Arctic, Antarctic, and Alpine Research, Vol. 33, No. 1, 2001, pp. 78–87

Soil Development in Low-Arctic Tundra of the Northern Brooks Range, Alaska, U.S.A.

J. S. Munroe

Department of Geology and Geophysics, University of Wisconsin, 1215 W. Dayton St., Madison, Wisconsin 53706, U.S.A.
jmunroe@geology.wisc.edu

J. G. Bockheim

Department of Soil Science, University of Wisconsin, 1525 Observatory Drive, Madison, Wisconsin 53706, U.S.A.

Abstract

Thirty-six Gelisols were investigated in the vicinity of Galbraith Lake and Toolik Lake (68°30′N, 149°30′W) in northern Alaska. The soils formed on surfaces previously interpreted as ranging from ~110 ka BP to late Holocene in age. Sixteen of the profiles (44%) contained evidence of cryoturbation and were classified as Turbels, while the others were classified as Orthels. While most of the Orthels are developed in coarse-textured outwash, all of the Turbels are restricted to fine-grained till and colluvium with ice-rich permafrost. There were no significant differences in profile quantities of weathering products, such as H^+ ion, clay, silt, silt-plus-clay, and loss on ignition, between Orthels and Turbels. However, there were significant or nearly significant differences in profile quantities of H^+ ion, silt, and silt-plus-clay as a function of age, with the lowest values in Holocene soils, intermediate values for the two younger drifts, and greater values for the oldest surface. A key finding of this study is that despite pervasive cryoturbation, soil properties can be used to determine relative age in the Low Arctic. Our results confirm previous age estimates that Itkillik II surfaces are of late Wisconsin age, with Itkillik I surfaces being somewhat older.

Introduction

Arctic soils are subject to unique conditions that markedly affect pedogenesis, including extreme cold, slow weathering rates, and cryoturbation. Low mean annual temperatures retard soil profile development (Tedrow et al., 1958). Cryoturbation, driven by repeated freezing and thawing and formation of segregated ice, creates highly contorted soil horizons and constitutes a specialized pedogenic process typical of the cold regions (Retzer, 1965; Tedrow, 1974; Bockheim et al., 1998b; Ping et al., 1998). Seasonal perched water tables and poor drainage related to underlying continuous ice-rich permafrost, combined with cold temperatures, produce saturated conditions that promote organic matter accumulation (Ovenden, 1990). Varying depths of thaw due to climate variability lead to incorporation of appreciable amounts of this organic matter into the near-surface permafrost (Tarnocai, 1994). Solifluction and thermokarst are additional agents of profile disruption that characterize Gelisols (Bockheim and Tarnocai, 1998).

Surficial materials on the north flank of the Brooks Range in northern Alaska include glacial sediments, alluvium, eolian deposits, and colluvium ranging in age from possibly latest-Tertiary to Holocene (Hamilton, 1986). The degree of soil development in arctic Alaska reflects a combination of more universal pedogenic processes such as translocation and organic matter accumulation, and ones that are controlled by low temperatures, such as cryoturbation.

Despite the uncertainties regarding the balance between cryoturbation and other pedogenic processes in areas of continuous permafrost, the degree of soil development has been used to determine the relative ages of glacial drift in arctic Alaska (Hamilton and Porter, 1975; Hamilton, 1986; Hamilton, 1994; Höfle and Ping, 1996). Because radiocarbon control on these drift units is almost entirely absent, accurate age assignments are paramount for geoecological investigations. Yet, little is known about the ability of traditional soil chronosequences to accurately reflect development of soils influenced by cryoturbation.

This study is the first to describe a soil chronosequence from the Low Arctic. A major objective of this work was to determine the applicability of the traditional soil chronosequence model to a sequence of cryoturbated and noncryoturbated Gelisols. The study was designed to investigate soils on four surfaces in the northeastern Brooks Range that were previously interpreted as having different ages (Hamilton, 1978). By testing the established surface relative age chronology for the region, the results presented here have implications for other research in the Kuparuk Basin that has identified landscape age as a major control on the development of arctic ecosystems (Walker et. al., 1995).

Study Area

SETTING

This research was conducted in the Arctic Foothills, approximately 240 km north of the Arctic Circle, along the Trans-Alaskan Pipeline corridor between Galbraith and Toolik Lakes (Fig. 1). The topography of the study area is gently rolling, with elevations ranging from 790 to 1060 m asl. Dominant vegetation is *Eriophorum vaginatum* tussock tundra and *Betula nana* low-shrub tundra, interspersed with *Salix*-dominated riparian shrublands (Walker et al., 1994; Gallant et al., 1995). Permafrost is inferred to be continuous beneath the entire area (Kreig and Reger, 1982). The depth of thaw ranged from 28 cm in early July to over 100 cm on the drier sites by late July. Soil parent materials include glacial till and outwash along with Holocene alluvium and colluvium (Hamilton, 1978; Munroe, 1996). Counts of 100 random pebbles from till exposed in three stream cut banks revealed an average of 72% coarse sandstone clasts with

1523-0430/01 $7.00

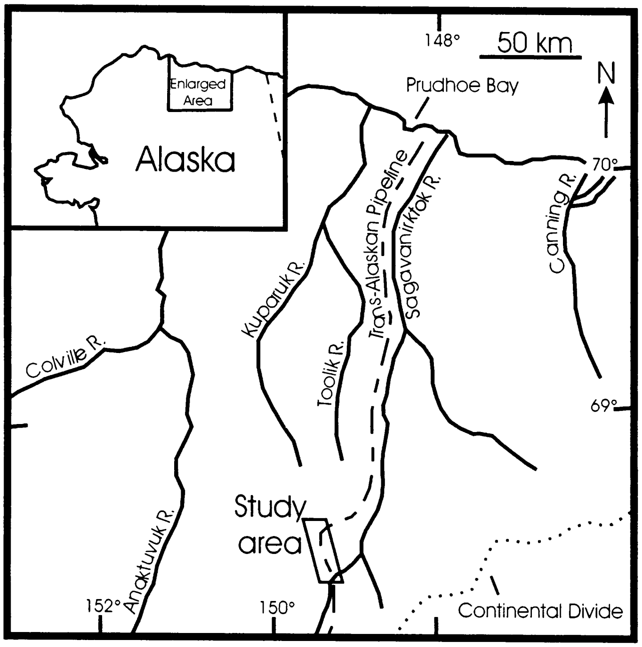

FIGURE 1. Location of study area on the north slope of Alaska.

