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Characteristics of cryogenic soils along a latitudinal transect in Arctic Alaska

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Abstract. The morphological, chemical, and physical properties of arctic tundra soils were examined along a 200-km latitudinal gradient in northern Alaska which includes two major physiographic provinces; the Arctic Coastal Plain and the Arctic Foothills. Annual air temperature and precipitation increase along the gradient from north to south. Soils on the Arctic Coastal Plain support wet, nonacidic tundra vegetation and have high carbonate contents. Soil on the Arctic Foothills support moist, nonacidic tundra in the northern part and moist acidic tundra in the southern part. Most arctic tundra soils are characterized by medium texture, poor drainage, and high organic matter content. From north to south along the transect, the base saturation of the active layer decreases and exchangeable aluminum increases from north to south. Most soils have strongly developed cryogenic features, including warped and broken horizons, ice lenses, thin platy structure, and organic matter frost-churned into the ice-rich upper permafrost horizons.

1. Introduction

Arctic tundra soils have unique properties that result from cryogenic processes, such as ground ice formation and cryoturbation. Cryoturbation causes mixing of soil material by repeated freezing and thawing, results in broken and irregular horizons, and mixing of soil materials; for example, organic material may be mixed into mineral soil, particularly near the permafrost table [*Tarnocai and Smith*, 1992; *Bockheim and Tarnocai*, 1998]. Cold temperatures slow the rates of other soil-forming processes such as podzolization, decalcification, and clay translocation [*Tedrow et al.*, 1958]. Most notably, cold temperatures and wetness reduce organic matter decomposition, thus facilitating the accumulation of peat in arctic regions [*Ovenden*, 1990]. Although most permafrost-affected soils, including those in Alaska, are located in regions with low precipitation, they commonly display redoximorphic features and horizons with reduced colors (Munsell hues of 2.5Y and 5Y, chromas of 2 or less, and values of 4 or more). This is caused by a seasonally perched water table on permafrost [*Everett et al.*, 1981; *Ping et al.*, 1993] and by concentration of soil moisture due to microtopography [*Tarnocai*, 1994]. In soils affected by permafrost, pedogenic processes primarily occur in the active layer which is the upper part of the soil profile subject to seasonal freeze and thaw. However, evidence of these processes also are observed in the upper permafrost as the results of permafrost table fluctuation due to climate change (C.L. Ping et al., manuscript in review, 1998).

Mineral horizons of permafrost-affected soils commonly have a platy structure that forms when water moves toward the freezing front as the active layer refreezes in the fall. Freezing occurs both from the surface down and from the permafrost table up [*Tarnocai*, 1994]. Repeated freezing and thawing is manifested by cryoturbation and results in particular soil structures and fabric such as granular, platy structures, ice nets, and ice lenses [*Gubin*, 1993; *French*, 1996]. At the landscape level, it leads to the formation of patterned ground [*Washburn*, 1980]. Patterned ground features common to arctic Alaska include ice wedge polygons, sorted and nonsorted polygons, and larger features such as thaw lakes [*French*, 1996]. Cryopedogenic processes in the arctic have received much attention [*Tedrow*, 1974; *Everett and Brown*, 1982; *Tarnocai et al.*, 1992, 1993; *Bockheim et al.*, 1998], and the cryoturbation phenomena have been proven useful in environmental reconstruction [*Hoefle et al.*, 1998; *Van Vliet-Lanoe*, 1988]. The soil character varies widely depending on location within these periglacial features and patterns. Drainage, organic matter thickness, and depth of the active layer can be quite variable within a small area [*Tarnocai*, 1994]. The concept of different but related soils within the same periglacial pattern is incorporated into Canadian soil classification [*Agriculture Canada*, 1987]. In the Canadian system the pedon for cryoturbated soils is defined to include the full cycle of patterned ground with a 2-m linear interval, or a half cycle with a 2- to 7-m linear interval. In the case of large-scale (>7 m) patterned ground, such as low-centered polygons, two pedons are established: one in the center of the polygon and the other in the wedge. This concept was adopted by the International Committee on Classification of Permafrost-Affected Soils [*ICOMPAS*, 1996] which introduced the Gelisol order to soil taxonomy [*Soil Survey Staff*, 1998].

Soils of arctic Alaska often have a greater amount of organic carbon than temperate soils [*Reiger*, 1983; *Ping et al.*, 1997b]. Organic matter decomposition in permafrost-affected soils is inhibited by a combination of factors, which include a short growing season, saturated soils due to the presence of permafrost, cold temperatures, and recalcitrant organic plant material. Organic material is often cryoturbated into lower parts of the active layer, which with time and changing environmental conditions can become encased in permafrost, sequestering the carbon more permanently [*Shur and Ping*, 1994; *Ping et al.*,

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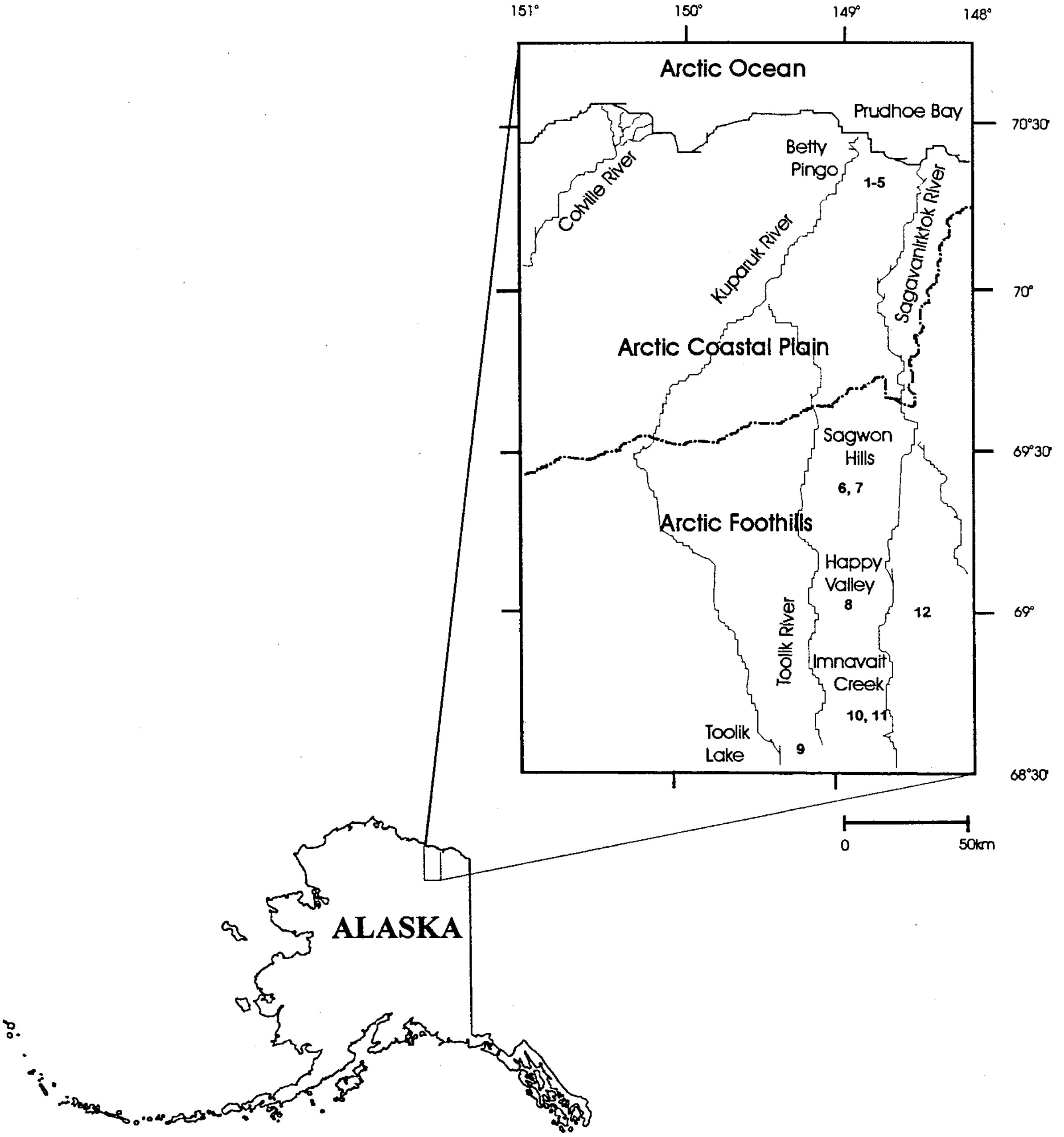

Figure 1. Location of study sites in arctic Alaska.

