The Effects of Periglacial Processes on Landforms, Soils, and Vegetation in Terrestrial Ecosystems

by Mark Cable Rains

INTRODUCTION TO THE PERIGLACIAL ENVIRONMENT

Glacial processes have had substantial effects on landform, soils, and vegetation development in the Copper River watershed (Trowbridge 2002, Winter 2002). However, most of the Copper River watershed has not been glaciated in the recent past. Meanwhile, the entirety of the Copper River watershed is in a periglacial environment, and conditions in the upper Copper River watershed are particularly severe. Thus, periglacial processes also have had substantial effects on landform, soils, and vegetation development in the Copper River watershed.

The term periglacial was first introduced to describe the climatic and geomorphic conditions peripheral to the late Pleistocene ice sheets (Lozinski 1912). Since that time, the term has undergone substantial revision and no universally accepted definition exists. Some researchers have suggested rigorous definitions based solely upon climate. Zeuner (1945), for example, suggested that the term be restricted to those environments having mean annual temperatures of -2 ^{o}C or colder. Most researchers, however, prefer more inclusive definitions based upon climate and dominant geomorphic processes. Thus, the term has been generalized to include those environments where climatic conditions result in severe frost action that dominates geomorphic processes (Frost 1976). Permafrost is not a prerequisite, but it is practically ubiquitous in the periglacial environment (Pewe 1975). Frost (1976) identified four types of periglacial environments.

1. High arctic climates with large seasonal but small diurnal temperature fluctuations (e.g., the Canadian arctic).
2. Continental subarctic climates with large seasonal but small diurnal temperature fluctuations (e.g., interior Alaska including the upper Copper River watershed).
3. Alpine climates in the middle latitudes with large seasonal and diurnal temperature fluctuations (e.g., the summits of the European Alps).

4. Other climates widely distributed with small seasonal and diurnal temperature fluctuations (e.g., some subarctic islands and some summits of the South American Andes and the Hawaiian Seamounts).

Taking this inclusive definition, approximately 25 percent of the earth's land surface qualifies as periglacial at this time (Gerrard 1992).

The severe frost action and frozen ground in fine-grained sediments promote significant mechanical weathering, fine- and coarse-grain sorting, and mass movements (Pewe 1975). The mechanical weathering contributes to the wide-spread distribution of fine-grained deposits. Fine- and coarse-grain sorting facilitates the development of localized patterned ground features. The low permeability of the fine-grained deposits restrict drainage, and undrained waters are locked up in permafrost in the shallow subsurface. The permafrost, in turn, further restricts drainage causing saturated soils and mass movements on hillslopes and on plains.

PERMAFROST

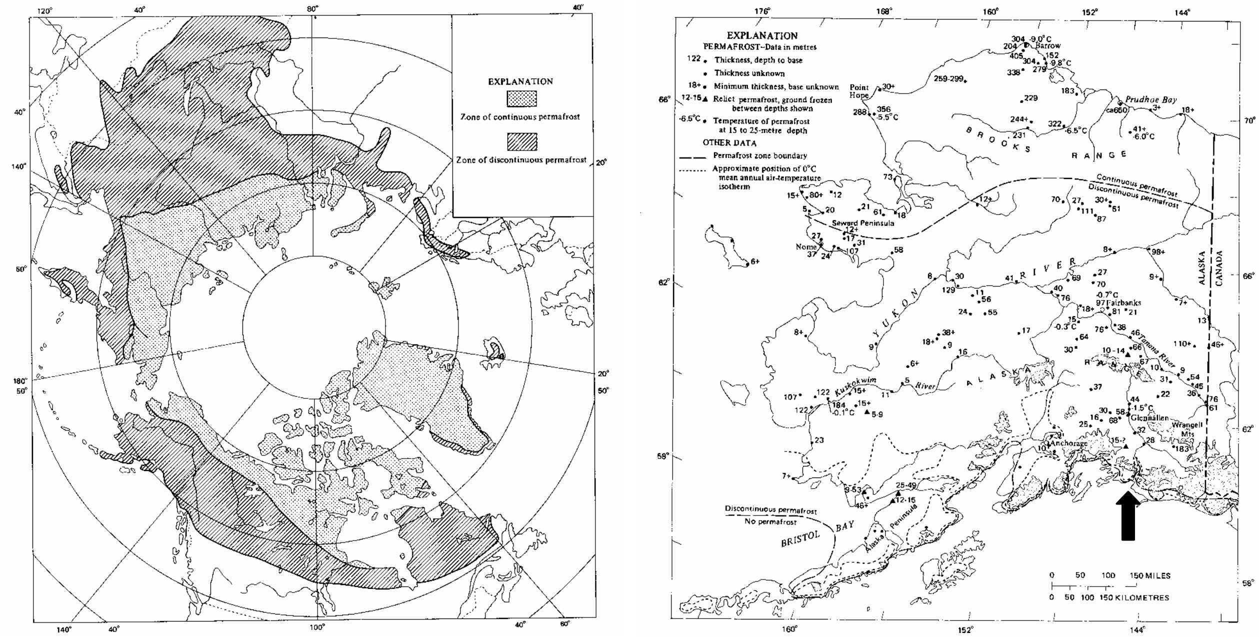
The term permafrost was first introduced to describe the condition of earth materials that remain below 0 ^{o}C continuously for at least two years (Muller 1945). It is defined exclusively on the basis of temperature, irrespective of the type of earth material, water content, degree of induration, or lithologic character. The distribution and thickness of the permafrost is governed by the energy balance between the earth and the atmosphere (Gerrard 1992). Above the permafrost is a seasonally frozen active layer, frozen in the winter and thawed in the summer. The seasonal frost must penetrate the entire active layer to contact the permafrost in most years or the permafrost will degrade (Mark Clark, personal communication, July 1995).