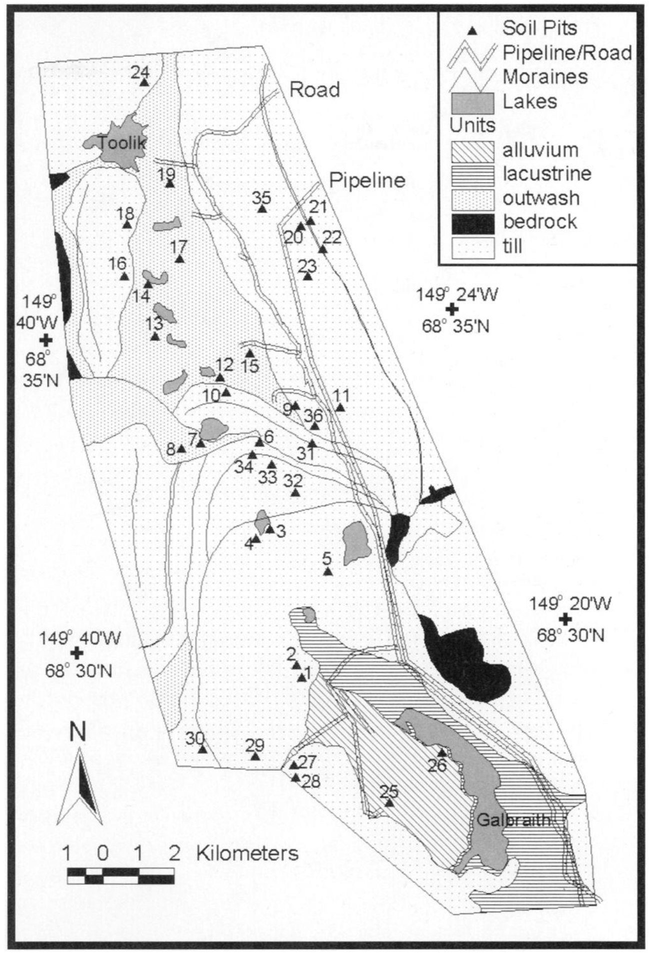

FIGURE 2. Simplified surficial geology of the study area and soil pit locations. Major types of surficial materials are identified by different patterns. Surficial geology is from Hamilton (1978) and Munroe (1996). Till includes drift of all three Itkillik advances in the area. Outwash includes sediment from the Itkillik II and late Itkillik II advances. Crests of major moraines of Itkillik I, Itkillik II, and late Itkillik II age are shown in dark lines. Locations of all 36 soil pits, with abbreviated profile numbers, are given.

the remainder composed of chert conglomerate and minor amounts of siltstone, iron-rich sandstone, and limestone.

Galbraith Lake is a remnant of a much larger lake that persisted into the Holocene behind the late Wisconsin moraine at the mouth of Atigun Valley (Hamilton, 1978; Hamilton, 1986). Toolik Lake, at the northern extreme of the field area, is a large compound kettle lake formed in late Wisconsin age outwash sediment (Brown and Kreig, 1983). It is the location of the University of Alaska-Fairbanks Institute of Arctic Biology field station and a Long-Term Ecological Research (LTER) site (Hobbie et al., 1991).

Drainage throughout the area is poorly developed and is interrupted by kettle lakes and thermokarst lakes. Some of these lakes are currently expanding, as evidenced by active slumping along their shorelines similar to that reported by Hamilton (1994). Extensive marshy areas demonstrate the youth of the drainage system and the influence of the underlying continuous permafrost on regional hydrology.

GLACIAL GEOLOGY

The study area has been glaciated repeatedly since the late Tertiary. Figure 2 presents the surficial geology of the study area. Drift sheets corresponding to the Gunsight Mountain, Anaktuvuk, and Sagavanirktok glaciations presumably lie buried beneath Itkillik-age sediments between Galbraith and Toolik lakes, or have been eroded by subsequent glacial advances. During each of these glacial events, an ice cap existed in the Brooks Range, centered slightly south of the present continental divide (Hamilton, 1986). This ice cap fed the northward flowing glacier in Atigun Valley that advanced beyond the range front at Galbraith Lake (Fig. 2).

A purpose of this study was to test the surface age designations given by Hamilton (1978) for the region. Geomorphic features in the field area record multiple advances attributed to the Itkillik I, Itkillik II, and late Itkillik II events (Fig. 2). Extensive outwash deposits and ice-stagnation features from the Itkillik II and late Itkillik II glaciations are present, as are moraines corresponding to all three Itkillik advances.

According to Hamilton (1994), the Itkillik I glaciation involved two separate advances. Because both of these are beyond the limit of radiocarbon dating, there remains considerable debate whether the Itkillik I glaciation occurred before or after marine isotope stage 5e (~125 ka BP). Hamilton (1994) summarized evidence for and against a late Wisconsin (stage 4) age for the Itkillik I glaciation. The primary evidence in support of a stage 4 age is that deposits of the Itkillik I glaciation are components of the same drift sheet as the younger Itkillik II drifts of late Wisconsin age (Hamilton, 1986; Hamilton, 1994). This observation indicated that it is probable that the early Itkillik I phase peaked after stage 5e around 100 ka BP, while the later phase reached its maximum closer to 60 ka BP during isotope stage 4 (Hamilton, 1994).

The Itkillik II advance occurred between 24 and 13 ka BP (Hamilton, 1994). Brooks Range glaciers during the Itkillik II glaciation were less extensive than those during the Itkillik I glaciation, suggesting somewhat milder climatic conditions (Hamilton, 1994).

The late Itkillik II event is poorly understood, but likely represents a stillstand or minor readvance during overall retreat from the Itkillik II maximum. Radiocarbon dates from several localities in the northern Brooks Range indicate that the late Itkillik II readvance occurred between 13 and 11.5 ka BP (Hamilton, 1979).

CLIMATE

The National Weather Service maintained an official recording station at the Galbraith Lake pipeline construction camp from 1976–1979. Mean annual temperatures for the 3-yr period averaged −10.1°C (Haugen, 1982). Mean July temperatures averaged 10.7°C, reflecting the relative warmth of the brief summer. Conditions at Toolik Lake, 18 km to the north, are probably similar (Hinkel et al., 1987).

CHRONOSEQUENCE

It is nearly impossible to identify areas where all of the soil-forming factors except time are constant, i.e., a soil chronosequence. Our study area comes as close as possible in achieving these conditions. The small size and minimal relief of the field area produced comparable climatic conditions for the pedons investigated, and sampling was limited to similar stable landscape positions. Vegetation was constant among the cryoturbated and noncryoturbated soils specifically, and the sedimentary parent materials, while different between the soil suborders, originated from the same bedrock source area. Because these pedogenic factors were reasonably constant within soil types across the study area, we feel confident that time was the major variable affecting development of these soil profiles, and that this suite of soils approximates a chronosequence for the geomorphic surfaces in this study area.

Field and Laboratory Methods

Field investigations were conducted in the area of Galbraith and Toolik Lakes area in July 1995. The study area totals approximately 120 km^2 and is covered by four U.S.G.S. 15-minute quadrangles: Philip Smith Mountains, B-4 and B-5, C-4 and C-5.

At thirty-six locations on various surfaces soil pits were dug to the base of the seasonal-thaw layer (Fig. 2). Sampling sites were located randomly on moraine crests, kame summits, gentle side slopes, outwash terraces, and naturally occurring stream cut bank exposures. In areas of patterned ground, soil pits were excavated in the least disturbed portion of the pedon, except for 95–019, 95–020, and 95–021, which were excavated in nonsorted circles. Vegetation, slope, landscape position, depth to the frost table, parent material and surficial geomorphology were recorded at each site. Pit faces were cleaned with a trowel, and described using procedures outlined in Birkeland (1999) and the Soil Survey Division Staff (1993). Munsell color was determined on moist samples. Epipedons and diagnostic subsurface horizons were identified, and the pedons were classified according to *Keys to Soil Taxonomy* (Soil Survey Staff, 1998). Samples were collected from each horizon of 22 pedons and analyzed for particle-size distribution, organic matter content, and pH.

Samples were analyzed in the Quaternary Laboratory at the University of Wisconsin-Madison Department of Geology and Geophysics. Grain-size distribution was recorded by a combination of dry sieving (>50 μm) and hydrometer analysis (Gee and Bauder, 1979). Samples with abundant organic matter were treated with hydrogen peroxide before grain size analysis. Subsamples were dried overnight at 105°C before they were combusted at 550°C for 1 h to determine loss on ignition (LOI) (Dean, 1974). The total percent LOI by this method is a proxy for organic matter content; dehydration of clays begins at temperatures above 550°C (Dean, 1974). Soil pH was determined potentiometrically on a saturated paste in distilled water.

Profile quantities of weathering products, H^+ ion, silt, clay, silt-plus-clay, and %LOI, were determined from the product of horizon thickness, bulk density and concentration of each specific soil property in individual horizons. These values were then summed to a depth of 60 cm. Bulk density was estimated from %LOI (Bockheim et al., 1998a). Profile quantities of weathering products between soil taxa (suborders) and among surface age groups were compared using one-way analysis of variance.