1997b]. In arctic Alaska, carbon stored in the upper permafrost within 1 m of the surface accounted for nearly 50% or more of the total pedon carbon storage [*Michaelson et al.*, 1996; *Bockheim et al.*, 1997b]. Therefore soils with permafrost may become potential carbon sources with climate warming and melting of the carbon-rich near-surface permafrost [*Oechel and Billings*, 1992: *Kimble et al.*, 1993; *Oechel et al*,. 1993; *Tarnocai*, 1994].

Because of oil exploration and other natural resource extraction the Alaskan North Slope has received considerable attention in recent decades. Most pedological investigations of permafrost-affected soils on the North Slope have been undertaken on the arctic coastal plains near Barrow and Prudhoe Bay [*Tedrow et al.*, 1958; *Douglas and Tedrow*, 1960; *Brown and Johnson*, 1965; *Brown*, 1967; *Everett*, 1975; *Parkinson*, 1977; *Walker et al.*, 1980; *Brown and Berg*, 1980]. Fewer studies have focused on the Arctic Foothills and the Brooks Range [*Brown*, 1966] and none on pedogenic relationships along a latitudinal transect. Most studies have examined the active layer, largely ignoring the near-surface permafrost zone. The objective of this study is to examine the characteristics of cryogenic soils along a north-south transect along the Dalton Highway and to relate these characteristics to the salient pedological processes.

2. Materials and Methods

2.1 Study Sites

Study-site locations are shown in Figure 1 with site descriptions in Table 1. Most sites are within the carbon flux study plots of the National Science Foundation, Arctic System Science Program, Land Atmosphere Ice Interaction study group (NSF, ARCSS-LAII). All sites were chosen as representative of the major land cover class units for the Kuparuk River basin

Table 1. Physical Environment, Land Cover Class, and Soil Classification of Study Sites

Site ID	Area	Land Cover Class[a] Soil Classification[b]	Microrelief Drainage	Permafrost Table cm	Latitude Longitude	Elevation m	Distance From Coast km
			Arctic Coastal Plain				
1	Betty Pingo Prudhoe Bay	moist nonacidic tundra Sapric Glacistel	flat-polygon rim poorly drained	50	70° 16' 52"N, 148° 53' 51"W	21	12
2	Betty Pingo Prudhoe Bay	moist nonacidic tundra Typic Molliturbel	high-center polygon somewhat poorly drained	35	70°17' 01"N, 148° 53' 57"W	12	12
3	Betty Pingo Prudhoe Bay	wet nonacidic tundra Typic Historthel	low-center polygon, center poorly drained	35	70° 16'50"N, 148° 55' 14"W	12	12
4	Betty Pingo Prudhoe Bay	wet nonacidic tundra Typic Molliturbel	low-center polygon, rim somewwhat poorly drained	43	70° 16' 50"N, 148° 55' 14"W	13	12
5	Betty Pingo Prudhoe Bay	wet nonacidic tundra Glacic Hemistel	polygon trough very poorly drained	30	70° 16'50"N, 148° 55' 14"W	12	12
			Arctic Foothills				
6	Sagwon Hills	moist nonacidic tundra Mollic Aquaturbel	ridge top, nonsorted circles poorly drained	58	69° 26' 46"N 148° 40' 22"W	269	110
7	Sagwon Hills	moist acidic tundra Ruptic-Histic Aquaturbel	tussock tundra, ridge top poorly drained	40	69° 26' 06"N, 148° 48' 34"W	359	112
8	Sagwon Hills	moist acidic tundra Typic Aquaturbel	tussock, hillslope poorly drained	40	69°08'47"N 148°51'14'W	300	143
9	Toolik Lake	moist acidic tundra Typic Aquaturbel	moraine, midslope poorly drained	35	68° 37' 44"N, 149° 37' 09"W	777	201
10	Imnaviat Creek	moist acidic tundra Typic Aquorthel	moraine mid-slope poorlyl drained	26	68° 36' 41.70"N, 149° 18' 26.46"W	938	201
11	Imnaviat Creek	wet acidic tundra Typic Fibristel	valley floor, sphagnum bog very poorly drained	50	68°36' 39" N 149°18" 45" W	903	201
12	Sag River	riparian shrub land Typic Cryothent	gravel-sand bar excessively drained	200+	69° 03' 87"N, 148° 44' 93"W	348	152

[a] *Auerbach and Walker* [1996].
[b] *Soil Survey Staff* [1998].

described by *Walker and Everett* [1991] and mapped by *Auerbach et al.* [1996]. The major land cover classes identified in the Kuparuk river basin, along with percentage of area, include barren (1%), moist nonacidic tundra and dry tundra (39%), moist acidic tundra (31%), shrub lands (17%), wet tundra (7%), and water (5%). The study area is within the continuous permafrost zone [*Péwé*, 1975] and is divided into two physiographic provinces: the Arctic Coastal Plain and the Arctic Foothills [*Wahrhaftig*, 1965]. *Ping and Moore* [1993] identified the study area as belonging to the pergelic soil climate zone because the mean annual soil temperature at 50 cm is below 0°C. *Zhang et al.* [1996] subdivided the Coastal Plain into Arctic Coastal and Arctic Inland based on climate. The southern portion of the Arctic Coastal Plain is more continental because of its location farther inland from the Arctic Ocean.

The climate of the area varies with distance from the Arctic Ocean and elevation. In the Arctic Coastal Plain the mean annual air temperature (MAAT) ranges from -12.8° to -10.3°C, and mean annual precipitation (MAP) ranges from 125 to 142 mm with 50% as snow [*Haugen*, 1982]. The mean annual soil temperature (MAST) at 50 cm estimated from the temperatures of permafrost ranges from -7° to -9°C [*Osterkamp and Romanovsky*, 1996; *Ping and Moore*, 1993]. The annual sum of growing degree days (GDD) (based temperature of >0°C) measured at Franklin Bluff, at the southern arctic Coastal Plain, is 121° day (L.D. Hinzman, unpublished data, 1998).

The MAAT of the Arctic Foothills is 2° to 4°C warmer than that of the Coastal Plain due to the greater distance from the ocean [*Zhang et al.*, 1996]. The MAST ranges from -5° to -7°C, and the MAP ranges from 140 to 270 mm with 40% falling as snow [*Ping and Moore*, 1993; *Haugen*, 1982]. The winter temperatures are much higher in the southern portion of the Arctic Foothills because of atmospheric temperature inversions. The GDD in this region ranges from 760o to 1125° day. Temperature-vegetation gradients on the Arctic Coastal Plain and the Foothills indicate that GDD accumulations are linearly related to the distance from the ocean. In general, MAP and diurnal temperature variations increase southward with distance from the coast.

The following is a brief description of the sampling sites along the latitudinal gradient. Sites 1-5 are located near Prudhoe Bay, east of the Kuparuk River, in moist and wet nonacidic tundra (Figure 1, Table 1). These sites represent the Arctic Coastal Plain which is dotted with oriented thaw lakes. This landscape is characterized by low-center, flat, and high-center polygons with diameters ranging from several to 25 m. Most of the soils are very poorly or poorly drained; the sites generally having either standing water or are saturated within 25 cm to the soil surface for more than 2 weeks. The dominant vegetation includes the sedges, *Carex aquatilis and Eriophorum angustifolium; and mosses, Drepanocladus spp.*, and *Scorpidium scorpoides*.

