Chapter 2. Cryosols in Alaska

Chien-Lu Ping[1], Mark H. Clark[2], and David K. Swanson[3]

[1]Professor, University of Alaska, Agric. & Forest Exp. Station, 533 E. Firewood, Palmer, Alaska 99645, USA; e-mail pfclp@uaa.alaska.edu.
[2]Soil Scientist, USDA - Natural Resources Conservation Service, 800 W. Evergreen Avenue, Suite 100, Palmer, Alaska 99645; e-mail mclark@ak.usda.gov.
[3]Ecologist, USDA Forest Service, P.O. Box 907, Baker City, Oregon 97814, USA; e-mail dkswanson@fs.fed.us.

1. Introduction

Permafrost, or perennially frozen ground, covers $9x10^5 km^2$ or 55% of the landmass of Alaska. The continuous zone of permafrost encompasses the physiographic subdivisions of the Arctic Coastal Plain, the Arctic Foothills, the northern Norton Sound Highlands, and the Brooks Range. The zone of discontinuous permafrost encompasses the physiographic subdivisions of the Interior Alaska Lowlands, the Interior Alaska Highlands, the Alaska Range, the Copper River Plateau, the Kuskokwin Highlands, the southern Norton Sound Highlands, and the Western Alaska Coastal Plains and Deltas (Wahrhaftg, 1965; Péwé, 1975) (see Figure 2.2.1).

The term *Cryosol* is used in this paper synonymously with *perennially frozen or permafrost-affected soils*. In the US soil classification system, *Soil Taxonomy* (Soil Survey Staff, 1999), Cryosols or permafrost-affected soils key out at the Gelisol Order. Gelisols are defined as soils having permafrost within 100 cm of the soil surface or having gelic materials within 200 cm of the soil surface. Gelic materials are defined as mineral or organic soil materials that show evidence of cryoturbation and/or ice segregation in the active layer and/or the upper part of the upper permafrost (Bockheim et al., 1997).

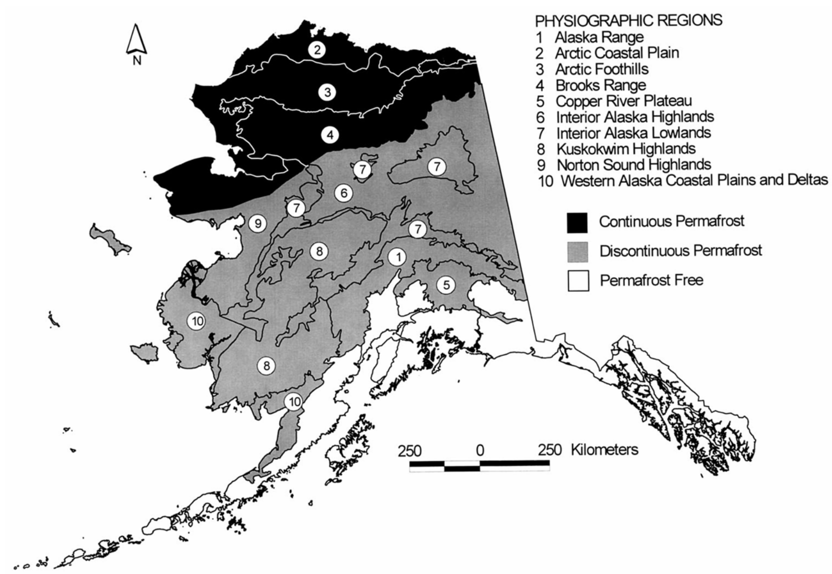

Figure 2.2.1. Distribution of Permafrost and Physiographic Regions with Permafrost in Alaska.

2. Cryosols in the Zone of Continuous Permafrost

2.1. Arctic Coastal Plain

2.1.1. Physical environment

This treeless area is characterized by multiple thaw lakes, many of them elongated in a north-northwesterly direction perpendicular to the prevailing winds. As much as 40 to 50% of the surface area is water. Low terraces, broad shallow depressions, and flood plains are typical of the landscape. Periglacial features appear, including frost polygons, hummocks, frost boils, and pingos. Thick permafrost (>600 m) underlies the entire area (Péwé, 1975). The drainage is poor or very poor. The dominant vegetation includes sedges (*Carex aquatilis*), cottongrass (*Eriophorum angustifolium*), and mosses (*Drepanocladus* spp. and *Scorpidium scorpoides*) (Walker, 1999).

2.1.2. Climate

The climate of the area varies with distance from the Arctic Ocean and elevation. In the Arctic Coastal Plain, the mean annual air temperature (MAAT) ranges from

-12.8^o to -10.3^{0}C, and mean annual precipitation (MAP) ranges from 12.5 to 14.2 cm, with 50% as snow (Haugen, 1982). The mean annual soil temperature (MAST) at 50 cm estimated from the temperatures of permafrost ranges from -7^o to -9^{o}C (Osterkamp and Romanovsky, 1996). The annual sum of growing degree days (GDD) (based on temperature of >0^{o}C) measured at Franklin Bluff, at the southern Arctic Coastal Plain, is 121^o days (L.D. Hinzman, unpublished data).

2.1.3. Soils

Two different soils are associated with low-center polygons on the coastal plain. The centers of the polygons are flat and poorly to very poorly drained, with water near or at the surface during most of the growing season. The dominant soils in the center of low-centered polygons and thaw lake basins are Typic Historthels (Hoefle et al., 1998; Ping et al., 1998). Table 2.2.1 provides a comparison among *US Soil Taxonomy* (Soil Survey Staff, 1999), the *World Reference Base* (FAO, 1998), and the *Canadian System of Soil Classification* (Soil Classification Working Group, 1998).

Typic Historthels consist of stratified peat and loamy sediments over medium-grained alluvium or lacustrine sediment that are gleyed with grayish colors (2.5Y 5/2, 2.5/2, and 5Y 2.5/1). The surface organic layer is generally 15 to 30 cm thick, with minimal cryoturbation. The active layer is about 35 cm thick, and the upper permafrost is ice-rich with thick ice lenses. The polygon rims are 20 to 40 cm above the polygon center. The soils on the polygon rim generally consist of 15 to 20 cm of organic material over 20 to 30 cm of an A horizon over a gleyed Bg horizon. The permafrost table is at 45 to 50 cm depth, and the upper permafrost (Cf) contains over 60% ice by volume.

Soil horizons in the polygon rim show a convex pattern, following the surface relief of the rim; thus the soils are cryoturbated and are classified as Aquic Molliturbels or Typic Histoturbels. Soils in the trough between polygons are very poorly drained and are characterized by 35 to 40 cm of organic material over an ice wedge. These soils are classified as Hemic Glacistels. Typic Aquorthels and Sulfuric Aquorthels occur along the river deltas and coastal estuaries (Ping, unpublished data).

Low-center polygons are common on the younger part of the Arctic Coastal Plain, whereas flat and high-centered polygons dominate the older part of this thaw-lake landscape. On flat-centered polygons, the soils are saturated throughout, during most of the growing season. Near the edge of the polygons, the organic layer is greater than 40 cm thick and overlays cryoturbated alluvium or lacustrine sediments with ice wedges. Thus, the soils are organic soils and are classified as Hemic Glacistels.

In the center of the polygons, the organic layer is sometimes thinner than 40 cm thick over mineral sediments, and the soils are classified as Typic Historthels; otherwise they are Histels (Soil Survey Staff, 1999) or Organic Cryosols (Soil Classification Working Group, 1998). On the better drained high-centered polygons are well developed "A" horizons. The subsoils show evidence of moderate cryoturbation, as manifested by broken and warped horizons. The permafrost table occurs at 45 to 50 cm, with organic matter frost-churned into the frozen "C" horizon; the "C" material is ice-rich, with about 60% ice by volume. These soils are either Aquic Molliturbels (Bockheim et al., 1998) or Ruptic-Histic Aquiturbels.

Soils formed in the Arctic Coastal Plain have reactions ranging from acidic to calcareous. Acidic soils in the Colville Delta formed in recently deposited alluvium on terraces (Jorgenson et al., 1996), and nonacidic soils are common on the broad alluvial fans (Ping et al., 1998). Soils on flood plains of major rivers throughout the coastal plains formed in carbonate rich parent materials, and marl

Table 2.2.1. A comparison of three approaches to classifying common soils in Alaska (subgroups).