Soil color was quantified using methods outlined in Buntley and Westin (1965) and Clark (1988). The Color Development Equivalent (CDE) of a soil horizon is the product of the numerical notation of hue and chroma. Hues encountered in the field area, and their corresponding numerical notations are: 10YR = 3, 7.5YR = 4, 5YR = 5.

A modified profile development index, based on Harden (1982), was developed that compared soil color (including hue, value, and chroma), texture, structure (shape, grade, and size), and pH with those of the parent material. Parent material properties were determined from excavations of soil C horizons and study of exposures in stream cuts. Because seasonally frozen soil prevented excavation down to C horizons in most of the soil pits excavated in fine-grained materials, profile development indices could only be calculated for the generally coarser Orthels.

Ten points were awarded for each step from the parent material value toward a redder hue, and 10 points added for each increase in chroma, to produce a measure of rubification. Following Harden (1982), 10 points were also awarded for each decrease in color value from that of the parent material to quantify melanization, i.e., the darkening of the soil due to organic matter accumulation. For soil texture, 10 points were awarded for each textural class encountered along a progression from the parent material toward increasing clay content. Soil structure was quantified as the sum of shape (5 points for platy, 10 points for granular and subangular blocky), size (30 points fine, 20 for medium, 10 for coarse), and grade (30 points strong, 20 moderate, 10 weak). Finally, the difference in pH between the parent material and each soil horizon was also recorded.

These values were normalized to the maximum attained by any soil horizon in the data set, summed within a horizon, and divided by the number of values (usually five) to yield a number between 0 and 1. This value was then multiplied by the horizon thickness and summed through the profile to yield a profile sum. Profile sums were normalized again by multiplying by the ratio of total mineral horizon thickness in a given profile to the maximum in the data set. Because the PDI deals only with mineral horizons, this step compensates for buried organic layers, the thickness and number of which varies between profiles. This final value represents total profile development from physical and chemical properties of the mineral soil in relation to the unaltered parent material, with higher values indicating more developed soils.

Results and Discussion

SOIL CLASSIFICATION

All 36 pedons described in this study are classified as Gelisols, reflecting the presence of permafrost within 1 to 2 m of

TABLE 1

Characteristics of soils of the study area

Profile Number	Taxonomy	Parent Material	Depth to Frozen Soil	Thickness of Organic Layer (cm)	Geomorphic Surface	Approximate Age (ka)	% Slope	Slope Position
95–001	Typic Aquorthel	alluvium	>100 (51)[b]	4	alluvium	Holocene	flat	toe
95–002	Typic Haplorthel	icsd[a]	>70	3	late Itkillik II	12	10	shoulder
95–003	Typic Aquiturbel	colluvium over till	55 (10)	6	late Itkillik II	12	5	side
95–004	Typic Haplorthel	colluvium over icsd	>100	5	late Itkillik II	12	4	shoulder
95–005	Typic Umbriturbel	colluvium	68	9	late Itkillik II	12	4	shoulder
95–006	Typic Haplorthel	colluvium over outwash	>100	6	Itkillik II	24–11.5	1	summit
95–007	Typic Historthel	organics interlayed with till	>100 (25)	26	Itkillik II	24–11.5	flat	toeslope
95–008	Typic Haplorthel	outwash	>46	5	Itkillik II	24–11.5	1	terrace
95–009	Typic Haplorthel	outwash and colluvium	>30	7	Itkillik I	110–60	3	shoulder
95–010	Typic Aquorthel	colluvium over till	60	2	Itkillik II	24–11.5	flat	summit
95–011	Typic Haplorthel	glaciofluvial sediment	>50	6	Itkillik I	110–60	2	shoulder
95–012	Typic Haplorthel	glaciofluvial sediment	>70	4	Itkillik I	110–60	3	summit
95–013	Aquic Haploturbel	colluvium over till	60	2	Itkillik I	110–60	4	side
95–014	Typic Haplorthel	outwash	>80	7	Itkillik II	24–11.5	4	side
95–015	Typic Haplorthel	outwash	>68	0	Itkillik II	24–11.5	flat	terrace
95–016	Typic Haplorthel	outwash	>48	2	Itkillik II	24–11.5	2	side
95–017	Typic Haplorthel	outwash	>70	0	Itkillik II	24–11.5	flat	terrace
95–018	Typic Aquorthel	colluvium over till	54	7	Itkillik I	110–60	2	side
95–019	Typic Haploturbel	colluvium	48	0	Itkillik I	110–60	flat	summit
95–020	Typic Haploturbel	till	>50	0	Itkillik I	110–60	flat	summit
95–021	Typic Haploturbel	till	>50	9	Itkillik I	110–60	flat	summit
95–022	Aquic Haploturbel	colluvium over till	30	10	Itkillik I	110–60	flat	summit
95–023	Aquic Haploturbel	colluvium over till	28	9	Itkillik I	110–60	3	side
95–024	Typic Histoturbel	till	70	24	Itkillik I	24–11.5	2	side
95–025	Typic Mollorthel	alluvium	>80	2	alluvium	Holocene	flat	terrace
95–026	Typic Haplorthel	lacustrine over glaciofluvial	>68	3	lake sed	Holocne	6	summit
95–027	Typic Haploturbel	till and/or icsd	>60	6	late Itkillik II	12	13	side
95–028	Aquic Haploturbel	loess over till	55	7	late Itkillik II	12	2	side
95–029	Typic Mollorthel	alluvium	>200	2	alluvium	Holocene	flat	terrace
95–030	Typic Histoturbel	colluvium over till	>50	26	late Itkillik II	12	6	side
95–031	Aquic Haploturbel	colluvium over till	>60	13	Itkillik II	24–11.5	4	summit
95–032	Aquic Haploturbel	colluvium over till	68	18	Itkillik II	24–11.5	7	side
95–033	Aquic Haploturbel	colluvium over till	>82	9	late Itkillik II	12	12	side
95–034	Aquic Haplorthel	till	>64	9	late Itkillik II	12	2	summit
95–035	Typic Haplorthel	till	>38	12	Itkillik I	110–60	5	side
95–036	Aquic Haploturbel	colluvium	62	0	Itkillik II	24–11.5	3	side

[a] icsd = ice contact stratified drift in kames.

[b] (x) is depth to frozen soil 1 m behind scarp where profile was described.

the surface (Table 1). Although ice-rich material was not encountered in all excavations, and soil temperature readings were not taken, the entire area is within the zone of continuous permafrost (Brown and Kreig, 1983). Therefore, it is likely that frozen ground would have been encountered in all of the pits had the excavations been deep enough. The five profiles in which permafrost was not encountered in the upper 100 cm (95–001, 95–004, 95–006, 95–007, and 95–029) were described from natural exposures rather than from fresh excavations; permafrost likely was present within 100 cm of the surface elsewhere in the pedon farther from the exposure.

Two suborders of the Gelisols are present in the study area, which are differentiated by the presence or absence of cryoturbation. Cryoturbated soils with irregular and broken horizon boundaries (Soil Survey Staff, 1998) are classified as Turbels, while noncyroturbated soils are classified as Orthels. Twenty (56%) of the soils investigated were Orthels and 16 (44%) were Turbels (Table 1). However, these percentages are not necessarily reflective of the distribution of these suborders within the study area as the sampling was restricted to moraine crests and other stable landscape positions where possible.

Ten soil subgroups were delineated, reflecting differences in soil moisture and organic matter accumulation (Table 1). Descriptions of representative pedons for each of the 10 subgroups are given in Table 2. Representative pedons were chosen as those that best represent the characteristics of that soil subgroup in the study area. Abbreviations follow Soil Survey Division Staff (1993). Soils with organic horizons between 20 and 40 cm thick are Historthels, and soils with dark-colored mineral horizons >18 cm thick are Mollorthels or Umbriturbels.