Sites 6 and 7 are in the Sagwon Hills in the northern Arctic Foothills. The area is about 110 km from the Arctic Ocean. The landscape is dominated by rolling hills with loess deposits more than 1 m deep over early Pleistocene Anaktuvuk drift [*Hamilton*, 1987]. There are two main types of vegetation in the region; moist nonacidic tundra and moist acidic tundra. The former is dominated by *Dryas integrifolia, Salix reticulata, Carex biglowii,* and *Tomentypnum nitens*. The latter is dominated by *Eriophorum vaginatum, Betula nana, Salix pulchra,* and *Hylocomium splendens*. The thickness of the organic layer is greater in moist acidic tundra, thereby reducing the amount of cryoturbation [*Bockheim et al.,* 1998]. The nonacidic tundra has 30% mudboils (nonsorted circles) on the surface, while there are only occasional mudboils in the acidic tundra.

Site 8 is also acidic tundra but is located farther south, about 143 km from the coast. It is on mid-Pleistocene Sagavanirktok drift, which contains rock fragments of mixed mineralogy, and most gravel is rounded. The vegetation is dominated by *Eriophorum vaginatum* tussocks.

Sites 9 and 10 are 200 km from the coast and on hillslopes. On the basis of maps by *Hamilton* [1987], site 9 is on a late Wisconsin moraine and site 10 is on an early Wisconsin moraine. Both drifts are rich in rock fragments, but more cobbles and boulders are visible on the surface of site 10. The vegetation is a moist acidic tundra, with *Eriophorum vaginatum, Betula nana, Hylocomium splendens,* and *Ledum decumbens*. The soils are poorly drained.

Site 11 is about 200 km from the coast and on valley bottom along Imnaviat Creek. The soil is formed in organic deposits. The vegetation is wet acidic tundra with *Sphagnum* mosses. Surface water is common during the early growing season.

Site 12 is about 160 km from the coast. It is on a vegetated gravel bar along the Sagavanirktok River. The soils are formed in fine-textured alluvium over gravel. The vegetation is dominated by willow shrubs and some forbs.

2.2 Soil Sampling

Pits of approximately 1 m^2 were excavated to a 1 m depth at each site using shovels in the active layer and a gasoline-powered chisel for the frozen layers. The excavations were made so that the vertical face exposed a complete cycle of the surface microrelief patterns (<2 m). Sites on the coastal plain with patterned ground cycles larger than 7 m were sampled by opening separate pits to examine major segments of the cycle (sites 3-5). Scale drawings were made of the exposed soil profiles which were then described according to the Soil Survey Manual [*Soil Survey Division Staff,* 1993]. The active layer thickness was determined as the depth to either the ice nets, ice-rich layers, or ice wedges [*Shur,* 1988]. Soil horizons in the upper permafrost and cryoturbated ones are designated by lowercase *f and jj,* respectively.. Rectangular soil block samples for bulk density and water content (average volume of 400 cm^3) were cut in triplicate from each of the undisturbed genetic horizons by using a serrated-edge knife. The sample taken for bulk density included ice when present in veins. The block dimensions were measured, recorded, and the samples sealed in waterproof bags for transport. Bulk density was reported on a stone-free basis.

2.3 Soil Analyses

Bulk samples from each horizon were transported to the laboratory, where they were weighed, air-dried, reweighed, and then crushed to pass through a 2-mm sieve. Subsamples of the air-dried ground samples were dried to 105°C; chemical and physical measurements expressed on an oven-dry basis. All samples were characterized according to the USDA National Soil Survey Laboratory procedures [*Soil Survey Laboratory Staff,* 1996]. Soil pH in a saturated paste was measured in the field. Total carbon and nitrogen were measured on a LECO 1000 CHN analyzer. Samples with neutral or alkaline reactions were pretreated with 0.1*M* HCl to remove carbonates prior to total C and particle size analyses. Cation exchange capacity (CEC) and extractable cations were determined by extracting with 1 *M* ammonium acetate at pH 7.0 and steam distillation and atomic absorption, respectively. Exchangeable acidity was determined by $BaCl_2$-triethanolamine and exchangeable aluminum by using 1 *M* KCl. Base saturation was calculated by dividing the sum of exchangeable cations by the CEC.

3. Results and Discussion

3.1. Morphological Properties

3.1.1. Soils of the Arctic Coastal Plain. There are two different soils associated with low-center polygons on the coastal plain: the polygon center and the rim-trough combination. The center of the polygons is flat and poorly to very poorly drained with water near or at the surface during most of the growing season. Soils of the polygon centers consist of stratified peats and loamy sediments over medium-grained alluvium or lacustrine sediment which are gleyed with grayish colors (2.5Y 5/2, 2.5/2, and 5Y 2.5/1). The surface organic layer is generally <20 cm with minimal cryoturbation. The active layer is about 35 cm thick and the upper permafrost is ice rich with thick ice lenses. In low-center polygons the polygon rims are 20 to 40 cm above the polygon center and are somewhat poorly drained: the water tables are more than 25 cm deep during most of the growing season. The soils on the polygon rim generally consist of 15-20 cm of organic material over 30 cm of an A horizon. The permafrost table is at 45 to 50 cm, and the upper permafrost contains over 60% ice by volume. Soil horizons in the polygon rim show a convex pattern following the surface relief of the rim; thus the soils are cryoturbated. The relationships of these three soils in the low-center polygons are shown in Figure 2. Soils in the trough between polygons are very poorly drained and are characterized by 35 to 40 cm of organic horizon over an ice wedge.

Whereas low-center polygons are common on the younger part of the Arctic Coastal Plain, flat and high-centered polygon dominate the older part of this thaw-lake landscape (sites 1, 3,

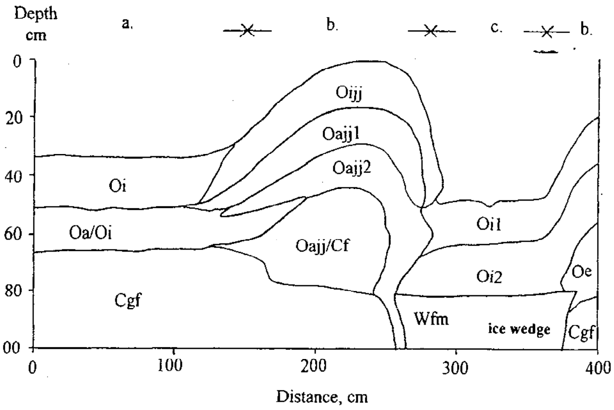

Figure 2. Relation between soil development and microrelief in a low-center polygon on the Arctic Coastal Plain, Alaska. (a) Site 3, polygon center: Typic Historthel; (b) Site 4, polygon rim: Typic Molliturbel; (c) Site 5, polygon trough: Glacic Histel.

and 4). On flat-centered polygons the soils are saturated during most of the growing season. Near the edge of the polygons the organic layer is >40 cm thick and overlays cryoturbated alluvium or lacustrine sediments with ice wedges. Thus the soils are organic soils. In the center of the polygons, the organic layer is sometimes thinner than 40 cm thick over mineral sediments. On the high-centered polygons (site 2) there are well-developed A horizons because the soils are better drained. The subsoils show evidence of moderate cryoturbation as manifested by broken and warped horizons. The permafrost table occurs at 45-50 cm, with organic matter frost-churned into the frozen C horizon; the C material is ice rich, with about 60% ice by volume.

