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Cryogenesis and soil formation along a bioclimate gradient in Arctic North America

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[1] In arctic tundra, cryoturbation resulting from frost heave, cracking, and other cryogenic processes produces patterned ground such as nonsorted circles, stripes, nonsorted polygons, and earth hummocks. We studied cryogenic structures and morphological properties of soils associated with patterned-ground features along a bioclimate gradient in Arctic Alaska and Canada from north (subzone A) to south (subzone E). Most of these soils have strongly developed cryogenic features, including warped and broken horizons, and organic matter moved into the upper permafrost. The expression of cryoturbation generally increases with the gradient southward. Soil color reflects the lithology of the soil, weathering, and accumulation of organic matter. The organic horizons form around the circles, and gleyed matrix with redoximorphic features develop in the lower active layers due to saturation above the permafrost. Cryostructure development depends more on hydrology controlled by microtopography than position along the gradient. The cryostructures form due to freeze-thaw cycles and ice lens formation, which include granular, platy, lenticular, reticulate, suspended (ataxitic), ice lens, and ice wedges. On the surface, the density of nonsorted circles reached their maximum in subzones C and D. However, once the vegetation cover was removed, the nonsorted pattern grounds reached their optimum stage and become closed packed in subzone E. Frost heave decreases in the south as the vegetation changes from tussocks to shrub tundra. Cryogenesis is the controlling factor in patterned ground formation resulting in cryoturbated soil profiles, cryostructures, and carbon sequestration in arctic tundra soils.

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1. Introduction

[2] Frost heave, cracking, and other processes caused by freeze and thaw cycles leads to the formation of patterned ground [*Washburn*, 1980]. Soils associated with patterned ground formation are characterized by irregular or broken horizons and incorporation of surface organic matter into the lower soil horizons, often with concentration of this material on top of the permafrost table and are the result of cryoturbation [*Tarnocai and Smith*, 1992]. Cryoturbation associated with patterned ground was recognized as one of the unique soil features in the Arctic [*Tedrow*, 1974; *Everett and Brown*, 1982]. Thus, at the pedon level, cryoturbation mainly caused by annual freeze and thaw cycles leads to cryoturbated soil profiles in which soil horizons are warped, broken and distorted [*Tedrow*, 1974; *Tarnocai and Smith*, 1992; *Bockheim and Tarnocai*, 1998; *Ping et al.*, 1998]. Patterned ground features common to Arctic Alaska and Canada include ice wedge polygons, sorted and nonsorted circles, stripes and desiccation polygons [*French*, 1986]. The vegetation and soil processes are both influenced by and contribute to the formation of patterned-ground features. *Walker et al.* [2008] review the trend in patterned ground features and the various hypotheses regarding their formation along the North American Arctic Transect. Generally, contraction cracking due to desiccation and/or freezing processes is most common in the far northern Arctic. These contraction cracks form polygons, with diameter sizes ranging from a few centimeters to several meters. Contraction cracking combined with eolian and erosional processes creates small turf hummocks [*Broll and Tarnocai*, 2002]. Nonsorted circles, also-called frost boils, are a form of patterned ground more common further south. They are more or less flat, bare soil patches 0.5 to

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3 m across and lack a border of stones. These features are a product of differential frost heave, which occurs when ice lenses form in the soils during winter [*Washburn*, 1973]. Nonsorted circles heave more than the surrounding tundra due to deeper thaw and more ice lenses within the barren circles and also due to migration of water from the intercircle areas [*Peterson and Krantz*, 2003, 2008]. Earth hummocks are well-vegetated, mound-shaped landforms up to 50 cm tall and 1–2 m in diameter which generally form in the warmer parts of the Arctic, where the plants are sufficiently robust to counteract the effects of frost-heaving and needle-ice formation. They usually have a mineral soil core and are thought to be caused by differential frost heave [*Mackay*, 1980].

[3] 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 can result in a variety of soil structures such as granular and platy [*Gubin*, 1993; *French*, 1986]. These cryoturbation phenomena have proven useful in environmental reconstruction [*Hoefle et al.*, 1998; *Van Vliet-Lanoe*, 1988]. The soil character varies widely depending on location within these cryogenic features and patterns. Drainage, organic layer 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]. The importance of cryogenic processes in soil formation in the arctic regions was recognized and was adopted as criteria of the Gelisol order in the U. S. soil classification system [*Bockheim and Tarnocai*, 1998; *Soil Survey Staff*, 2006].

[4] 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]. Soils of arctic Alaska and the Low Arctic of Canada often have a greater amount of organic carbon than temperate soils [*Reiger*, 1982; *Ping et al.*, 1997a; *Tarnocai and Smith*, 1992]. Organic material is often incorporated into lower parts of the active layer through cryogenic processes, which with time and changing environmental conditions can become encased in permafrost, sequestering the carbon more permanently [*Shur and Ping*, 1994; *Ping et al.*, 1997a]. Therefore the Arctic tundra soils may become potential carbon sources with climate warming and thawing of the carbon-rich near-surface permafrost [*Oechel and Billings*, 1992; *Kimble et al.*, 1993; *Oechel et al.*, 1993; *Tarnocai*, 1994].

[5] The soil character varies widely depending on location within these periglacial features and patterns. Drainage, organic horizon thickness, and depth of the active layer can be quite variable within a small area [*Tarnocai*, 1994]. 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 caused by a seasonally perched water table on permafrost [*Tedrow*, 1974; *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 was also observed in the upper permafrost as the results of permafrost table fluctuation due to disturbance or climate change [*Ping and Moore*, 1993; *Ping et al.*, 1998]. This zone of permafrost table fluctuation is known as the intermediate layer [*Shur*, 1988] and has been used to identify the paleo-permafrost table [*Hoefle et al.*, 1998], and later referred to as the transition layer [*Bockheim and Hinkel*, 2005]. However, the intermediate layer encompasses more than the transition layer; it also includes the upper permafrost that fluctuates on a decadal and century scale.

[6] Different bioclimate subzones are identified on vegetation maps of the Arctic [*CAVM Team*, 2003; *Walker et al.*, 2005], and a multidisciplinary team used these subzones as a framework to study the complex interactions between vegetation, soils, cryogenic processes, and the morphology of small patterned-ground features across the entire Arctic bioclimate gradient [*Walker et al.*, 2004]. The objectives of this paper are to relate the soil morphological properties to their genesis (morphogenesis) and to demonstrate the influence of cryogenesis as expressed by cryogenic features in soil formation along a bioclimate transect in the arctic tundra zone of North America. The carbon stocks and chemical and physical properties will be presented in separate papers.

2. Materials and Methods

2.1. Study Sites

[7] Study locations are in northwestern Arctic Canada and Arctic Alaska (Figure 1); the physical environments of study sites are summarized in Table 1. Most sites are associated with the vegetation plots of the Biocomplexity project, and some are associated with the earlier ATLAS and FLUX projects of the National Science Foundation, Arctic System Science Program, Land Atmosphere Ice Interaction study group (NSF, ARCSS-LAII) and the USDA Wet Soils Monitoring project. At each study location, vegetation plots were established along a toposequence on the representative landform. Major segments of the landform include the dry or barren summit, zonal (mesic) back slope, and wet toe slopes or bottom land. All the sites except site 22 were keyed into the bioclimate subzones from A to E along a N - S transect [*Walker et al.*, 2003]. The following is a brief description of the sampling sites along the latitudinal gradient. Sites 1–3 are located at Isachsen in the southwestern part of Ellef Ringnes Island, and sites 4–6 are located at Mould Bay in the southwestern part of Prince Patrick Island, of Nunavut, Canada. Sites 7–9 are located at Green Cabin in the northeastern part of Banks Island, Northwest Territory, Canada. Site 10 is on Howe Island near Prudhoe Bay, northern Alaska. Site 11 is on a coastal marsh, and site 12 is located 8 km south of Prudhoe Bay. Sites 13–16 are on the south fringe of the Arctic Coastal Plain and the northern fringe of the Arctic Foothills. Site 17–23 are located across the latitudinal span of the Arctic Foothills. Site 22 is at the southern end of the Arctic Foothills and has a wet nonacidic tundra landcover type with vegetation dominated by sedge. Site 22 has a shrub