SOIL MORPHOLOGY

All but four of the 36 profiles investigated (two Orthels and two Turbels) had an O horizon ranging from 2 to 26 cm thick. Total organic horizon thickness averaged 5 cm for Orthels and 10 cm for Turbels. Some of the Turbels have a histic epipedon

TABLE 2

Physical properties of representative soils of the Galbraith-Toolik lakes area

Horizon	Depth	Contact	Color	Mottles	Texture	Structure	Roots
Typic Aquorthel 95–010 (n = 3)[a]							
Oe	0–2	—	10YR2/2	—	hemic	—	—
Bw	2–15	gw	10YR5/3	—	CL	3mgr	3m
Bg	15–38	gw	N 5/	5YR5/8	CL	2mgr	2c
BCg	38–60	aw	10YR3/3	5YR5/8	L	1mgr	2f
Cgf	60+	—	—	—	—	—	—
Typic Haplorthel 95–004 (n = 13)							
Oi	0–1	—	—	—	fibric	—	—
Oa	1–5	—	10YR3/2	—	sapric	—	—
Bw1	5–10	gs	2.5YR4/2	—	L	2mgr	2f, m
Bw2	10–40	aw	2.5YR4/2	—	L	2msbk	2m
Bg	40–75	ci	10YR4/1	10YR5/8	SCL	2msbk	1f, m
Oab	75–77	—	10YR2/1	—	sapric	—	—
C	77–100	—	10YR3/3	—	SL	sg	—
Typic Historthel 95–007 (n = 1)							
Oi	0–4	—	—	—	fibric	—	—
Oe	4–26	aw	10YR2/2	—	hemic	massive	2f
BC	26–56	cs	10YR3/2	—	SiL	1fpl	none
Oeb	56–95	aw	10YR2/1	—	hemic	—	none
2Cg	95–103	—	10YR3/2	10 YR5/8	SCL	sg	—
2C	103+	—	—	—	—	—	—
Typic Mollorthel 95–029 (n = 2)							
Oi	0–1	—	—	—	fibric	—	—
Oe	1–2	—	—	—	hemic	—	—
A	2–20	cw	10YR2/1	—	SCL	2fgr	2f, m
C	20–200	—	—	—	—	sg	—
Aquic Haplorthel 95–034 (n = 1)							
Oi	0–4	—	—	—	fibric	—	—
Oe	4–9	—	10YR2/2	—	hemic	—	—
A	9–22	gw	10YR4/2	—	SCL	2fgr	2m
Bg	22–28	gw	10YR4/2	—	L	2mgr	2m
BCg	28–60	aw	10YR4/3	7.5YR5/8	CL	1mgr	2m
Cg	60–64	—	10YR3/1	7.5YR5/8	C	1mpl	1f
Typic Aquiturbel 95–003 (n = 1)							
Oi	0–6	—	—	—	fibric	—	—
A	6–13	aw	10YR2/1	—	SiL	none	2f, m
Bgjj	13–30	ci	N 4/	5YR5/8	SCL[b]	2mgr	1m
2Bg	30–45	ci	10YR4/2	5YR5/8	SL[b]	2mgr	1m
3Cg	45–55	as	10YR4/2	—	SCL[b]	none	none
3Cgf	55–60	—	—	—	—	—	—
Typic Umbriturbel 95–005 (n = 1)							
Oi	0–1	—	—	—	fibric	—	—
Oa	1–9	aw	10YR2/1	—	saprc	—	2f
Bwjj	9–16	cw	10YR3/3	—	SiL[b]	2fgr	1mv
BCjj	16–68	—	10YR3/3	—	SCL	1csbk	1m
Cf	68–70	—	—	—	—	—	—
Typic Haploturbel 95–027 (n = 4)							
Oi	0–3	—	—		fibric	—	—
Oe	3–6	—	10YR2/1	—	hemic	—	—
Ajj	6–13	ci	10YR4/2	—	SL	1fgr	3f
2Bwjj	13–35	gw	10YR4/4	—	SCL	2mgr	1f
2BCjj	35–50	gw	10YR3/2	—	C	1msbk	1f
2C	50+	—	10YR3/2	—	SL	sg	none
Aquic Haploturbel 95–013 (n = 8)							
Oi	0–1	—	—	—	fibric	—	—
Oe	1–2	aw	10YR2/1	—	hemic	—	2f
Bwjj	2–8	cs	10YR5/3	—	SCL	2fgr	3m
Bgjj	8–27	ci	10YR5/4	7.5YR5/8	L	1fgr	—
BCjj	27–60	—	2.5Y5/2	10YR5/4	SCL	2msbk	none
Cf	60+	—	—	—	—	—	—
Typic Histoturbel 95–024 (n = 2)							
Oi	0–8	—	—	—	fibric	—	—
Oe	8–20	—	10YR2/1	—	hemic	—	—

TABLE 2

(Cont.)

Horizon	Depth	Contact	Color	Motles	Texture	Structure	Roots
Oa	20–24	—	10YR2/1	—	sapric	—	—
Bwjj	24–36	gw	10YR4/2	—	L	2f-mgr	3m
Bgjj	36–50	gw	10YR3/3	7.5YR5/8	L	1f-msbk	3m
Cg	50+	—	5Y4/1	5YR5/8	L	massive	2m

[a] n = number of profiles in this subgroup.

[b] Field estimation given where lab analyses not performed.

(i.e. 95–007 Typic Historthel) (Table 2). Five of the 16 Turbels contain buried organic material.

Ten of the Orthels and eight of the Turbels had an A horizon ranging from 2 to 29 cm thick. Orthels lacked A horizons in excessively drained areas where a thin layer of organic material lay directly on top of coarse fluvial or glaciofluvial sediment (e.g., 95–029, Table 2).

Cambic (Bw) horizons occurred in coarse-grained Orthels under dry tundra and gleyed (Bg) horizons in fine-grained Turbels under moist tundra, marking the maximum extent of pedogenesis in the study area.

Samples chipped from just below the frost table suggest that soil parent materials have been affected by growth of ice lenses and interstitial ice. Samples with greater than 50% ice by volume were encountered. Organic matter and mineral soil were incorporated as fine laminations, streaks, and discrete inclusions in many of these samples, indicating periods of deeper cryoturbation later in the summer, or during years with greater depth of thaw.

SOIL ANALYTICAL PROPERTIES

Soil textural class ranged broadly from sand to clay (Table 3), due primarily to variations in the parent materials but also to particle comminution from subaerial weathering. Whereas sandy loam and loam textural classes were most common in Orthels, clay loam and clay classes were most frequent in Turbels. However, there were no differences in average clay (23.3 vs. 25.2%) or silt (32.1 vs. 33.1%) concentrations in the Bw horizon of Orthels and Turbels, respectively (Table 4).

Bw horizon pH was similar for the Orthels (average of 5.31) and Turbels (average of 5.63) (Table 3). Total profile pH (weighted for horizon thickness) averaged 5.92 for Orthels (range of 5.30–7.50) and 5.55 for Turbels (range 4.50–6.94). Horizon pH increased regularly with depth in most of the Orthels, but not in the Turbels where cryoturbation disrupted soil horizons (Table 3). LOI ranged from 1.3 to 22% for mineral soil horizons and was comparable for the Bw of Orthels (average of 5.7%) and Turbels (average of 5.4%). The differences in pH and %LOI reflect differences in landcover type with moist acidic tundra occupying the most acidic and organic-enriched soils, moist nonacidic tundra the least acidic soils, and dry tundra the soils with low organic matter contents.

