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Edited by Sarah J. Woodin and Mick Marquiss

Excerpt

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## I. Arctic soils and permafrost

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### INTRODUCTION

One of the most striking features of the arctic environment is the occurrence of a unique range of soils and surface features. Probably the most important feature in terms of soil development and geomorphology of the Arctic is the presence of permafrost or permanently frozen subsoil, which in places like Svalbard extends to depths of hundreds of metres. This continuously frozen barrier frequently leads to impeded drainage, reducing conditions, salinity and efflorescences of salts on soil surfaces. This chapter provides an introduction to the soils and permafrost of the Arctic. It describes the processes which lead to formation of the unique surface and subsurface features generally known as *periglacial features*. This is followed by a brief description of the major soils found in the region, and their relationships to the periglacial features and vegetation.

The Arctic is generally considered to be the region north of the 14°C July isotherm and is known as a periglacial environment. The term periglacial was introduced by Lozinski (1912). It has no specific definition, although it has come to mean those Arctic and Antarctic areas that have an *active layer* at the surface and subsurface *permafrost*. However, some maritime areas that are generally regarded as a part of the Arctic do not have permafrost. The active layer freezes every winter and thaws every summer, while the permafrost remains permanently frozen. The term periglacial also includes those high mountain areas that have a very cold climate, even though permafrost may be absent.

Precipitation in the Arctic varies from 50 to 1200 mm year<sup>-1</sup> with mean annual temperatures of < 0°C, and minimum winter temperatures < -40°C. Areas with a maritime climate have higher rainfall which is evenly distributed throughout the year, while the cold continental climates have low rainfall with most of it occurring during the short cool summers (Tedrow 1977). The classical works about arctic geomorphology include those of Geikie (1894), Högbom (1914), Taber (1929, 1930, 1943), Leffingwell (1919) and Lachenbruch (1962). General accounts of the periglacial environment have been given by Embleton and King (1975), French (1996) and Washburn (1973).

In the Arctic, Tedrow (1977) recognizes three main climatic subzones: polar desert, subpolar desert and the tundra, each of which has a number of important distinguishing features.

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**1** The polar desert subzone is characterized by barren rocky surfaces, intensely cold, strong winds and low rainfall. Algae and lichens are the principal components of the plant life. The soils are unleached and carbonates are often present. Salt efflorescences and desert varnish also occur. The main soils are Leptosols, Regosols and Solonchaks.

**2** The subpolar desert is dominated by mosses, lichens, sedges and grasses, with occasional shrubs, birch and dwarf willows. The main soils are Leptosols, Cambisols, Gleysols, some Histosols and rarely Solonchaks.

**3** The tundra subzone is characterized by mosses, sedges, grasses, shrubs, birch, black spruce, white spruce, pine, larch and willows. Salt accumulations occur in the very dry areas. The dominant soils are Cambisols, Gleysols and Histosols, which occur mainly in oceanic areas and depressions. Podzols and Luvisols are rare, shallow, and show clear evidence of winter freezing. Phaeozems and Andosols are very rare. Throughout these subzones there are Fluvisols associated with the rivers.

There is some variability in the climate of these subzones, particularly in the amount of precipitation which increases towards the oceanic areas.

## PERIGLACIAL PROCESSES IN THE ARCTIC

The change in state of water to ice upon freezing, and the accompanying change in density with its 10% increase in volume, are very important processes. With a further reduction in temperature, ice behaves like a normal solid and decreases in specific volume but it has a very high coefficient of linear expansion ( $51 \times 10^{-6} \text{ K}^{-1}$ ), thus with a 30°C fall in temperature, cracks at least 1.5 mm wide will form in the soils. These unique contraction–expansion properties of water result in many of the processes and features developed in the Arctic.

### *Physical processes in arctic soils*

#### *Freeze–thaw processes*

The results of these processes depend upon both the amount of water in the soil system, and the rate of decrease in temperature. When there is an adequate supply of water, and the temperature of the soil falls rapidly overnight to less than 0°C, the surface freezes, forming a massive structure in which there is an intimate mixture of ice and soil. When cooling is slow, ice crystals with a characteristic elongate form, or piprake, more than 5 cm long, grow out from the surface carrying a small capping of soil or gravel. Alternatively, they may grow beneath stones heaving them to the surface, where a continuous layer of stones and boulders may form as in the polar desert subzone.