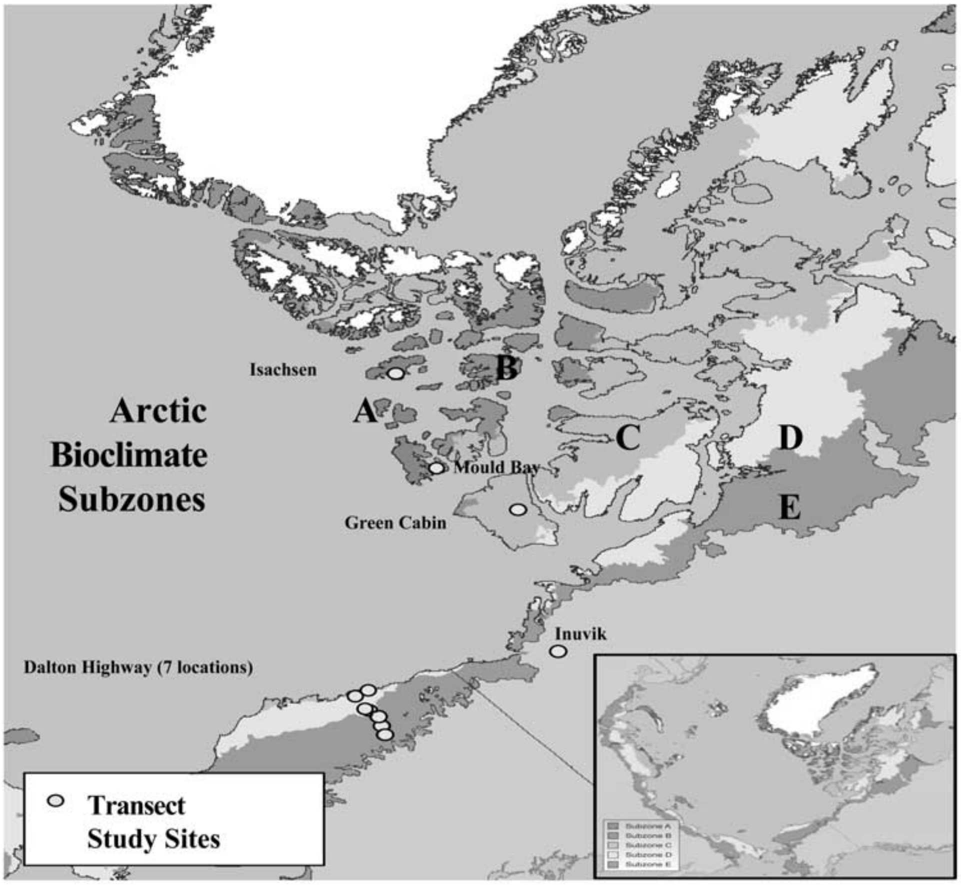

Figure 1. The distribution of bioclimate subzones and study locations in Arctic North America.

tundra land cover type and is located on an old terrace in the southern foothills of the Brooks Range. Site 23 is located on the coastal lowland, north of Inuvik, Northwest Territory. The landcover types and vegetation of sites 1 to 20 were described by *Auerbach et al.* [1996], *Kade et al.* [2006], *Vonlanthen et al.* [2008], and *Walker et al.* [2004].

2.2. Soil Morphological Study and Sampling

[8] At each study site, a 1 × 2 m square soil pit was excavated to a 1.5 m depth or bedrock, whichever was shallower. The excavations were made so that the vertical face exposed a complete cycle of the surface microrelief patterns. For example, in a nonsorted circle complex, the pit extended from the center of a nonsorted circle to the center of intercircle area and to the substratum that contains no more cryoturbated organics. The active layer thickness was determined as the depth to either the ice nets, ice-rich layers, or ice wedges [*Shur*, 1988]. Scale drawings were made of the exposed soil profiles which were then described according to the Soil Survey Manual [*Soil Survey Division Staff*, 1994] and cryogenic structures according to *French* [1986] and *Shur* [1988]. Soil horizons in the upper permafrost and cryoturbated horizons are designated by lowercase *f and jj,* respectively. The pit was first opened by stripping off its vegetation mat to expose the surface of the seasonal frozen layer between the patterned-ground features. Then the excavating was done in 20–30 cm depth increments to expose the variation of active layer thickness and the cryostructures. Soil samples were taken from each genetic horizon or zone. 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. All samples were sealed in plastic freezer bags, kept in a cooler and transferred to a freezer after leaving the field camp. Soil samples were analyzed in both the University of Alaska Fairbanks Palmer Research Center laboratory and the USDA-Natural Resources Conservation Service (NRCS) National Soil Survey Center (NSSC) Laboratory in Lincoln, NE. Analyses were performed according to USDA National Soil Survey Laboratory procedures [*Soil Survey Laboratory Staff*, 1996]. All soil morphological properties and laboratory data including chemical, mineralogical and physical properties were archived in the USDA National Soils Survey Center (http://vmhost.cdp.state.us.ne.96/state.htmp) and the National Snow and Ice Data Center website: (http://nsidc.org/data/across074.htmp), with the exception of the cryogenic structure and ice contents.

3. Results

3.1. Cryoturbation and Patterned Ground

[9] The abundance of patterned ground differs in each subzone. In subzones A through C, the nonsorted circles are

Table 1. Physical Environment, Land Cover, and Soil Classification of Study Sites[a]

Site Number	Location Cover Type	Latitude Longitude	Elevation (m, asl)	Annual ToC		Annual ppt (cm)	Landform Landscape Position	Patterned Ground, Size (cm)	Parent Material	Drainage
				Air	Soil					
Subzone A										
1 - A	Isachsen barren	78.78°N 103.55°W	35				Piedmont saddle	Cracking polygon, 10-20	Glaciomarine/shale	Well
2 - A	Isachsen mesic	78.79°N 103.55°W	35	−19.2 (1)	–	11.3 (1)	Piedmont Back slope	Cracking polygon, 10-20	Glaciomarine/shale	Somewhat poor
3 - A	Isachsen wet	78.78°N 103.55°W	32				Piedmont Toe slope	Small hummock, 15-22	Glaciomarine/shale	Poor
Subzone B										
4 - B	Mould Bay barren	76.23°N 119.56°W	30				Fan/terrace	Nonsorted Circle, 140	Alluvium/colluvium	Mod. well
5 - B	Mould Bay mesic	76.22°N 119.30°W	40	−17.8 (1)	–	9.3 (1)	Hills shoulder	Nonsorted circle, 150	Residuum	SW poor
6 - B	Mould Bay wet	76.23°N 119.33°W	5				Coastal plain	Hummock, 140 W 200–400 L	Marine sediment	Poor
Subzone C										
7 - C	Banks Island Barren	73.20°N 119.56°W	59				Hills shoulder	Small polygon, 40. Nonsorted circle, 200	Glaciofluvial	Well
8 - C	Banks Island Mesic	73.22°N 119.56°W	54	−14.1 (1)	–	11.4 (1)	Hills interfluve	Small polygon, 25. Nonsorted circle, 160	Glaciofluvial/lacustrine	Mod well
9 - C	Banks Island wet	73.23°N 119.56°W	22				Fan	Low–center polygon, 1500, Nonsorted circle, 200	Alluvium	Poor
10 - C	Howe Island Barren	70.32°N 147.00°W	3	−11.3	−6.7	15.0	Terrace	Small polygon, 25. Nonsorted circle, 120	Alluvium	SW poor
Subzone D										
11 - D	W. Dock WNT	70.37°N 148.55°W	1	−11.3	−6.7		Coastal marsh	Ice–wedge polygon 1500–1800	Organics/sediment	Very poor
12 - D	Prudhoe B. WNT	70.16°N 148.47°W	3	−9.9	−4.5	20.0	Fan	Nonsorted circle 120	Alluvium	Poor
13 - D	Franklin Bluff, Dry	69.67°N 148.72°W	91				Natural levee	Nonsorted circle	Alluvium	Somewhat poor
14 - D	Franklin Bluff, moist	69.67°N 148.72°W	91	−9.5	–		Natural levee	Nonsorted circle	Alluvium	Poor
15 - D	Franklin Bluff, wet	69.67°N 148.72°W	89			20	Fan	Nonsorted circle	Alluvium	Very poor
16 - D	Sagwon Hill MNT	69.34°N 148.75°W	330	−9.2	−4.8		Hill back slope	Nonsorted circle	Loess	Somewhat poor
Subzone E										
17 - E	Sagwon Hill MAT	69.42°N 148.66°W	350	−9.3	−4.8		Hill back slope	Nonsorted circle 120	Loess	Poor
18 - E	Happy Valley MAT	69.13°N 148.84°W	320	−10.3	−3.7	30	Hill back slope	Nonsorted circle, 120	Glacial moriane	Poor
19 - E	Toolik Lake MAT	68.63°N 149.58°W	760	−10.3	−5.0		Hill back slope	Nonsorted circle 80–120	Glacial moriane	Poor
20 - E	Imnavit Creek MAT	68.64°N 149.56°W	910	–	–	35	Hill back slope	Nonsortedcircle, strips	Glacial moriane	Poor
21 - E	Galbraith LK WNT	68.48°N 149.47°W	812	−8.3	−4.0	30	Lake basin	Nonsorted circle 60–130	Lacustrine	Poor
22 - E	Chandalar Shelf Shrub tundra	68.07°N 149.99°W	1030	−6.8	−2.9	40	Terrace	Hummock 120	Lacustrine	Somewhat poor
23 - E	Parsons Lake Shrub tundra	68.97°N 133.54°W	65	−10.9 (1)	–	13.7 (1)	Coastal plain	Hummock 160	Glacial till	SW Poor