The distribution and thickness of the permafrost and the thickness of the active layer are determined by factors that control soil temperature fluctuations such as vegetation cover, thermal conductivity of the earth materials, and aspect. Vegetation cover may be the single most important controlling influence (French 1976). In interior Alaska, grasslands have widely varying seasonal soil temperatures (-14 to 10 ^{o}C), while forests have narrowly varying seasonal temperatures (-2.5 to 0.5 ^{o}C) (Sharratt 1998). Organic mats are critical components of the vegetation cover because they have extremely low thermal conductivities, with dry peat having thermal conductivities that may be an order of magnitude lower than the lowest values reported for mineral soils (Gerrard 1992). Thermal conductivity of the earth materials, too, has a primary controlling influence, with fine-grained deposits having thermal conductivities that are one-half those of coarse-grained deposits and several times less than those of bedrock (Gerrard 1992). Aspect also is a controlling influence, with permafrost often occurring on north-facing slopes but not occurring on adjacent south-facing slopes (Brown 1969). Thus, permafrost is most typically associated with heavily vegetated plains with fine-textured soils and with heavily vegetated, gentle, north-facing slopes with fine-textured soils (Swanson 1996).

Permafrost underlays approximately 20 percent of the earth's land surface and approximately 82 percent of Alaska's land surface (Figure 1) (Muller 1945, Pewe 1975). Alaska is divided into continuous, discontinuous, and sporadic or no permafrost zones (Black 1950, Pewe 1975). The continuous permafrost zone is located in the far north, generally north of the crest of the Brooks Range. The discontinuous permafrost zone is located in the interior and includes the upper Copper River watershed. Permafrost, though discontinuous, is prevalent wherever there are heavily vegetated plains or gentle slopes with fine-textured soils. The sporadic or no permafrost zone is located in the south and includes the lower Copper River watershed. Permafrost occurs in this zone, but only locally where conditions permit.

PERIGLACIAL LANDFORMS

Periglacial landforms can be subdivided into two main groups: slope landforms and patterned ground landforms. Slope landforms include cryoplanation terraces, gelifluction terraces, and cryopediments. These slope landforms are similar to slope landforms found in other warmer, semi-arid environments. Patterned ground landforms include thermokarsts, pingos, palsas, earth hummocks, and polygonal ground. Most of the patterned ground landforms are completely unique to the periglacial environment. All of the slope landforms and some of the patterned ground landforms can be observed in the Copper River watershed. Some of the major slope and patterned ground landforms are described below.



(a) (b)

Figure 1. Distribution of permafrost in (a) the Northern Hemisphere and (b) Alaska (Pewe 1975). The black arrow indicates the approximate location of the Copper River delta.