US Soil Taxonomy **(Soil Survey Staff, 1999)**	***World Reference Base*** **(FAO, 1998)**	***Canadian System of Soil Classification*** **(Soil Classification (Working Group, 1998)**
Aquic Haplorthels	Haplic Gleyic Cryosols	Regosolic Static Cryosols
Aquic Haploturbels	Gleyic Turbic Cryosols	Gleysolic Turbic Cryosols Orthic Eutric Turbic Cryosols Orthic Dystric Turbic Cryosols Brunisolic Eutric Turbic Cryosols Brunisolic Dystic Turbic Cryosols
Aquic Molliturbels	Gleyic Turbic Cryosols	Gleysolic Turbic Cryosols
Glacic Fibristels	Gelic Glacic Histosols	Fibric Organic Cryosols
Glacic Hemistels	Gelic Glacic Histosols	Mesic Organic Cryosols
Hemic Glacistels	Gelic Glacic Histosols	Mesic Organic Cryosols
Humic Eutrocryepts	Mollic Cambisols	Orthic Sombric Brunisols
Ruptic-Histic Aquiturbels	Turbic Histic Cryosols	Gleysolic Turbic Cryosols
Sulfuric Aquorthels	Thionic Gleyic Cryosols	Gleysolic Static Cryosols
Typic Aquiturbels	Gleyic Turbic Cryosols	Brunisolic Turbic Cryosols Dystric Turbic Cryosols Eutric Turbic Cryosols Gleysolic Turbic Cryosols Orthic Turbic Cryosols
Typic Aquorthels	Haplic Gleyic Cryosols	Gleysolic Static Cryosols
Typic Dystrocryepts	Dystric Cambisols	Orthic Dystric Brunisols
Typic Eutrocryepts	Eutric Cambisols	Orthic Eutric Brunisols
Typic Fibristels	Fibric Gelic Histosols	Fibric Organic Cryosols
Typic Haplocryolls	Haplic Chernozems	Orthic Melanic Brunisols
Typic Haploturbels	Haplic Turbic Cryosols	Orthic Turbic Cryosols
Typic Historthels	Histic Cryosols	Gleysolic Static Cryosol
Typic Histoturbels	Turbic Histic Cryosols	Histic Eutric Turbic Cryosols Histic Dystric Turbic Cryosols Gleysolic Turbic Cryosols

commonly appears on the soil surface and as heavy coatings on vegetative parts below the water table and rock fragments (Ping et al., 1998).

2.2. Arctic Foothills and northern Norton Sound Highlands

2.2.1. Physical environment

The Arctic Foothills includes an area along the northern foot slopes of the Brooks Range and the northern Norton Sound Highlands that encompasses the northern part of the Seward Peninsula. These physiographic regions include broad sloping valleys separated by moderately steep to steep ridges, hills, and knolls. Elevations range from sea level to about 900 m, and these areas are within the zone of continuous permafrost.

There are two main types of vegetation in the region, moist nonacidic tundra and moist acidic tundra. Mixed dwarf shrub-sedge (*Dryas integrifolia, Salix reticulata, Carex biglowii*, and *Tomentypnum nitens)* dominates the former, and mixed cottongrass-shrub (*Eriophorum vaginatum*, *Betula nana, Salix pulchra*, and *Hylocomium splendens)* dominates the latter (Swanson et al., 1985; Walker, 1999).

The dominant parent material in valleys and on long foot slopes is loamy colluvium. On hills and ridges, parent materials include gravelly colluvium and residuum weathered from sedimentary rocks. Glaciated hills and plains of early to mid Pleistocene times (Anaktuvik and Sagavanirktok ages) are common elsewhere (Hamilton, 1987) and often are mantled with loess deposits a meter or more thick.

2.2.2. Climate

The mean annual air temperature (MAAT) of the Arctic Foothills is 2^{o} to 4^{o}C warmer than that of the Coastal Plain, due to the greater distance from the ocean (Zhang et al*.,* 1996). The mean annual soil temperature (MAST) ranges from -4^{o} to -7^{o}C, and the mean annual precipitation (MAP) ranges from 14 to 27 cm, with 40% falling as snow (Haugen*,* 1982). The winter temperatures are higher in the southern portion of the Arctic Foothills because of atmospheric temperature inversions.

The growing degree-days (GDD) in this region range from 760^{o} to 1125^{o} days. Temperature-vegetation gradients on the Arctic Coastal Plain and the Foothills indicate that GDD accumulations linearly relate to the distance from the ocean. In general, MAP and diurnal temperature variations increase southward with distance from the coast.

2.2.3. Soils of the Arctic Foothills and northern Norton Sound Highlands

The Sagwon Hills encompass a major part of the Arctic Foothills. This landscape consists of hills dissected into Tertiary age gravelly outwash deposits of mixed mineralogy and blanketed with loess (Hamilton*,* 1987). Along the northern edge of this hilly upland, the vegetation is dominantly nonacidic tundra (Bockheim et al., 1998) characterized by dwarf shrub (*Dryas spp.* and *Lupinus spp.)*, in addition to other tundra types. Low, flat polygons about 40 to 100 cm across, with 15% bare soil in mudboils or frost scars, characterize the microrelief.

The soils associated with dwarf shrub vegetative types are strongly cryoturbated, as warped and broken soil horizons indicate throughout the entire profile. Under a discontinuous organic layer, portions of the profile have a high chroma color, indicating oxidation of iron minerals, while adjacent zones are gleyed.

The dominant soils are Aquic Molliturbels and Ruptic-Histic Aquiturbels (Ping et al., 1998). The former have an active layer more than 50 cm deep, and the later are interspersed with acidic tundra soils. Cryoturbated organic matter or humus scatters throughout the mineral horizons, and a second concentration of organic matter occurs directly above the permafrost table, at about 60 cm. This suggests the frost churning of humus and sequestration of carbon into the permafrost (Ping et al., 1997).

Soil structure is massive in the upper part of the active layer in mudboils and between tussocks, due to the constant wetness. Elsewhere, a strongly developed platy structure is common in the active layers of upland soils, as a result of lower relative wetness and higher exposure to annual freeze and thaw cycles. In the lower portion of the active layer above the permafrost table, the structure is reticular, as the result of vertical and horizontal vein-ice formation, due to frost cracks caused by freeze-back from the permafrost table in the fall (Zhestkova*,* 1982). The upper 30 to 40 cm of permafrost is very ice-rich, and soil aggregates appear suspended in ice; this has been identified as an "ataxitic" cryogenic fabric (Gasanova*,* 1963).

The ataxitic fabric forms (1) from freeze-back of the active layer from below, with the rise of the permafrost table due to vegetative succession and the formation of the O horizon (Shur, 1988) and (2) from gradual movement of water into the upper permafrost. The resulting structures of the thawed soil provide channels for soil water after the permafrost thaws; thus, biogeochemical weathering, mainly reduction-oxidation, can penetrate into the upper permafrost layer when it periodically thaws.

On similar landforms and loess parent materials farther to the south, the vegetation changes to acidic tundra. The region has patterned ground, with occasional frost boils and acidic tussock tundra. Soils associated with this land cover have a thick, but discontinuous, organic horizon commonly ranging from 15 to 30 cm. Cryoturbation is more pronounced than in the nonacidic soils. The permafrost table occurs at 45 to 50 cm, and cryoturbation has enriched the upper 20 cm with well humified organic matter. These soils are dominantly Ruptic-Histic Aquiturbels. In the acidic tundra there is better moss growth, hence a thicker organic horizon. In both soils, the upper permafrost layers have an ataxitic fabric, with ice content generally 60% or more by volume.

Soil texture suggests a uniform parent material for soils in the northern Arctic Foothills. The predominantly silt loam textures in both acidic and nonacidic tundra suggest a common source, loess. In general, the acidic tundra occurred to the south of the nonacidic tundra and the differentiation of the soil acidity was attributed to snow depth (Walker et al., 1998) and weathering (Ping et al., 1998).

The silt content in these soils ranges from 60 to 70% but is slightly higher in the nonacidic tundra because it is closer to the Sagavanirktok River (Walker and Everett, 1991). However, in the northern Norton Sound Highlands, the parent material is colluvium rather than loess (Reiger et al., 1979). Pebbles and gravel occur throughout the lower profile, but their position suggests that frost heave moved them upward in the soil profile. Sorted circles are common in areas of nonacidic tundra.