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When freezing takes place over a number of days beneath the surface or under controlled laboratory conditions a variety of patterns develop, as determined by the speed of freezing, particle size distribution and water content. In very sandy material the ice fills the large pores giving a massive structure. In loams and silts a distinctive lenticular structure develops, with lenses of soil surrounded by continuous more or less horizontally bifurcating sheets of pure ice. In silty clays, ice segregates mainly vertically to give a prismatic structure. In clays, ice segregates in both vertical and horizontal layers to isolate subcuboidal blocks of frozen soil (Kokkonen 1926; Taber 1929). In some situations distinctive subspherical aggregates are formed (Morozova 1965; Van Vliet-Lanoë, Coutard & Pissart 1984).

The thickness of the ice segregations is a function of the speed of freezing as well as the water content. When the water content is low there is no ice segregation. When freezing is very slow and progressive over months or years and there is a plentiful supply of water, thick sheets of ice form, since water is steadily drawn up to the freezing front. The thickness of the ice sheets and soil lenses increases gradually with depth; they may be 1–2 mm thick at the surface and increase to over 1 cm at about 50 cm deep. However, sheets > 10 m thick occur in parts of Siberia and northern Canada. This segregation and growth of ice causes the soil to lift and is known as frost heaving. The amount of heaving varies from site to site with about 25 mm in mud circles to 26 cm in frost boils (Czeppe 1960; Everett 1965; Washburn 1967; Benedict 1970). This is one of the most important processes in the Arctic and in many areas immediately to the south. It is the mechanism that is responsible for the break-up of many roads and is therefore of immense economic importance.

The water in soils contains dissolved air, and usually some extra CO<sub>2</sub> derived from respiring roots and decomposing organic matter. These gases are expelled from solution when the water freezes, and form gas bubbles or vesicles in both the ice and the soil. When the soil thaws the vesicular structure in the soil is maintained, while some of the air bubbles in the ice may coalesce to form larger vesicles in the recently melted, and almost fluid, soil. Lamellar pores are also created by the melting of the ice sheets.

Ice segregates as the result of the formation of ice crystals that grow and elongate about their *c*-axes in a manner similar to quartz or calcite. The elongation is in the direction of heat loss which is usually vertically. Thus, in thin sections of permafrost cut normal to the surface it is possible to see vertically elongated ice crystals (E.A. FitzPatrick unpublished data). Ice segregations also cause a reorganization of the soil by withdrawing water and compacting the lenticular or subcuboidal soil units. This may cause some of the fine sand and silt grains to become orientated parallel to the surfaces of the soil aggregates. These units are so well developed and compressed that they maintain their form when the soil thaws. Lenticular and subcuboidal peds released by melting permafrost at the end of the last glaciation are still present in the soils of a great many areas (FitzPatrick 1956, 1993). The

amount of segregation depends also on the texture of the material with little taking place in sands, some in clays and considerable segregation in silts. The materials that develop large segregations and hence considerable heaving of the surface are said to be frost susceptible (Penner 1974).

In polar areas freezing of the surface soil during the winter and thawing during the summer creates an annual cycle which, coupled with ice segregations, cause profound disturbance of the soil surface and the formation of a number of characteristic features. Since stones have a lower specific heat than the surrounding soil, they cool down and heat up more quickly, thus attaining 0°C before the surrounding soil and therefore form loci for the formation of ice. This ice can become quite thick around the stone and displaces the surrounding soil. Repeated freezing and thawing, resulting in the formation and disappearance of ice, can cause the reorientation of the stones which in flat situations develop a vertical orientation of their long axes and simultaneously are gradually forced to the surface. Thus, typical permafrost will be composed of bifurcating sheets of ice surrounding compact lenses of soil, both of which will have vesicles of gases. If stones are present they will have a complete sheath of ice which will also have gas vesicles.