Slope Landforms

Cryoplanation Terraces

Cryoplanation terraces are erosional surfaces caused by freeze-thaw activity (Photograph 1) (Gerrard 1992). Cryoplanation terraces are composed of risers (i.e., vertical or steeply sloped surfaces in step-like landforms) and treads (i.e., flat or gently sloped surfaces in step-like landforms). Soils tend to be increasingly well-developed from the toeslopes of the risers to the far-reaches of the treads. Soils on the toeslopes of the risers tend be poorly to undeveloped, the materials typically having been recently deposited. Risers, themselves, tend to be too steep and/or unweathered to support any soil at all. Soils on the treads tend to be transport limited and better developed with distance from the riser.

Gelifluction Terraces

Gelifluction is the slow, down-slope movement of waterlogged soils which typically occurs where permafrost restricts drainage and frost heave of the overlying waterlogged soils initiates slow, down-slope movement (Photograph 2). Gelifluction terraces typically occur where local relief is so great that large lobes of waterlogged soils can move relatively rapidly down slope, creating steep terrace risers on their down-slope edges (Gerrard 1992). Tread slopes range from 3 to 25 percent, and risers may be as high as 4 m (Gerrard 1992). Sections cut through gelifluction terraces may show buried organic and mineral soil layers over-ridden by the gelifluction lobes.

Photograph 1. Cryoplanation terrace, northern Alaska. Photograph courtesy of the University of Alaska-Fairbanks.

Photograph 2. Gelifluction terraces in the Richardson Mountains, Canada. Photograph by S. Johnson.

Cryopediments

Cryopediments are gently-sloped surfaces in footslope and toeslope positions, and range in size from local features covering tens of m^2 to regional features such as the 50,000 km^2 Old Crow Pediments in northern Yukon (French 1987). Cryopediments are erosion and transport surfaces, with sheet wash and gelifluction being the dominant erosion and transport processes (Gerrard 1992). Cryopediments, like most footslope and toeslope positions, are gently concaved and support integrated drainage systems (Gerrard 1992). With the exception of gelifluction, cryopediments are similar to other pediment features in other warmer, semi-arid environments.

Patterned Ground Landforms

Thermokarsts

Thermokarst is a general term that refers to the many landforms that develop in response to the melting of ground ice (Pewe 1975, Gerrard 1992). Thawing permafrost creates uneven surfaces that primarily consist of subsidence features that collect water such as collapse scar bogs and small thermokarst lakes (Photograph 3). Two cases are presented to demonstrate the development of thermokarst features.

In one case, as described by Gerrard (1992), massive ice wedges thaw, perhaps in response to climate change or a change in vegetative cover. High-centered polygons, which are described below, begin to develop, separated by troughs over the melting massive ice wedges. The troughs collect water during the summer, thereby intensifying the melting. Eventually, enough of the ice melts that the entire area subsides. In another case, as described by Post (1996), a regional ground water flow system develops, perhaps on a glaciofluvial fan. Ground water is recharged on the high fan, warmed at depth, and discharged on the low fan. The discharge of the warm, regional ground water locally melts the permafrost and the entire area subsides. In both cases, water collects in the large subsidence features and either a collapse scar bog or a thermokarst lake develops.

Photograph 3. Thermokarst features on the Tanana Flats, interior Alaska. Photograph by M.C. Rains.

Pingos

Pingos are conical, ice-cored earthen mounds or hills, that may be 400 m in diameter and 70 m in height, that form where massive ice accumulates near the ground surface (Photograph 4) (Pewe 1975, Gerrard 1992). There are two types of pingos: closed-system and open-system. Closed system pingos tend to form on plains in the continuous permafrost zone where permafrost is shallow and severe winter cold causes intense frost action in the active layer. As the active layer freezes, it expands, and high hydraulic pressures are created between the seasonal frost and the permafrost. The high hydraulic pressures force water to move laterally to where it is forced toward the ground surface. As the water approaches the surface, it freezes and forms a conical, ice-cored earthen mound or hill. Open-system pingos tend to form on gently sloping surfaces in the discontinuous permafrost zone. Regional ground water from beneath the permafrost discharges to the surface under high hydraulic pressures. Again, as the water approaches the surface, it freezes and forms a conical, ice-cored earthen mound or hill. Typically, the tip of the cone, with a high surface area to volume ratio, melts in the summer and collapses, creating a volcano-like appearance.

Photograph 4. Open-system pingo on the Tanana Flats, interior Alaska. Photograph by M.C. Rains.