2.2.4. Soils of the southern Arctic Foothills

Glaciated rolling hills make up a large portion of the southern part of this region. The drift is Middle or Late Wisconsin in age (Hamilton, 1987) and contains coarse fragments from pebbles to boulders in size. Soil texture changes from silt loam or silty clay loam in the northern part of the area to sandy loam in the southern part, with an associated increase in coarse fragments. Soils of the moist acidic tundra in the southern Arctic Foothills have more strongly oxidized colors (higher chroma), i.e., are redder, indicating longer periods of oxidation than equivalent soils in the northern foothills.

Discontinuous surface organic horizons are common in the southern foothills, due to cryoturbation under tussock tundra and dwarf shrub. In addition, organic matter is frost-churned into the underlying mineral soil horizons and commonly concentrates in the upper permafrost. Interspersed within large areas of acidic tundra are small areas of nonacidic soils formed in calcareous drift and alluvium on till plains, fans, and alluvial basins (Ping, unpublished data).

Soils in the southern foothills have similar cryogenic structures as soils in the northern foothills, including ice lenses, reticular and blocky structures in the lower portions of the active layer, and ataxitic fabric in the upper permafrost. However, the layers with ataxitic fabric are generally thinner, ranging from 20 to 30 cm. This indicates a variety of causes: less fluctuation of permafrost tables occurs in the southern portion of the foothills, possibly due to thicker snow cover and better insulation; drier conditions result from the landscape position; or less time has gone by for soil development.

The dominant soils associated with tussock tundra and shrub tundra are Ruptic-Histic Aquiturbels. Histic Aquorthels are found along waterways. Glacic Fibristels and Glacic Hemistels are common in valley bottoms and depressions. Ridge tops and windswept valleys are exposed to a more severe climate and commonly contain mudboils. Typic Aquiturbels and Typic Haploturbels are common to these areas (Ping et al., 1998).

3. Cryosols in the Zone of Discontinuous Permafrost

3.1. Western Alaska

3.1.1. Physical environment

Western Alaska includes the Western Alaska Coastal Plains and Deltas, the southern part of the Norton Sound Highlands, and the southern part of the Kuskokwim Highlands physiographic regions (Figure 2.2.1). The Western Alaska Coastal Plains and Deltas are along the western Alaskan coast, north of the Alaska Peninsula, and south of the Seward Peninsula. They include deltas of the Yukon and Kuskokwim rivers and coastal plains and deltas along the north side of the Alaska Peninsula. The area is below 50 m elevation, of low relief with irregular micro-relief, and has many lakes and ponds connected by a maze of waterways. It supports shrub and sedge tundra, alder and willow shrub, and, in a few places along streams, stunted spruce (*Picea glauca*) and paper birch (*Betula paperifera*) forest.

The southern Norton Sound Highlands is along the southern part of the Seward Peninsula and extends south along Norton Sound to the northern and eastern edge of the Yukon-Kuskokwim Delta. Elevation ranges from sea level to 900 m, with a few peaks as high as 1200 m. The area consists of steeply sloping hills and low mountains. Bedrock types include schist, dolomite, graywacke, mudstone, and sandstone (Beikman, 1980). Most of the area supports shrub and sedge tundra, with minor areas of spruce forests along lower slopes of inland valleys. Detailed soil information is generally unavailable for these physiographic regions. General soil descriptions here are based on information from Rieger et al. (1979).

3.1.2. Climate

The climate within these physiographic regions is influenced by the Bering Sea to the west. Cooler summer temperatures and the predominance of tundra vegetation are features that help distinguishes Western Alaska from Interior Alaska. Mean summer temperatures are significantly lower, 11.7 °C at Bethel, compared to 15.2°C for Fairbanks. Average annual temperatures range from -4°C in the north to more than 0°C in the south. Average annual precipitation ranges from 25 to 5 cm (Soil Conservation Service, 1981).

3.1.3. Soils of Western Alaska Coastal Plains and Deltas

The landscape is nearly level coastal plains and deltas, interspersed with small lakes and river channels. Soil occur in a complex pattern, depending on local drainage. Typic Fibristels are in meander scars and broad depressions and along the margins of shallow lakes with sedge (*Eriophorum* spp.) tussock or shrub tundra. Intermixed on micro-highs are Typic Historthels and Typic Histurbels, formed in nonacidic sandy and silty alluvium with shrub tundra. Ice-cored mounds, or *pingos,* occur in some areas (modified from Rieger et al., 1979).

3.1.4. Soils of the southern Norton Sound and southern Kuskokwim Highlands

Landforms include rolling to steep mountains and glaciated plains. Soil parent materials include glacial drift, as well as colluvium from argillite, shale, graywacke, sandstone, quartzite, conglomerate, and tuff (Beikman, 1980). In the Kuskokwim portion, parent materials are mantled with a silty mantle consisting of loess and volcanic ash. Steep high mountains with alpine shrub vegetation generally lack permafrost, and common soils are Typic Humicryepts and Typic Cryorthents.

More gently sloping mountains and plains have a complex array of soils with and without permafrost. Coarsely textured soils formed in silty volcanic ash over sandy and gravelly outwash, are generally free of shallow permafrost, are strongly acidic, and have bog birch (*Betula glandulosa*) shrub vegetation. These are classified as Typic and Andic Haplocryods. Adjoining broad valleys have soils formed in loamy and gravelly substratum and often are poorly drained with shallow permafrost. These soils have tussock or shrub tundra vegetation and are classified as Aquic Haploturbels and Typic Histurbels.

3.2. Interior Alaska

3.2.1. Physical environment

Interior Alaska lies between the Alaska Range on the south and the Brooks Ranges on the north, and between the Canadian Border on the east and the first occurrence of lowland tundra in the west (Figure 2.2.1). Interior Alaska consists of several broad, nearly level lowlands, with elevations mostly below 500 m, and rounded mountains with elevations up to about 2000 m asl (Wahrhaftig, 1965). Steep mountainous areas, though not extensive, occupy the southwestern part. The region conveniently divides into these three physiographic regions for discussion of its soils (Soil Conservation Service, 1981).

Soil morphological studies are few and far between in Interior Alaska, with most work concentrated near Fairbanks. Information here without citation comes from unpublished Natural Resources Conservation Service soil survey data and Rieger, et al. (1979).

3.2.2. Climate

This region has discontinuous permafrost (Brown et al., 1997). Mean annual soil temperatures at the top of the permafrost as low as -3.5^{o}C have been recorded at valley-bottom stations, although most soils with permafrost have mean annual temperatures between -2^{o}C and 0^{o}C (Brown et al., 1997; Osterkamp and Romanovsky, 1999). Vegetation is dominantly boreal forest, with tundra at higher elevations; tree line occurs at about 900 m elevation over much of the region. Climate is continental, with mean temperatures at valley bottom stations ranging from 15 to 17°C in July, from -23 to -28°C in January, and -2.5 to -6°C annually (Owenby and Ezell, 1992).

Mean annual precipitation at valley bottom stations typically ranges from about 23 to 34 cm per year (Owenby and Ezel, 1992) but ranges as low as 17 cm per year in the most continental basin, Yukon Flats (National Climatic Data Center, 2000). While precipitation totals are low, the abundant surface water and predominance of acidic soils over most of the area indicate an excess of annual precipitation over evapotranspiration. Data from higher elevations are sparse, but they indicate warmer winters, cooler summers, and higher precipitation than at valley bottom stations.

3.2.3. Soils of the Interior Alaskan Lowlands

Soils with permafrost dominate the wet, nearly level lowlands of Interior Alaska. The parent material in these lowlands is mostly alluvium or loess over alluvium, with thick eolian sand or silt or glacial deposits in some areas (Péwé, 1975).

On active floodplains there is typically a sequence from well drained, permafrost-free soils on the most frequently flooded surfaces near the river, to progressively colder, wetter soils with permafrost on higher and less frequently flooded surfaces; surface organic horizons thicken along this same sequence (Péwé, 1948; Viereck, 1970; Viereck et al., 1983; Viereck et al., 1993). This perhaps counterintuitive toposequence (i.e., wettest soils at the highest positions) results from the greater age and different vegetation of the higher surfaces, both of which facilitate accumulation of a surface organic layer, cooling of the soil, formation of permafrost, and wetness due to perching of water on the permafrost.