3.1.2. Soils of the northern Arctic Foothills. The Coastal Plain grades into a subdued dissected upland in Sagwon Hills area. The area is blanketed with loess deposited over tertiary outwash consisting of rounded gravel of mixed mineralogy [*Hamilton*, 1987]. Along the northern edge of this hilly upland, the vegetation is dominantly nonacidic tundra [*Auerbach et al.*, 1996] characterized by *Dryas* and *Lupinus* in addition to other tundra species. The microrelief is characterized by low, flat polygons about 40 to 100 cm across with 15% bare soil in mudboils or frost scars. The soils associated with this vegetation are strongly cryoturbated as indicated by warped and broken soil horizons throughout the entire profile (Figure 3). Under a discontinuous organic layer, portions of the profile have a high chroma color, indicating oxidation of iron minerals, while adjacent zones are gleyed. The gleyed soil material developed a pink color within 30 s when sprayed with alpha-alpha-dipyridyl, indicating a positive test of reducing conditions. Cryoturbated organic matter or humus is scattered throughout the mineral horizons and a second concentration of organic matter is found directly above the permafrost table at about 50 cm (site 6, Table 2). This suggests the frost churning of humus and sequestration of carbon into the permafrost [*Ping et al.* 1997b].

Soil structure is massive in the upper part of the active layer where it is located below the surface of the mudboils and in between low tussocks due to the constant wetness. However, a strongly developed platy structure is found through most part of the active layer as a result of freezing and thawing. In the lower active layer above the permafrost table the structure is angular blocky as the result of vertical and horizontal vein-ice formation due to frost cracks caused by freeze-back from the permafrost table in the fall [*Zhestkova*, 1982]. The upper 30-40 cm of permafrost is very ice rich, and soil aggregates appear suspended in ice; this has been identified as "ataxitic" cryogenic fabric [*Gasanova*, 1963]. This ataxitic fabric is formed from repeated freezing and thawing and indicates a fluctuating permafrost table due to climate changes [*Shur*, 1988]. The resulting structures of the thawed soil provide channels for soil water after the permafrost thaws, thus biogeochemical weathering, mainly reduction-oxidation, can penetrate into upper permafrost layer periodically.

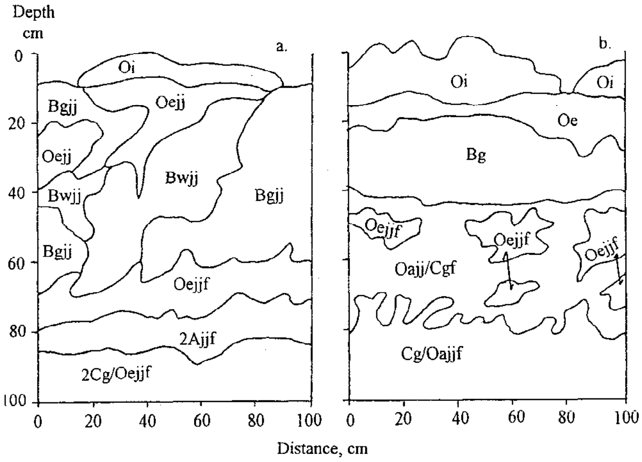

Figure 3. Soil profiles of cryoturbated soils on Arctic Foothills, Alaska. (a) Site 6, moist nonacidic tundra: Mollic Aquaturbel; (b) Site 7, moist acidic tundra: Ruptic-Histic Aquaturbel.

On similar landforms and loess parent materials farther to the south (Figure 1), the vegetation changes to acidic tundra (site 7). The region has patterned ground and less than 1% frost boils. In some areas there are tussocks in the acidic tundra. Soils associated with this land cover have a thick but discontinuous organic horizon commonly ranging from 15 to 20 cm. Cryoturbation is less pronounced than in the nonacidic soils. The permafrost table occurs at 45 to 50 cm, and the upper 20 cm of the permafrost is enriched in well-humified organic matter from cryoturbation. Deposition of calcareous loess originating from braided portions of the Sagavanirktok River is greater in nonacidic tundra than in acidic tundra [*Walker and Everett*, 1991]. In the nonacidic tundra area, vegetational succession toward a more acidic type is "masked" by the continuously deposited loess. In the acidic tundra there is better moss growth; hence there is a thicker organic horizon. In both soils the upper permafrost layers have an ataxitic fabric. The ice content in ataxitic fabric is generally over 60% by volume.

Soil texture suggests a uniform parent material for soils in the northern Arctic Foothills (Table 2). The predominantly silt loam textures in both acidic and nonacidic tundra suggests their common source, loess. The silt content ranges from 60 to 70% but is slightly higher in the nonacidic tundra because it is closer to the Sagavanirktok River [*Walker and Everett*, 1991]. Pebbles and gravel occur throughout the lower profile but their position suggests that they were moved up by frost heave. There is a concentration of rock fragments around the mudboils (nonsorted circles) on the surface of the nonacidic tundra which is indicative of the effect of cryoturbation on an exposed surface.

3.1.3. Soils of the southern Arctic Foothills. Soils of the southern Arctic Foothills are on the rolling hills on moraines south of Gunsight Mountain. The drift is middle to late-Wisconsin in age [*Hamilton*, 1987] and contains coarse fragments from pebble to boulder in size. Soil texture changes from silt loam or silty clay loam in the northern part of the foothills to sandy loam in the southern part with increased coarse fragments in the soil profiles and on the soil surface. This indicates the loess layer is thinner in the south due to erosion or that there is less loess deposition. Soils of the moist acidic tundra in the southern Arctic Foothills have more strongly oxidized colors (higher chroma), i.e., redder, indicating longer periods of oxidation than equivalent soils in the northern foothills. Most of these soils have a well-developed ataxitic fabric in the upper permafrost layers and weak ice nets above the ataxitic horizons. The ice-net fabric is so named because the ice veins are interwoven like a net when viewed from the top of the soil pit [*Gasanova*, 1963]. The ice-net fabric has more mineral material than ice, whereas the ataxitic fabric has more ice than mineral material. The ice-net fabric is caused by freeze-back of the permafrost table and has been used to determine the position of the permafrost table [*Hoefle et al.*, 1998].

Discontinuous surface organic horizons are common in the southern foothills, but broken and irregular subsurface horizons are not so common as in the soils of the northern foothills. This may be due to the fact that the soils have better drainage due to their coarser textures and better insulation from greater amounts of snow in the south. In addition to surface organic layers, organic matter is also frost-churned into the underlying mineral soil horizons and is commonly concentrated in the upper permafrost. The subsoil accumulation of carbon results from cryoturbation.

Soils in the southern foothills have similar cryogenic structures as soils in the northern foothills, including ice lenses, blocky structure to the top of the permafrost table, and ataxitic structures in the upper permafrost. However, the layers with ataxitic fabric are generally thinner than those in the northern foothills, ranging from 20 to 30 cm. This indicates that there is less fluctuation of permafrost tables in the southern portion of the foothills, possibly due to thicker snow cover and better insulation. Ridge tops and windswept valleys are exposed to a more severe climate and commonly contain mudboils.

3.2. Chemical and Physical Properties

3.2.1. Soils of the Coastal Plain. Soils on the Arctic Coastal Plain have nearly neutral (pH 6.6-7.3) to slightly alkaline (pH 7.4-7.8) reactions (Table 3). The sampling sites are close to the Sagavanirktok River which is the source of carbonate-bearing silt [*Walker and Everett,* 1991]. The prevailing wind direction is NE-SW; thus the area is downwind of the Sagavanirktok River. *Parkinson* [1977] showed that soil pH values decrease with increasing distance from the calcareous loess source. Carbonate coatings are common on the aquatic vegetation and on the soil surface in wet areas, and appreciable amounts of free carbonates are also present in the soils (sites 1 and 2). Because of the presence of carbonates the exchange complexes, mainly on humus and clays, are saturated with calcium. The exchangeable acidity is low, generally <20 cmol kg^{-1}, and there is no exchangeable aluminum. The base saturation for all of the soils is nearly 100% except for site 2, which has better drainage on the high-center polygon. There the pH values in the subsurface horizons are <7, and the base saturation is about 75%.