Palsas

Palsas are ice-cored peat hummocks, that may be 50 m in diameter and 7 m in height, that form where massive ice accumulates near the ground surface (Pewe 1975, Gerrard 1992). Palsas form where wind blows snow off a portion of a peat bog allowing intense frost action to penetrate deeply. As the ice freezes locally, it expands, and a mound develops. This mound protrudes above the peat bog surface and is more likely to be blown clear of snow in subsequent winters, creating a positive feedback that enlarges the feature.

Earth Hummocks

Earth hummocks are domed, non-sorted circles, that may be 1.5 m in diameter and 0.8 m in height (Washburn 1956). Earth hummocks result from the downward movement of soil in depressions and the upward movement of soil in mounds, but the specific processes involved are poorly understood. In permafrost areas, freeze-thaw of ice lenses at the top and bottom of the active layer may produce gravity-induced, cell-like movements since the tops and bottoms of the freeze-thaw zone have opposite curvature (Figure 2) (MacKay 1980). However, earth hummocks develop in non-permafrost areas, too, and no adequate processes for their development have been proposed.

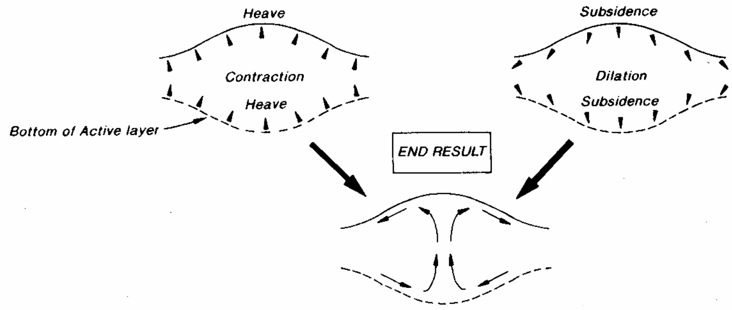


Figure 2. Cross-section view of earth hummock formation by gravity-induced, cell-like movements (MacKay 1980).

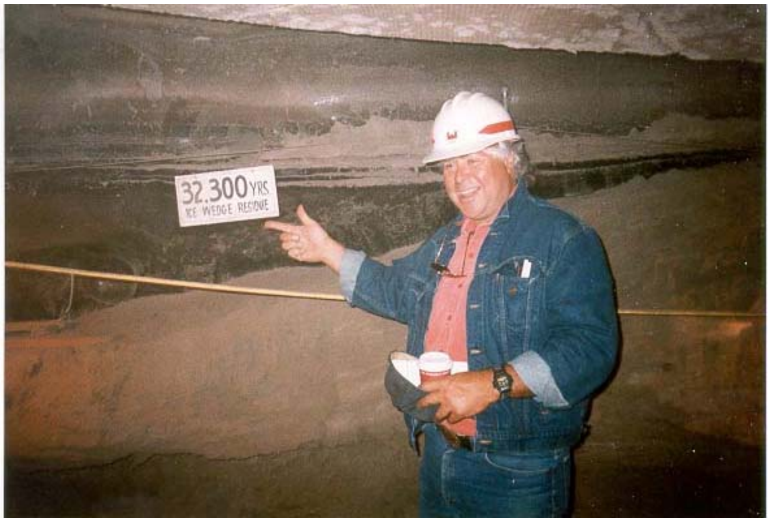
Polygonal Ground

Polygonal ground refers to cell-like, surface microrelief features 3-30 m in diameter, that form over massive ice wedges in the shallow subsurface (Photograph 6) (Pewe 1975). Massive ice wedges tend to be vertical, although they may appear to be horizontal when seen in transverse cross-section (Photograph 7). These ice wedges form polygonal networks in the shallow subsurface that are reflected in the conspicuous polygonal microrelief features on the surface. There are low-centered and high-centered polygons. Low-centered polygons form where actively growing massive ice wedges upturn surface deposits, resulting in low earthen walls that surround the cells. High-centered polygons form where actively melting ice wedges result in shallow troughs that surround the cells.

PERIGLACIAL SOILS

The low temperatures and severe frost action of the periglacial environment are so dominant that they may overwhelm or obliterate all other soil forming processes (Rieger 1974). Thus, the macromorphology and micromorphology of periglacial soils are dominated by frost action, rather than by the more familiar processes such as parent material, relief, and time.

