of the major conditions for their formation is poor surface drainage. Since many landscapes have been free of glacial ice only within the past 10,000 years there are many depressions in the landscape, water-impoundment areas, and flat plains with sluggish surface drainage. Recently deglaciated landscapes generally have poorly developed surface drainage patterns and these result in water-saturated environments and the formation of Bog soils (Olenin, 1968). Soviet investigators commonly refer to the presence of organic deposits in sectors that have "sculpture-accumulative" relief.

Gorodkov (as quoted by Dokturowsky, 1938) and Kats (1958, 1960) reported a zonality and symmetry in the distribution of bogs in a north-south direction. The northern sectors were very swampy but accumulated peat slowly. Gorodkov divided peat bogs and related wet conditions of the tundra and forest-tundra into the following groups:

1) Shallow peat bogs subject to "solid freezing" (*festfrierende*), possessing a thin active layer in the northern part of the area. Bogs in the tundra zone of Eastern Europe, western Siberia, and the northern Urals are predominantly fossil.
2) Areas of sporadic permafrost in the mineral soils, but permafrost in the bogs. This group is found in the forest-tundra of Eastern Europe, western Siberia, the mountains of Scandinavia, and other alpine sectors. The organic deposits are known as shallow-hill peat bogs (*flachhügelige Torfmoore*).
3) Areas of sporadic permafrost in the peat mosses, but no permafrost in the mineral soils. This group is found in the forested areas of Europe and western Siberia as well as in the subalpine of Scandinavia. It is designated as bog-hill peat bogs (*Grosshügelmoore*).
4) Rapidly thawing peats found in the areas without permafrost.

Gorodkov believed that the bogs of the typical tundra are relics of a former period and are presently being denuded, but it is highly doubtful if this is the case on a global basis. Gorodkov reported that many peat hillocks of the forest-tundra region consist almost exclusively of peat or a deposit of loose diatomite.

Andreev, as quoted by Dokturowsky (1938), classified the bog complexes in the northern Kanin Peninsula as follows: (1) tussock-tundra (<5 cm of peat); (2) big-hill tundra, a part of the low-lying tundra; (3) sedge-moss of the level terrain mantled with sedge-hypnum or sedge sphagnum peats; and (4) *Jora* (*Salix*) of the swampy slopes. Brown (1966) divided the organic soils of northwestern Alaska into (1) Sod peat, (2) Moss peat, (3) High moss peat, and (4) Dry peat and Bog.

The classification of bog soils throughout the globe has been based on a number of criteria, the most common being the thickness of the organic deposit, the nature of the vegetation, and the peat fabric. Waksman (1942) lists more than a hundred terms used to designate various types of bogs and related deposits. Few terms have been widely accepted. Chemical-biological approaches have also been used in bog classification. Parameters such as humus forms, degree of humification, and chemical composition, including elemental ratios, pH values, and eutrophism or oligotrophism, are used by various investigators.

The genesis of organic deposits varies. Waksman (1942) outlined a possible basis for classifying peats:

I. Autochthonous or true peats
   A. Lowmoor peat (limnic, telmatic, and terrestrial)
   B. Highmoor peat (moss, forest-moss)
II. Allochthonous or sedimentary peats
   A. Gyttja (organo-mineral)
   B. Dy (chocolate-brown and granular)

A modified version of Waksman's work appears to be a logical approach to the classification of peats and Bog soils of the tundra. Bogs that form *in situ*, as in the wet meadow and lowlands, are generally colonized by marsh vegetation (Tedrow & Cantlon, 1958) consisting of *Carex aquatilis, C. rotundata, C. rariflora, Carex* spp., *Eriophorum angustifolium, E. scheuchzeri, Arctophila fulva, Dupontia fischeri, Hypnum* spp., and *Sphagnum* spp. Brown (1962) designated peat soil in which the peat consists largely of sphagnum as Moss peat soil. Most of the peat deposits display only a slight degree of humification, and the plant residues are generally identifiable. The layered appearance of the fabric of the bogs in many locations results from the peat buildup over long periods of time.

Where shorelines are elevated, the organic deposits are usually intermixed with windblown sand. A typical example of this condition is in the Cape Sabine sector of northwestern Alaska.

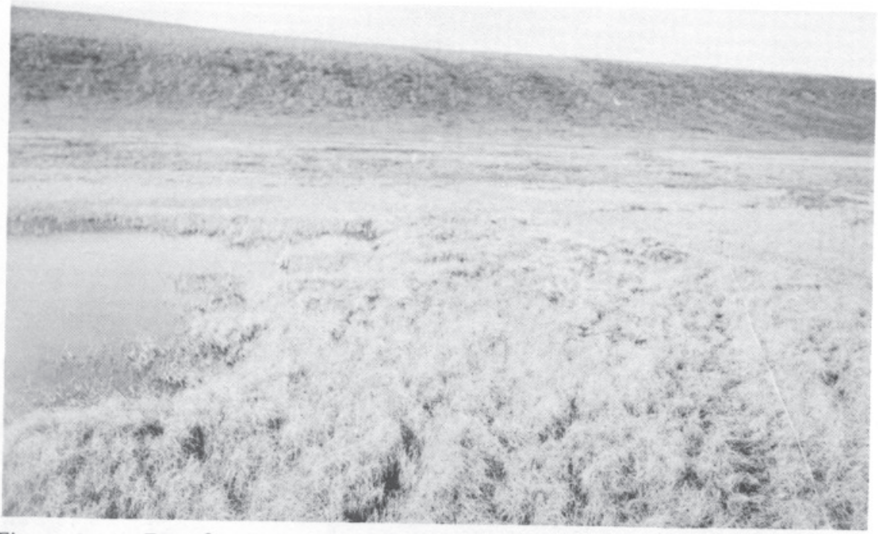


Figure 9-14 Peat formation on a poorly drained terrace along the Colville River, northern Alaska. (Photo J. E. Cantlon.)

The plant residues of most of the peat bogs of the tundra zone are mixed, that is, they formed from different plant species. The principal type of peat in most of the tundra region is undoubtedly one composed of a sedge-sphagnum mixture (Fig. 9-14), but several varieties of these can be identified from place to place, as outlined by Brown (1966). In the coastal sectors, however, sphagnum is uncommon and most of the peats are derived from a mixture of *Dupontia*, *Carex*, and *Eriophorum*.

In some sectors of northern Alaska the peat deposits are more than 30 feet thick. Bogs as much as 80 feet thick have been reported in the

Figure 9-15 Peat about 4 feet thick along the Colville River at Umiat, Alaska.

Figure 9-16 Peat ridge along the margin of an Arctic Coastal Plain lake in Alaska. The peat had been shoved up along the shoreline by ice.

Kotzebue area of northwestern Alaska. The most extensive bogs of the tundra zone are probably 2 to 4 feet thick (Fig. 9-15).

Many peat deposits have been transported from the place in which they formed to a new location. Such peats belong to the allochthonous group of Waksman (1942). Some peats in the shallow waters of lacustrine environments are sedimentary in character. Organic debris floating in quiescent and protected environments will range from colloidal size to slabs of peat 3 feet or more across. Lakes in thermokarst or frost-collapse areas contain several feet or more of accumulated organic matter (Carson & Hussey, 1962; Hussey & Michelson, 1966; Tedrow, 1969). This type of bog-like material is also a form of allochthonous peat. The ice-push ridges of peat peripheral to lakes in the Arctic Coastal Plain of Alaska constitute still another form of allochthonous peat (Fig. 9-16); the peat ridges are formed inland as the ice is pushed ashore by strong winds.