[a] Notes: Climate data (1) Atmospheric Environment Service, 1982. Canadian Climate Normals 1951–1980: Temperature and precipitation, the North Y.T. and N.W.T. Environment Canada, Atmospheric Environment Service, Canadian Climate Program, Canadian Climate Centre, Downsview, Ontario, number UDC:551.582(712), 55 pp.

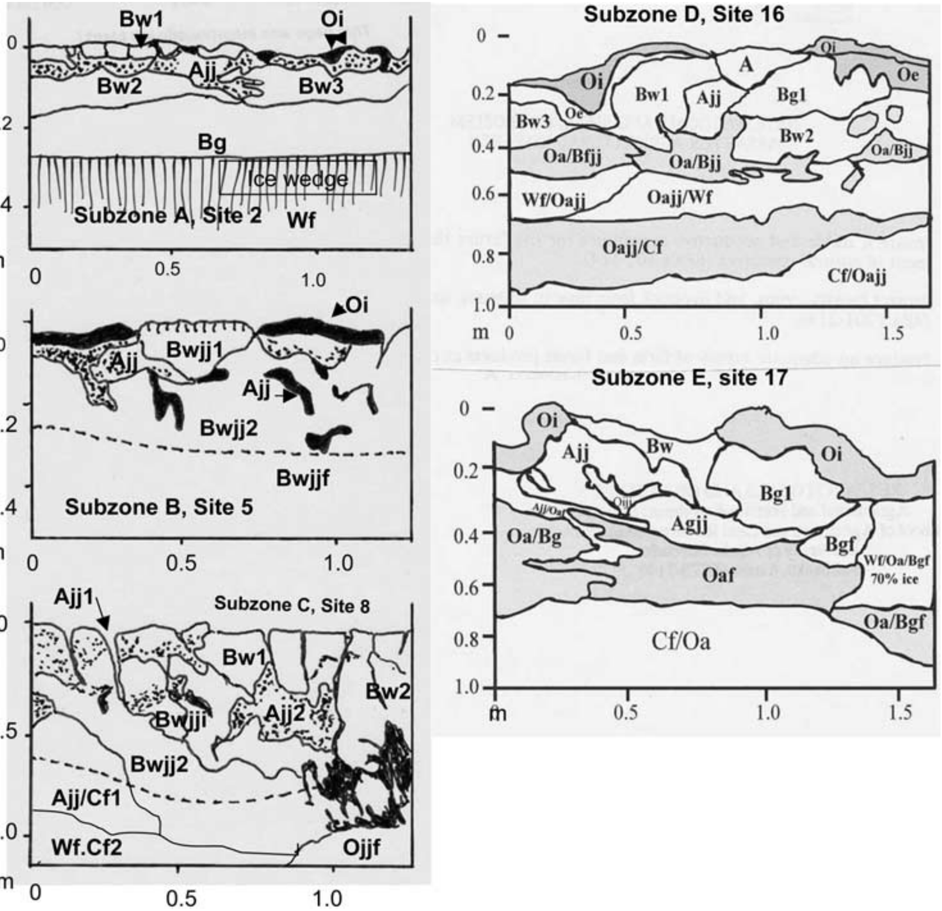

Figure 2. Cryoturbated soil profiles of selected study sites along the bioclimate transect.

well defined because of the scarcity of vegetation; thus their percentage cover can be directly measured either on the ground or from aerial photos. In subzone A as in Isachsen (Table 1), the zonal vegetation site (2) is dominated by small frost polygons and there are only a few scattered nonsorted circles. On the dry site (3), the landscape is dominated by well-defined cracking polygons about 20–30 cm in diameter with very little relief, and the wet site is dominated by turf hummocks. On the adjacent hills dominated by fractured gabbro and sedimentary rocks, sorted circles are rather common, about 10 to 25% of the surface area. A plausible reason for this is that the exposed ridges and high plateaus have high amount of rock fragments but minimum snow cover in the winter so the ground freezes rapidly; a condition favors the formation of sorted circles. On some south-facing terrace surfaces, small cracking polygons occur within well defined stripes of 1.5 m wide and several meters long. In subzone B as in Mould Bay, the zonal site is dominated by small frost circles with higher relief (5 cm) and larger diameters (25–35 cm) with 30 percent of the total area occupied by nonsorted circles. Flat nonsorted circles with diameters 1.5–2 m dominate the dry site on an alluvial fan with coarse-loamy soils. Well developed nonsorted circles with raised centers and a close-packed arrangement dominate the moderately well drained alluvial/colluvial fan with loamy texture. On the lower terrace next to the colluvial fan, earth hummocks occur in clay-rich marine sediment with poor drainage.

[10] Our soils investigation revealed that the apparent percentage of nonsorted circles does not reflect the true density of the cryogenic features in subzone D and E because most of the nonsorted circles are overgrown with vegetation and barely identifiable from the vegetation or microrelief. Once the vegetation cover was stripped, the circles appeared as close-packed network of frost-rings with bowl shaped centers, a condition described early by *Shilts* [1978]. Taking the average size of frost boils at Toolik Lake (site 19) of 1.5 m with 30 cm of organic band overlying an elevated ice-rich ridge at the contact of the ring, there are 36 frost boils in a 9 × 9 m^2 area; 55% of the total area are occupied by frost boils and the remaining 45% is interboils.

3.2. Cryoturbation and Soil Horizonation

[11] Soil horizonation differs among the bioclimate subzones (Figure 2 and Table 2). Surface organic (O) horizons dominate the soils in subzone E and gradually decrease in both thickness and coverage northward in subzone D. In subzone D, the surface O horizons were replaced by a humus-rich A horizon on the drier sites (site 13). In subzone A, B and C, an A horizon formed in the upper active layers around the circles and the top of the circles. Organic horizons generally are very thin (<5 cm) in intercircles of zonal and wet sites.