Photograph 6. High-centered polygons, approximately 15 m in diameter, near Inuvik and Tuktoyaktuk, Northwest Territories, Canada. Photograph by S. Johnson.



Photograph 7. Massive ice wedge in the Fox Permafrost Tunnel, interior Alaska. Photograph by M.C. Rains.

Macromorphology of Periglacial Soils

Drainage Considerations

Periglacial soils can be divided into two primary groups: dry permafrost and wet permafrost soils (Gerrard 1992). Dry permafrost soils are well-drained. Though frozen at some depth, moisture contents are low and ice does not form. Wet permafrost soils are poorly-drained with thin or moderately thick active layers over ice-rich permafrost. The ice-rich permafrost acts as a perching layer limiting vertical ground water flow. Wet permafrost soils form in fine-grained deposits, often glaciolacustrine deposits or aeolian deposits blown off of glaciofluvial outwash plains, so hydraulic conductivities are low limiting lateral ground water flow, too (Douglas and Tedrow 1960). Thus, the active layers tend to be very moist to saturated and are therefore susceptible to severe disruption by annual freeze-thaw actions.

Organic Matter Accumulation

Organic matter accumulation is an important characteristic of periglacial soils (Gerrard 1992, Buol et al. 1997). Organic matter accumulates due short growing seasons, low temperatures, and typically wet conditions, all of which slow decomposition processes. Organic matter tends to concentrate on the surface in deep organic mats composed of vascular and non-vascular plants (Photograph 8). Organic mats may be deep enough to form histic epipedons (i.e., thick surface accumulations of organic matter) or Histosols (i.e., soils that are predominantly composed of organic matter) (Buol et al. 1997). Organic matter tends to move slowly into the soil profile due to low precipitation and a relative lack of vascular plants (Gerrard 1992).

Cryoturbation

Cryoturbation is the mixing of soil due to intense frost action. The effects of cryoturbation are varied, and include the disruption of soil horizons and the incorporation of coarse fragments of organic matter into the lower portions of the active layer (Buol et al. 1997). The net effect is that soil profiles can be quite complex, and it can be difficult to infer pedogenic histories and processes (Figure 3).

Micromorphology of Periglacial Soils

Massive Structure

The active layer freezes by downward extension of the freezing front and by slow upward extension of cementing ice above the permafrost table, and this convergence of freezing fronts creates high hydraulic pressures on soils in the active layer. Centuries of this type of annual pressure often results in heavy compaction and the development of massive soil structure (Buol et al. 1997). Massive soil structure is a condition where the pedons (i.e., the smallest volumes that can be considered soil individuals) are extremely large. Stated more simply, massive soil structures mean that large volumes of soil act as single units. Wet, fine-grained, massive soils often exhibit thixotropy. Thixotropy is a property where soils change from a jelly-like material to a fluid-like material when disturbed. Thus, thixotropic soils tend to flow like a viscous fluid when disturbed (Photograph 9).

Photograph 8. Upper part of an organic mat in the Yukon-Tanana Uplands, interior Alaska. Photograph by M.C. Rains.

Platy or Lenticular Structure

Again, the active layer freezes by downward extension of the freezing front and by slow upward extension of cementing ice above the permafrost table, and this convergence of freezing fronts creates high hydraulic pressures on soils in the active layer. Centuries of this type of annual pressure often results in heavy compaction and the development of platy or lenticular soil structure (Gerrard 1992). Platy or lenticular soil structure is a condition where the pedons are arranged horizontally and may be separated by planar voids and/or ice lenses (Photograph 10).