Whereas the mode of formation of the various peats is clear, not very much is known as yet about their humification and chemical properties.

Arctic Brown Soil

Whereas well-drained soils of the tundra soil zone have been recognized only within comparatively recent years by pedologists,

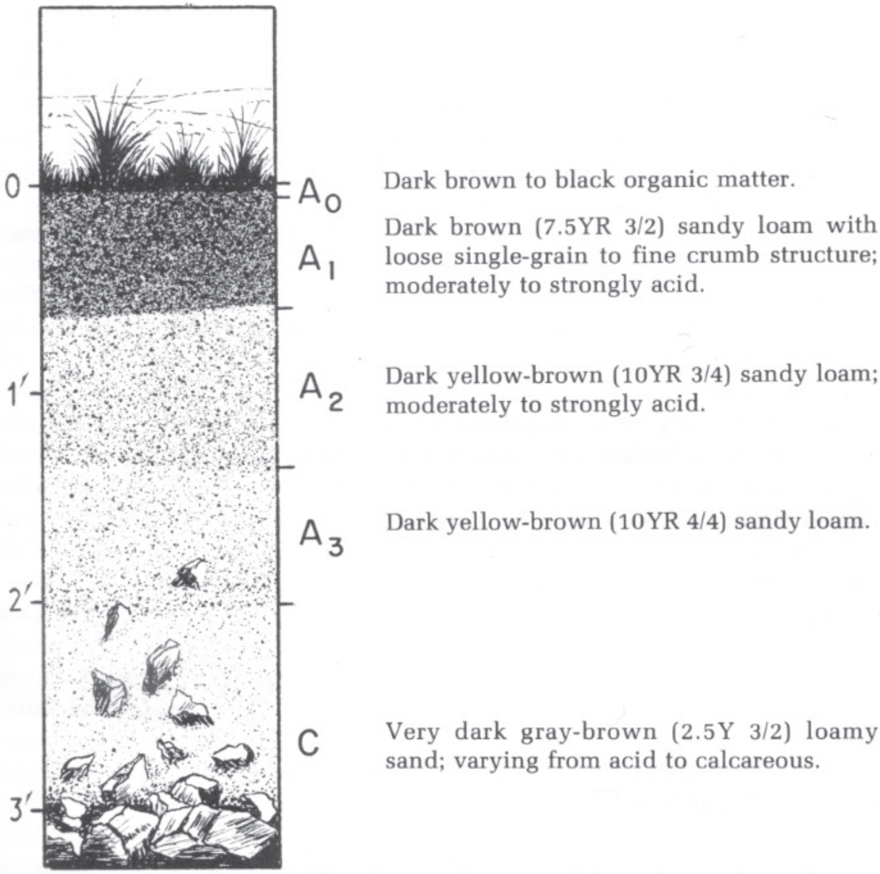


Figure 9-17 Idealized profile of Arctic brown soil from the tundra soil zone.

naturalists—particularly botanists—have spoken of *dry tundra* since the days of Alexander von Middendorf and probably before. The pioneer work of Grigor'ev (1930), Sochava (1933), Polyntseva & Ivanova (1936), and Gorodkov (1939) reported the presence of soils with brown surfaces in the arctic regions, and later Soviet investigators proposed such specific names for brown soils of the alpine regions as *Brown tundra* (Petrov, 1952) and *Sod–bare-rock* soil (Karavaeva, 1958). Most of their reports were based on work in the subarctic and alpine regions of Siberia. Retzer (1965) was the first to show a genetic linkage between the well-drained soils of the tundra and certain alpine soils in North America.

Well-drained terrestric soils have been observed throughout the tundra zone. In some sectors they occupy less than 1 percent of the landscape, but in areas of sandy materials, especially where there are positive relief elements, the percentage is much higher. (These well-drained soils are equivalent to the nongleyic soils described by Targulian [1971] in the East European tundras.) These are nongleyic soils which form on well-drained sites with little direct influence of permafrost. Accordingly, their genesis follows evolutionary pathways like those of the zonal soils to the south.

Arctic brown soil was first described in northern Alaska (Tedrow & Hill, 1955). This soil is deep and freely drained, and some of its properties are like those of soils of the northern forests (Plate IC). Where the permafrost is deep, the soil develops a strong brownish color and is without gley, indicating free air and water exchange.

Arctic brown soil thaws early and rapidly during the summer season (Fig. 9-1). It may thaw to depths of 1 to 2 feet while the Tundra soils are still completely frozen. This means that conditions conducive to Arctic brown soil formation are limited to narrow crests, ridges, gravelly kames, escarpment edges, and other sites where the permafrost table is at least some 2 to 3 feet below the surface. Not all well-drained sites of the tundra region, however, have Arctic brown soil. Active dunes, floodplains, areas recently free of glacial ice, and related situations generally do not have a well-developed soil.

Arctic brown soil generally forms under a complete vegetative cover, but in some localities the vascular plant cover is incomplete because the substrate is exceptionally gravelly. The plant communities associated with Arctic brown soil in northern Alaska are as follows (Tedrow & Hill, 1955):

Noncoastal Areas	1) Xerophytic mosses, lichens, dwarf heaths, herbs.
	2) Dwarf heaths, Bigelow sedge, mixed herbs.
	3) *Dryas*, *Cladonia*, dwarf heaths, herbs.
Coastal Areas	4) Mixed herbs, lichens, dwarf willows.

The profile and morphology of a typical Arctic brown soil are shown in Fig. 9-17 and in Plate IC. A decided accumulation of organic matter is usual at the surface of Arctic brown soil, but at depth may drop to less than 1 percent. The highly organic surface horizons may contain 10 to 20 percent organic matter, but less than 1 to 2 percent immediately beneath the organic mat (Tedrow & Hill, 1955; Drew & Tedrow, 1957; Hill & Tedrow, 1961; Brown & Tedrow, 1964). Whereas the C:N ratios of Arctic brown soils may be as extreme as 10:1 to 25:1, values in the 15 to 18 range are more common; ranges generally do not follow any specific trend with respect to depth of mineral composition.

The organic material in Arctic brown soil is very slow in undergoing mineralization. Carbon 14 dating of the surface gave 2,000 ± 150 years B.P. as the age of the humic portion of Arctic brown soil at Point Barrow, and 2,900 ± 130 years B.P. for the nonhumic portion (Tedrow & Douglas, 1958). Studies of organic matter decomposition rates in Arctic brown soil at Barrow (Douglas & Tedrow, 1959) have indicated the rate of decomposition to be about 1,350 pounds per acre per year; of this amount, about 1,050 pounds were from the 1-inch organic mat and the remainder from the upper horizons of strictly mineral character.