Table 2. Cryogenic Features and Structures in Studied Soil Profiles Along the Bioclimate Gradient, North America[a]

Site Number	Location Cover Type	Upper Active Layer	Lower Active Layer	Upper Permafrost
1 - A	Isachsen barren	Crust, 3C columnar Bw: 2F subangular blocky	C: 3M lenticular	Frozen fractured shale @56 cm
2 - A	Isachsen Zonal, moist	A, 3F granular, 1M subangular Bw crust, 3C columnar, 3Fcrumbs Int: A: 3F granular, 1m subangular	Bg: 2M lenticular	Ice–wedge @56 cm
3 - A	Isachsen wet	Small hummocks, Ajj 3F granular	Bw, 3M lenticular	Bgf 3Mlenticular, suspended, ice > 60%; ground ice @ 40 cm,
4 - B	Mould Bay barren	Cryptogamic crust, sand wedges, 2F lenticular, broken A at edge	2F lenticular and 2M angular blocky, Ajj	Massive Cf1 @65 cm and suspended Cf2, 65% ice
5 - B	Mould Bay Zonal, moist	Cryptogamic crust breaking into 2M granular, Ajj	1F platy, Ajj	Ice wedge at 65 cm
6 - B	Mould Bay wet	Broken O horizon in interhummock, 2M reticulate	3M reticulate, suspended, 70% ice lens, Oajj	3M lenticular and coarse reticulate
7 - C	Banks Island Barren	Cryptogamic crust into granular, sand wedge and broken Ajj	1M lenticular	Massive frozen @ 88 cm
8 - C	Banks Island Zonal, moist	broken Ajj around NSC, cryptogamic crust into granular, 2F platy and lenticular with 2M angular blocky, open cracks to 30 cm	Massive with streaks of humus and clay intruding upward, Ajj,	Massive frozen @75 cm
9 - C	Banks Island wet	Broken O around NSC, crumbs and salt crust on surface of NSC (sat'd)	Bg: 2F lenticular	Cf: microlenticular, 60% ice at 60 cm
10 - C	Howe Island Barren	Cryptogamic crust with 3M granular, Bw with 2M lenticular and 2C subangular blocky	2M lenticular and reticulate	Cf: frozen @ 80 cm, massive under NSC and ice wedge under intercircle
11 - D	W. Dock WNT	Continuous O horizon over Coprogenous material	Cryotubated O horizon, Oajj	Cf @ 40 cm, ice-rich suspended sediment
12 - D	Prudhoe B. WNT	Broken O around NSC and lenticular in Bw	Reticulate in Bg, cryoturbated O along edge of intercircle and above ice wedge	Ice wedge
13 - D	Franklin Bluff, Dry	Cryptogamic crust into 3M granular, lenticular and Ajj	Reticulate in Bw and Ajj, Oajj along edge of intercircle and at bottom	Massive, frozen @80 cm
14 - D	Franklin Bluff, zonal, moist	Cryptogamic crust into 3M granular, lenticular in Bw broken O and Ajj around NSC	Reticulate in Bg and Ajj, Oajj along edge of intercircle and at bottom	Cryoturbated Oajj in frozen mineral matrix (Oajj/Cf), ice–rich Cf
15 - D	Franklin Bluff, wet	Broken O around NSC, 2F granular in A, 2M lenticular in Bg	1F lenticular in Ajj and 2M lenticular in Bg, Oajj along edge of intercircle and at bottom	Cf @ 60 cm, 1F lenticular and 2C coarse platy
16 - D	Sagwon Hill MNT	Broken O around NSC, cryptogamic crust with 2F granular in A and Ajj, 2M lenticular in Bg and Bw	2Fand M lenticular in Bg, 1F granular in Ajj, Ojj along intrecircle and concentrate at bottom	Cf @ 80 cm, lenticular grading into reticulate suspended, 70% ice, cryoturbated Ojj
17 - E	Sagwon Hill MAT	Broken O around and on NSC, cryptogamic crust with 2F granular, 3F lenticular in Ajj, Bw, 1M subangular in Bgjj	Cryoturbated O along edge of NSC and concentrated at bottom, 3M lenticular in Bg	Ojj/Cf @ 50 cm, 3M lenticular, suspended, Ice–rich Cf@80–100 cm, microlenticular
18 - E	Happy Valley MAT	Broken O around and on NSC, freshly exposed mineral soils in the middle of NSC, 1M subangular in Bgjj	Cryoturbated O along edge of NSC and concentrated at bottom,3M lenticular in Bg and Oajj,	Ojj/Cf @ 45 cm, 3M lenticulate and suspended wit Oajj, 40% ice wedge
19 - E	Toolik Lake MAT	Broken O around and on NSC, freshly exposed mineral soils in the middle of NSC, 1M lenticular in Bgjj and Bwjj	Cryoturbated O along edge of NSC and concentrated at bottom,3M lenticular in Bg and Oajj,	Oajj/Cf @ 45 cm. medium and coarse reticulate and suspended in Cf, microlenticular in lower Cf, ice–rich > 50%

Table 2. (continued)

Site Number	Location Cover Type	Upper Active Layer	Lower Active Layer	Upper Permafrost
20 - E	Imnavit Creek MAT	Broken O around NSC and stripes,	Cryoturbated Oajj below intercircle and concentrate at bottom, 2M reticulate	Cf @ 50 cm with ice rich reticulate, Oajj
21 - E	Galbraith LK WNT	Mounded NSC, desiccation cracks with 3C columnar breaking into 3M granular, 2M lenticular in Bw, broken O around the mound	3M and C lenticular and subangular blocky in Bg	Cgf @ 80 cm, ice–rich reticulate and suspended, 1/3 ice wedge
22 - E	Chandalar Shelf, Shrub tundra	Mounded NSC with 3M granular in top rooting zone (A), 1F lenticular and 2M subangular blocky in Bw	2M lanticular in Bg, cryoturbated Oajj at bottom	Cf @70 cm, microlenticular
23 - E	Parsons Lake Shrub tundra	Thin broken O on top of hummock, broken Ojj in interhummock depression, streaks of Ajj intruding upward in Bw, 2M granular	2F subangular blocky to 2F granular in Bwjj; cryoturbated Ojj and Ajj, granular	Cf: frozen at 70 cm suspended, 60% ice. Cf @ 50 cm interhummock

[a]Notes: Structure expression and size follow *Soil Survey Division Staff* [1994]; example, 1F granular, where 1, 2, and 3 stand for weak, moderate, and strong, respectively; F, M, and C stand for fine, medium, and coarse, respectively. O, A, B, and C horizons stand for organic, humus-rich mineral, altered by weather, and substratum horizons, respectively. The subscripts of w, f, and jj stand for weathered, frozen, and cryoturbated, respectively.

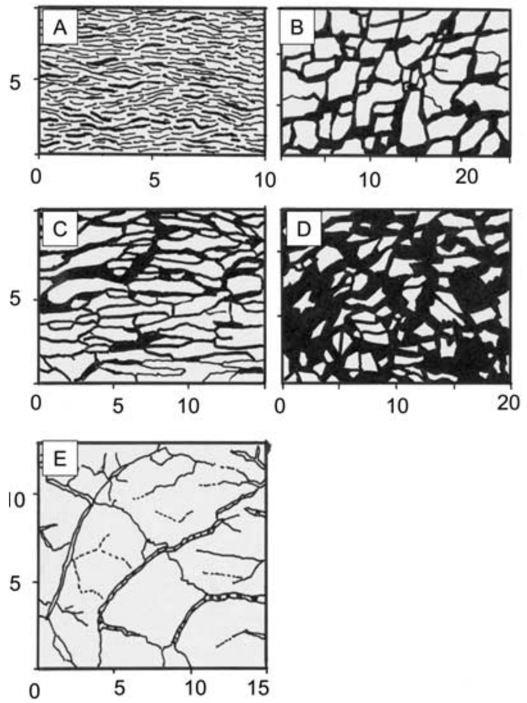

Figure 3. Cryogenic structures; (a) microlenticular, (b) reticulate, (c) lenticular, (d) suspended (ataxitic), and (e) ice net appears on top of frozen layer (all scale are in cm) and ice lens in black.

3.3. Soil Structure and Cryostructures

[12] The cryogenic features/structures of the soils studied along the gradient are summarized in Table 2 and the commonly encountered cryostructures are shown in Figure 3. Soil structure can be observed in thawed and generally unsaturated soils whereas cryostructure can only be observed in frozen soils. The kinds and forms of cryostructure reflect the cryogenic processes in the active layer.