COMPARISONS OF SOIL DEVELOPMENT

Analysis of soil weathering products in the horizons for which laboratory results are available showed no significant differences in mean profile quantities of silt, clay, silt-plus-clay, %LOI, and H^+ ion between Orthels and Turbels (Table 4). This suggests that cryoturbation has not affected profile accumulation of weathering products, only the distribution of these weathering products.

In contrast, analysis of variance showed significant differences in profile quantities of clay ($P = 0.021$), silt ($P = 0.015$), and silt-plus-clay ($P = 0.011$), and probably significant differences in H^+ ion concentration ($P = 0.084$) in relation to age group (Table 5). However, other quantitative analyses of soil properties failed to distinguish among the geomorphic surfaces. Bivariate plots of CDE and horizon thickness for Bw horizons on the Itkillik I, Itkillik II, and late Itkillik II surfaces exhibited no significant clustering which would be expected if soils on the different surfaces varied significantly (e.g., Clark, 1988). Because the thickness of the Bg horizon was indeterminate due to extension of gleyed material below the frost table in most fine-grained soils, CDE could not be determined for gleyed soils.

Attempts to differentiate the soils on the various surfaces from thickness of the A+B horizons, the organic layer thickness, color of the Bw horizon, and color of the Bg horizon were unsuccessful. Plots of A+B horizon thickness, organic horizon thickness, and Bw horizon color exhibited no age-related trends.

The results obtained by application of the profile development index to these soils are equivocal. Because cryoturbation in the Turbels forms broken and irregular horizon boundaries and redistributes weathering products throughout the solum, the profile development index was only applied to the noncryoturbated Orthels. Laboratory data allowed calculation of the PDI for nine of the Orthels. Development indices for profiles on Itkillik II and late Itkillik II surfaces are not significantly different (Table 5), although the average value for the three soils on the Itkillik I surface is greater, as would be expected for older soils. However, the small number of samples makes extrapolation from these results tenuous.

PROFILE QUANTITIES OF WEATHERING PRODUCTS IN RELATION TO LANDSCAPE AGE

As noted above, physical properties of soils developed on all four surfaces in the study area are quite similar. No major systematic differences in color, structure, horizonation, and texture were noted in the field between soils on the different surfaces. Bivariate plots of CDE and various combinations of horizon thickness also failed to differentiate soils on the Itkillik I, Itkillik II and late Itkillik II glacial surfaces. These results suggest that characteristics of low-arctic soils, including low degrees of overall weathering, darkening due to incorporated organic matter, and low-chroma gleyed colors make it difficult to assess relative age based entirely upon field descriptions.

However, the significant and nearly significant differences in weathering products with surface age demonstrated by the analysis of variance (Table 5) indicate that weathering products are accumulating as these soils age. Significant increases in pro-

TABLE 3

Analytical properties of representative soils of the Galbraith-Toolik lakes area

Profile	Horizon	Sand %	Silt %	Clay %	Texture	pH	%LOI
			Orthels				
95–004	Bw2	46.04	32.29	21.67	L	5.15	3.35
	Bg	49.25	19.76	30.99	SCL	5.66	11.40
	C	74.19	10.41	15.40	SL	5.69	3.87
95–010	Bw	35.51	37.51	26.98	L	5.05	4.81
	Bg	30.31	43.20	26.49	L	5.10	4.70
	BCg	32.91	49.52	17.56	L	5.66	9.72
95–014	Bw	55.00	30.86	14.14	SL	4.88	4.50
	BC	82.93	12.65	4.42	LS	6.69	1.26
	2C	55.70	32.18	12.12	SL	6.88	2.01
95–015	A	30.31	49.43	20.26	L	5.41	20.18
	Bw	71.71	18.72	9.57	SL	5.33	4.02
	BC	89.30	7.11	3.59	S	5.54	2.79
	C	93.48	0.49	6.03	S	6.97	2.38
95–017	A	67.00	14.91	18.09	SL	6.36	10.73
	Bw1	57.62	29.27	13.11	SL	4.74	4.29
	Bw2	34.31	49.78	15.91	L	5.30	3.03
	Bw3	41.58	39.42	19.00	L	5.45	3.00
	BC	54.02	35.08	10.90	SL	5.80	2.12
	C	69.33	22.53	8.14	SL	6.46	1.93
95–018	Bw	34.10	40.29	25.61	L	5.54	5.58
	BC	31.68	40.58	27.74	CL	5.71	4.21
	C	35.98	36.02	28.00	CL	5.22	4.20
	Cg	30.82	38.93	30.25	CL	6.24	4.76
95–025	A1	63.75	28.70	7.55	SL	7.42	11.73
	A2	64.93	26.06	9.01	SL	7.50	9.89
	Ck	83.29	12.68	4.03	LS	7.10	2.13
95–029	A	56.28	20.44	23.28	SCL	7.50	7.99
95–034	A	48.91	24.56	26.53	SCL	5.10	5.12
	Bg	45.18	33.91	20.91	L	5.68	3.71
	BCg	40.05	31.20	28.75	CL	5.58	5.19
	Cg	28.32	25.43	46.25	C	5.15	12.20
95–035	Bw	12.02	33.46	54.52	C	6.10	15.17
	C	35.55	34.89	29.56	CL	6.00	5.77
			Turbels				
95–013	Bwjj	53.65	21.82	24.53	SCL	4.53	6.93
	Bgjj	48.95	28.27	22.78	L	4.61	4.27
	BCjj	50.80	26.00	23.20	SCL	4.65	4.41
95–019	C1jj	8.95	45.16	45.89	SiC	4.45	8.95
	C2jj	5.55	69.40	25.05	SiL	5.62	20.80
	C3jj	3.80	57.65	38.55	SiCL	5.72	23.32
	Oebjj	2.58	65.39	32.03	SiCL	5.56	33.23
95–020	Bwjj	39.32	42.07	18.61	L	4.64	2.20
95–021	Oa	54.53	26.44	19.03	SL	4.60	12.28
	Bwjj	41.34	42.40	16.26	L	5.00	2.7
	BCjj	42.18	40.39	17.43	L	4.30	2.02
95–024	Bwjj	39.06	36.07	24.87	L	6.13	7.93
	Bgjj	35.40	40.11	24.49	L	6.20	4.48
	Cg	38.00	35.52	26.48	L	6.86	3.83
95–027	A	68.98	19.81	11.21	SL	4.64	3.55
	2Bwjj	56.48	18.39	25.13	SCL	5.04	8.26
	2BCjj	24.86	32.06	43.08	C	5.92	18.18
	2C	85.39	1.53	13.08	LS	6.00	2.40
95–028	A	44.59	18.50	36.91	CL	5.53	22.00
	Bwjj	56.35	24.21	19.44	SL	6.15	3.32
	BCjj	50.58	28.37	21.05	L	4.92	4.52
	BCgjj	48.20	27.77	24.03	SCL	4.88	4.60
	Oebjj	16.65	25.95	57.40	C	4.71	35.50
95–030	Oa	12.58	52.61	34.81	SiCL	6.80	36.66
	Bwjj	33.83	33.71	32.46	CL	6.78	8.02
	BCg	42.84	24.82	32.34	CL	7.15	4.23
95–031	Ajj	15.97	14.90	69.13	C	5.71	19.06
	BCgjj	31.51	39.26	29.24	CL	6.02	5.12

TABLE 3

(Cont.)