Particle-size analyses of the Arctic brown soils do not show translocations of clay within the profile. The analyses of Tedrow & Hill (1955), Hill & Tedrow (1961), and Drew & Tedrow (1957) indicate that the variations in particle size with depth are related to the geologic history of the site rather than to pedogenic processes. On very gravelly material there may be silt accumulations underneath the gravel fragments, indicating some downward movement of soil moisture, but such a condition is uncommon. There is no evidence of clay skins in Arctic brown soil.

Most Arctic brown soils tend to be loose and friable but seldom display well-defined structural units. The nature of the surface horizon generally ranges between single grain and a weak crumb structure, but the lower horizons are loose to firm, without defined compound structure.

Because Arctic brown soil formation is closely dependent upon unrestricted drainage conditions, it is unusual for such a soil to be present on clayey material. Sandy loams and loamy sands, often with a prominent gravel component, are the most common Arctic brown soil textures, but a few examples of silt loam textures have been observed.

The pH values of Arctic brown soil vary considerably. They may be as low as pH 3.5, but values of 5 to 6 are more common. The soils may be alkaline in carbonate-bearing soil material, and pedogenic carbonates may be present on windswept spurs. The surface material on the spurs may react to hydrochloric acid. Thus it is clear that a considerable range of pH values is found in Arctic brown soil.

Leaching in Arctic brown soil is of a low order and reaches only to shallow depths. Soviet investigators (Gorodkov, 1939; Filatov, 1945) have long indicated that some of the water in arctic soils is derived from condensation. Summer fog is characteristic of the arctic, particularly in the coastal sectors (Kumai & Glienna, 1972). The relative humidity is above 90 percent during the summer months, and condensed moisture collects in the surface soil. Since the amount of water condensed probably is not very large, only slight leaching takes place at depth. Where the soil texture is very gravelly, the surface of the soil may be as low as pH 4.3, but carbonates may be present at depth (Drew

Figure 9-18 Encrustations of carbonate on the undersides of gravel in the B horizon of Arctic brown soil, Anaktuvuk Pass, Brooks Range, Alaska.

& Tedrow, 1957). Douglas (1956) spread sodium chloride on the surface of Arctic brown soil at Point Barrow in late June, 1956; and by late August of the same year, chlorides had penetrated to a depth of 25 inches, indicating that highly soluble constituents are mobile within this soil.

Carbonate precipitation is generally perceptible in the B or C horizon of Arctic brown soil (Fig. 9-18). Usually the carbonates are in stalactite-like form on the undersides of cobbles, but the calcite does not form a continuous indurated horizon within the soil. The carbonates found underneath the surface boulders on rocky ridges are amber to black because humus is associated with the carbonates. A coating of dolomite was identified on the sand grains in the lower horizons of Arctic brown soil at Point Barrow. The dolomite was so fine that it could not be detected by normal optical methods, but its presence was verified by X-ray techniques (Drew & Tedrow, 1957).

The total chemical composition of an Arctic brown soil formed on glacial drift south of Nigu Bluff, northern Alaska, is given in Table 9-11.

TABLE 9-11 Total chemical composition of an Arctic brown soil formed on glacial drift, Nigu River area, Alaska. (Data expressed on an organic matter-free basis.) (Tedrow & Thompson, 1969.)

Depth (inches)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	Na_2O (%)	K_2O (%)	Cu (ppm)	Co (ppm)	B (ppm)
0–10	70.68	13.12	7.39	0.25	0.38	1.38	0.86	11	4	17
10–14	78.63	8.09	5.22	0.48	0.30	1.14	1.12	6	1	8
14–20	74.73	8.03	10.71	0.10	4.18	1.29	0.72	10	1	9

Depth (inches)	Ga (ppm)	Pb (ppm)	Zr (ppm)	Ni (ppm)	Sn (ppm)	Zn (ppm)	Mo (ppm)	Mn (ppm)	V (ppm)	Cr (ppm)	Sr (ppm)	Ti (ppm)
0–10	309	7	19	151	2	800	3	176	92	86	33	1,000
10–14	218	6	15	12	1	285	3	59	37	78	45	1,000
14–20	122	6	15	30	1	362	3	75	48	77	56	1,000

TABLE 9-12 Chemical data on an Arctic brown profile from Barrow, Alaska (<2 mm). (Drew & Tedrow, 1957.)

Horizon	Depth (inches)	pH	Cation Exchange Capacity (meq/100 g soil)	Exchangeable Cations (meq/100 g soil)				Base Saturation (%)	% Organic Matter (organic C × 1.724)	N (%)
				Na	K	Ca	Mg			
A_1	1–8	4.3	19.92	0.26	0.20	1.05	0.70	11.09	11.48	0.38
A_2 (B_1?)	8–18	6.1	3.36	0.15	0.18	1.88	0.92	93.15	0.68	0.03
A_3 (B_2?)	18–27	7.2	1.82	0.15	0.16	*	*	*	0.37	0.01
C	27 +	8.2	1.82	0.03	0.10	*	*	*	0.57	0.02

*Free carbonates present.

Base saturation values indicate some form of shallow leaching in Arctic brown soil. Table 9-12 gives data on a profile of Arctic brown soil from Barrow, Alaska, which had only 11 percent base saturation in the 1- to 8-inch depth, but complete saturation below the 18-inch depth.

The shallow leaching in Arctic brown soil is considered a very weak form of podzolization. Since leaching generally has not progressed to the point of forming a bleached horizon, the solubilization-precipitation-translocation within the soil can be established only by using rather sensitive criteria. For example, determinations of the amount of reducible iron and manganese in the various horizons show that certain elements have translocated (Drew & Tedrow, 1957; Hill & Tedrow, 1961; Brown & Tedrow, 1964). Hill & Tedrow (1961) found that the amount of reducible iron and manganese increased more than fourfold with depth in the clay from the A and B horizons of certain Arctic brown soils; however, the reducible iron was quite constant throughout the solum of other Arctic brown soils (Brown & Tedrow, 1964).

Commenting on some of the above reports, Mikhailov (1961) questioned the validity of recognizing a "podzolic process" in Arctic brown soil. Using published reports by this author and colleagues from northern Alaska, Mikhailov stated, however, that the "soddy process" is clearly expressed in Arctic brown soil. Soviet investigators generally speak of three subtypes of podzolic soils: (1) Sod or Sod-podzolic soils with few visible signs of podzolization; (2) Podzolic soils with a recognizable podzolic horizon; and (3) Podzols which are strongly podzolized. Sibirtsev (1900) stated that the term "Sod-podzolic" can indicate various degrees of weak podzolization. Thus, the application of the term "podzolic process" is primarily a matter of semantics rather than fundamentals.

Clay Mineralogy

Arctic brown soil has clays mainly of the allogenic type. The first published clay analyses of Arctic brown soil from northern Alaska (Tedrow & Hill, 1955) showed that hydrous mica was the major component, together with small quantities of clay-size quartz; montmorillonite is present in local concentrations. Payne *et al.* (1951) list the principal interstitial material in the Colville group of rocks in northern Alaska as illite, with some chlorite, kaolinite, and montmorillonite. The clay content of Arctic brown soil formed on the Gubik (Quaternary) deposit of northern Alaska consists mainly of 2:1 layer silicates with some kaolinite (Drew & Tedrow, 1957).

TABLE 9-13 Clay and clay-size minerals in Arctic brown soil profiles in northern Alaska. (Hill & Tedrow, 1961.)