3.3.1. Crumb Soil Structure

[13] The crumb structure has the appearance of bread crumbs. It was found along the studied transect on the surface of exposed mineral soils that usually are associated with sorted and nonsorted circles that lack vegetation cover. It can also be found on sites that have been disturbed by removal of the organic horizons and by seasonally soil freezing. Thus crumb structures are found not only in the permafrost-affected regions but also in areas with seasonal soil freezing. The size of the crumbs varies from 2 to 8 mm. Some soils have crust-like surface horizon that consists of aggregated fine granular structures. The crumb structure usually forms a thin layer on the surface, less than 1 cm thick with the morphology of an A horizon and has a consistence of soft when dry and very friable when moist. In most of the nonsorted circles (frost boils) studied, the soil under cryptogamic crusts are composed of crumbs. The crumbs have a very friable moist consistence in medium textured soils, i.e., they are easily destroyed by disturbance.

3.3.2. Granular Structure

[14] In permafrost-affected soils, granular structures are found on the surface horizons under tundra vegetation cover, especially on loamy, well-drained, convex-shaped

centers of nonsorted circles (sites 2, 5, 7, 10, 13, 14, and 16) and the surface horizons (usually A) of hummocks (sites 22 and 23) The elements of granular structures have a nearly rounded shape usually from 3 to 5 mm in diameter with a firm moist consistence. Thus they differ from the crumb structure by their more rounded shape and firmer consistence.

3.3.3. Platy Soil Structure and Lenticular Cryostructures

[15] Along the transect, platy structure is most common in upper mineral soil horizons and lenticular cryostructure (Figure 3c) is the dominant cryostructure in the active layers when frozen. They are better developed in the zonal and wet sites than the drier sites. The thickness of platy structure generally ranges from 1 to 4 mm and both moist and dry consistence are friable. In frozen state, the lenticular cryostructures were separated by ice lens ranges from less than 1 to 2 mm thick. Occasionally the horizon with platy structure may be separated by thicker ice lenses up to 1 cm. The visible ice content in platy structure-dominated horizons generally is less than 30%. The dimension of the lenticular structures ranges from 2 to 8 mm thick and 7–15 mm long. Ice content ranges from 30 to 50%. Soil with lenticular structure usually has a moist consistence of friable to slightly firm and very firm when frozen.

3.3.4. Massive Structure

[16] Massive and coarse platy structures with or without ice lenses were found in the middle active layers and upper permafrost of well-drained sites along the transect (Table 2). Often sublimation ice, ice that crystallizes in open cavities, was found in these structures. The massive and coarse platy structures and sublimation ice usually are found in the middle active layers of the well-drained sites and frozen organic layers. The ice content is usually <20% in frozen state and most of it is pore ice. The vertical dimension of the blocky structure is greater than the horizontal.

3.3.5. Reticulate Cryostructure and Ice Nets

[17] Ice nets are formed by vertical or diagonal desiccation cracks due to freeze back in early winter. The cracks forming the polygons can be viewed from the top of the excavated soil pit in late summer (Figure 3e). The diameters of most polygons range from 2 to 5 cm. Cracks are filled with sublimation or segregation ice in winter. Then the vertical or diagonal cracks are further dissected by horizontal ice lenses resulting in reticulate structure (Figure 3b) as defined by an ice net. The ice net leaves a strong medium to coarse angular blocky soil structure after thawing. The vertical axis of the blocky structure is usually longer than the horizontal axis. This blocky structure usually appears at the permafrost table over the top of the suspended ice-rich layer. In areas where there is more water in the lower active layers due to either the topographic position or percolating water from the late fall precipitation, horizontal ice lenses forms due to upward freeze-back from the permafrost table. The soil structures left after the ice melting are blocky. The thickness of the ice vein/lens ranges from 1 to 3 mm and the ice content of the horizon dominated by reticulate structure ranges from 30 to 50%. Reticulate cryostructure is common to soils in the zonal and most wet sites and not common on dry sites along the transect (Table 2).

3.3.6. Suspended (Ataxitic) Cryostructure

[18] After repeated freeze-thaw cycles, more water accumulates and both vertical and horizontal ice veins/lens become thicker and eventually the ice contents exceeds 50% and up to 70%. The remaining mineral soil masses in reticular shape appear suspended in an ice matrix (Figure 3d). The suspended structure is commonly found in most soils of mesic and wet tundra sites of all subzones and some drier sites as in subzones C and D. This structure invariably occurs right on top of the permafrost table and often found on top of ice wedges.

3.3.7. Microlenticular Cryotructure

[19] The microlenticular structure (Figure 3a) is characterized by alternating very thin ice lenses and soil, usually <2.0 mm thick, and ice content is greater than 60%. The thin ice lens and soil plates appear to be slightly wavy but generally continuous and in some cases they maybe cross-bedded. Thus these horizons have either thin platy or lenticular structure. It usually has an extremely firm consistence when excavated. Along the transect it was found in the Cf horizons of the hummock site (3) in subzone A and the loess-derived soils in subzones C-E. It occurs in loamy textures soils but not in sandy or clayey soils.

3.4. Soil Color

[20] The soil colors were recorded according to Munsell Color in Table 3 but only descriptive terms are given in the text. Soil colors in the upper part of the active layers of patterned grounds, mostly nonsorted circles, have brighter colors indicating some degree of oxidation (Table 3). In subzones C to E, the surface O horizons generally have a dark brown to black color indicating the high organic carbon content. The color of organic horizons reflects the source plants and degree of decomposition. In subzones E and wet sites of subzone D, where the biomass is derived from mosses, the organic horizon tends to be reddish brown and where the biomass was derived from herbaceous vegetation the color tends to be darker. The cryoturbated organics have similar colors regardless of depth. On the mesic sites in subzones A to C, the surface horizons are dominated by dark mineral A horizons. The cryoturbated A horizons have the same values and chroma but tends to be more gray as indicated by 2.5Y hue because of periodical wetness beneath the surface.

3.5. Active Layer Dynamics

[21] There is a general trend of increased active layer depth from subzone A to C then decrease in subzone D and E (Table 3). The active layer depth in subzone A and B ranges from 33 to 42 cm in interboil areas and 44 to 49 under the frost boil. The active layer in subzone C at Green Cabin increased to 70 cm due to its position on a drier site.

[22] Then from subzone C the active layer decreased to 40 cm at the southern end of the bioclimate gradient in subzone E. The 2 sites monitored by the LTER program near Fairbanks in the boreal region were listed for comparison. Under the black spruce the active layer depth averaged from 43 to 50 cm.

4. Discussion

4.1. Cryoturbation and Patterned Ground

[23] The intensity of cryoturbation can be measured in several ways. It can be measured by the surface expression of patterned ground features by determining the percentage cover of patterned-ground features in a specific area.

Table 3. Soil Color and Redoximorphic Features of Studied Soil Profiles Along the Bioclimate Gradient[a]