Profile	Horizon	Sand %	Silt %	Clay %	Texture	pH	%LOI
95–032	Ajj	15.84	49.80	34.36	SiCL	6.65	15.83
	Bgjj	35.17	34.86	29.97	CL	6.01	4.66
	Oabjj	6.23	16.63	77.14	C	5.27	22.40
	Oabf	28.21	8.51	63.28	C	5.34	16.97
95–033	Ajj	4.77	5.79	89.44	C	6.34	21.03
	Bwjj	27.97	39.81	32.22	CL	6.56	5.39
	BCg	28.70	33.34	37.96	CL	6.85	5.33
95–036	Bw	33.79	37.85	28.36	CL	5.41	4.50
	BCg	33.93	38.11	27.96	CL	5.24	5.96
	Cg	34.69	36.94	28.37	CL	5.02	5.58
	Oejj	9.86	19.96	70.18	C	5.79	47.80

file quantities of clay, silt, and silt-plus-clay with surface age indicate that comminution of larger clasts, or eolian dust inputs, are enriching the soils in fines over time. Moreover, the values for profile quantities of silt and silt-plus-clay increase unidirectionally with surface age (Table 5) as would be expected if fines accumulate through time.

The nearly significant ($P = 0.084$) increase in profile quantities of H^+ ion reflects the progressive acidification of the soils due to leaching of bases and release of protons from organic matter weathering reactions (Jenny, 1980). The values for profile quantities of H^+ ion are quite similar for the surfaces considered closest in age (Itkillik II and late Itkillik II). The results from the calculation of profile quantities of weathering products demonstrate that the soil chronosequence model is applicable to low-arctic soils, including those affected by cryoturbation.

The demonstrated increase of weathering products also corroborates the existing surface relative age framework for the Galbraith and Toolik Lakes area. Figure 3 plots average profile quantities of H^+ ion, silt, and silt-plus-clay against surface age, assuming an age of 1 ka for the Holocene alluvium, 12 ka for late Itkillik II, 20 ka for Itkillik II, and 60 ka for Itkillik I (dates for glaciations from Hamilton, 1994). Profile quantities of silt and silt-plus-clay increase logarithmically with the most abrupt increase occurring in the first 20 ka. Proton concentration appears to increase linearly, although the similarity of values from late Itkillik II and Itkillik II surfaces makes more precise determination of the relationship between concentration and age impossible. It can be inferred from these results that soils forming under the low-arctic climate conditions of the Galbraith and Toolik Lakes region develop rapidly for 10–20 ka before rates of pedogenesis decrease. Additional study of soils forming on surfaces between 20 and 60 ka in age would provide a good test of the strength of this relationship.

PROFILE DEVELOPMENT INDICES IN RELATION TO LANDSCAPE AGE

The results from the calculation of profile development indices for the four surfaces also support the established glacial chronology, and corroborate the results from the weathering product analysis. As noted above, the mean profile development indices for soils formed on Itkillik II (23.9) and late Itkillik II (22.3) surfaces are not significantly different (Table 5). The similar PDIs for these two surfaces indicate that soils on the Itkillik II deposits were not appreciably developed when the late Itkillik II advance occurred. This result suggests that the interval between the two advances was short, and supports an age for the

TABLE 4

Comparison of average profile quantities of weathering products between Orthels and Turbels using analysis of variance in arctic Alaska.

Property	Units	Orthels	Turbels	Mean square* between groups	Mean square* within groups	F**	P***
Profile clay	Mg ha^{-1}	1154	1450	449160	209158	2.15	0.159
Profile loss on ignition	Mg ha^{-1}	288	312	2935	6076	0.483	0.495
Profile H^+ ion	mol(+) ha^{-1}	224	647	920569	502910	1.83	0.192
Profile silt	Mg ha^{-1}	1737	1791	14920	510437	0.0292	0.866
Profile silt-plus-clay	Mg ha^{-1}	2891	3241	620100	972087	0.647	0.431

* Based on single-factor analysis of variance.

** F statistics.

*** Probability of significantly larger F statistic.

Itkillik II advance in Atigun Valley near the younger end of the accepted 24- to 11.5-ka range, i.e. closer in time to the late Itkillik II advance.

This result may also reflect the severity of the local climate during the interval between the two advances. Modern rates of pedogenesis are reduced in the cold climate of arctic Alaska relative to that at lower latitudes (Tedrow and Brown, 1962). Birkeland (1978) reported that 10 ka was required to produce a weak, thin, cambic horizon on southeastern Baffin Island. Bockheim (1979) mentioned that the degree of development of 60- to 100-ka-old soils under polar desert conditions on Cumberland Peninsula is similar to that of Holocene soils of the Rocky Mountains. During the period between the Itkillik II and late Itkillik advances, the climate in the study area would certainly have been more severe than it is today. Even if 10 ka elapsed between the Itkillik II and late Itkillik II advances, pedogenesis on the Itkillik II deposits would have been minimal if the climate was more similar to that of the modern High Arctic.

In contrast to the younger surfaces, the average value (30.4) for the soils of Itkillik I age is greater, as would be expected for older soils. However, the small number ($n = 3$) of samples makes extrapolation from these results difficult. Indeed, the standard deviation of this sample (7.1) is so wide that the range overlaps the Itkillik II values at one sigma. Because the profile quantities of weathering products indicate an advanced age for the surface designated as Itkillik I, it seems likely that the greater mean PDI for these three soils accurately reflects a greater degree of pedogenesis. However, description of additional soils on Itkillik I surfaces, combined with more extensive lab analyses, are necessary to unequivocally state that deposits attributed to the Itkillik I glaciation are universally much older than those of Itkillik II age.

CRYOTURBATION AND SOIL DEVELOPMENT

Much of the landscape in the Galbraith Lake area is undergoing active cryoturbation. Nonsorted circles cover up to 50% of the landscape. Slightly less than half (44%) of the soil profiles contain evidence of cryoturbation, including wavy/irregular horizon boundaries, involutions, and inclusions of organic matter. It was not possible to determine in the field whether or not this cryoturbation was modern or relict. Some of the involutions and irregular horizon boundaries in the profiles developed on the steeper slopes may have been produced or enhanced by gelifluction.

All of the Turbels were developed in fine-grained materials. Although some of the Orthels were developed on fine-grained parent materials, no Turbels occurred on coarse-textured outwash (Table 1). Measurement of active layer thickness in the Orthels was impossible because the soil probe could not penetrate into these clast-rich soils limiting observations of active layer thickness to the depth of excavation.

The results of the %LOI analysis reveal the amount of diffuse organic matter contained within the mineral soil of the Turbels. The product of %LOI and thickness of mineral horizons in Turbels averaged 137 %LOI-cm compared with 94 in Orthels. This difference reflects the pervasiveness of diffuse organic matter within the mineral soil and demonstrates the efficacy of cry-

TABLE 5

Comparison of average profile quantities of weathering products as a function of age using analysis of variance.

Property	Units	Drift unit: Holocene	Drift unit: Late Itkillik II	Drift unit: Itkillik II	Drift unit: Itkillik I	Mean square*: between groups	Mean square*: within groups	F**	P***
Profile clay	Mg ha^{-1}	335	1463	1226	1442	730462	175588	4.16	0.021
Profile loss on ignition	Mg ha^{-1}	193	342	284	292	11596	6435	1.80	0.182
Profile H^+ ion	mol(+) ha^{-1}	2	229	202	996	1077577	413916	2.60	0.084
Profile silt	Mg ha^{-1}	659	1279	1880	2182	1693372	372299	4.55	0.015
Profile silt-plus-clay	Mg ha^{-1}	994	2742	3106	3624	3747483	756908	4.95	0.011
Profile development index[a]	—	28.9	22.3	23.9	30.4	35.8	20.6	2.42	0.184

* Based on single-factor analysis of variance.

** F statistics.

*** Probability of significantly larger F statistic.

[a] PDI statistics do not include the one Holocene-age Orthel.