Arctic Brown–Shallow Phase, on Calcareous Sandstone			
Clay-size Minerals	**A_1**	**A_2**	**C**
Hydrous Mica*	++	++	++
Kaolinite	+	+	+
Feldspar	+	+	+
Quartz	+	+	+
Goethite	+	–	–

Arctic Brown–Shallow Phase, on Gabbro		
Clay-size Minerals	**A_1**	**A_2-C**
Hydrous Mica	++	++
Kaolinite	+	+
Feldspar	+	+
Quartz	+	+
Goethite	+	–

Arctic Brown on Till			
Clay-size Minerals	**A_1**	**A_2**	**C**
Hydrous Mica	++	++	++
Kaolinite	+	+	+
Quartz	+	+	+
Goethite	+	–	–

Arctic Brown on Kame Terrace			
Clay-size Minerals	**A_1**	**B**	**C**
Hydrous Mica	++	++	++
Chlorite	+	+	+
Kaolinite	+	+	+
Quartz	+	+	+

*As defined by G. W. Brindley, *The X-ray Identification and Crystal Structures of Clay Minerals* (1951), Mineral. Soc., British Mus. (London), p. 55.

Table 9-13 gives the clay composition of different profiles of Arctic brown soil in northern Alaska. The kame terrace site, although listed as having Arctic brown soil, has some visible podzolic affinities. Hydrous mica, kaolinite, and quartz were present in all the samples. Feldspar persisted in the clay-size range on two of the soils formed on feldspathic materials. Chlorite was present in one soil, and goethite had formed as an authigenic mineral in certain areas (Hill & Tedrow, 1961).

Genetic Processes

After the term Arctic brown soil was introduced, many soil conditions were so designated; consequently, the term lacks the specificity it once had. Fundamentally, the soil process involves organic material accumulation and a low order of leaching. The organic matter usually exists in the form of a continuous mat at the surface (Fig. 9-19), with a

Figure 9-19 Arctic brown soil formed on glacial drift of the Arctic Foothills.

A_0 Dark brown to black organic matter.

A_1 Dark brown (7.5YR 3/2) sandy loam with loose single-grain to fine crumb structure.

A_2 Dark yellow-brown (10YR 3/4) sandy loam.

C Very dark gray-brown (2.5Y 3/2) loamy sand.

D Bedrock.

Figure 9-20 Idealized profile of an Arctic brown soil—shallow phase.

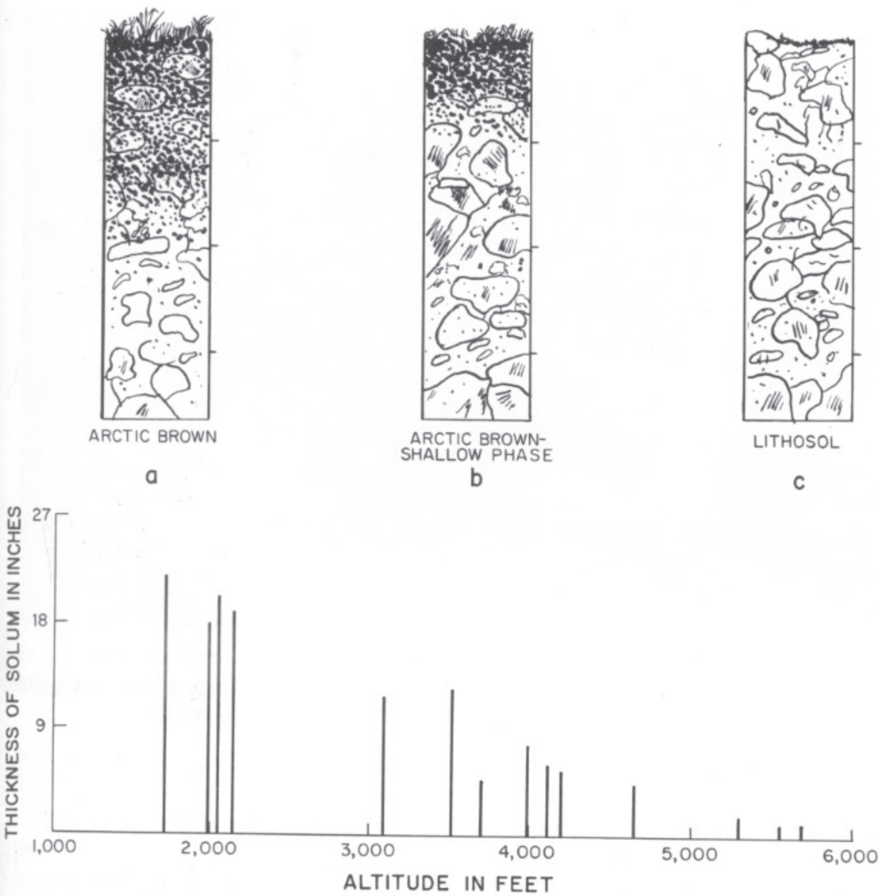


Figure 9-21 Idealized profile of Arctic brown soil. *a*. At altitudes of about 2,000 feet, the maximum solum thickness is about 20 inches. *b*. With increased altitudes, the solum thickness diminishes. *c*. At altitudes of 5,500 feet and above, there is virtually no soil development. The bar graph indicates measurements of maximum solum thickness in various locations of the Brooks Range. (Tedrow & Brown, 1962.)

slight redistribution of the humus compounds at depth. There is no other zone of organic accumulation in Arctic brown soil, unless massive permafrost underlies the soil. If such is the case, well-humified organic matter may accumulate above the frost table in a 1- to 4-inch band; however, such accumulations are generally found only with gravelly material that allows rapid percolation.

Insofar as leaching is concerned, there is usually an acid reaction in the upper horizons, and, depending upon the conditions, there may be

Figure 9-22 Ranker soil, North Slope of Alaska, at an altitude of some 3,500 feet. The acid organic mat shows virtually no signs of decomposition. Note the presence of rock fragments and the absence of fine mineral material.

a slight degree of translocation of iron within the soil. On carbonate rock or in windswept positions, the carbonates not only may persist but may accumulate within the soil. If carbonates accumulate in the organic matter, the soil will assume Rendzina-like characteristics. Pedogenic carbonate accumulation is common in the "B/C" horizon of Arctic brown soil if a potential supply of calcium is available for recycling. Mineral weathering involves a slight alteration of mica clays in the surface horizon, plus the formation of goethite and possibly other iron-bearing minerals.

Arctic Brown Soil–Shallow Phase

Arctic brown soil is frequently so shallow that the entire genetic profile is less than 1 foot thick (Fig. 9-20). The vegetative cover consists mainly of a barrens type, reflecting the semixeric environment (Tedrow & Cantlon, 1958). The soil profile represents an A/C condition, the B horizon being rather indistinct or absent. The depth of Arctic brown soil–shallow phase is controlled not only lithologically but also altitudinally and chronologically.