Site Number and Subzone	Location Cover Type	Soil Horizon, Munsell Color, and Redoximorphic Features		
		Upper Active Layer	Lower Active Layer	Upper Permafrost
1 - A	Isachsen barren	Surface A, 10YR3/2; Bw, 10YR4/3	Bg, 10YR3/2	Frozen fractured shale, N2/0
2 - A	Isachsen Zonal, moist	Surface A, 10YR3/2; Bw, 10YR4/3	Bg, 10YR3/2, $\alpha\alpha$D+	Ice–wedge
3 - A	Isachsen wet	Surface Ajj, 10YR4/3, 3/2	Bw, 10YR4/3	Bg 10YR4/2, $\alpha\alpha$D++
4 - B	Mould Bay barren	Surface A, 10YR4/3 Intercircle surface A, 10YR4/2; Bw 10YR4/4; Ajj 10YR3/2	BC 10YR5/6, 5/2, 4/4 Fe conc. and depletions in masses	Cf1 10YR4/1; Fe–depletion 2.5Y4/1; Mn–conc. 10YR2/1
5 - B	Mould Bay Zonal, moist	Surface Bw (crust) 10YR4/4; Ajj 10YR3/1; intercircle Bw 10YR4/4; Ajj 10YR3/2	Bw 10YR3/2; Ajj 10YR2/1	Cf 2.5Y3/1, 4/1, depleted matrix, $\alpha\acute{a}$D++
6 - B	Mould Bay wet	Hummock surface O, 7.5YR2.5/3; interpattern O, 7.5YR2.5/1; Bg 2.5Y4/1, 4/3 as pore lining in Bw 10YR4/3; Bg matrix 5Y5/1; Bg $\alpha\alpha$D++	Bg matrix 5Y4/1; Ajj 10YR2/1; Ojj 10YR3/1; Bg $\alpha\alpha$D+++	Cf, 5Y4/1, $\alpha\alpha$D+++, Ojj 10YR3/1
7 - C	Banks Island Barren	Surface A (crust) 10YR 4/3; Ajj 10YR 3/3; Bwjj 2.5Y4/4, 4/3	Bwjj 2.5Y4/4, 10YR5/3, 4/3	Cf, 10YR4/3 Ajj 10YR3/2
8 - C	Banks Island Zonal, moist	Ajj 10YR3/2; Bwjj 2.5Y4/4 (crust)	Bwjj 2.5Y4/2; Ajj 10YR2/1	Cf 2.5Y4/2; Ajj 10YR2/1
9 - C	Banks Island wet	Surface O, 7.5YR3/2; NSC Bk, 10YR6/2; Bw 10YR4/3	Bw 10YR4/3, 2.5Y5/3; Ajj 10YR3/2	2Cf, 2.5Y5/1
10 - C	Howe Island Barren	NSC crust 2.5Y4/2, intercircle A,10YR3/2	Bwjj 10YR4/2 Oajj 7.5YR3/2	Cf 2.5Y4/1
11 - D	W. Dock WNT	Surface O, 7.5YR2.5/1	Bg 5Y4/1, 2.5Y3.5/1 Reduced matrix, $\alpha\alpha$D+++	Cf 5Y4/1, $\alpha\alpha$D+++
12 - D	Prudhoe B. WNT	NSC 2.5Y3/3; intercircle O, 7.5YR2/1; Bg, 2.5Y 4/2	Bg, 2.5Y	Cf, 5Y4/1
13 - D	Franklin Bluff, Dry	NSC surface A, 10YR2/2 Bw 10YR3/3	Bw 10YR4/3; Bg2.5Y3/3	Cf
14 - D	Franklin Bluff, zonal	NSC surface A, 10YR3/2; intercircle O, 7.5YR2.5/1	Bg2.5Y3/2	Cf 5Y4/1
15 - D	Franklin Bluff, wet	NSC A, 2.5Y3/2; intercircle O, 10YR2/2; Bg5Y4/2,4/1, $\alpha\alpha$D+++	Bg2.5Y3/2; $\alpha\alpha$D++, mottles 10YR4/4, 3/1, 2.5Y3/2; Ajj 10YR3/1	Ojj 10YR2/2
16 - D	Sagwon Hill MNT	Surface O, 7.5YR2.5/1; Bw10YR4/2, 5/6 Fe-conc. in pore lining;; Ajj10YR3/2	Bw 10YR3/2, 2.5Y3/2, Fe-conc. 7.5YR4/6 pore lining; Ojj10YR2/1	Ojj 7/5YR3/2; Bgf, 2.5Y4/1, 3/1 in matrix
17 - E	Sagwon Hill MAT	NSC surface A, 2.5Y5/4; intercircle surface O, 10YR2/1; Ajj 10YR3/2; Bwjj 10YR4/3Fe-conc. 10YR4/6; $\alpha\alpha$D++	Bwjj 10YR4/3, 3/2; Fe conc. 10YR4/6 as pore lining; Ojj 10YR2/1; $\alpha\alpha$D+++	Bgf, 2.5Y5/1, 3/2; $\alpha\alpha$D+++; Ojj 10YR3/2
18 - E	Happy Valley MAT	Surface O, 10YR2/1; Bw, 2.5Y5/4; 10YR5/2 pore lining; Bg	Bg 10YR4/2; Fe-conc. 10YR3/6 pore lining; Ojj 10YR3/2; $\alpha\alpha$D++	Cf 2.5Y3/3; $\alpha\alpha$D+++; Ojj 10YR2/2, 2/1, 3/2.
19 - E	Toolik Lake MAT	Surface O, 10YR2/1; Bw, 2.5Y5/4; Fe-conc. 10YR4/6, Fe-deletion 5Y4/2 as pore lining;	Bg 2.5Y4/2; Fe-conc. 10YR4/6 pore lining; Ojj 10YR3/2; $\alpha\alpha$D++	Cf 2.5Y4/1, $\alpha\alpha$D++
20 - E	Imnavit Creek MAT	Surface O, 7/5YR2.5/2	Bg2.5Y4/2	Cf 2.5Y3/1, $\alpha\alpha$D++
21 - E	Galbraith LK WNT	NSC crust Bw, 2.5Y3/1, 3/2; Surface O around NSC 7.5YR3/2; Bk 7.5YR4/1, 10YR5/8, 6/2; $\alpha\alpha$D++	Bg 5Y4/1, 2.5Y3/2, 3/1; $\alpha\alpha$D+++	Cf 2.5Y4/1, $\alpha\alpha$D+++
22 - E	Chandalar Sh	A on hummock 10YR3/2; O around hummock 7/5YR2.5/2, Bw 10YR4/3	Bg 2.5Y4/2	Cf 5Y4/1
23 - E	Parsons Lake mesic	Hummock surface O 10YR2/1; interhummock Ojj 5YR3/2; Bw 2.5Y3/2	Bwjj 10YR3/2; Ojj 5YR3/1, N2/0; Ajj 10YR2/1	5Y3/2

[a] Notes: NSC, nonsorted circle; $\alpha\alpha$D, α,α-Dipyridyl; +, slightly reactive; ++, moderately reactive; +++, strongly reactive.

According to *Chernov and Matveyeva* [1997], small frost cracking polygons dominate subzone A and larger polygons form with increasing vegetation growth and more pronounced development of nonsorted circles toward subzone E, so there are fewer patterned-ground features per unit area toward the south. This method, however, mixes patterned ground developed by cracking with patterned-ground developed by frost heave and other processes. Also the surface expression is not necessarily an accurate representation of the total area affected by the patterned-ground features because toward the south the vegetation often masks the features. *Walker et al.* [2004] found that the total percentage of vegetated and nonvegetated frost boils declined southward from 25% at Howe Island (subzone C) to 5% at Sagwon MAT and 13% at Happy Valley (subzone E). In an early study, *Bockheim et al.* [1998] indicated that percentage cover of frost boils at Sagwon MNT (subzone D) is more than that of Sagwon MAT (subzone E). However, our results indicated otherwise because of the masking effect of the vegetation cover and this agrees with the early findings of *Shilts* [1978]. The total surface of the close packed frost boils in subzone E accounts for more than 50% of the total land surface area.

[24] In summary, the relative proportion of the patterned grounds on each particular sites is more dependent on soil moisture, the zonal condition favor the development and sustaining of the nonsorted circles. The size and relative relief of the nonsorted circles and hummocks across do not follow the climate gradient; rather, they are closely related to clay content [*Michaelson et al.*, 2008]. This is not surprising in that clay has more cohesive force and the consistence to maintain the shape of earth hummocks or the bulged center of the nonsorted circles [*Ping et al.*, 2003]. Whereas soils with coarser textures, such as sandy loam, has less viscosity thus end up with flat circles.

4.2. Cryoturbation and Soil Horizonation

[25] One of the most striking features of cryogenic soils is the cryoturbated soil profile in that the surface organic horizons and the underlying mineral horizons are broken across the interface of nonsorted circles and adjacent tundra, the surface organic masses are "dragged" downward at the edges of the nonsorted circles discrete masses of organics are mixed in a mineral matrix, the cryoturbated organic matter are concentrated in upper permafrost, clay-rich layers intrude upward, and cryostructures form in the frozen part of the profile [*Tarnocai and Smith*, 1992; *Hoefle et al.*, 1998; *Ping et al.*, 1998, 2004].