Vegetation on the most frequently flooded, youngest surfaces without permafrost is typically deciduous shrubs (*Salix* spp.) or trees (*Populus balsamifera*). Older and less frequently flooded surfaces with permafrost often have forest of white or black spruce (*Picea glauca* or *Picea mariana*) on Aquic Haplorthels or Typic Aquorthels. The oldest and least frequently flooded surfaces typically have very sparse black spruce with low shrubs, sedges, and moss on Typic Histoturbels. Thermokarst is common on these older surfaces (Péwé, 1948), although patterned ground is not prominent, other than organic microtopography composed of tussocks and small peat mounds.

Organic soils (i.e., Histels [US], Organic Cryosols [Canadian]) form in nearly level surfaces with rare or no flooding and finely grained mineral substratum (silty alluvium or loess) in Interior Alaskan lowlands. The degree of thickness and decomposition of the peat vary greatly.

The most common peatland morphologic type is the peat plateau (Zoltai, 1972; Zoltai and Tarnocai, 1975). The plateaus consist of a nearly level surface, with active layers of about 0.5 m, interrupted by occasional thermokarst pits. The soils of the plateau surface are extremely acidic in the active layer (typically with pH in water of about 4.0), and the vegetation consists of acid-tolerant black spruce, ericaceous shrubs, mosses, and lichens.

Unlike most organic soils, these soils often have no water table, due to drainage of water into the thermokarst pits. Soils in the thermokarst pits are also organic but commonly have a water table near the surface and may lack permafrost entirely. Degrading peat plateaus in a few areas are less acidic and have been colonized by birch forest (Racine et al., 1998; Walters et al., 1998).

Some parts of the Interior Alaskan lowlands consist of plains with very thick loess deposits that accumulated primarily during the Pleistocene (Péwé, 1975). The topography is gently rolling, due to thermokarsting of sediments with tremendous quantities of ground ice. These soils typically have a thick surface organic horizon, mineral soil material that is dull gray due to the reducing condition, and permafrost at about 0.5 m depth. Profiles are acidic, with pH values (in water) as low as 4 in the organic horizons and 5 to 7 in the mineral soil material. These soils classify mostly as Typic Aquiturbels and Typic Histoturbels. Permafrost is typically ice-rich, and thermokarst is widespread. Distinct thermokarst depressions contain a wide variety of wet soils that mostly lack permafrost, while nearly level low areas have peat plateau soils as just described.

Some nonflooded terraces with coarsely grained substrata in the Interior Alaskan lowlands have soils that contain permafrost but are drier than the terraces' soils just described (Schoephorster, 1973). They support black spruce forest on Aquic Haploturbels and Typic Aquiturbels. Unpublished NRCS data suggests that soils with less than about 0.5 m of loamy mantle over sand and gravel are unlikely to have permafrost, while soils with more than 0.5 m of loamy mantle usually have permafrost if an intact organic horizon and late-successional vegetative community is present (see below for more on the effects of disturbance on these soils).

Portions of the Interior Alaskan Lowlands are covered with sand dunes or glacial moraines, the latter being extensive only near the Alaska and Brooks Ranges (Coulter et al., 1965). Soils with permafrost are present mostly in the depressions between dunes (Furbush et al., 1980) or between moraine ridges, and the taxa are mostly Typic Aquiturbels and Typic Histoturbels.

3.2.4. Soils of the Interior Alaskan Highlands and northern Kuskokwim Highlands

The Interior Alaskan Highlands and northern Kuskokwim Highlands consist of crystalline igneous and metamorphic rocks and non-calcareous sedimentary rocks (Beikman, 1980) and a loess cover that ranges from many meters thick near loess sources (primarily large braided glacial outwash rivers) to less than 0.5 m distant from loess sources (Péwé, 1975). Pleistocene glaciation was limited to a few high cirques (Coulter et al., 1965).

The most widespread soils with permafrost occur on finely grained loess and colluvium on lower slopes in valleys. These soils resemble those in the loess lowlands described above (Dyrness and Grigal, 1979; Swanson, 1996b). Permafrost is typically ice-rich, and thermokarst is widespread. Patterned ground generally is not strongly expressed, with earth hummocks the most common type. Large ice wedges often are hidden beneath the surface and become apparent only after disturbance of the surface (Péwé, 1954; 1982).

Vegetation consists of sparse, stunted black spruce (*Picea mariana*) trees with low shrubs, sedges, and moss (including *Sphagnum* spp. and others). Figure 2.2.2 shows the soil-landscape relationship of the Interior Alaskan Highlands.

Soils with permafrost also occur on sites that are warmer and drier than those just described, as a result of being higher on the slope or on a convex position, having south aspect, or having thinner finely grained surface mantle over bedrock. In such soils, surface organic layers are thinner, active layers are thicker, and soils are better drained, although still generally dull gray in color (Swanson, 1996b). Common classifications are Aquic Haploturbel and Typic Aquiturbel.

Soils with permafrost also occur on steep, north-facing slopes (Krause et al., 1959). These soils resemble those of the lowlands, in that they have a thick organic surface layer, dully colored mineral soil, and permafrost at about a 0.5-m depth, but they differ by having bedrock within the first meter below the surface. These soils are striking because their vegetation closely resembles that of lowland black spruce wetlands, but they can occur on slopes in excess of 30^o.

Tundra soils occupy significant areas at higher elevations in the Interior Alaskan Highlands and southern Kuskokwim Highlands, but they have received little attention beyond two studies in the foothills of the Brooks Range (Drew and Shanks, 1965; Ugolini et al., 1981). Unpublished NRCS data suggest that soils are mostly stoney with a loamy matrix; surface organic layers are thinner and active layers thicker than those of lowland soils with permafrost. Patterned ground is common, consisting primarily of sorted circles, nets, stripes, and nonsorted circles. Reactions are mostly acidic, due to the mainly acidic nature of parent materials in this region.

Soils with permafrost in Interior Alaska can change markedly in response to forest fires or other disturbance and post-fire plant succession. Active-layer thickness often increases greatly after fire, from about 0.5 m to 2 m or more (Dyrness, 1982; Viereck, 1982), soils become drier, and oxidation of previously reduced soils may occur. The soils that show the greatest change after fires are those at the warmest and driest end of the continuum of permafrost soils before the fire.

For example, soils on terraces with 0.5 to 1.0 m of loamy material over gravel or soils on gentle sloping hill slopes at mid-slope, shoulder, or summit positions often thaw and dry markedly after fire, while soils with thick surface organic horizons in lowlands on thick silty deposits often thaw little after fire (Swanson, 1996a). In some cases, retreat of the permafrost table below a 2-m depth after disturbance can cause the soil classification to change greatly, from Gelisol to Inceptisol (US) or Cryosol to Brunisol (Canadian) (Ping, 1987).

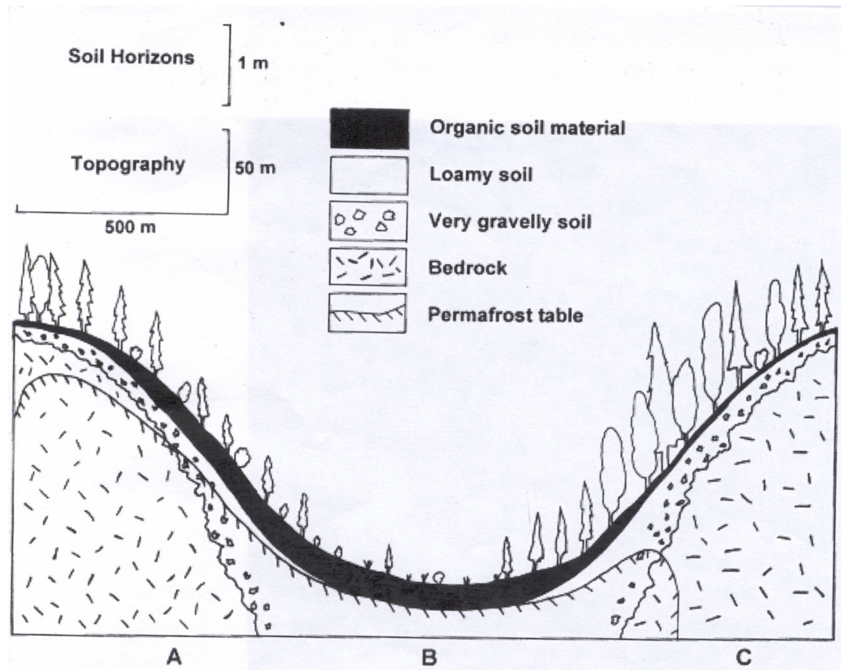

Figure 2.2.2. Soil-landscape diagram of the Interior Alaskan Highlands. Soils on steep, north-facing slopes (A) have a surface organic layer about 0.2 to 0.4 m thick; both permafrost and weathered bedrock occur within 1 m of the surface. Vegetation is sparse black spruce (*Picea mariana*) forest with moss ground cover. Soils in finely grained deposits on lower slopes and valley bottoms (B) have a surface organic layer generally 0.2 to 0.4 m thick and permafrost at 0.3 to 0.5 m deep. Vegetation is low shrubs, sedges, and moss with scattered black spruce. Soils on steep, south-facing slopes have thin surface organic layers and lack permafrost. Trees there are larger and may be white spruce (*Picea glauca*), birch (*Betula papyrifera*), or aspen (*Populus tremuloides*).