Vertical Zonation of Arctic Brown Soil

Pedologists have recognized the principle of vertical soil zones since it was advanced in the time of Dokuchaev. The Brooks Range of Alaska is an ideal place for studying the effects of altitude on soil development. The mean July temperature approximates some 52°F or more in the valleys, but the high mountains have a more rigorous climate, with a mean July temperature approximating 40°F at 6,000 feet. At selected well-drained, stable sites, one can follow the soil-forming potential at different altitudes. Arctic brown soils have a maximum solum thickness of about 18 inches on the gravelly, glacial, and stream deposits of the valleys, but on analogous positions higher up on the mountains the solum thickness decreases (Fig. 9-21). The solum is only 1 to 2 inches thick at an altitude of 5,500 feet and consists of grayish loamy material, plus a fibrous organic matter interspersed with fresh mineral grains (Tedrow & Brown, 1962).

Vascular plants are rare, and the entire landscape is barren above 5,500 feet altitude in the Brooks Range. This condition has been referred to as polar desert, but it is caused by erosion as well as by low temperatures. The soils have a raw appearance, as in the mountains of Scandinavia, and do not possess the good horizonation of the other terrestric soils of the arctic.

Arctic Brown Soil–Moderately Well-Drained Phase

In some places, Arctic brown soil has a gley condition at depth, particularly in the lower B horizons, as well as in the C horizon. Such a condition represents a transitional condition between Arctic brown and Upland tundra soils. The soil has uniform oxidized colors in the A horizon and in part of the B horizon. The gley condition results from the accumulation of moisture immediately above the permafrost table.

Ranker

Ranker soils, consisting of a thick, tough, fibrous mat or of roots and stems of heaths and grasses covering silicate boulders and shattered bedrock, are present in the mountainous areas of the tundra soil zone. Kubiëna (1970a, b) describes a variety of Ranker soils, including Arctic ranker and Alpine ranker. The best example of Ranker soil in the tundra soil zone is probably located at an altitude of 3,000 to 5,000 feet in the Brooks Range (Fig. 9-22). The soil consists of a 4- to 8-inch acid organic mat over broken rock. It contains virtually no fine mineral material.

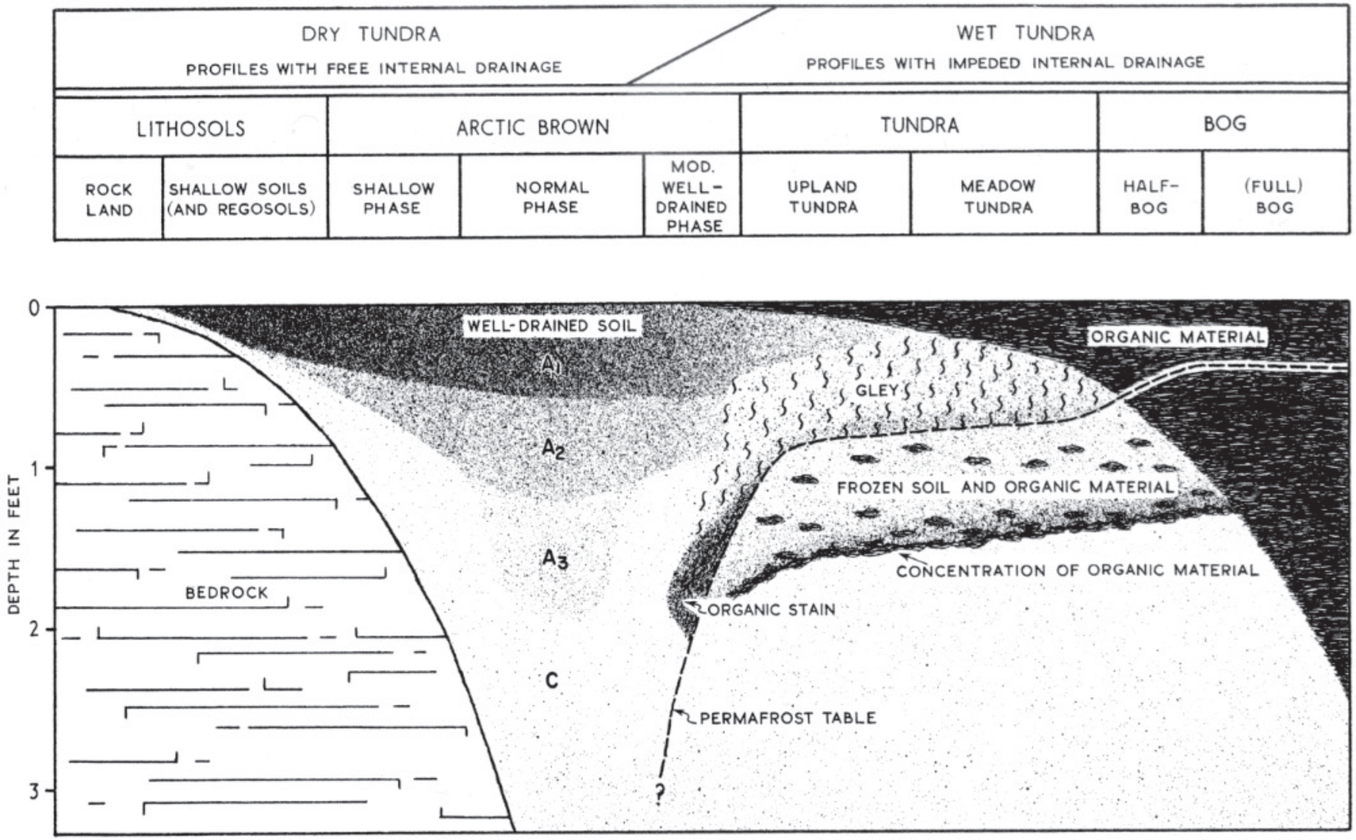


Figure 9-23 Major genetic sequence of soils in the tundra zone. (Tedrow *et al.*, 1958.)