[26] Because of the apparent colors of the O and A horizons against the mineral horizons, the cryoturbated O or A horizons serves as an indicator of the degree of cryoturbation. From subzone E to A there is a decreased trend of cryoturbated organic rich materials into the lower and upper permafrost (Table 2 and Figure 2). In the zonal and wet sites in subzone A, there is very little or no cryoturbated organics but most of the organic rich materials are on the surface and in the cracks of the small frost polygons. A plausible explanation for this trend is the water content of the active layers during freezeup. The surface or upper active layers in the High Arctic desiccate rapidly and crack - thus limiting the frost-churning process. In subzone D and E, most of the cryoturbated organics are organic in nature (%C > 15% for loamy soils) but in dry and zonal sites in subzones A through C, the cryoturbated organic rich material is humus-rich mineral (A) horizons. Such a change across the bioclimate gradient reflects the quantity (%C) and quality (O versus A horizons) of organic matter accumulation as affected by the vegetation type and biomass production under the cold and dry environment.

4.3. Cryogenic Structures and Cryopedogenesis

[27] In soils of the temperate regions, soil structure in the surface (A) horizon, are typically produced by soil invertebrates while in the subsurface (B) horizon, are produced by shrinking and swelling due to the wetting and drying of clay minerals. In contrast, in the arctic tundra soil structures are mainly the result of freezing and thawing and formation and melting of ice lenses. The thaw depth reaches the maximum in September and persists till the end of October or early November [*Reiger*, 1982], but most field work is done during the summer. Thus an analysis of the cryostructure can help identify cryogenic processes, such as water movement during freezing, and infer the cryostructures present in other seasons. The structure faces and cleavages in soil after thawing of ice lenses provide passages for water and air thus enhance biogeochemical weathering.

4.3.1. Crumb Structure and Needle ice Formation

[28] The primary mechanism of crumb structure formation is needle ice formation [*Washburn*, 1973; *Williams and Smith*, 1989]. Needle ice often develops on the surface of the ground during night frosts mainly in autumn. They may reach several cm in length, and often coarse size aggregates occur on the top of the vertical ice crystals. Elongation of the crystal is perpendicular to the cooling surface, commonly producing nearly vertical ice needles on a horizontal surface. There may be several tiers of needle ice separated by a thin layer of mineral soil, each tier representing a different freezing cycle. Soil particles lying on the ground surface can be lifted by needle ice crystals and then fall to the ground surface when thaw commences. In the investigated areas, crumb structures are found to form in soils with medium textures ranging from sandy loam to silt loam but never in clayey soils. This agrees with *Gradwell's* [1954] finding that needle ice was best developed in loamy soil where fines exceed 30% but high content of fines may inhibit needle ice formation.

4.3.2. Granular Structure and Bioturbation

[29] The formation of granules requires alternate freeze and thaw with bioturbation from the dense herbaceous roots. The granules appear to be coated or mixed with humus as indicated by dark gray colors. The mineral soils below the organic horizons first form a platy structure due to ice lens formation. The platy structures are then broken into pieces due to horizontal stress during refreezing. Then the broken plates are moved around by the root mat action and gradually become spheroidical with repeated freeze-thaw cycles [*Gubin*, 1993]. Thus the formation of granular structures in arctic tundra soils is the combined effects of cryogenesis and bioturbation and conditioned by hydrological conditions. The moist acidic tundra generally is wetter and poorly drained, the granular structures are found only as a thin layer (usually <1 cm) between the vegetation mat and the underlying mineral soils in nonsorted circles (frost boils) with a lighter color. The longer period of saturation during

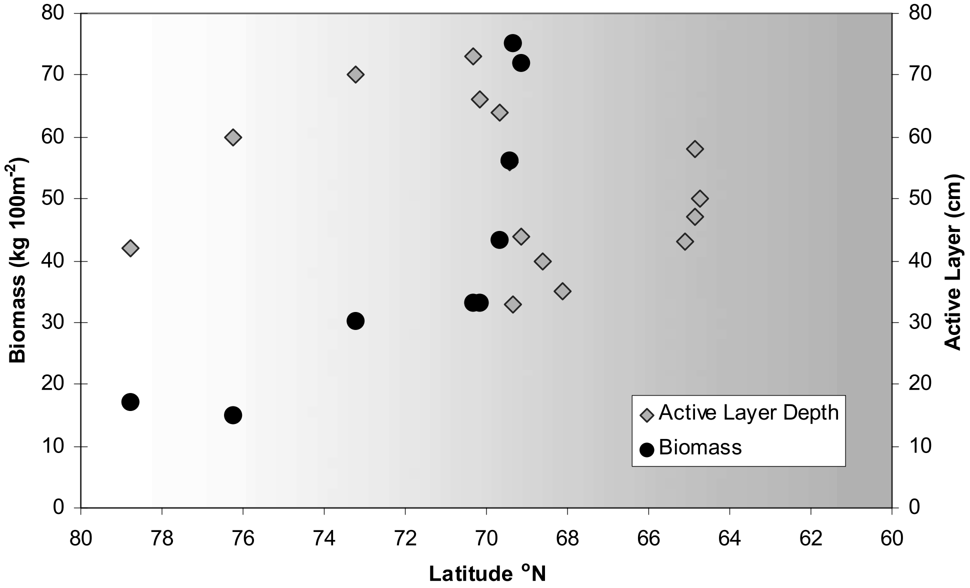

Figure 4. Relationships between active layer depth and latitudes, active layer and organic layer thickness and biomass production along the bioclimate gradient, Arctic North America.

the growing season in moist acidic tundra deters the formation of granules. Although the granular structures in the arctic and the temperate regions share similar shape and size but their formations are different. Granular structure forms in the temperate regions as a result of bioturbation, mainly due to soil fauna.

4.3.3. Platy and Lenticular Structures and Ice Lens Formation

[30] Platy structure is most common in upper mineral soil horizons in both seasonally and permafrost-affected soils. Platy structures in frost-affected soils form due to ice lens formation. Ice lenses form perpendicular to the direction of freezing front advance, thus their orientation is generally parallel to the ground surface. When soils at the ground surface start to freeze, water, either in liquid or vapor forms, moves toward the freezing front and form a thin layer of ice. At the same time a thin layer or finer particles may move with the freezing front and concentrate at the bottom of the thin layer [*Reiger*, 1982]. More ice lenses form as the frost penetrates deeper. Soil aggregates become somewhat orientated as a result of repeated freeze-thaw cycles. Thus the plates appear to have "memory" and maintain its shape year after year [*Reiger*, 1982]. The platy structures are fractured into discontinuous and curved lenses due to horizontal stress caused by volume change from ice lens formation. Owing to its slightly curved shape, this is referred to as "fish scale" structure in the Chinese literature [*Qiu and Cheng*, 1993]. Lenticular structure forms in both upper and lower parts of active layers. In frozen state lenticular fabrics are separated by not only horizontal ice lenses but also by diagonal ice veins. The combined horizontal and vertical or diagonal ice lenses from an ice net (Figure 4).

4.3.4. Massive Structure and Sublimation Ice

[31] In areas with cold permafrost, water in the freezing active layer moves to two freezing fronts in soils during freezing at the end of fall and early winter; one from surface and the other from permafrost table. Thus a desiccation zone is formed in the middle of the active layer resulting in a massive soil structure with the lowest water contents. However, this two-front freezing process does not totally remove all the water and sometimes ice accumulates in the contraction cracks that run vertically and horizontally. Thin ice veins and ice lens with a spacing of 4–6 cm are often found. As a result, coarse blocky or platy structures may form and the frost cracks are filled with sublimation ice, an indication of vapor movement.

4.3.5. Reticulate and Ice Net Formation

[32] Ice nets are formed by vertical or diagonal desiccation cracks due to freeze back in early winter and the cracks form polygons as viewing from the top of the excavated soil pit (Figure 3e). The diameters of most polygons range from 2 to 5 cm. In winter, cracks are filled with sublimation or segregation ice in winter. Then the vertical or diagonal cracks are further dissected by horizontal ice lens resulting in reticulate cryostructure (Figure 3b) as defined by an ice net. The ice net leaves a strong medium to coarse angular blocky soil structure after thawing. The vertical axis of the blocky structure is usually longer than the horizontal axis. This blocky structure usually appears at the permafrost table over the top of the suspended ice-rich layer. In areas where there is more water in the lower active layers due to either the topographic position or percolating water from the late fall precipitation, horizontal ice lenses form due to upward freeze-back from the permafrost table. The thickness of the ice vein/lens ranges from 1 to 3 mm and the ice content of the horizon dominated by reticular structure ranges from 30 to 50%. Reticulate cryostructure is common to soils in the zonal and most wet sites and not common to dry sites along the transect (Table 3). Since the reticulate cryostructure is caused by back freeze from the permafrost table, it remains frozen in normal years but can be part of the lower active layer during years when the active layer depth is greater than average.