4. Alaska Range

4.1. Physical environment

The Alaska Range includes a north-trending mountainous arc that extends from the Alaska Peninsula on the west to the border of Canada on the east (Figure 2.2.1). Mountains consist of a variety of crystalline igneous, metamorphic, and sedimentary rocks (Beikman, 1980). The Alaska Range divides the Cook Inlet-Susitna Lowlands and Copper River Plateau regions to the south from the Interior Alaska and Western Alaska regions to the north and west.

North of the crest of the Alaska Range, the glaciers were essentially alpine in character; they filled the mountain valleys and in places spread as piedmont lobes in adjoining lowlands. South of the crest, glaciers originating in the mountains filled adjoining lowland basins, such as the broad Susitna Valley (Péwé, 1975).

A majority of the Alaska Range consists of alpine and sub-alpine shrub vegetation at elevations above about 550 meters, with less extensive areas of boreal forest below.

4.2. Climate

Along its western part, the Alaska Range divides the transitional maritime-continental climate to the south from the continental climate to the north. Along the eastern part, the climate is continental throughout.

This mix of climates, in conjunction with high mountainous topography, results in diverse microclimates with variable patterns of wind, temperature, and precipitation. Permafrost is generally absent where the climate is transitional maritime-continental and has a discontinuous distribution where continental conditions prevail. This discussion pertains to that portion of the Alaska Range that lies within the continental climate zone and thus the zone of discontinuous permafrost.

Long-term climatic data is available for the forested portion of the Alaska Range but is unavailable for the alpine zone. Mean annual air temperature at Denali Park Headquarters, located in the upper limit of the boreal forest zone, is -3.0°C with mean winter and summer air temperatures of -16.4°C and 11.3°C, respectively (National Climatic Data Center, 2000).

4.3. Soils of the Central Alaska Range

The core of the Alaska Range includes steep, rocky mountains, with elevation ranging from 900 to 6100 m asl. Slopes above about 1300 meters elevation are mostly barren, with scattered small islands of dwarf willow (*Salix reticulata* and *arctica*) and dryas (*Dryas* spp.) shrub. Below this is an assemblage of alpine and subalpine vegetation, including dwarf willow and dryas shrub, mixed ericaceous-bog birch (*Betula glandulosa*) shrub, and alder (*Alnus* spp.) shrub, interspersed with areas of barren rock and talus.

Lithology is diverse, with schist, shale, conglomerate, and diorite (Beikman, 1980) the major rock types and colluvium the dominant soil parent material. Based on initial soil survey information for Denali Park and Preserve and Delta River Areas (Clark and Duffy, in press) within the continental climate portions of this section, permafrost is of minor extent and limited primarily to the lower slopes.

A majority of soils lack shallow permafrost and are classified as Typic Dystrocryepts and Typic Eutrocryepts, Humic Eutrocryepts, and Typic Haplocryolls. These soils are devoid of surface organic mats and have gravelly surface textures and are well drained, and permafrost is absent within two meters of the surface. Though shallow permafrost is absent, mean annual soil temperatures (MAST) are below 0°C, and minimum winter soil temperatures are generally below -4°C. Seasonal soil temperature extremes measured in typical soils of the region ranged from maximums of about 9°C during summer to minimums of about -19°C during winter, with overall mean annual soil temperatures (MAST) from -1 to -3°C (Clark and Duffy, in press).

Consistent with the findings by French (1970), these gravelly soils with no appreciable organic mat at the surface are found to be warmer during summer than would normally be expected for the latitude. High thermal conductivity of this gravelly surface material (Jury et al., 1991) is thought to be an important contributor to the extreme seasonal temperatures and general lack of permafrost in these soils. Also important are winds that remove snow from the surfaces of these soils during winter, leaving the ground exposed to extreme winter air temperatures (MacKay and MacKay, 1974; Nichols and Moore, 1977).

Soils with shallow permafrost occupy less than about 15% of the landscape and are limited to benches, summits, saddles, and gently sloping foot slopes with convergent-plain to concave surface shapes. These landscape positions accumulate snow during winter and receive excess moisture as run-in from surrounding slopes during late spring and summer. Surface micro-relief is generally smooth but includes areas of turf hummocks with less than 30 cm relief.

Parent materials include colluvium from a host of rocks with a thin mantle of loess and eolian organic deposits. Eolian deposits accumulate each winter in snowdrifts and are deposited on the soil surfaces during the spring thaw.

The permafrost is at one to two meters depth, and Aquic Haplorthels and Histic Haplorthels are common soils. Vegetation is dwarf willow (*Salix reticulata*, *Salix Arctic*) and dryas shrub (*Dryas* spp.) and dwarf willow shrub-sedge (*Carex* spp.). Both Aquic Haplorthels and Histic Haplorthels have neutral to alkaline soil reactions in surface layers, from nutrient rich run-in water, compared to adjacent well drained Typic Distrocryepts and Eutrocryepts.

The upper mineral layers, or “A” horizons, in Aquic Haplorthels are black (10YR 2/2) silt loam with reactions that range from strongly through slightly acidic (pH 5.3 to 6.4). Histic Haplorthels have very dark brown (10YR 2/2) or black (10YR 2/1) surface organic mats and a thin underlying silt loam mineral layer with a reaction ranging from strongly acidic through neutral (pH 5.3 to 6.6). Substrata of both soils have variable color depending on lithology and have a strongly acidic through neutral reaction (pH 5.3 to 6.6).

4.4. Soils of the Outer Mountains, Glacial Plains, and Basins

Rounded glaciated mountains, glaciated plains and hills, and bedrock cored low mountains occupy much of the fringe of the Alaska Range at elevations from about 300 to 1300 meters. Common parent materials include gravelly till, loess, cryoturbate, and colluvium. Periglacial features, including gelifluction lobes, stripes, and steps, are common on this assemblage of landforms.

Equally represented on periglacial landforms are soils with and soils without permafrost. Common soils with shallow permafrost include Typic Histoturbels, and soils on periglacial features include Ruptic-Histic Aquiturbels. Aquic Haplorthels and Histic Haplorthels are common in basins. Alpine and subalpine vegetation comprises much of the area, with less extensive areas of boreal forest at elevations below about 550 m asl.

Soils lacking significant cryoturbation include Aquic Haplorthels and Histic Haplorthels. These soils are common on gently sloping mountain foot slopes, till plains, glaciated hills, and broad, mountain summits. Surface micro-relief is generally smooth but includes areas of turf hummocks with less than 30 cm relief. Vegetation is mixed bog birch (*Betula glandulosa*)-ericaceous shrub or alpine-mixed ericaceous shrub-sedge (*Carex* spp.) types.

These soils do not receive the nutrient rich run-in water described for similar soils in the “Steep Mountains” section and therefore are measurably more acidic in the upper soil horizons. Organic mats have very strongly or strongly acidic soil reaction (pH 4.3 to 5.5), and soil color is very dusky red to black (2.5YR 3/2 to 10YR2/1). Reaction in substrata is very strongly through moderately acidic (pH 4.7 to 6.0) and soil color is dark grayish brown to very dark gray (2.5Y 4/2 to 5Y 3/1) (Clark and Duffy, in press).