Compared with organic soils in the southern Arctic Foothills (site 11), organic carbon concentrations in the organic soils are lower on the Coastal Plain, usually less than 25%. This is due to the continuous addition of loess to the surface. The dominance of silt (40-60%) and fine sand in the mineral part of the organic horizons indicates its eolian origin. The high mineral content in the organic horizons is also reflected by bulk densities that range from 0.3 to 0.7 Mg m^{-3}. In areas with little or no loess influence, the bulk density of the surface organic horizon (Oi) is less than 0.1 Mg m^{-3} (Table 3). The textures of the mineral substratum are sandy, which indicates alluvium, thawed lake sediments, or a mixture of the two.

The carbon:nitrogen (C:N) ratio for most horizons is nearly constant at about 16:1. This value reflects the lower degree of decomposition of the organic materials [*Ping et al.,* 1997c]. More carbon accumulates in soils on flat- and high-centered polygons because they are older than the low-center polygons. Soils on the rim of the low-centered polygons have high amount of organic carbon because of frost heave which has concentrated the organic layers here.

3.2.2. Soils of the northern Arctic Foothills. The two most dominant vegetation communities on the Arctic Foothills are moist acidic and moist nonacidic tundra. Moist nonacidic tundra occurs predominantly in the northern fringe of the foothills where strong winds prevail. Thus moist nonacidic tundra occurs on exposed slopes and in areas of active loess deposition [*Walker and Everett,* 1991; *Bockheim et al.,* 1998]. Loess deposition affects the chemical properties of nonacidic tundra soils (site 6). Free carbonates present in mineral horizons result in an ample supply of bases, primarily Ca and Mg, which saturate the exchange complex. The base saturation of all mineral horizons is 100% and that of the organic horizons is 90% or higher. Acidic and nonacidic tundra soils have similar silty parent material based on particle size analyses (sites 6-8, Table 3). However, there is more chemical weathering, e.g., acid dissolution of secondary and primary minerals, in moist acidic tundra soils. In soils of the acidic tundra (sites 7-10), base saturation decreases and the exchangeable acidity and aluminum increase toward the south (Figure 4). This may be the combined effects of decreased carbonate-rich loess deposition and the glacial till parent material being less effective in neutralizing organic and carbonic acids

Table 2. Morphological Properties of Cryogenic Soils in Arctic Alaska

Site	Horizon[a]	Depth cm	Thickness cm	Bound-ary[b] cm	Cryotur-bation %	Munsell Color	Field Texture	Structure	Consistence Moist	Consistence Wet	Roots	Ice Vol. %	Gravel Vol. %
						Arctic Coastal Plain							
1	Oa1	0-18		cs	0	5YR 3/1	muck	1fgr	vfr	so,po	3vf,f,1m	-	-
	Oa2	18-39	14-21	as	0	10YR 2/1	mk sil		fr	ss,sp	2vf,f	-	-
	Oajjf	50-80	0-30	ab	100	N 2/0	muck		fr	so,po	1f	-	-
	2Cf	39-80	0-50	ab	75	2.5Y 5/2, 5/3	sl		vfr	so,po	-	-	-
	Wfm	50-100	0-50+		50			(ice)					
2	A	0-22	0-21	ab	20	2.5YR2.5/1	sil	2mgr	fr	ss,ps	3vf,2f	-	-
	Oa/A	0-24		ab	20	7.5YR3/2	sil	2msbk	fr	ss,ps	2vf	-	-
	O'i	22-42		as	5	2.5YR 2.5/1	peat		vfr	so,po	3vf	-	-
	2AC	0-42	0-11	ab	20	7.5YR 3/1	pt ls	sg	vfr	so,po	2vf	-	-
	2Oejj/Cf	43-50			100	7.5YR 2.5/1	mk ls	sg	vfr	so,po	-	70	-
3	Oi	0-21	18-41	as	0	2.5YR2.5/1	peat		fr	so,po	3vf,f	-	-
	Oa/Oi	21-39	0-22	ab	0	10YR3/1	sil	m	fr	ss,ps	3vf	-	-
	Oajj/Cgf	39-67			0	10YR3/2	sil	m	efi	ss,ps	-	80	-
4	Oijj	0-17	12-17	aw	0	2.5YR2.5/1	peat		vfr		3vf,2f	-	-
	Oajj1	17-30	9-14	aw	0	5YR2.5/1	sil	2msbk,2fgr	fr	ss,ps	2vf,f	-	-
	Oajj2	30-49	8-12	aw	0	7.5YR2.5/1	sil	2msbk	fr	ss,ps	-	-	-
	Oajj/Cgf	49-82		as	0	7.5YR2.5/1		m	efi		2vf	84	-
5	Oi1	0-25	17-35	as	0	2.5YR2.5/1	peat	m	fr	so,po	3vf,f	-	-
	Oi2	25-35	0-13	ab	0	5YR3/1	peat	m	fr	ss,ps	3vf,f	-	-
	Wfm	35-50										-	-

Table 2. (Continued)

Site	Horizon[a]	Depth cm	Thickness cm	Bound-ary[b] cm	Cryotur-bation %	Munsell Color	Field Texture	Structure	Consistence Moist	Consistence Wet	Roots	Ice Vol. %	Gravel Vol. %
						Arctic Foothills							
6	Oi	0-9	0-10	ab	25	5YR3/3	peat		vfr	so,po	3vf,f	-	-
	Oejj	9-21	0-31	ab	40	5YR2.5/2	pt mk		vfr	so,po	3vf	-	-
	Bwjj	21-47	0-52	ab	10	10YR4/2	sil	2fsbk	fi	ss,ps	1vf	-	-
	Bgjj	47-56	0-49	ab	20	10YR4/2	sil	1mpl	fi	s,p	2vf,f	-	-
	Oejjf	56-74	7-19	ab	100	5YR2.5/2	mk pt		fr	so,po	2vf	-	-
	2Ajjf	74-86	6-14	ab	100	5YR3/1	sil	m	fi	ss,ps	0	-	-
	2Cg/Oejjf	86-100			100	2.5Y3/1	mk grsil	m	fi	ss,ps	0	76	-
7	Oi	0-11	0-18	aw	0	YR3/3	peat		vfr	-	2vf,f,3m	-	-
	Oe	11-18	3-18	aw	0	2.5YR2.5/1	mk pt	2fgr	vfr	-	2vf,f,1m	-	-
	Bg	18-41	13-25	aw	0	10YR4/1	sil	1fsbk	fi	ss,ps	2vf	-	-
	Oejjf	41-56	0-16	ab	100	2.5YR2.5/1	mk pt	1fgr	vfr	-	3vf	-	-
	Oajj/Cgf	56-65	13-30	ab	100	5YR2.5/1	mk sil	1cabk	efi	ss,ps	0	79	-
						2.5Y5/1						-	-
	Cg/Oajjf	65-100		ab	100	2.5Y4/1	mk sil	m	efi	ss,ps	0	84	-
						5YR2.5/1							
8	Oe	0-10		ai	0	5YR3/2	mk pt	1mgr	vfr	so,po	3vf,f	-	-
	Bwjj		0-10	ab	25	10YR4/4	sil	2msbk	sfi	ss,ps	2vf,f	-	-
						2.5Y5/2 (40%)							
	Bgjj	20-34	0-20	ab	50	10YR4/4,2.5Y5/2	sil	1mpl	sfi	ss,ps	1f	-	-
	Cgjjf1	34-47	0-27	ab	100	10YR4/6,5Y4/1		1cpl	fi	ss,ps	1f	-	-
	Cgjjf2	47-57		aw	100	5Y4/1	sicl	2cpl	fi	ss,ps	0	-	-
	Oejj/Cf	57-100			100	2.5Y5/2	sil	m	fi	ss,ps	0	-	-
9	Oi	0-12	7-10	as	0	2.5YR 2.5/2	peat					-	-
	Oe	12-14	1-4	as	0	2.5YR 2.5/4	mk pt					-	-
	Bg	14-28	9-20	aw	5	10YR 4/2	sil	1fpl	sfi	s,p	3vf,f,m,c	-	-
	Oi2	28-30	1-5	as	0	5YR 3/2	peat				3vf,f,m	77	-
	C/Ajjf	30-44	13-16	ai	100	10YR 3/2 (60%)	mksl	m	efi	ss,ps	3vf,f,2m	84	-
	Cg/Ojjf	44-50	0-7	ab	100	10YR 4/4(60%)	mksl	m	efi	ss,ps	3vf,f,m	53	-
	Cgf	50-70			100	10YR 3/2	sl	m	efi	ss,ps	1f		
10	Oi	0-7	6-20	aw	0	7.5 YR 3/3	pt		vfr	so,po	3vf,fm	-	-
	Oe1	7-13	3-8	aw	0	2.5 YR 2.5/2	mkpt		vfr	so,po	3vffm	-	-
	Oe2	13-18	3-9	aw	10	7.5 YR 3/2	mkpt	1mp1	vfr	so,po	2vf,2f,3	-	-
	Bw	18-30	0-14	ab	0	7.5 YR 4/4	sil	2mp1	fr	so,sp	2vf,f	-	-
	Bgjj	30-35	4-12	aw	25	10YR 4/3	sil	3mp1	sfi	ss,ps	1vf	-	10
	Cgf1	35-62	25-29	cs	10	5Y 4/1	gsl	m	fi	ss,ps	0	71	17
	Cgfm2	62-82			0	5Y 3/2	gsl	m	efi	ss,ps	0	71	22
11	Oi1	0-10		as		5YR 3/3	pt		vfr	so,po	3vf,f	-	-
	Oi2	10-20		cs		7,5YR 4/3	pt		vfr	so,po	3vf,f	-	-
	Oi3	20-29		as		7,5YR 4/3	pt		vfr	so,po	3vf,f	-	-
	Oa	29-50		as		5YR 3/2	pt,mk		fr	so,po	2f	-	-
	Oaf	50-80					mk		fi	so,po		-	-
12	A	0-1	1-3	as		10YR 3/1	sil	1fgr	fr	ss,ps	2vf,f,3m	-	-
	C1	1-43	33-42	as		7,5YR 3/1	sl	1fpl	vfr	so,po	1vf,f 2m	-	4
	C2	43-75	28-38	gs		10YR 3/1	vks	sg	lo	so,po	1vf,f 2m	-	56
	C3	75-192				7,5YR 3/1	vks	sg	lo	so,po		-	71
						7,5YR 3/1							