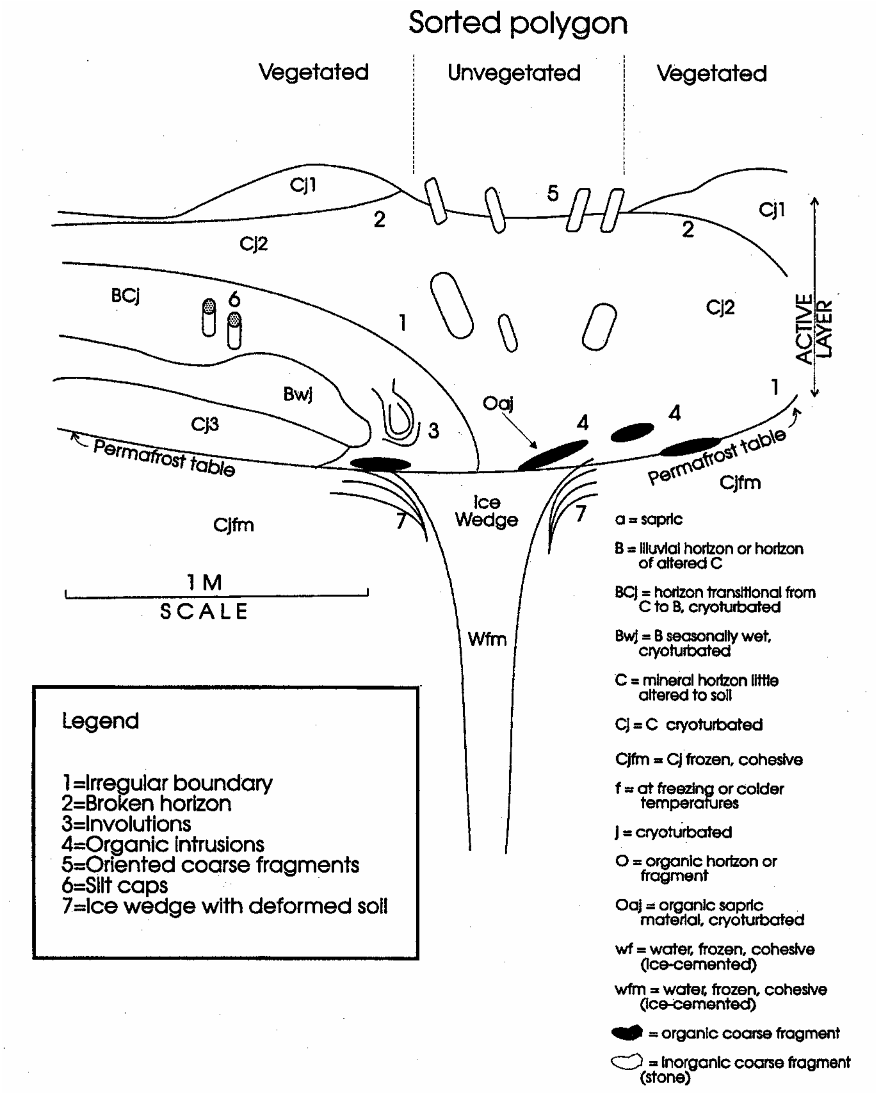


Figure 3. Typical pedon in a periglacial soil with permafrost and intense cryoturbation (Buol et al. 1997).

Vertical Reorientation of Grains

Grains may become vertically oriented because of differential movement of fine and coarse materials (Figure 3). The downward penetrating freezing front tends to push fine grains down and coarse grains up (Gerrard 1992). The coarse grains become vertically oriented because that is the orientation in which drag is minimized. This process can occur in very large grains such as the vertically oriented rocks at the summit of Finger Mountain which are large enough to be used for navigational purposes by small-craft pilots flying between Fairbanks and Deadhorse, Alaska.

Photograph 9. Massively structured, thixotropic soil in the Yukon-Tanana Uplands, interior Alaska. Photograph by J. Schively.

Photograph 10. Play or lenticular structured soil sample from the Yukon-Tanana Uplands, interior Alaska. Photograph by J. Schively.

THE EFFECTS OF PERMAFROST ON VEGETATION

The vegetation characteristics of glacial and periglacial environments in general and the Copper River watershed in particular are discussed more completely elsewhere in this volume (Trowbridge 2002). Nevertheless, the interactions between vegetation and permafrost are so critical that they deserve further discussion herein. It has already been shown that vegetation cover may be the single most important controlling influence on the distribution of permafrost (French 1976). Similarly, the distribution of permafrost may be the single most important controlling influence on the distribution of vegetation. There are three basic plant communities that occur on permafrost in interior Alaska: sedge tussock, shrub, and forest (Lee et al. 1999).