*Frost shattering (frost wedging)*

The occurrence in polar and alpine regions of extensive surfaces strewn with angular rock fragments is generally interpreted as being due to freeze–thaw processes. As water freezes, pressures of over 500 kg cm<sup>-2</sup> are created and it is assumed that these pressures exist in the pores of the rocks causing them to split apart, leaving a number of loose fragments as it thaws. Therefore the amount of fragmentation will increase as the number of freeze–thaw cycles increases. This explanation, however plausible, does not stand up to careful analysis since many areas in the middle latitudes that have more frost–thaw cycles than polar areas do not have the same extensive occurrence of angular rock debris. Everett (1961) suggested that the active agent is the steady growth of ice crystals in the fine pores of the rocks during prolonged periods of low temperatures. This creates high pressures which severely weaken the rocks causing them to split apart. Probably the main mechanism for shattering is the very wide temperature fluctuations that take place, from about +50°C at the surfaces of rocks on a hot summer day to –50°C during the winter. This 100°C variation causes great thermoelastic stress and probably leads to the development of a contraction crack system in the rocks that can be exploited by the formation of ice crystals (McGreevy 1981; Hallet 1983; Hallet, Walder & Stubbs 1991). Rock fragments in soils and other unconsolidated materials can also be frost shattered. Further, it has been shown that over a long period rocks can be reduced by freeze–thaw processes to accumulations of silt- and clay-size particles (Lautridou 1982; Lautridou & Ozouf 1982; Fukuda 1983).

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This is the process whereby material is moved down the slope, and is now used as an umbrella term to include gelifluction and soil creep. Gelifluction is the rapid movement of material downslope, and creep is the slower and more insidious process in the active layer (Baulig 1956; Harris 1981). However, neither of these is used for the flow of permafrost down the slope, although this could be included in creep since this is a very slow process. Thus, there is gelifluction, active-layer creep and permafrost creep as described below. In addition there is movement of material by surface wash, mud-flows and land slides.

On slopes, repeated freezing and thawing cause mass movement of material downslope forming stratified slope deposits. The exact nature of the mechanism involved is gradually being understood through the use of laboratory experiments (Harris, Gallop & Coutard 1993; Harris, Davies & Coutard 1995, 1996). Different soils behave differently, and mass movement rates are strongly related to the content of silt. Coarse materials tend to move by creep due to the formation of needle ice, whereas with fine material gelifluction tends to take place due to the melting of the segregated ice. Creep takes place at an annual rate of 4–10 mm at dry sites, and 20–30 mm at wet sites, but there is considerable annual variation. Gelifluction takes place at an annual rate of 10–40 mm at dry sites and 30–70 mm at wet sites. Gelifluction can be accelerated in the presence of permafrost which is impermeable and causes water to accumulate within the surface horizons. Jahn (1960) has shown that the rate of solifluction in Spitsbergen is about 1–3 cm year<sup>-1</sup> on slopes of 3–4°, and 5–12 cm year<sup>-1</sup> on slopes of 5–7°. In all the measurements that have been made on solifluction it has been shown that the rate of movement is greatest at the surface and decreases with depth attaining zero at about 1 m. When the movement of material downslope is gradual, the stones tend to become orientated with their long axes parallel to the slope and normal to the contour. In addition, the surfaces of such areas are characterized by a number of lobes and terraces produced by differential movement.

The characteristic arcs at depths of 1–3 m in the permafrost on slopes in Arctic areas are attributed to movement resulting from freezing and thawing, and therefore regarded as normal solifluction. It is more likely that these arcs are due to plastic deformation and slow flow of the permafrost downslope. Since the depth of summer thawing in the Arctic seldom exceeds 1 m and the arcs occur below this depth, it is difficult to explain their presence as due to freezing and thawing. However, the temperature in the upper 1 m of the permafrost in the summer is only a few degrees below freezing, therefore it could flow by plastic deformation during this period of the year. The warmer and less viscous upper part would flow more rapidly than the cooler and deeper more viscous part, thus accounting for the arcs. In addition, these arcs are destroyed when they are incorporated in the active layer with its

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annual freeze–thaw cycle. Therefore, on slopes there is an upper part of the soil that has an annual freeze–thaw cycle and can move slowly or rapidly and disruptively, and a lower frozen part that moves very slowly by plastic deformation to form the arcs (FitzPatrick 1971, 1983; Thompson & Sayles 1972).