Highly cryoturbated soils, including Typic Histoturbels and Ruptic-Histic Aquiturbels, are common in area with periglacial features. They formed in frost-churned sediments from a variety of rocks and till. Cryoturbation resulted in multiple buried, mixed, and convoluted organic and mineral horizons. Hummocks and non-sorted steps are periglacial features most commonly associated with Typic Histoturbels. Vegetation on these soils includes alpine-ericaceous shrub or alpine-mixed ericaceous shrub-sedge types.

Nonsorted circles, another common periglacial feature, occur on mountain footslopes, toeslopes, and broad summits. These consist of a repeating pattern of convex circular barren soil areas about one to three meters in diameter encircled by concave troughs one to two meters across. Circle centers have well drained soils and permafrost at depths of 1.5 m or more and are often barren of vegetation. Soils in troughs have histic epipedons, shallow permafrost, saturated conditions above the ice, and bog birch (Betula glandulosa)-ericaceous shrub vegetation.

Soils with shallow permafrost within the boreal forest zone are common along mountain foot slopes and basins at elevations between 300 and 550 m asl. Soil materials include gravelly till, silty loess, and silty colluvium derived from loess. Distribution and kinds of soils found here are similar to those described in the “Interior Alaska Highlands” section.

5. Copper River Plateau

5.1. Physical environment

The Copper River Plateau refers to the Copper River Basin and adjacent uplands rimmed by the Alaska Range on the north, the Talkeetna Mountains on the west, the Chugach Range on the south, and the Wrangell Mountains on the east (Figure 2.2.1). This region includes the upper drainage basin of the glacially fed Copper River and tributaries at elevations from about 170 to 1100 m asl.

Vegetation is dominantly boreal forest, with alpine areas above about 700 m. Landforms of the basin floor include narrow river valleys entrenched tens of meters within finely textured lacustrine basin sediments. Broad, nearly level to undulating lacustrine terraces are the most extensive landform of the basin floor above the river canyons.

Extensive areas of soils formed in calcareous glaciolacustrine sediments are a unique feature of the Copper River Plateau. Lacustrine terrace sediments consist of clayey and loamy calcareous materials that were deposited within a large proglacial lake that occupied the basin during the Pleistocene from about 35,000 to 9,000 years ago (Ferrians et al., 1983). Scattered throughout the basin are sandy strandline or beach deposits associated with fluctuating lake levels during this glacial period. Skirting the basin to about 900 meters elevation are glacial landforms including drumlins, outwash plains, till plains, and hills.

Mountains bordering the Copper River Plateau consist of schist, greenstone, graywacke, shale, sandstone, and andesite rocks (Beikman, 1980). Many upland landforms are mantled with a thin layer of calcareous loess, ranging from a few meters thick on lacustrine terraces adjacent to the Copper River to a few millimeters on lacustrine, glacial, and mountain landforms more distant from the river (Clark and Kautz, 1990).

This region is included within the zone of discontinuous permafrost (Péwé, 1975), and permafrost underlies most of the plateau at varying depths, except on floodplains and under lakes. Permafrost is thought to have formed in the recent epoch or following the end of the last glaciation, since, during that period, the basin was under either the waters of the proglacial lake or glacial ice. Permafrost occurs as finely segregated ice crystals and thin discontinuous ice lenses.

In clayey lacustrine deposits, ice content can average as high as 30 to 60% of the dry weight of the soil (Nichols, 1956). Though massive ground ice has been observed in area soils, massive ground ice formations or thermokarsts are localized features and not extensive.

5.2. Climate

The climate of the Copper River basin is subarctic continental characterized by long cold winters and short warm summers, a climate similar to the Interior physiographic area. January temperature is -23°C at Glennallen and -17°C at Paxson.

Daily low temperatures of -46°C or less occur frequently at Glennallen during the winter and may last for two or more weeks (National Weather Service). Winter temperature inversions result in the lower average temperatures at Glennallen, in the basin bottom, than those measured for Paxson, which is at a higher elevation near the mountains.

Mean July temperature is 13°C at Glennallen and 12°C at Paxson; daily high temperatures on occasion exceed 30°C in Glennallen. Although the daily minimum temperature in summer averages less than 10°C, freezing temperatures have been recorded in every month.

Mean annual precipitation measurements for the plateau range from about 280 mm in the basin bottom at Glennallen to about 540 mm in upper elevations at Paxson. Though precipitation totals are low, abundant surface water on landscapes of the region suggests that evapotranspiration is less than the annual precipitation.

5.3. Soils

Permafrost is generally absent on low to mid-level flood plains and common on high flood plains and stream terraces. The sequence of soils and permafrost along high flood plains and stream terraces on the Copper River Plateau is similar to that previously discussed in the “Interior Alaska Lowlands” section.

Soils on lacustrine terraces, till plains, and hills consist of a dark grayish brown (2.5Y 4/2) through olive gray (5Y 5/2) lacustrine and till deposits mantled with dark brown (10YR 3/3) and black (10YR 2/2) loess of variable thickness. Permafrost at a shallow depth and poorly drained conditions are common but highly variable over short distances. Recurring wild fires have created a complex mosaic of permafrost states and soil drainage conditions, similar to those described previously for Interior Alaska.

In most places, across lacustrine terraces and till plains, soils potentially alter between shallow permafrost and a permafrost-free state (Clark and Kautz, 1990). Soils under late succession dwarf black (*Picea mariana*) and white spruce (*Picea glauca*)-forest and shallow permafrost have histic epipedons and shallow permafrost and are classified as Typic Historthels.

Reaction in soils is relatively high, compared to similar soils in Interior Alaska. In Typic Historthels on lacustrine terraces, reaction in surface organic mats ranges from strongly through slightly acidic (pH 5.1 to 6.2), slightly acidic to moderately alkaline (pH 6.1 to 8.4) in the loess mantle, and mildly or moderately alkaline (pH 7.4 to 8.4) in lacustrine materials. Free calcium carbonate occurs disseminated throughout soil materials and occasionally as local white concentrations. Soils lack appreciable cryoturbation and structure, with the exception of weak platy structure in loess mantles.

In areas of these soils recently affected by fire of moderate or severe intensity, vegetation is commonly altered to willow shrub and aspen or mixed white spruce-aspen forest types. Combustion and consolidation of the insulating organic mat results in warming of underlying soils, lowering of the permafrost table, and a transition to a well drained and permafrost-free state.

Rate of change from the permafrost rich, poorly drained condition to a well drained, ice-free state was observed at the Wilson Camp fire burn near Glennallen, which burned in July of 1981. Soils showed an increase in the depth of thaw the first year after the burn. Depth to permafrost in August, in similar unburned forest adjacent to the burn, averaged 40 cm below the mineral surface. In August of 1982, within the burned area, depth to permafrost averaged 80 cm; in August of 1983, depth to permafrost averaged 100 cm (Clark and Kautz, 1990).

This alteration results in a change in the classification of soils from Typic Historthels to Pachic Haplocryolls, Typic Haplocryolls, or Typic Eutrocryepts. Soil reaction in the surface organic ranges from moderately alkaline (pH 7.9 to 8.4) immediately following fire, decreasing to slightly acidic levels (pH 6.1 to 6.5) several years following fire. Reaction in subsurface layers is similar to that in preburn levels. Thawed soil materials exhibit minimal cryoturbation. Soil structure is platy in loess material, with strongly expressed subangular blocky structure in underlying lacustrine deposits and massive or weak platy structure in till materials.

Permafrost-affected soils of lesser extent include very poorly drained Typic Histoturbels in broad depressions and toeslopes on hills with cottongrass tussocks (*Eriophorum* spp.); very poorly drained Typic Hemistels with wet willow shrub (*Salix* spp.) vegetation; and, Ruptic-Histic Aquiturbels on mudboils or nonsorted circles with spruce (*Picea* spp.)-shrub bog birch (*Betula glandulosa*) woodland. The occurrence of fire and alteration of soil properties and vegetation is infrequent on these soils.

6. Summary

Five soil-forming factors, parent material, topography, climate, biota, and time, usually are used to define the state of the soil system. Though often described independently, they are related, and the relative importance of each factor varies with location.