Sedge tussock communities occur in local lows that collect water, such as valley bottoms and collapse scar bogs. Sedge tussock communities are dominated by a few sedge genera, typically *Eriophorum* and *Carex* (Photograph 11) (Lee et al. 1999). Sedge tussock communities have unique hummock-hollow microrelief, with sedge tussocks forming elevated hummocks surrounded by depressed hollows that frequently contain ponded water. Shrub communities also occur in local lows that collect water, such as valley bottoms and collapse scar bogs. Shrub communities are dominated by a variety of shrub genera, including *Betula*, *Vaccinium*, *Ledum*, and *Potentilla*, and typically support sedge genera such as *Eriophorum* and *Carex*, too (Photograph 12) (Lee et al. 1999). However, forest communities – specifically, black spruce (*Picea mariana*) forest communities – predominate, covering 44 percent of interior Alaska (Post 1996, Lee et al. 1999). Black spruce on permafrost soils tend to be stressed and stunted. Stressed and stunted black spruce can be quite small, even at maturity (Photograph 13). Due to shallow rooting zones, moist and possibly thixotropic soils, and high winds, black spruce often lean leading some to refer to black spruce forests as “drunken forests”.

THE EFFECTS OF FIRE ON PERMAFROST

Fire is the most common natural disturbance in interior Alaska (Foote 1983). Fires in interior Alaska tend to be high intensity crown fires (Viereck and Schandelmeier 1980). Lower landscape positions tend to be wetter, so some vegetation and/or organic material may persist to provide insulating properties to the permafrost, but higher landscape positions tend to be drier, so little vegetation and/or organic material may persist to provide insulating properties to the permafrost (Swanson 1996). In these higher landscape positions, the loss of the vegetation and the organic mat can cause the permafrost to degrade and the site to enter into a well-drained, ice-free state (Figure 4) (Swanson 1996). After the vegetation and the organic mat recover, the permafrost can aggrade and the site can return to a poorly-drained, ice-rich state (Viereck 1973).

Photograph 11. Sedge tussock community in a collapse scar bog on the Tanana Flats, interior Alaska. Photograph by M.C. Rains.

Photograph 12. Shrub community in a valley bottom in the Yukon-Tanana Uplands, interior Alaska. Photograph by J. Schively.

Photograph 13. Black spruce, approximately 70 years in age and 2 Bills in height, in the Yukon-Tanana Uplands, interior Alaska. Photograph by M.C. Rains.

CONCLUSIONS

The periglacial environment is extremely severe. Severely low temperatures cause severe frost action which dominates landform, soil, and vegetation development. The entirety of the Copper River watershed is in a periglacial environment. Conditions in the upper Copper River watershed are particularly severe and, as expected, this has a profound effect on landforms, soils, and vegetation (Pewe 1975, Clark and Kautz 1998). Permafrost is ubiquitous, underlying most the upper Copper River watershed with the exception of lakes and floodplains (Clark and Kautz 1998). Glacial and glaciofluvial processes are more commonly associated with the Copper River watershed, but it is the periglacial processed that dominate most of the terrestrial ecosystems today.

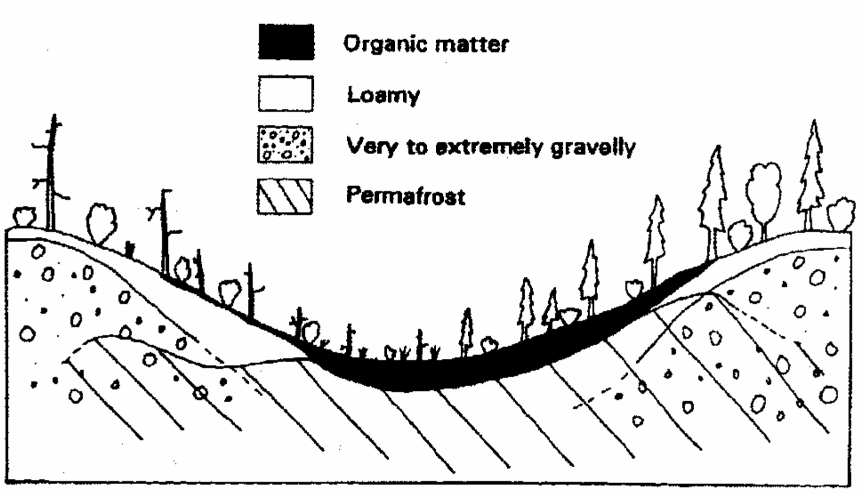


Figure 4. Conceptual cross-section showing the effects of fire on the vegetation, organic mat, and underlying permafrost. Note that the vegetation and the organic mat were burned off of the left side of the diagram and the underlying permafrost degraded. Also, note that the organic mat in the valley bottom survived the fire and the underlying permafrost did not degrade (Swanson 1996).

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