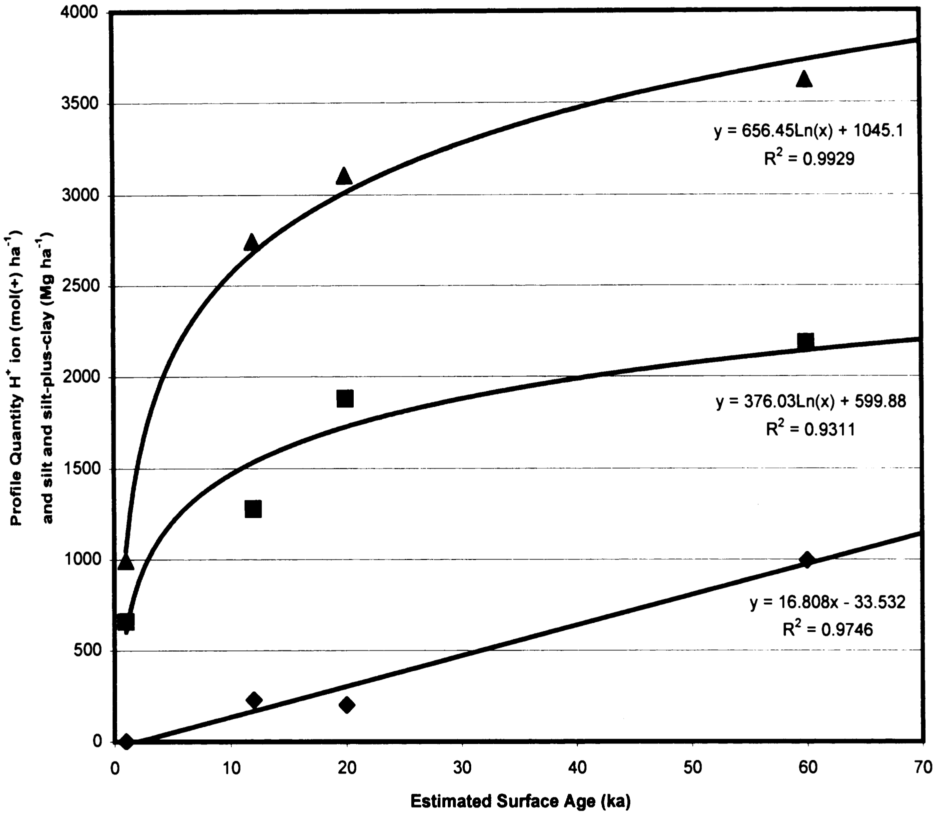

FIGURE 3. Relationship between estimated surface age and profile quantities of weathering products. Profile quantities of H^+ ion (diamonds), silt (squares), and silt-plus-clay (triangles) (from Table 5) are plotted against estimated surface age: Holocene alluvium, 1 ka; late Itkillik II, 12 ka; Itkillik II, 20 ka; Itkillik I, 60 ka (dates for glaciations from Hamilton, 1994). Linear and logarithmic regressions are displayed, as well as values of the regression coefficients.

oturbation as a mechanism for organic matter incorporation in Turbels.

The lack of A horizons in 47% (7 of 16) of the Turbels is also evidence of present or recent cryoturbation. Turbels lack A horizons where soil mixing induced by cryoturbation has been severe enough to have disseminated organic matter throughout the mineral soil (Bockheim et al., 1998a; 1998b). Evidence for this process is seen in the %LOI data for profiles 95–013, 019, 020, 021, 024, 030, and 036, all of which lacked A horizons (Table 3). Five of the seven profiles exhibit somewhat regular decrease in organic material (as evidenced by %LOI) in the subsurface. Profile 95–019 contains a marked increase in organic content with depth, culminating in a buried hemic layer just above the frost table.

Finally, the %LOI ratio in Turbels (%LOI surface mineral horizon / minimum %LOI subsurface) highlights the effects of mixing in the Turbels. Turbels with A horizons have an average %LOI ratio of 4.4 (σ 1.5) while those lacking A horizons average 1.4 (σ 0.7) reflecting a more uniform distribution of organic matter with depth resulting from more severe or recent cryoturbation.

Conclusion

All soils investigated in the vicinity of Galbraith Lake and Toolik Lake are classified as Gelisols. Turbels containing wavy or irregular horizon boundaries and incorporated organic matter comprise 44% of the soils studied. The other 56% or the profiles are classified as Orthels. Turbels are always formed in fine-grained materials containing ice-rich permafrost. While some Orthels are found on fine-grained substrates, they are most common on coarser sediments deposited as late Pleistocene outwash gravels and Holocene alluvium.

Calculation of profile quantities of weathering products (H^+ ion, clay, silt, silt-plus-clay, and loss on ignition) revealed no significant difference between Orthels and Turbels. Apparently cryoturbation acts to redistribute weather products throughout the solum, but does not affect overall profile accumulation of these products.

In contrast, there are significant differences among profile quantities of soils as a function of age. The amounts of H^+ ion, silt, and silt-plus-clay are lowest in the Holocene alluvial soils, intermediate for the two younger drifts, and slightly greater for the oldest drift. These results suggest that despite the degree of cryoturbation evidenced in the Turbels, weathering products accumulating in these soils can be used to determine relative age.

Acknowledgments

This research was part of the senior author's Masters thesis at the University of Wisconsin-Madison under the guidance of D. M. Mickelson. Funds for field expenses and travel were provided by Exxon Foundation Grant 133-S317 to the Department of Geology & Geophysics, and the ARCSS/LAII program of the National Science Foundation to F. E. Nelson. D. A. Walker provided helpful discussions. D. C. Douglass helped with the digitizing of Figure 2.

References Cited

Birkeland, P. W., 1978: Soil development as an indication of relative age of Quaternary deposits, Baffin Island, N.W.T., Canada. *Arctic and Alpine Research,* 10: 733–747.

Birkeland, P. W., 1999: *Soils and Geomorphology.* New York: Oxford University Press. 430 pp.

Bockheim, J. G., 1979: Properties and relative age of soils of southwestern Cumberland Peninsula, Baffin Island, N.W.T. *Arctic and Alpine Research,* 11: 289–306.

Bockheim, J. G. and Tarnocai, C., 1998: Recognition of cryoturbation for classifying permafrost-affected soils. *Geoderma,* 81: 281–293.

Bockheim, J. G., Walker, D. A., and Everett, L., R., 1998a: Soil carbon distribution in nonacidic and acidic tundra of arctic Alaska. *In* Lal, R., et al. (eds.), *Soil Processes and the Carbon Cycle.* Boca Raton, FL: CRC Press, 143–155.

Bockheim, J. G., Walker, D. A., Everett, L. R., Nelson, F. E., and Shiklomanov, N. I., 1998b: Soils and cryoturbation in moist nonacidic and acidic tundra in the Kuparuk River Basin, arctic Alaska, U.S.A. *Arctic and Alpine Research,* 30: 166–174.

Brown, J. and Kreig, R. A., 1983: Guidebook to permafrost and related features along the Elliott and Dalton Highways, Fox to Prudhoe Bay, Alaska. *Fourth International Conference on Permafrost,* University of Alaska-Fairbanks, July 18–22. 230 pp.

Buntley, G. J. and Westin, F. C., 1965: A comparative study of developmental color in a Chestnut-Chernozem-Brunizem soil climosequence. *Soil Science Society of America Proceedings,* 29: 579–582.

Clark, P. U., 1988: Glacial geology of the Torngat Mountains, Labrador. *Canadian Journal of Earth Sciences,* 25: 1184–1198.

Dean, W. E., Jr., 1974: Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition; comparison with other methods. *Journal of Sedimentary Petrology,* 44, 1: 242–248.

Gallant, A. L., Binnian, E. F., Omernik, J. M., and Shasby, M. B., 1995: Ecoregions of Alaska. *U.S. Geological Survey Professional Paper,* 1567. 73 pp.