#### *Wind action*

Average wind speeds of about  $18 \text{ km h}^{-1}$  with maxima up to  $72 \text{ km h}^{-1}$  occur in the Arctic (Filstrup 1953). These winds deflate the surfaces of alluvium and other deposits, leading to the formation of sand dunes and loess that accumulate to over 30 m, as in parts of central Alaska. The particles carried by the very strong winds cause abrasion of surfaces with the formation of wind-faceted stones or ventifacts, which are very common on strand flats and raised beaches.

#### *Chemical processes in arctic soils*

The main chemical processes that take place in soils generally, also occur in the Arctic and include the following: solution, hydration, hydrolysis, oxidation, reduction, carbonate accumulation, salinization, salt wedging, cavernous weathering, case hardening, desert varnish formation and biological weathering.

#### *Solution, hydration and hydrolysis*

Solution is the process that dissolves the soluble minerals in soils. It affects particularly salts, carbonates and primary minerals such as apatite, but these are usually present in very small amounts. Thus, this process is generally of minor importance except where the rocks contain much carbonate or soluble salts. It should be pointed out that quartz weathers by solution, but it is very sparingly soluble; hence, it accumulates in soils while the other minerals steadily decline in volume. However, there is usually enough silica in solution in the Arctic to support populations of diatoms in many wet situations.

Hydration is the process whereby minerals take up water from their surroundings. This applies particularly to primary minerals, such as biotite, and to the secondary oxides and oxyhydroxides of iron and aluminium. This is also of minor importance in the Arctic.

Hydrolysis (proton donation) is the most important process affecting the primary minerals in soils generally. During this process, dissociated hydrogen ions in the soil solution replace basic cations such as calcium, sodium and potassium on the surface of a mineral. These basic ions may form an integral part of the mineral or they may form part of the exchange complex with clay minerals. The lower the pH of the soil solution, the more rapid the decomposition of the minerals. The

pH of arctic soils varies from about 5 to 7 and in a few situations it may be as low as 3.0. It is determined in part by the  $\text{CO}_2$  concentration derived mainly from the atmosphere, which may be the only source of  $\text{CO}_2$  in polar desert areas where there is little or no vegetation and very low microbial activity. However, it is supplemented considerably from decomposing organic matter and respiring roots where vegetation is present. Since some arctic soils contain large amounts of organic matter it would be expected that the rate of hydrolysis would be high, but this is not the case because of the low temperatures which reduce both the rate of organic matter decomposition and the reaction rate between the hydrogen ions and the minerals.

Other elements, such as iron and aluminium, are also released by the hydrolysis of the primary minerals and may stay in solution, or may be complexed with organic compounds or precipitated as hydrated oxides on surfaces of rock fragments or soil aggregates. These three processes are active throughout the Arctic, but at a much reduced rate as compared with areas immediately to the south. This is due to the lower temperatures and to the small amounts of water in some areas, particularly in the polar deserts subzone. However, there are sufficient dissolved acids and water movement in many places in the subpolar desert and tundra subzones to cause most of the soils to be acid and for a range of ions to be translocated to waterways as shown in Figs 1.1 and 1.2 (Brown *et al.* 1962). Figure 1.1 shows that the concentrations of the main cations in the waterways in northern Alaska are low and seldom exceed  $5 \text{ mg l}^{-1}$ . The streams at Barrow have high concentrations of calcium and magnesium and, as expected, those influenced by calcareous materials have the highest, up to  $30 \text{ mg l}^{-1}$ . Figure 1.2 shows that the concentrations of the main microelements are also generally low, except for that of iron, which