[a] Soil horizon descriptions according to *Soil Conservation Service* [1993].

[b] Abreviations of soil horizon boundary distinctness: a, abrupt; c, clear; d, diffuse. Soil horizon boundary: s, smooth;w, wavy; i, irregular; b, broken. Soil texture: v, very; g, gravelly; k, cobbly; s, stony; s, sand; sl, sandy loam; sil, silt loam; sicl, silty clay loam. Soil structure grade: sg, single grain; 1, weak; 2, moderate; 3, strong. Soil structure size: f, fine; m, medium; c, coarse. Soil structure type: gr, granular; pl, platy; abk, angular blocky; sbk, subangular blocky. Consistence (moist): lo, loose; vfr, very friable; fr, friable; fi, firm; vfi, very firm. Consistence (wet): so, nonsticky; ss, slightly sticky; s, sticky; vs, very sticky; po, nonplastic; sp, slightly plastic; p, plastic; vp, plastic. Roots: 1, few; 2, common; 3, many; vf, very fine; f, fine; m, medium; c, coarse.

than the calcareous loess. A third factor is that because moist nonacidic tundra occurs in more exposed landscape positions, the soils may be more subject to cryoturbation, as evidenced by the occurrence of frost boils, than those in moist acidic tundra [*Bockheim et al.*, 1998]. Continued cryoturbation would preclude the development of a *Sphagnum* mat which ultimately results in soil acidification.

In soils of nonacidic and acidic tundra (sites 6 and 7), there is a double accumulation of organic carbon, including surface horizons (O and A horizons) and on top of the permafrost table (Oejj/Cf). This is supported by both chemical and morphological properties (Tables 2 and 3). The average radiocarbon age of the humus in cryoturbated horizons at 70-90 cm at sites 6 and 7 is 7000 yr B.P. [*Ping et al.*, 1997a]. Below the permafrost table, one sample had a radiocarbon age of 12,700 yr B.P. [*Ping et al.*, 1997b]. The organic matter may represent a widespread paleosol in the Sagwon Hills area or may suggest that cryoturbation was more pronounced during the warmer early Holocene along the North Slope [*Zoltai et al.*, 1978].