In the high latitudes, climate plays an important and often overriding role in soil formation, since permafrost is a prevalent feature in landscapes. Permafrost, acting as a barrier for water movement, creates restricted drainage and often wet soil morphology. Most soils affected by permafrost have very poor to poor drainage and are classified within the "Aqui" Great group of the Gelisol Order.

In the zone of continuous permafrost, the cold ambient temperature, usually < $-20^{o}C$ during fall freeze-up, induces frost-churning or frost heave processes and cryoturbated soil profiles. These soils are keyed into the Turbic Suborder of the Gelisol Order.

In the Arctic Foothills, the soils are classified as Aquiturbels. Along the Arctic Coastal Plain, the cold environment in conjunction with level or concave surface relief contributes to the accumulation of organic matter into thick surface organic mats or Histic epipedons that qualify these soils to be classified as Histels or Typic Histoturbels. Cryosols lacking cryoturbation, or Orthels, are not extensive and only form on young landscapes, such as floodplains.

Soil temperatures in the zone of discontinuous permafrost are generally "warmer," compared with those of the zone of continuous permafrost. They range from a fraction of a degree below freezing to -2^{o}C in most cases. Variation in soil temperature and the presence of permafrost often are associated with landscape position, parent material, and fire history.

On hills and mountains, incidental solar radiation and evapotranspiration differ significantly, based on exposure. Northerly exposures are often cooler, with relatively low rates of evapotranspiration, and have permafrost at a shallow depth and dwarf spruce forests. Histic Haplorthels and Typic Histoturbels are the common Subgroups represented.

Southerly exposures are generally warmer, drier, and permafrost free, with mixed hardwood and white spruce forests. These soils lack permafrost, and Typic Dystrocryepts and Typic Eutrocryepts are the common Subgroups.

The kind and thickness of parent material influences whether permafrost will form in soils. Generally, soils with < 0.5 meters of loamy loess or alluvium over coarse texture tills, alluvium, or bedrock have relatively warm summer soil temperatures and lack permafrost, due to high thermal conductivity properties of coarse texture materials. Well to excessively drained soils common to these parent material types include Typic Dystrocryepts, Typic Eutrocryepts, and Typic Haplocryods with spruce and dwarf birch vegetation.

Upland soils with 0.5 to 1.0 m of loamy material over gravel or soils on gentle sloping hill slopes at mid-slope, shoulder, or summit positions have permafrost that is sensitive to disturbance and have been observed to recede below 2 m and dry markedly after fire or land clearing. Recession of the permafrost table to below 2 m depth after major disturbance can cause the soil classification to change from the Gelisols before disturbance to Inceptisols in the years following. Soil subgroups and vegetation include Typic Historthels with dwarf spruce forest before fire and Typic Dystrocryepts and Typic Eutrocryepts with mixed forest several years following fire.

Soils with thick surface organic horizons over thick silty loess deposits have low thermal conductivity and often thaw little after fire (Swanson, 1996a). Thus some of the Typic Historthels may change to Typic Aquorthels, due to the loss of the organic horizon following fire.

Cryoturbation is less extensive in soils of the Subarctic zone, compared to those of the Arctic, especially in the boreal forest zone. This is attributed to the combined insulating effect of the mineral soil by a stable winter snow pack and thick organic horizons. Historthels are common in the boreal forest on flat or gently sloping areas. Cryoturbated soils are limited to steeper northerly exposures, where mixed horizons are generally attributed to downslope movement of saturated soil material over permafrost or gelifluction. Highly cryoturbated soils are also common on exposed alpine landscapes, where wind removes the snow cover (Ruptic-Histic Aquiturbels), and under sedge tussock and dwarf spruce-sedge tussock vegetative types (Typic Histoturbels) where standing water between tussocks freezes, causing differential lateral pressures and cryoturbation.

References

Beikman, H.M. 1980. Geologic map of Alaska. U.S. Dept. of Interior, Geological Survey. Scale 1:2,500,000.

Bockheim, J.G., C. Tarnocai, J.M. Kimble, and C.A.S. Smith. 1997. The concept of gelic materials in the new Gelisol order for permafrost-affected soils. Soil Sci. 162: 927-939.

Bockheim, J.G., D.A. Walker, L.R. Everett, F.E. Nelson, and N.I. Shiklomanov. 1998. Soils and cryoturbation in moist nonacidic and acidic tundra in the Kuparuk River Basin, Arctic Alaska, U.S.A. Arc. Alp. Res. 30: 166-174.

Brown, J., O.J. Ferrians, J.A. Heginbottom, and E.S. Melnikov. 1997. Circum-arctic map of permafrost and ground-ice conditions. U.S. Dept. of Interior, Geological Survey Map CP-45. Scale 1:10,000,000.

Clark, M.H., and M. Duffy. In press. Soil resources and ecosystems of Denali National Park, Alaska. National Park Service. Anchorage, AK.

Clark, M.H., and D.R. Kautz. 1990. Soil Survey of Copper River Area, Alaska. USDA, NRCS. US Gov't Prntg. Ofc. Washington, D.C.

Coulter, H.W., D.M. Hopkins, T.N.V. Karlstrom, T.L. Péwé, C. Wahrhaftig, and J.R. Williams. 1965. Extent of glaciation in Alaska. U.S. Dept. of Interior, Geological Survey Miscellaneous Geologic Investigations Map I-415, Scale 1:2,500,000.

Drew, J.V., and R.E. Shanks. 1965. Landscape relationships of soils and vegetation in the forest-tundra ecotone, upper Firth River valley, Alaska-Canada. Ecol. Mon. 35:285-306.

Dyrness, C.T. 1982. Control of depth to permafrost and soil temperature by the forest floor in Black Spruce/Feathermoss communities. U.S. Dept. of Ag., Forest Service, Research Note PNW-396. Pacific Northwest Forest and Range Experiment Station. Portland, OR

Dyrness, C.T., and D.F. Grigal. 1979. Vegetation-soil relationships along a spruce forest transect in interior Alaska. Can. J. of Bot. 57(23):2644-2656.

FAO. 1998. World Reference Base for Soil Resources. World Soil Resource Reports 84. Food and Agriculture Organization of the United Nations. Rome.

Ferrians, O.J., D.R. Nichols, and J.R. Williams. 1983. Copper River Basin, resume of Quaternary geology. In Guidebook to permafrost and Quaternary geology along the Richardson and Glenn Highway between Fairbanks and Anchorage, Alaska. Vol. 1. Dept of Natural Resources. Fairbanks, AK.

French, H.M. 1970. Soil temperatures in the active layer. Beaufort Plain. Arctic. 23:229-239.

Furbush, C.E., B.E. Koepke and D.B. Schoephorster. 1980. Soil survey of Totchaket area, Alaska. USDA, SCS. U.S. Gov't Prntg. Ofc. Washington, D.C. 68 pp.

Gasanova, S.S. 1963. Morfogeneticheskaya klassifikatsiya kriogennykh tekstur pykhlykh otlozherny. In: Trudy Severo-Vostochnogo Kompleksnogo Nauchno-Issledovatelskogo Instituta, VYP 3. Magadan, Russia. pp. 53-62.

Hamilton, T.D. 1987. Surfacial geologic map of the Philip Smith Mountains Quadrangle, Alaska. U. S. Geol. Surv. Misc. Field Stud. Map MF-879A. Scale 1:125,000. 1 pp.

Haugen, R.K. 1982. Climate of remote areas in north-central Alaska: 1975-1979 Summary. U.S. Army Cold Regions Research and Engineering Laboratory Rep. 82-35. Hanover, N.H. 114 pp.

Hoefle, C.M., C.L. Ping, and J.M. Kimble. 1998. Properties of permafrost soils on northern Seward Peninsula, northwest Alaska. Soil Sci. Soc. Am. J. 62(6):1629-1639.

Jorgenson, M.T., J.E. Roth, E.R. Pullman, R.M. Burgess, M.K. Raynolds, A.A. Stickney, M.D. Smith, and T.M. Zimmer. 1996. An ecological land survey for the Colville River Delta, Alaska. Final Report prepared for ARCO Alaska, Inc. Kuukpik Unit Owners. ABR, Inc. Fairbanks, AK.

Jury, W.A., W.R. Gardner, and W.H. Gardner. 1991. Soil Physics. John Wiley and Sons, Inc. New York.