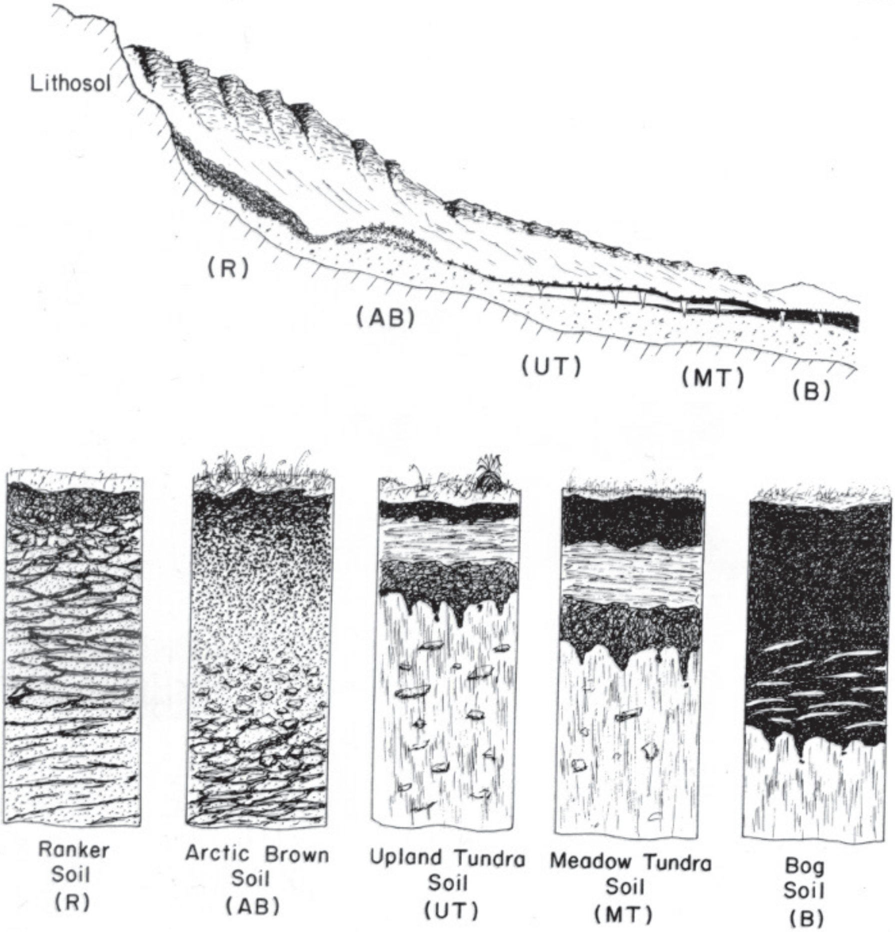


Figure 9-24 Idealized profiles of the major genetic soils of the tundra zone and their position in relation to relief elements.

Catenary Arrangement of Major Soils of the Tundra Zone

The major genetic soils (excluding Ranker) of the tundra zone can be arranged in catenary form as shown in Fig. 9-23. Arctic brown represents the zonal soil, and Tundra represents hydromorphic conditions. A diagram of the general position of various soils in the tundra zone with respect to landscape elements is given in Fig. 9-24, together with typical soil profiles.

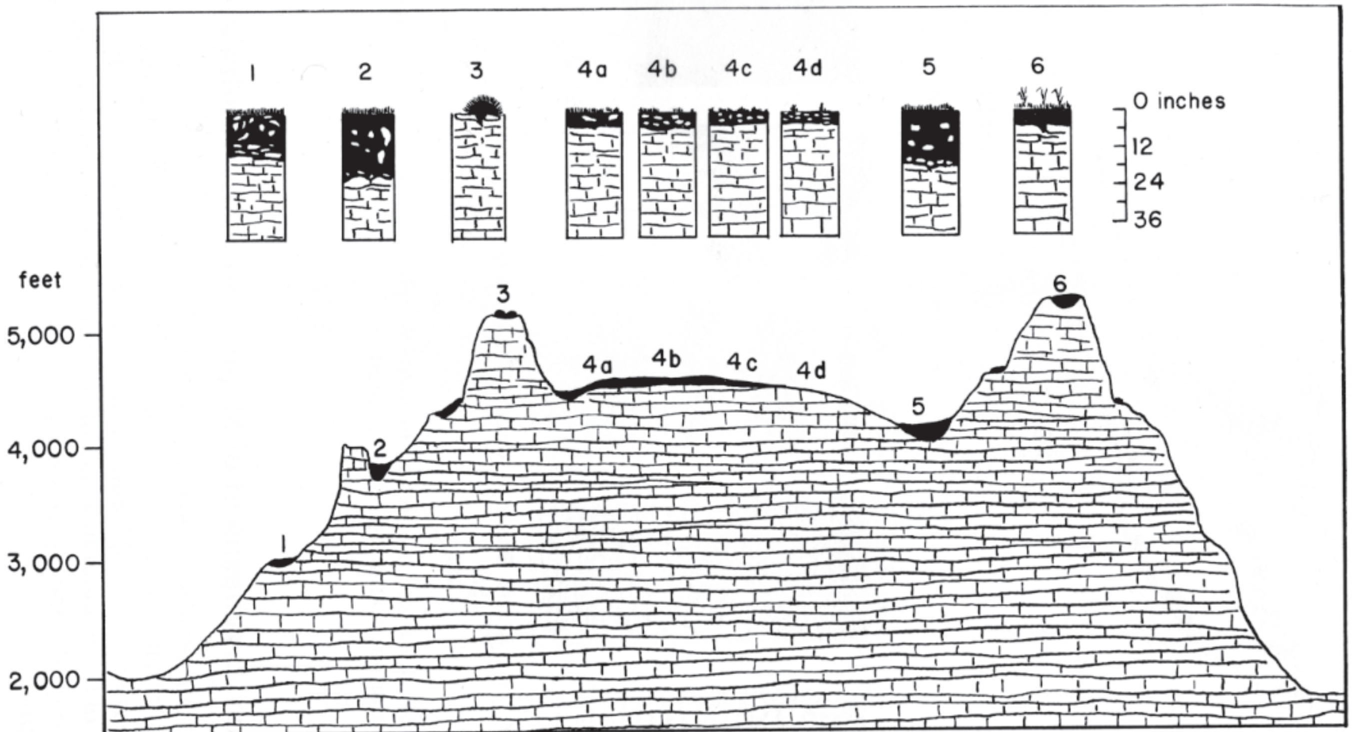


Figure 9-25 Idealized soil-landscape diagram showing the occurrence and position of some Rendzina soil profiles in the tundra soil zone, northern margins of the Brooks Range, Alaska. See Table 9-14 for chemical data on the soils. The numbers are keyed to the table. (Ugolini & Tedrow, 1963.)

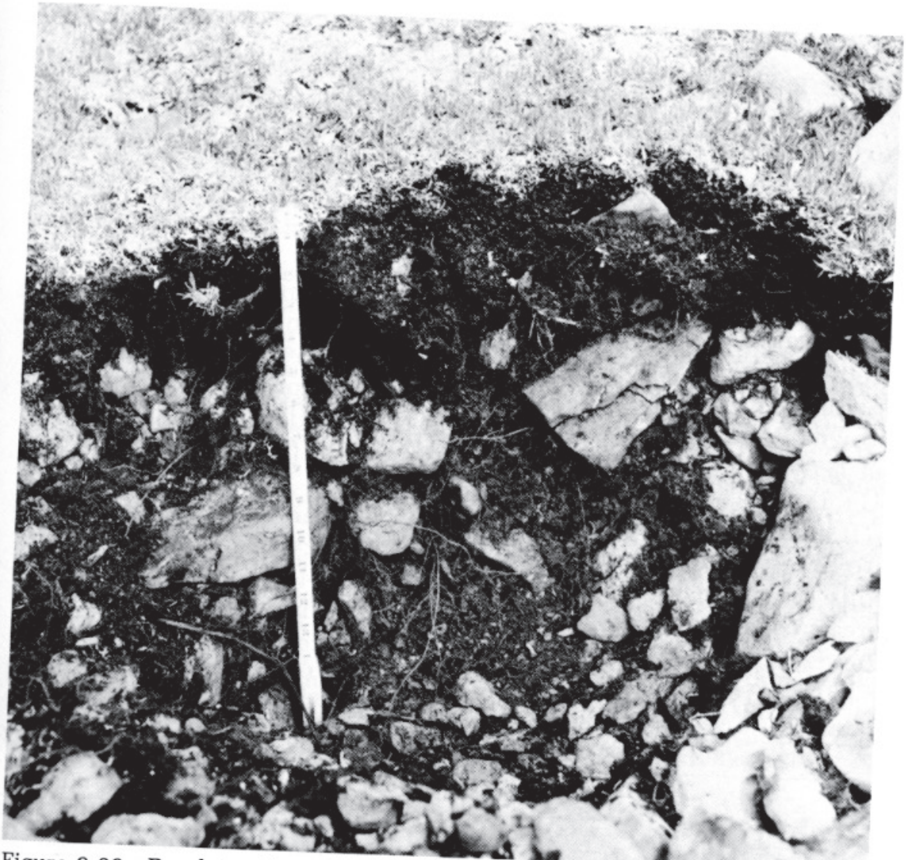


Figure 9-26 Rendzina formed on Lisburne limestone at an altitude of about 4,000 feet, Anaktuvuk Pass, Brooks Range, Alaska.