Gee, G.W. and Bauder, J. W., 1979: Particle size analysis by hydrometer; a simplified method for routine textural analysis and a sensitivity test of measurement parameters. *Soil Science Society of America Journal,* 43: 1004–1007.

Hamilton, T. D., 1978: Surficial geologic map of the Philip Smith Mountains quadrangle, Alaska. *U.S. Geological Survey Miscellaneous Field Studies Map,* MF-879A Scale 1:250,000.

Hamilton, T. D., 1979: Radiocarbon dates and Quaternary stratigraphic sections, Philip Smith Mountains quadrangle, Alaska. *U.S. Geological Survey Open File Report,* 79–866. 43 pp.

Hamilton, T. D., 1986: Late Cenozoic glaciation of the central Brooks Range *In* Hamilton, T. D., Reed, K. M., and Thorson, R. M. (eds.), *Glaciation in Alaska: the Geologic Record.* Anchorage: Alaska Geologic Society, 9–49.

Hamilton, T. D., 1994: Late Cenozoic glaciation of Alaska. *In* Plafker, G. and Berg, H. C. (eds.), *The Geology of North America, v. G-1. The Geology of Alaska.* Boulder, Colo.: Geological Society of America, 813–844.

Hamilton, T. D. and Porter, S. C., 1975: Itkillik glaciation in the Brooks Range, northern Alaska. *Quaternary Research,* 5: 471–497.

Harden, J. W., 1982: A quantitative index of soil development from field descriptions: examples from a chronosequence in central California. *Geoderma,* 28: 1–28.

Haugen, R. K., 1982: Climate of remote areas in north-central Alaska, 1975–1979 summary. *U.S. Army Cold Regions Research and Engineering Laboratory Report,* 82–35. 110 pp.

Hinkel, K. M., Nelson, F. E., and Outcalt, S. I., 1987: Frost mounds at Toolik Lake, Alaska. *Physical Geography,* 8: 148–159.

Hobbie, J. E., Peterson, B. J., Shaver, G. R., and O'Brien, W. J., 1991: The Toolik Lake Project: terrestrial and freshwater research on change in the Arctic. *In* Weller, G., Wilson, C. L., and Severin, B. A. B. (eds.), *International Conference on the Role of the Polar Regions in Global Change: proceedings of a conference held June 11–15, 1990, at the University of Alaska.* Fairbanks: University of Alaska: II, 378–383.

Höfle, C. and Ping, C.L. 1996: Properties and soil development of late-Pleistocene paleosols from Seward Peninsula, northwest Alaska. *Geoderma,* 71: 219–243.

Jenny, H., 1980: *The Soil Resource, Origin and Behavior.* New York: Springer-Verlag. 377 pp.

Kreig, R. A. and Reger, R. D., 1982: Air-photo analysis and summary of landform soil properties along the route of the Trans-Alaskan Pipeline System. *Alaska Division of Geological and Geophysical Surveys Geologic Report,* 66. 149 pp.

Munroe, J. S., 1996: Glacial geology and soil development in the Arctic foothills between Galbraith and Toolik Lakes, Alaska. *AMQUA 1996: program and abstracts of the 14th biennial meeting; Global warming; interglacials, interstadials, climatic optima, and other events*: 112.

Ovenden, L., 1990: Peat accumulation in northern wetlands. *Quaternary Research,* 33: 377–386.

Ping, C. L., Bockheim, J. G., Kimble, J. M., Michaelson, G. J, and Walker, D. A., 1998: Characteristics of cryogenic soils along a latitudinal transect in Arctic Alaska. *Journal of Geophysical Research,* 103, D22: 28,917–28,928.

Retzer, J. L., 1965: Present soil-forming factors and processes in arctic and alpine regions. *Soil Science,* 7: 22–32.

Soil Survey Division Staff, 1993: *Soil Survey Manual.* U.S. Department of Agriculture Handbook 18. Washington, D.C.: U.S. Government Printing Office. 437 pp.

Soil Survey Staff, 1998: *Keys to Soil Taxonomy.* 8th ed. Washington, D.C.: U.S. Department of Agriculture, Soil Conservation Service. 326 pp.

Tarnocai, C. 1994: Genesis of permafrost-affected soils. *In* Kimble, J. M. and Ahrens, R. J. (eds.), *Proceedings of a Meeting on Classification, Correlation and Management of Permafrost-Affected Soils, July, 1993.* Lincoln, NE: USDA-SCS, NSSC, 143–154.

Tedrow, J. C. F., 1974: *Soils of the Polar Landscapes.* New Brunswick, NJ: Rutgers University Press. 638 pp.

Tedrow, J. C. F., Drew, J. V., Hill, D. E., and Douglas, L. A., 1958: Major genetic soils of the arctic slope of Alaska. *Journal of Soil Science,* 9: 33–45.

Tedrow, J. C. F. and Brown, J., 1962: Soils of the northern Brooks Range, Alaska; weakening of the soil-forming potential at high arctic altitudes. *Soil Science,* 93: 254–261.

Walker, M. D., Walker, D. A., and Auerbach, N. A., 1994: Plant communities of a tussock tundra landscape in the Brooks Range, Alaska. *Journal of Vegetation Science,* 5: 843–866.

Walker, D. A., Auerbach, N. A., and Shippert, M. M., 1995: NDVI, biomass, and landscape evolution of glaciated terrain in northern Alaska. *Polar Record,* 31(177): 169–178.

Ms submitted February 1999
Revised ms submitted March 2000

LINKED CITATIONS

You have printed the following article:

Soil Development in Low-Arctic Tundra of the Northern Brooks Range, Alaska, U.S.A.
J. S. Munroe; J. G. Bockheim
Arctic, Antarctic, and Alpine Research, Vol. 33, No. 1. (Feb., 2001), pp. 78-87.
Stable URL:
http://links.jstor.org/sici?sici=1523-0430%28200102%2933%3A1%3C78%3ASDILTO%3E2.0.CO%3B2-Q

References Cited

Soil Development as an Indication of Relative Age of Quaternary Deposits, Baffin Island, N.W.T., Canada
Peter W. Birkeland
Arctic and Alpine Research, Vol. 10, No. 4. (Nov., 1978), pp. 733-747.
Stable URL:
http://links.jstor.org/sici?sici=0004-0851%28197811%2910%3A4%3C733%3ASDAAIO%3E2.0.CO%3B2-3

Properties and Relative Age of Soils of Southwestern Cumberland Peninsula, Baffin Island, N.W.T., Canada
J. G. Bockheim
Arctic and Alpine Research, Vol. 11, No. 3. (Aug., 1979), pp. 289-306.
Stable URL:
http://links.jstor.org/sici?sici=0004-0851%28197908%2911%3A3%3C289%3APARAOS%3E2.0.CO%3B2-F

Soils and Cryoturbation in Moist Nonacidic and Acidic Tundra in the Kuparuk River Basin, Arctic Alaska, U.S.A.
J. G. Bockheim; D. A. Walker; L. R. Everett; F. E. Nelson; N. I. Shiklomanov
Arctic and Alpine Research, Vol. 30, No. 2. (May, 1998), pp. 166-174.
Stable URL:
http://links.jstor.org/sici?sici=0004-0851%28199805%2930%3A2%3C166%3ASACIMN%3E2.0.CO%3B2-%23

LINKED CITATIONS

Plant Communities of a Tussock Tundra Landscape in the Brooks Range Foothills, Alaska
Marilyn D. Walker; Donald A. Walker; Nancy A. Auerbach
Journal of Vegetation Science, Vol. 5, No. 6. (Dec., 1994), pp. 843-866.
Stable URL:
http://links.jstor.org/sici?sici=1100-9233%28199412%295%3A6%3C843%3APCOATT%3E2.0.CO%3B2-K