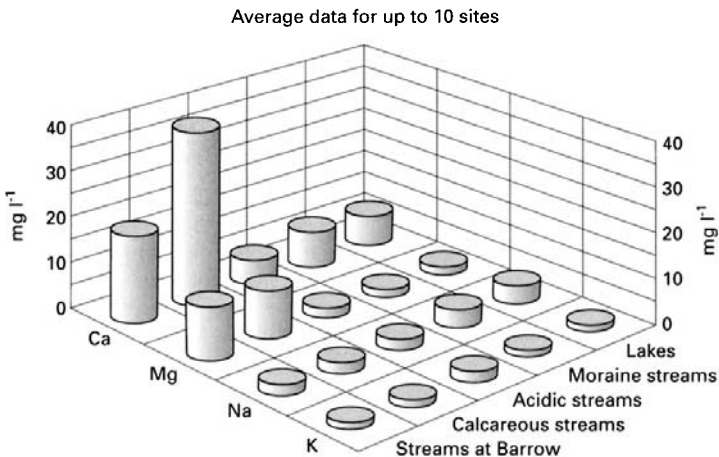


FIG. 1.1. The major cations occurring in the streams and lakes of northern Alaska.

Average data for up to 10 sites

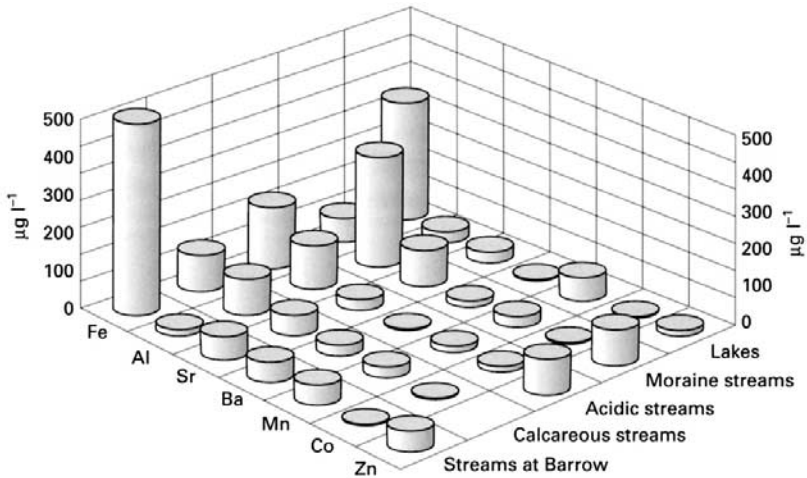


FIG. 1.2. The microelements occurring in the streams and lakes of northern Alaska.

is high in the streams at Barrow, the acidic streams and in the lakes. The aluminium concentration is highest in the streams from the moraines, probably because of the high surface area of this relatively fresh glacial material containing many feldspars. These low figures for most elements may represent the low degree of weathering that is taking place. On the other hand, they could indicate that there is little tendency for ions to accumulate in the environment in that part of Alaska. Ugolini, Stoner and Marrett (1987) identify a number of factors which severely restrict the rates of chemical weathering in the Arctic.

#### *Oxidation and reduction*

Iron is the main mineral that undergoes oxidation and reduction in soils. In aerobic soils, such as Cambisols in upland and moderate to strongly sloping situations, the small amount of iron that is released by hydrolysis is usually oxidized to give yellow and brown oxides and oxyhydroxides in the upper and middle parts of the soil. It should be mentioned that most of the primary minerals containing iron are greenish in colour, indicating that the iron is in the reduced,  $\text{Fe}^{2+}$  form. When it is released by hydrolysis in an aerobic environment, it is almost immediately oxidized to give yellow and brown oxides, which give the coloration to many of the freely draining soils, including the Cambisols. In the tundra subzone, iron exists mainly in a reduced form in the soils on flat and gently sloping situations that are wet or saturated with water for most of the summer. The middle and lower horizons in these soils are grey and blue, and may have yellow and brown mottles. In these



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situations most of the iron released by hydrolysis stays in the grey or blue  $\text{Fe}^{2+}$  state because of the restricted entry of oxygen into pores filled with water. The yellow mottling is produced in the short periods of aeration and oxidation of the iron to lepidocrocite during the latter part of the summer.