Podzol-like Soils

Podzol-like soils (Plate ID) are found mainly in the southern portions of the tundra zone (Brown & Tedrow, 1964), but they can occur elsewhere in the zone on stable, well-drained, quartzose material. Although the Arctic Coastal Plain of Alaska has extensive well-drained areas of quartzose sands, aeolian activity is primarily responsible for its having few Podzol-like soils. Nevertheless, where conditions are stable, incipient podzol development can be detected.

Rendzina Soils

Rendzina is a term used to describe humus carbonate soil. Whether or not it existed in the north was unknown for many years, but it is now known that this soil is common along the northern margins of the

Brooks Range in Alaska where the Lisburne limestone is present (Fig. 9-25). Rendzina soil was first identified in the arctic near the Anaktuvuk Pass area (Ugolini & Tedrow, 1963), and it has subsequently been found in the vicinity of Howard Pass (MacNamara, 1964) and Cape Lisburne (Holowaychuk *et al.*, 1966; Kubiëna, 1970b). The soil consists primarily of a well-drained black humus carbonate as much as 1 foot thick (Fig. 9-26).

The distribution of Rendzina soil closely follows lithologic patterns. Within a distance of some five miles in northern Alaska, the following well-drained soils are present: Arctic brown on ferruginous sandstone (Sadlerochit formation); Rendzina on limestone (Lisburne); Arctic brown–Podzol-like on quartzite (Kayak formation), and Arctic brown on a pyrited phyllite and quartz-mica schist (Neruokpuk formation) (Ugolini & Tedrow, 1963).

It has long been agreed that high pH values and a Ca-organo complex are necessary for Rendzina formation. Chemical data on the Rendzina soils are given in Table 9-14. Edelmann (1943) pointed out that the presence of carbonate rock is not necessarily sufficient to produce Rendzina. He suggested that the rock must contain a black, insoluble

TABLE 9-14 Chemical data on selected Rendzina soil profiles along the northern margins of the Brooks Range, Alaska (see the soil landscape diagram in Fig. 9-25). (Ugolini & Tedrow, 1963.)

Depth (inches)	pH	Carbonates (%)	C (%)	N (%)	C:N
		Stable Ledges (1)			
0–4	7.5	16.3	23.9	1.3	18.3
4–8	7.7	50.9	8.7	0.4	21.7
8–12	7.9	59.4	6.5	0.2	32.5
		Protected Sites (2)			
0–4	6.4	1.1	31.3	2.1	14.9
4–7	6.5	0.5	25.8	2.1	12.2
7–11	7.6	3.6	24.5	2.0	12.2
11–15	7.5	5.3	21.8	1.8	11.6
		Windswept Peaks (Cushion rendzina) (3)			
0–3	6.7	2.8	31.4	1.3	24.1
3–6	7.8	2.2	24.0	1.6	15.0
		Crests (4)			
0–3	7.6	25.2	22.2	1.6	13.8
3–6	7.8	29.2	11.9	1.0	11.9
		Owl Perches, etc. (6)			
0–3	4.7	3.6	29.0	2.8	10.3
3–6	4.9	3.3	22.6		
6–10	6.6	2.1	15.9	1.5	10.6

residue which persists after the carbonates have been leached. Krynine & Folk (1950) reported that a dark slime is present in the Lisburne limestone; when acid-treated, the limestone had a residue containing 23 percent organic carbon.

Shungite Soil

Shungite soil has been identified in a few valleys of the Brooks Range (Ugolini, Tedrow & Grant, 1963); it is not widely distributed. The outstanding property of the soil is a black, peaty character that persists throughout the profile. This condition is produced by the combined effects of the humic substances derived from present-day vegetation and the black carbonaceous material derived from the weathering of the black shale. In comparable positions in northern Alaska, the soils formed on sandstone, crystalline rock, and glacial drift are Arctic brown soil.

Soils similar to those derived from black shale in northern Alaska have been reported in eastern Karelia and Belorussia under the name Shungite (Toikka, 1957). Many of their morphological as well as chem-

TABLE 9-15 Chemical composition of black shale from the Brooks Range, Alaska. (Ugolini, Tedrow & Grant, 1963.)

Element	Soft Black Shale	Hard Black Shale
	(%)	(%)
SiO_2	58.97	33.00
Al_2O_3	17.0	13.1
Fe_2O_3	2.57	2.08
CaO	1.89	18.2
MgO	2.40	3.89
K_2O	2.15	0.46
Na_2O	1.06	0.83
S	0.80	—
TiO_2	0.26	0.11
Ignition Loss	9.96	5.29
	(ppm)	(ppm)
Ba	1310	1120
Co	6.0	6.2
Cr	408	281
Cu	134	155
Ga	8.2	0.85
Mn	142	75
Mo	5.2	—
Ni	159	261
Sn	0.35	1.8
Sr	172	282
V	845	160
Zn	1680	665

Figure 9-27 Shungite soil formed on black shale, Porcupine Lake area, Brooks Range, Alaska. The soil is shown to a depth of about 15 inches. (Ugolini, Tedrow & Grant, 1963.)

ical features are similar to those of Rendzina. The soils are well drained, are rich in organic matter, and have a poor horizon differentiation.

Shungite is both a geologic and a pedologic term. Geologically, it is a term used to describe a pre-Cambrian crystalline carbon that is less graphitized than graphite. Rankama (1948) states that this coaly matter is interstratified with dolomite limestone and that it is separable into varieties according to morphology and carbon content. Rankama & Sahama (1950) report that the carbon content of shungite may be as high as 98.77 percent, with a concentration of titanium, vanadium, molybdenum, copper, nickel, zirconium, and barium. The chemical analysis of shungite (black shale) from the Brooks Range is given in Table 9-15.

Shungite soil looks like a dry peat (Fig. 9-27), and its vegetative cover is composed of *Dryas, Salix, Oxytropis, Potentilla, Saxifraga,* and *Polygonum*. The profile in the Brooks Range was described by Ugolini, Tedrow & Grant (1963):

Depth (inches)	*Morphology*
0–12	Moist black peaty material with partially decomposed plant remains; more humified material at depth. Many fine roots throughout.
12–14	Moist black humified material mixed with lobes of shaley material.
14–18	Flaky, fragmental black shale resting on frozen black shale.