4.3.6. Suspended (Ataxitic) Cryostructure

[33] The Russian geocryologists and cryopedologists have named this cryostructure as "ataxitic" [*Shur*, 1988] and also-called "suspended" aggregates [*Murton and French*, 1994]. Early studies summarized by *Murton and French* [1994] indicate that suspended cryostructures are common in the layer of the upper permafrost, with ice lenses thickness ranging from about 0.5 to 1.5 cm. This so-called intermediate layer [*Shur*, 1988] is rich in aggradational ice and is formed due to the decrease of the active layer thickness with development of the organic horizons at the soil surface. Some buried horizons also have ataxitic structure. The ataxitic cryostructure is considered as a late stage of reticulate cryostructure development.

4.3.7. Microlenticular Structure

[34] This is typical for syngenetic permafrost which develops simultaneously with accumulation of loess or other sediment. The permafrost table gradually rises due to thickening of the overburden deposits [*Zhestkova*, 1982]. It is typical for Late Pleistocene syngenetic permafrost as observed and recorded in this study. The Cf horizon at 80–100 cm of site 17 has microlenticular cryostructure with a radiocarbon dates of 12,740 YBP [*Ping et al.*, 1997b].

4.4. Soil Color, Redoximorphic Features, and Drainage

[35] Soil color is one of the most useful diagnostic soil properties. It reflects the lithology of the parent material, the organic matter contents, kinds and degree of weathering such as the reducing and oxidation (redox) conditions, hydrology and sometimes salt contents [*Soil Survey Division Staff*, 1994]. Soil colors and redoximorphic features of the study sites are summarized in Table 3.

[36] The cambic horizons (Bw) in the upper active layers generally have a brownish color indicating less organic influence but oxidized iron. In early studies those arctic soils with brownish B horizons were called "Arctic Brown" soils [*Tedrow*, 1974]. However, most of these Bw horizons experience saturation in the early growing season then desaturation in later part of the growing season thus the alternate wet and drying process permits reducing and then oxidation reactions. The net result is redoximorphic features that include Fe concentration in masses (rusty or reddish mottles) and Fe depletions (grayish masses or around root pores). In the early growing season when the upper active layers are either saturated or wet because of the perched water table above the seasonal frost, the reducing condition in the mineral soils in the poorly drained sites all tested positive to α,α-dipyridyl that reacts with ferrous iron to produce a reddish color [*Childs*, 1981]. In contrast, during the middle or late growing season, a test on the same soils was either weak or negative because of the drop in the water table.

[37] In the lower active layers the soils are more grayish than those of the upper active layer because of increased degree of reduction due to their approximate closeness to the permafrost table. The gleyed matrix color of the Bg horizons in the lower active layers indicates most of the free iron are reduced. Some of the Bg horizon have stronger redoximorphic features with reddish ferric Fe concentration filling the root pores. In the field, all the Bg horizons tested α,α-dipyridyl positive indicating the lower active layers experience prolonged saturation and only occasionally desaturation during the growing season.

[38] The colors of the upper permafrost are gray to bluish gray because these layers are constantly under anaerobic or reducing condition. The frozen samples often developed strong red color when in contact with the α,α-dipyridyl dye indicating active biogeochemical processes under frozen conditions. This is possible because of the presence unfrozen water in permafrost [*Reiger*, 1982] and the active microbial activities under subzero temperatures [*Michaelson and Ping*, 2003]. The freshly exposed frozen organic matter often has a reddish color. But once it is exposed to the air for more than 20–30 s the color turns black indicating the presence of reduced Mn (Mn^{2+}) that quickly oxidized to Mn^{5+}.

[39] Soil color in arctic soils affected by ice-cemented permafrost have one common feature gleyed lower active layers; with or without redoximorphic features, and mottled upper active layers. These features are evidence of hydromorphism and constitute aquic condition in which elements (Fe, S and C) were reduced coupled by oxidation of organic carbon under an anerobic condition induced by saturation above the permafrost or seasonal frost [*Ping et al.*, 1993]. In Soil Taxonomy [*Soil Survey Staff*, 2006], there are two aquic conditions recognized; epiaquic that is caused by surface water, and endoaquic caused by groundwater at depth below 1 m. However, along the entire gradient, this reducing condition and redoximorphic features always showed up at 40–80 cm, right above and in the upper permafrost. The formation of this aquic condition caused by permafrost is different from either the epiaquic or the endoaquic conditions and we propose the term "geliaquic" referring to the aquic condition caused by permafrost.

4.5. Biotic Factor in Cryopedogenesis and Active Layer Thickness

[40] The biotic factor contributes to soil formation in the arctic environment in both biogeochemical and physical processes. Biogeochemically, the accumulation and decomposition of organic matter play a controlling role in the weathering of mineral soils and the resulting soil chemical properties [*Ping et al.*, 1998, 2005]. The accumulation of surface organic matter and subsequent cryoturbation that leads to the churning of organics to deeper parts of the soil profile thus sequesters the organic carbon and protects it from further decomposition. This is the reason that the Arctic tundra has such major terrestrial carbon storage [*Michaelson et al.*, 1996]. The organic matter contributes to the binding of soil aggregates as mentioned in a previous section. But the most notable effect of organic matter is the dynamic relationship between surface organic layer and the active layer. Theoretically, the active layer thickness would increase southward due to increased temperature. However, the depth of active layer reached a maximum in subzone C then it decreased further south (Table 3 and Figure 4). The relationship between active layer depth and surface layer thickness (Figure 4) generally follows the latitudinal trend (Figure 4). However, surface organic layer thickness increased with biomass production (Figure 4). Such relationships indicate that with scarce of vegetation cover in the subzone A through C, the active layer increases southward due to increased temperature. The n-factor, which is the

ratio of the thawing degree-day sums at the mineral soil surface to that in the air, reflects the insulative effect of vegetation and soil organic matter on mineral soils in the summer, and the insulative effects of snow in the winter. The O horizon will increase the n-factor thus reducing the active layer thickness and amount of frost heave [*Kade et al.*, 2006]. The result is that a southward increase in mean temperature is counteracted in the soils by increasing biomass, which mutes any north-south trend in active layer thickness.

5. Conclusion

[41] Cryopedogenesis is the soil formation processes affected by permafrost and frost heave. The processes are reflected by a cryoturbated soil profile and formation of cryogenic structures. Cryoturbation as expressed on soil morphology increased along the bioclimate gradient from the north to south. Frost-churned organic and A horizons provided the evidence for cryoturbation due to their color and texture differences.

[42] Soil structures are derived mainly from cryogenesis rather than biotic activity or wetting/drying cycle. Soil structure (aggregation of soil when thawed) mimics the form of the cryostructures (the occurrence and orientation of ice). These structures are quite uniform across the wide latitudinal range of our transect. Cryogenic structures reflect the local hydrology rather than the position along the gradient. Well developed cryostructures are found in zonal and wet sites because there is adequate water supply for ice lens formation which is the key to the cryostructure development. Thus soil formation in the Arctic can be characterized by cryoturbated profiles with warped or broken horizons, weak weathering as indicated by soil color and redoximorphic features, accumulations of surface organic matter or humus and translocation of them to the lower active layers and upper permafrost through frost-churning and in the case of the High Arctic, through accumulation in between the frost cracks.

[43] Soil color reflects the degrees of weathering of the mineral soils. Owing to the cold climate, only weak cambic (Bw) formed in the upper active layers dominated by mineral soils. Gleyed horizons (Bg) are common to lower active layers due to the reducing condition caused perched water table on permafrost. Such aquic conditions (requiring both saturation and reduction) persist through out the gradient in all the mesic and wet sites and some dry sites. The aquic conditions developed in soils affected by permafrost differ from that caused by topographic positions in the temperate regions.

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