Site 8 is an acidic tussock tundra located south of site 7 and

Table 3. Chemical and Physical Propertites of Cryogenic Soils in Arctic Alaska

Site	Horizon	pH	O.C.	C/N	CEC	Ex. Acidity	Ex.Al	Extractable Cations				B.S.	$CaCO_3$	Clay	Silt	B.D.
								Ca	Mg	Na	K					
		(paste)	%		......	....	cmol(+)kg^{-1}	....		....		%	%	%	%	Mg/m^3
								Arctic Coastal Plain								
1	Oa1	7.1	23	15	79	17	0	85	4.3	1.0	0.3	100	17	-	-	0.4
	Oa2	6.6	15	19	29	13	0	16	1.3	0.8	0.1	61	2	11	47	0.5
	Oaf	6.6	22	14	49	18	0	43	4.3	0.7	0.1	99	n.d.	7	42	0.4
	2Cf	8.1	0.3	11	2	0	0		0.9	0.3	0.1	100	22	1	10	1,8
2	A	7.3	21	16	90	21	0	79	3.3	0.2	0.1	90		16	48	0.46
	Oa/A	7.4	15	14	62	13	0	50	2.3	0.1	0.1	84	3	13	32	0.56
	O'i	6.7	26	14	72	24	0.1	51	2.9	0.1	0.2	75	-	-	-	0.26
	2AC	6.6	7	15	26	8	0	18	1.2	tr	tr	73	5	4	10	0.95
	2Oejj/Cgf	6.5	10	16	29	10	0	20	1.6	tr	tr	76	10	4	17	-
3	Oi	7.5	23	15	59	17	0.1	56	3.4	0.4	0.1	100	-	-	-	0.32
	Oa/Oi	7.1	18	16	54	10	0	68	1.9	0.2	tr	100	-	20	53	0.62
	Oajj/Cgf	7.1	14	16	42	7	0	68	1.9	0.1	0.1	100	-	19	65	-
4	Oijj	7.7	26	16	78	16	0.1	87	4.1	0.9	0.2	100	-	-	-	0.4
	Oajj1	7.5	18	16	66	11	0	63	2.6	0.3	0.1	100	-	19	53	0.7
	Oajj2	7.4	17	16	54	9	0	69	1.5	0.2	0.1	100	-	18	63	0.6
	Oajj/Cgf	7.3	17	16	51	8	0	74	2.3	0.1	0.1	100	-	21	58	-
5	Oi1	7.3	25	16	83	21	0.1	84	3.2	0.8	0.1	100	0.1	-	-	0.3
	Oi2	7.3	18	15	55	12	0.1	70	1.6	0.4	tr	100	0.2	-	-	0.4
								Arctic Foothills								
6	Oi	7.4	36	29	113	16	0.1	84	15.4	0.2	1.5	95	-	-	-	0.2
	Oejj	7.2	24	19	102	12	0.1	84	6.8	0.3	0.2	90	-	-	-	0.2
	Bwjj	7.3	4	15	22	1	0	47	3.1	tr	0.1	100	0.1	20	70	1.1
	Bg	7	4	13	24	3	0	36	2	tr	0.2	100	0.1	23	70	1.2
	Oejj2	7.2	20	16	98	14	0.1	81	5.1	0.1	0.3	88	1	-	-	0.4
	2Ajjf	6.9	7	19	30	4	0	55	2.3	tr	0.2	100		17	69	1.1
	2Cg/Oejjf	6.8	11	15	51	7	0	70	3.8	tr	0.2	100	3	18	70	-
7	Oi	4	47	41	80	74	1	33	6.1	0.3	2.8	49	-	-	-	0.1
	Oe	5.7	42	21	97	68	0.3	63	5.7	0.3	0.6	71	-	-	-	0.2
	Bg	5.5	4	13	29	18	0.2	16	1.6	tr	0.1	62	-	27	65	1
	Oejjf	5.9	20	16	76	52	0.4	33	1.9	tr	0.1	46	-	-	-	-
	Oajj/Cgf	6.4	23	18	97	46	0	63	4.4	0.1	0.2	69	-	24	57	-
	Cg/Oajjf	6.8	10	21	36	5	0	65	2.3	tr	0.2	100	-	16	77	-
8	Oe	5.1	45	27	81	70	0.7	22	4.7	0.6	0.9	36	-	-	-	-
	Bwjj	5.1	4	21	19	21	1.5	4	1.5	0.2	0.3	33	-	28	63	1.3
	Bgjj	4.7	3	17	15	17	2.8	3	0.9	0.2	0.2	25	-	26	66	-
	Cgjjf1	4.7	3	18	14	15	3.5	2	0.9	0.2	0.2	26	-	25	66	-
	Cgjjf2	4.9	4	22	16	18	2.5	3	1.1	0.3	0.3	29	-	24	65	1.3
	Oejj/Cf	4.9	18	25	39	43	2.7	8	1.4	0.3	0.5	26	-	11	62	-
9	Oi	5	39	31	69	87	0.5	8.8	4.9	0.4	2.8	20	-	-	-	0.16
	Oe	6.6	34	30	89	59	0.6	9.3	2.4	0.5	0.4	13	-	-	-	-
	Bg	5	9	18	25	29	6	1.2	0.4	0	0.1	8	-	17	64	0.83
	Oi2	5.5	15	16	42	45	6.5	2.9	0.7	0.1	0.1	9	-	-	-	-
	C/Ajjf	6.6	9	17	28	29	4.5	1.4	0.4	0	0.1	6	-	25	46	-
	Cg/Ojjf	6.2	7	15	23	25	3.2	1.2	0	0	tr	5	-	16	32	-
	Cgf	5.6	2	19	8	9	1.8	0.5	0	0	tr	1	-	7	19	-
10	Oi	4.6	47	57	103	82	2.3	20.8	8.1	0.2	2.4	28	-	-	-	0.04
	Oe1	4.9	44	25	70	55	0.2	13.8	3.3	0.2	0.3	25	-	-	-	0.15
	Oe2	4.9	25	17	58	56	4.8	7.9	1.9	0.1	0.3	17	-	-	-	0.4
	Bw	4.9	7	20	22	24	2.4	1.9	0.4	0.1	0.1	11	-	14	40	1.14
	Bgjj	5.6	5	20	17	21	4.1	1.2	0.4	0.1	tr	10	-	18	37	1.06
	Cgf1	6.5	4	20	12	14	2.3	1.2	0.4	0	0.1	13	-	16	32	-
	Cgf2	6.5	3	20	13	13	1.5	2.2	0.4	0	0.1	20	-	15	38	-
11	Oi1	4.8	44	67	109	57	4.5	6.4	3.4	0.1	1.1	3	-	-	-	0.12
	Oi2	4.7	45	17	77	107	4.8	2.7	1.0	0.1	0.2	12	-	-	-	0.15
	Oi3	4.4	22	18	72	72	6.9	2.3	0.5	0.1	0.1	4	-	-	-	0.25
	Oa	4.5	25	22	51	75	9.0	1.8	0.2	0.1	tr	8	-	-	-	-
	Oaf	4.5	18	18	47	58	9.0	1.5	0.3	tr	tr	7	-	-	-	-
12	A	7.3	6	21	19	2	-	49	2.0	tr	0.3	100	19	14	62	0.65
	C1	8.1	2	34	5	-	-	40	1.0	tr	tr	100	22	3	12	1.24
	C2	8.1	2	76	3	-	-	29	0.4	0	tr	100	11	2	2	1.2
	C3	7.4	2	106	2	-	-	29	0.4	0	0.1	100	21	1	2	1.3

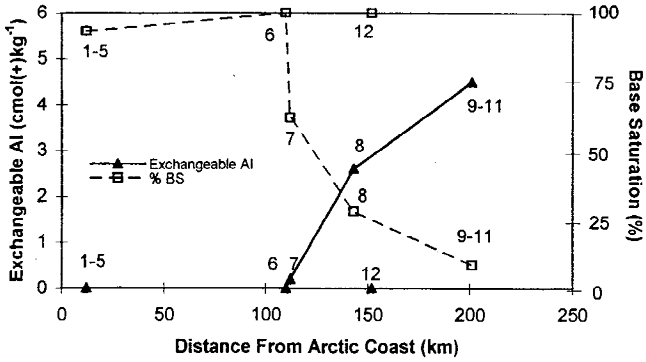

Figure 4. Relationship between base saturation (percentage) (calculated by averaged weight basis for all A and B horizons in mineral soils and for the active layers in organic soils) and distance (kilometers) to the ocean. Site locations are indicated by pedon numbers.

the parent material is loess over glacial drift identified by *Brown and Kreig* [1983] as being of early Wisconsin age. The soil reaction ranges from strongly to very strongly acidic, with high exchangeable acidity. The exchangeable aluminum ranges from 1.5 to 3.5 cmol kg^{-1} in the mineral horizons (Table 3). The base saturation is less than 33% in the mineral horizons. The differences in base saturation and pH between this site and the other acidic tundra sites (sites 6 and 7) to the north are likely due to differences in the parent material.

3.2.3. Soils of the southern Arctic Foothills. Soils of the southern Arctic Foothills support dominantly acidic tundra (sites 9 and 10) but are formed in younger glacial drift than in the northern Arctic Foothills [*Hamilton,* 1987]. These soils are more acidic than those in the northern foothills, possibly due to the higher elevation resulting in less loess being added to the soil and higher precipitation. Soil pH ranges from very strongly to slightly acidic, and the base saturation ranges from 1 to 28%. The greater leaching in these soils is reflected by lower exchangeable Ca and Mg and higher exchangeable acidity than in soils of the northern foothills. The cation exchange capacity and the exchangeable aluminum in sites 9 and 10 in the southern Arctic Foothills are higher than in sites 7 and 8 in the northern Arctic Foothills (Table 3).

The high amount of exchangeable aluminum in soils of the southern Arctic Foothills may result from dissolution of aluminosilicates by organic and carbonic acids, followed by forming complexes with humus [*De Coninck,* 1983]. A higher base saturation was noted in the surface organic horizons and this is likely the result of dust deposit from the nearby Dalton Highway. The nature of the parent material of the southern Arctic Foothills is reflected in the particle size distribution. There is increased sand in the profile from north to south and the textures change from silt loam in the north to sandy loam in the south (Table 3). The rock fragments are greater in soils of the south, indicating a thin loess cap over young coarse-textured glacial drift [*Hamilton,* 1987].