Krause, H.H., S. Regier, S.A. Wilde. 1959. Soils and forest growth on different aspects in the Tanana watershed of interior Alaska. Ecol. 40(3):492-495.

MacKay, J.R., and D.K. MacKay. 1974. Snow cover and ground temperatures, Garry Island, N.W.T. Arctic. 27, 287-296.

National Climatic Data Center. 2000. Climatological Data Annual Summary, Alaska. NOAA. Asheville, NC.

Nichols, D.R. 1956. Permafrost and ground water conditions in the Glennallen area, Alaska. Preliminary report. U.S. Dept. of the Interior Geol. Survey. Fairbanks, AK.

Nichols H.M., and T.R. Moore. 1977. Pedogenesis in a subarctic iron-rich environment, Schefferville, Quebec. Can. J. Soil Sci. 57:35-45.

Osterkamp, T. E., and V.E. Romanovsky. 1996. Characteristics of changing permafrost temperatures in the Alaskan Arctic, U.S.A., Arc. Alp. Res. 28:267-273.

Osterkamp, T.E., and V.E. Romanovsky, V.E. 1999. Evidence for warming and thawing of discontinuous permafrost in Alaska. Permafrost and Periglacial Processes. 10:17-37.

Owenby, J.R., and D.S. Ezell. 1992. Monthly station normal of temperature, precipitation, and heating and cooling degree-days, 1961-1990: Alaska. Climatography of the United States No. 81. U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, National Climatic Data Center. Asheville, NC.

Péwé, T.L. 1948. Terrain and permafrost of the Galena Air Base, Galena, Alaska. U.S. Dept. of Interior, Geological Survey Permafrost Program Progress Report 7. 52 pp.

Péwé, T.L. 1954. Effect of permafrost on cultivated fields, Fairbanks, area, Alaska. U.S. Dept. of Interior. Geol. Survey Bull. 989-F. pp. 315-351.

Péwé, T.L. 1975. Quaternary geology of Alaska. U.S. Department of Interior, Geological Survey Professional Paper 835. U. S. Gov. Print. Ofc., Washington, D. C. 145 pp.

Péwé, T.L. 1982. Geologic hazards of the Fairbanks area, Alaska. Alaska Division of Geol. and Geophys. Surveys Special Report 15. College, Alaska. 109 pp.

Ping, C.L. 1987. Soil temperature profiles of two Alaskan soils. Soil Sci. Soc. Am. J. 51(4):1010-1018.

Ping, C.L., J.G. Bockheim, J.M. Kimble, G.J. Michaelson, and D.A. Walker. 1998. Characteristics of cryogenic soils along a latitudinal transect in arctic Alaska. J. Geophys. Res. 103(D22):917-928.

Ping, C.L., G.J. Michaelson, and J.M. Kimble. 1997. Carbon storage along a latitudinal transect in Alaska. Nutrient Cycling Agroecosyst. 49:235-242.

Ping, C.L., G.J. Michaelson, P.P. Overduin, and C.A. Stiles. 2003. Morphogenesis of frost-boils in the Galbraith Lake area, Arctic Alaska. Proceedings of the eighth international conference on permafrost, Zurich, Switzerland.
Racine, C.H., M.T. Jorgenson, and J.C. Walters. 1998. Thermokarst vegetation in lowland birch forests on the Tanana Flats, Interior Alaska, U.S.A. In: Proceedings of Permafrost: Seventh International Conference, June 23-27, 1998, Yellowknife, Canada. Centre d'etudes nordiques, Universite lavel. pp. 927-933.
Rieger, S., D.B. Schoephorster, and C.E. Furbush. 1979. Exploratory soil survey of Alaska. U.S. Dept. of Agriculture, Soil Conservation Service. U.S. Gov't Prntg Ofc. Washington, D.C. 213 pp.
Schoephorster, D.B. 1973. Soil survey of Salcha-Big Delta area, Alaska. U.S. Dept. of Agriculture, Soil Conservation Service. U.S. Gov't Prntg Ofc. Washington, D.C. 51 pp.
Shur, Y. L. 1988. The upper horizon of permafrost soils, in Proceedings of the Fifth International Conference on Permafrost, vol. 1. Tapir. Trondhiem, Norway. pp. 867-871.
Soil Classification Working Group. 1998. The Canadian system of soil classification. Agriculture and Agri-Food Canada Publication 1646 (Revised). 187 pp.
Soil Conservation Service. 1981. Land resource regions and major land resource areas of the United States. USDA Ag. Hndbk. 296. U.S. Gov't Prntg Ofc. Wash. D.C.
Soil Survey Staff. 1999. Soil Taxonomy: A basic system of soil classification for making and interpreting soil surveys. 2nd ed. USDA, NRCS. Ag. Hndbk. 436. U.S. Gov't Prntg Ofc. Washington, D.C. 869 pp.
Swanson, D.K. 1996a. Susceptibility of permafrost soils to deep thaw after forest fire in interior Alaska, U.S.A., and some ecologic implications. Arct. and Alp. Res. 28(2):217-227.
Swanson, D.K. 1996b. Soil geomorphology on bedrock and colluvial terrain with permafrost in central Alaska, USA. Geoderma. 71:157-172.
Swanson, J.D., M. Schuman, and P.C. Scorup. 1985. Range survey of the Seward Peninsula reindeer ranges, Alaska. USDA. SCS/ Anchorage, Alaska.
Ugolini, F.C., R. Reanier, G. Rau, and J. Hedges. 1981. Pedological, isotopic, and geochemical investigations of the soils at the boreal forest and alpine transition in northern Alaska. Soil Sci. 131:359-374.
Viereck, L.A. 1970. Forest succession and soil development adjacent to the Chena River in interior Alaska. Arct. and Alp. Res. 2(1): 1-26.
Viereck, L.A. 1982. Effects of fire and firelines on active layer thickness and soil temperatures in interior Alaska. Proceedings Fourth Canadian Permafrost Conference, Calgary, Alberta, March 2-6, 1981. pp. 123-135.
Viereck, L.A., C.T. Dyrness, and M.J. Foote. 1993. An overview of the vegetation and soils of the floodplain ecosystems of the Tanana River, interior Alaska. Can. J. Forest Res. 23:889-898.
Viereck, L.A., C.T. Dyrness, K. Van Cleve, and M.J. Foote. 1983. Vegetation, soils, and forest productivity in selected forest types in interior Alaska. Can. J. Forest Res. 13:703-720.
Wahrhaftig, C. 1965. Physiographic divisions of Alaska. U.S. Dept of Interior, Geological Survey Professional Paper 482. 52 pp.
Walker, D.A. 1999. A integrated mapping approach for northern Alaska. Int. J. Remote Sensing. 20:2895-2920.
Walker, D.A., N.A. Auerbach, J.G. Backheim, F.S. Chapin III, W. Eugester, J.Y. King, J.P. Mcfadden, G.J. Michaelson, F.E. Nelson, W.C. Oechel, C.L. Ping, W.S. Reeburg, S.

Regli, N.I. Shiklomanov, and G.L. Vourlitis. 1998. Energy and trace-gas fluxes across a soil pH boundary in the Arctic. Nature. 394:469-472.

Walker, D. A., and K. R. Everett. 1991. Loess ecosystems of northern Alaska: Regional Gradient and Toposequence at Prudhoe Bay, Ecol. Monogr. 61:437-464.

Walters, J.C., C.H. Racine, and M.Y. Jorgenson. 1998. Characteristics of permafrost in the Tanana Flats, Interior Alaska. In: Permafrost: Seventh International Conference, June 23-27, 1998. Proceedings. Yellowknife, Canada. Centre d'etudes nordiques, Universite lavel. pp. 1109-1114.

Zhang, T., T.E. Osterkamp, and K. Stamnes. 1996. Some characteristics of the climate in northern Alaska, USA., Arct. and Alp. Res. 28:509-518.

Zhestkova, T.N. 1982. Formirovaniye Krigennogo Stroyeniya Gruntov. Formation of cryogenic soil structure. Nauka. Moscow. (In Russian.)

Zoltai, S.C. 1972. Palsas and peat plateaus in central Manitoba and Saskatchewan. Can. J. Forest Res. 2(3):291-302.

Zoltai, S.C., and C. Tarnocai. 1975. Perennially frozen peatlands in the western arctic and subarctic of Canada. Can. J. Earth Sci. 12:28-43.