*Carbonate deposition*

Carbonate accumulation is very common in soils of the polar desert subzone and extends into the subpolar desert subzone. It may form a continuous horizon or pendants under stones and boulders. In many of the Cambisols of the drier areas, there is some calcium carbonate deposition within the soil, particularly where the permafrost is deep and there is very low precipitation (Courty *et al.* 1994).

*Salinization*

In dry areas, evaporation during the later part of the summer often leads to the formation of efflorescences of salts on soil surfaces. There may be a gradual growth and accumulation on the surfaces or there may be periodic drying out of surface water that has accumulated in shallow depressions or around tussocks. Where this process has been continuous for a long period there may be over 10 cm of accumulated salts, with thenardite ( $\text{Na}_2\text{SO}_4$ ) being the principal component. The salts originate from a variety of sources: they may accumulate from weathering, be present in geological strata or be derived from sea spray.

*Salt wedging* takes place when salts crystallize in the pores and joints of rocks creating high pressures similar to those caused by freezing, and results in the physical break down of the rocks. It is of greatest importance in the polar subzone with sulphates producing more disintegration than chlorides or carbonates. The outer surface of many rocks is *case hardened*, caused by the deposition of material by evaporation of solutions containing minerals. Many rocks, particularly in the polar subzone, develop a cavernous appearance as a result of *salt fretting*. The effect is sometimes enhanced when the original rock has been case hardened. The loosened material may accumulate around the base of the rocks or it may be removed by wind.

*Desert varnish formation*

Desert varnish is a very dark, most often black, coating on the surfaces of rocks and rock fragments. It seems to be composed mainly of varying amounts of manganese, iron and aluminium and forms by the migration of material from inside the rock fragment to its surface. Desert varnish formation takes place only on very old land surfaces and thus seems to require a considerable period of time to develop.

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Further, it only forms in the very driest sites, and thus is present mainly in the polar desert subzone where the coated stones and boulders may form a continuous layer or hamada at the surface.

### *Biological processes*

The main biological processes associated with soil formation are the accumulation of litter, nitrogen cycling and biochemical weathering, all of which are associated with plants. The plant communities in the Arctic vary from a sparse covering of lichens on rock surfaces in the polar desert subzone to well-developed forest communities of spruce, pine and larch in the southern part of the tundra subzone. Thus, the contribution of litter is equally variable but it seldom exceeds  $2 \text{ t ha}^{-1} \text{ year}^{-1}$  in the forested areas. This is relatively small as compared with a tropical rainforest which contributes about  $25 \text{ t ha}^{-1} \text{ year}^{-1}$ . On the other hand, the soils of the tundra subzone may contain several centimetres of free organic matter at the surface while a tropical soil may only contain  $<5\%$  organic matter mixed with the mineral soil. The difference between these sites is due to differences in the rate of decomposition which is much more rapid in the tropics. The type of organic matter is also important. In the cold areas of the world the organic material is usually acid to very acid which helps mineral weathering, but the low temperatures tend to retard weathering and soil formation generally. Thus, in the Arctic there is a relatively small production of organic matter but a relatively large amount in soils. Figure 1.3 shows the amount of carbon in a transect from the polar desert subzone to the southern boreal forest (Giblin *et al.* 1991). It shows an almost steady increase in the amount of biomass with a slight peak in the tussock areas. However, the dead organic matter shows two distinct peaks, one in the area of tussock vegetation in the tundra subzone and a second much higher peak in the northern boreal forest. The high amounts of dead organic matter are related both to the rate of addition as well as the slow rate of decomposition. As the rate of addition increases so does the amount of dead organic matter, indicating that decomposition is less than addition. This seems related to the increase in wetness and decrease in decomposition rate from the polar desert to the wet tussock vegetation. The rapid fall in dead organic matter in the tall shrub vegetation is due to drier conditions which reduce plant growth but increase the rate of decomposition. There is then a steady increase in the addition of organic matter, but a marked jump in the amount of dead organic matter in the northern boreal forest again associated with wetter soils. Thereafter, the amount of dead organic matter decreases as the rate of decomposition increases commensurate with the increase in temperature. This transect clearly demonstrates the varied relationships between organic-matter accumulation, rate of decomposition, temperature, soil water and plant growth in the Arctic.