More peat has accumulated along water tracks and lakes in the Arctic Foothills (site 11) than adjacent to thaw lakes in the Arctic Coastal Plain (sites 1 and 2). This is probably due to a combination of factors, including climate, topography, and especially vegetation. *Sphagnum*, which is associated with peat accumulation in the arctic, is more abundant in the southern Arctic Foothills. Thus the amount of carbon stored in soils at site 11 is higher than in soils at sites 1 and 2 in the Coastal Plain soils [*Michaelson et al,* 1996; *Bockheim et al.,* 1997b]. Another major difference between the inland organic soils and those in the coastal plain is that they are acidic rather than alkaline. The very strongly acidic soil reaction results from organic acids contributed by the *Sphagnum* peat which receives less calcareous loess than soils to the north. The abundant exchangeable aluminum, which ranges from 4.5 to 9 cmol kg^{-1}, likely originates from leaching of adjacent upland soils formed in acidic tundra and weathering of mineral particles in the peat.

Soils formed on floodplains (site 12) along major rivers have neutral to moderate alkaline reaction because of the carbonate-rich alluvial deposits which are the least weathered parent materials in the Arctic Foothills. The organic carbon content is very low in these soils in comparison with other mineral soils. Free carbonate contents are high in the soil, ranging from 11 to 22%. The base saturation is 100%, and there is no exchangeable Al. There is no evidence of cryoturbation in these soils because of their coarse texture, and low moisture-retention permit thawing during warmer summer periods to depths in excess of 1 m.

3.3 Pedogenesis in Arctic Alaska

Soils form through the combined effects of parent material, climate, vegetation (biota), landform, and time [*Jenny,* 1941]. In the northern Arctic Foothills, loess which has a silt loam texture, is the dominant parent material. South of the active loess belt, glacial drift becomes the dominant parent material, and soil textures vary from silty clay loam in the Happy Valley area (Figure 1) to sandy loam in the southern foothills with abundant coarse fragments ranging from gravel to boulders. This gradient of textural change from north to south indicates decreasing loess deposition with distance from the Arctic Coastal Plain. *Walker and Everett* [1991] observed a loess deposit gradient from northeast to southwest in the North Slope. *Walker et al.* [1998] found that soil pH is the controlling factor in the distribution of the dominate tundra vegetation type on the Arctic Foothills: moist acidic tundra and moist nonacidic tundra. They attributed the soil pH difference to the loess deposition gradient. However, the pattern of loess deposition is far more complex due to the combined effects of marine, fluvial, eolian, glacial, and thaw lake processes over the complicated terrain conditions [*Rawlinson,* 1993; *Kreig and Reger,* 1982]. The relative importance of pedogenic processes, particularly the addition versus the loss of carbonates in relation to sources of loess and landscape evolution deserve further investigation.

In the Arctic Foothills, increased amounts of coarse fragments in the soil profile and on the surface from north to south indicates there may be mixing of the loess with the underlying drift through solifluction, frost heave, and erosion. The finer-textured soils have slower permeability, are somewhat poorly to poorly drained, and have colors.. The presence of coarse fragments and the mixing of coarse textured soils result in soils with a higher permeability. Thus soils of the southern foothills with medium textures have increased leaching, high exchangeable aluminum, and more oxidized colors.

Landform controls the hydrological conditions and thus drainage. The formation of organic soils is largely controlled by landscape position, i.e., depressions with restricted drainage. Reducing conditions occur in soils with restricted drainage. In the Arctic microtopography due to patterned ground is another manifestation of the effects of climate and landform. Patterned ground forms as a result of frost heaving and creates microenvironments that affect the distribution of vegetation species and percent cover. Differences between the microhigh and microlow sites have produced different soils within short distances, usually within 1 m.

Vegetation plays a major role in the biogeochemical properties and weathering of soil. Vegetation also insulates the soil and affects the degree of cryoturbation and depth of permafrost. Vegetation has an effect on the quality of soil organic matter [*Ping et al.*, 1997c] in that grasses and sedges produce humus with a narrow C:N ratio, whereas shrub vegetation produces those with a wider C:N ratio.

In the arctic environment the most important effect of climate on soil formation is the presence of permafrost and cold temperatures. A direct effect of the low temperatures is the accumulation of organic carbon due to a slow rate of decomposition. Much of the arctic topography is the result of the aggredation of icy sediments and massive ice bodies [*French*, 1996]. The formation of ground ice, including ice wedges and ataxitic layers, significantly changes the volume of frozen soil and resulting in "buckling up" of the ground surface due to frost heaving. Results from long-term permafrost monitoring indicate that there is a steady warming trend over the last 30 years [*Osterkamp and Romanovsky*, 1996]. If the warming trend continues, as predicated by scientists [*IPCC*, 1992], then massive scale thermokarst and subsidence may occur in the arctic and result in more wet soils. Organic carbon sequestered in the upper permafrost layers would also become part of the active layer and contribute to the nutrient cycles of the arctic ecosystems [*Ping et al.*, 1997c]. Permafrost not only provides a barrier to root penetration and related biological and biochemical reactions but also to water movement. Thus the zone above the permafrost table is often saturated, and the prolonged wetness during the growing season leads to reducing conditions. These conditions occur on a wide scale in contrast to a limited extent of well-drained soils with dry permafrost found in association with dune sand near the arctic coast [*Van Patten*, 1990] and on sorted circles on exposed ridges [*Tarnocai et al.*, 1992].

Time dominates all other soil-forming factors. The age differences in parent materials are reflected in their chemical properties. The younger loess to the north is high in carbonates and the older loess to the south has lost carbonates and become more acidic due to leaching. Along this north-south gradient, the base saturation decreases and the exchangeable aluminum increases (Figure 4). These trends indicate an increased degree of weathering continuing south until the barrier imposed by the Brooks Range changes the environment.

3.4. Soil Classification

Because of their unique properties and processes, soils of the polar regions have recently been classified into a separate order in soil taxonomy [*Soil Survey Staff*, 1998], the Gelisols (from the Latin gelidus, meaning cold). Gelisols are divided into three suborders: Histels, the organic soils containing permafrost within 1 m of the surface; Turbels, mineral soils with one or more cryoturbated horizon and permafrost within 2 m of the surface; and Orthels, other mineral soils with permafrost within 1 m of the surface [*Bockheim et al.*, 1997a]. These soil suborders are analogous to Histic, Turbic, and Static or Orthic classes identified in the Canadian soil taxonomic system [*Agriculture Canada*, 1987].

About 38% of the soils in the Kuparuk River basin are classified as Turbels, primarily Aquaturbels; 58% are Orthels, primarily Aquorthels and Historthels; and 4% are Histels [*Bockheim et al.*, 1997b]. Mineral soils examined in this study included Molliturbels, Molliorthels, and Historthels in the Arctic Coastal Plain and Aquaturbels in the Arctic Foothills (Table 1). The organic soils were classified as a Hemistel (site 5) and a Fibristel (site 8) on the coastal plain and foothills, respectively. The soil on recent alluvium at site 12 does not contain permafrost in the upper 1 m and therefore is classified as a Typic Cryorthent.

4. Conclusions

In conclusion, the dominant soil-forming processes in arctic Alaska include freeze-thaw processes, organic matter accumulation, and reduction-oxidation. Cryogenesis results in patterned ground, causing microrelief and soil drainage differentiation, ice wedges, ice lens, ataxitic fabric and distorted horizons. The cryogenic processes and the resulted features increase the heterogeneity of the soils in the arctic. Soil types change over a short distance. Because of cold climate and slow decomposition rate, organic matter accumulates not only on the soil surface but also in the lower profile as results of cryoturbation and burial by rising permafrost tables. A large portion of the soil carbon sequestered in the permafrost by cryoturbation could be released upon climatic warming. Elevated soil carbon concentrations are often observed at the top of the permafrost table due to cryoturbation. Cryoturbation redistributes soil carbon by frost-churning and results in discontinuous soil horizons in arctic tundra soils. The organic soils are highly reduced in the subsurface horizons due to saturation during the growing season. Moist tundra soils experience a fluctuating water table in upper active layers during the growing season, thus redox processes control biogeochemical weathering in the active layers, as indicated by their redoximorphic features. However, the lower profiles are mostly saturated and reduced due to the perched water table above the permafrost.

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