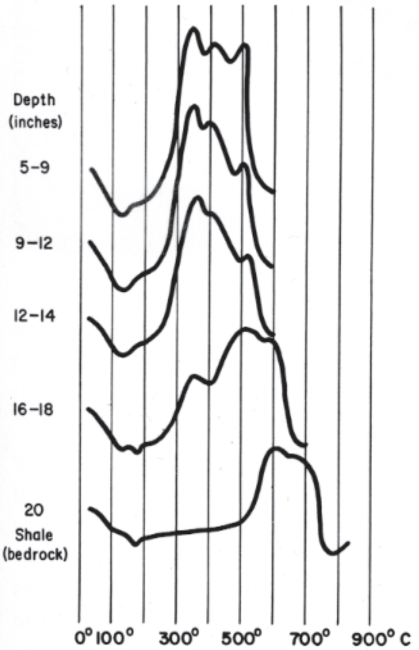


Figure 9-28 Differential thermal analyses of the <0.05 mm fraction of Shungite soil at various depths. Analyses made in an argon atmosphere. (Ugolini, Tedrow & Grant, 1963.)

Chemical data on this soil are given in Table 9-16. The cation exchange capacity of the soil is very high at the surface and decreases with depth. The soil varies between neutral and subalkaline, tending toward higher pH values with depth. The clay consists of dioctahedral illite in hydrated form, plus a little montmorillonite, dolomite, calcite, calcium-orthophosphate, gypsum, and whewellite (Ugolini, Tedrow & Grant, 1963).

By selective treatments followed by differential thermal analyses, it was possible to separate approximately the organic matter contributed by the present-day vegetation from the carbon inherited from the parent rock (Fig. 9-28). Leaching removes the most soluble salts such as gypsum from the upper part of the profile, and there is partial solubility of the carbonates.

Grumusol

Oakes & Thorp (1950) define Grumusol as a dark clay soil formed under a relatively warm climate with alternating wet and dry seasons

TABLE 9-16 Chemical properties of Shungite soil (<2 mm) on black shale, Brooks Range, Alaska. (Ugolini, Tedrow & Grant, 1963.)

Depth (inches)	pH	C (%)	N (%)	Cation Exchange Capacity (meq/100 g)	Exchangeable Na (meq/100 g)	Exchangeable K (meq/100 g)	Free Carbonates (%)
5–9	7.2	22.9	1.45	184	0.62	0.17	2.24
9–12	7.4	17.9	1.34	144	0.59	0.11	1.36
12–14	7.6	11.2	0.86	92	0.48	0.78	9.33
16–18	7.5	6.2	0.34	22	0.59	0.12	11.02
20+	7.7	5.3	—	—	—	—	8.76

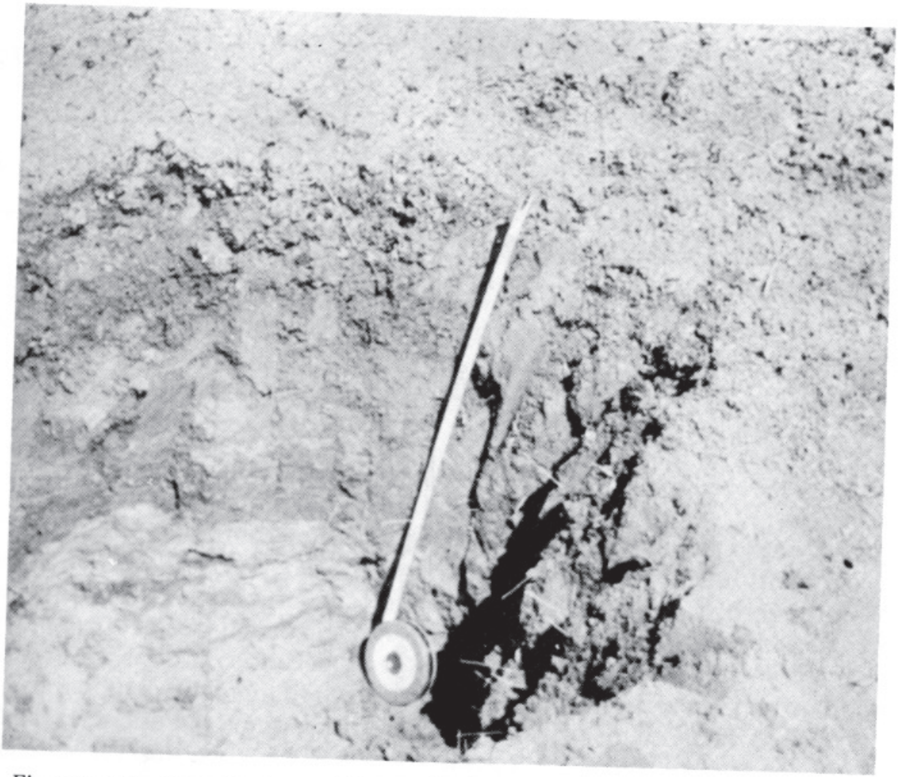


Figure 9-29 Grumusol near Umiat, Alaska. (MacNamara & Tedrow, 1966.)

where there is gilgai (micro knob-basin or micro ridge-valley) relief. Grumusol is also present in isolated locations of the tundra soil zone (MacNamara & Tedrow, 1966).

A soil observed near Umiat, Alaska, consisted of a heavy, plastic clay without much soil horizon differentiation (Fig. 9-29). The clay is a nearly pure grade of montmorillonite (Anderson & Reynolds, 1967), sometimes reaching the 80 percent level (Tedrow & Hill, 1954). Arctic sites with an extremely high clay content are nearly bare of plant cover and resemble a raw spoil bank. Where silts are present with the clay, a microrelief pattern of polygons forms and *Carex* and *Arctagrostis* colonize the channels surrounding the polygons.

The dominant process in the Grumusol is physical mixing of the solum induced by freeze-thaw cycles and desiccation. The material is usually strongly acidic. The soil may have zones of soluble salts—usually made up of sodium and sulfate (Table 9-17). During rainless periods, thenardite crystallizes on the surface of the soil, forming a light gray to white veneer. The porosity of the soil totals 63 to 86 percent (MacNamara & Tedrow, 1966).

TABLE 9-17 Chemical properties of an arctic equivalent of the Grumusol near Umiat, Alaska. (MacNamara & Tedrow, 1966.)

Depth (cm)	pH	pH*	Organic Matter (%)	Water-Soluble Cations and Anions† (meq/100 g)					
				Na	K	Ca	Mg	Cl	SO_4
0–5	4.8	5.7	0.60	0.1	0.02	0.05	0.01	2.3	0.01
5–15	4.2	4.8	0.24	47.8	0.13	2.00	1.50	2.3	37.30
15–30	4.2	5.6	2.80	31.9	0.13	0.20	1.20	2.3	31.50
30–86	4.1	5.8	0.40	2.1	0.13	0.40	1.20	2.3	6.40

Depth (cm)	Cation Exchange Capacity (meq/100 g)	Exchangeable Cations after Water-Soluble Cations Removed‡ (meq/100 g)			
		Na	K	Ca	Mg
0–5	22	0.2	0.30	1.25	1.16
5–15	147	12.0	1.80	4.60	13.00
15–30	131	17.4	1.50	6.55	11.40
30–86	21	0.4	0.50	8.50	3.30

*After removal of water-soluble salts (negative test for SO_4).
†5 g sample leached with 250 ml distilled water.
‡5 g sample leached twice (250 ml N NH_4Ac, pH 7) with the difference between first and second leachings reported as exchangeable cations.