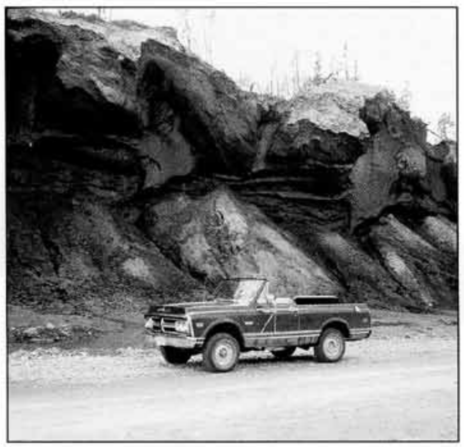
PERMAFROST

A Guide to Frozen Ground in Transition



by Neil Davis

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Land Forms Created by Cryogenic Action

Introduction

Cryogenic action in the active layer and in permanently frozen ground produces a variety of geomorphic features unique to cold lands, and also a few that appear very similar to landforms created by geological processes not related to freezing and thawing. Some of the cryogenically caused landforms and effects are relics of past times when the climate was colder; many others are the consequence of ongoing processes that wax and wane with variation in weather and climate. Cryogenic processes continuously operate to modify the land surface and the ground below wherever the temperature of the ground dips below freezing, even if just for a few hours. Some changes occur rapidly, in a matter of hours or days, and others proceed slowly, over the course of thousands of years. But be they fast or slow, the changes wrought by the freezing and thawing of the ground lend special interest to the overall topic of perennially and annually frozen ground.

The formation of pipkrakes described in Chapter 3 is an example of a fast-acting and readily observed cryogenic process that operates over much of the earth's land surface, and it provides obvious demonstration of the profound effect of cryosuction on movement of water through the ground—typically in the direction toward the cold. That movement is crucial to the formation of most if not all transient and long-lasting

landforms generated by freezing and thawing of the ground. As we now explore their distribution and characteristics it is good to keep in mind that the various kinds of landforms, like the different kinds of ground ice, may intermingle, and so what a person sees in any one place may be the result of several generative processes. Also it may be comforting to keep in mind that the names attached to these various landforms are important only to the extent that they may be useful to the discussion of the formative processes.

Ice Wedges and Polygons

Ice-wedge arrays

Ice-wedge arrays are widespread in permafrost, and one geocryologist has estimated that ***ice wedges*** comprise a volume that is 10% of the top few meters of permafrost on the northern coastal plain of Alaska.[1] In that region and in many other areas the polygonal pattern in which ice wedges form expresses itself on the ground surface so that it is readily recognized, especially when seen from the air. Ice wedges also can lie unseen in the permafrost—down beneath an insulating cover of soil, moss, and trees—capable of destroying the works of the unsuspecting engineer or homeowner who disturb its environment by placing a heated structure overhead or removing the overlying insulative cover.

The generally accepted explanation of how ice wedges form is a simple one: a wedge begins when water freezes in a crack opened in the ground when it contracts from the cold.[2] The ice-filled crack is weaker than the surrounding frozen soil so it breaks open again when the ground next cools enough to cause cracking. Thus the process cycles on year after year to build a tapered wedge of ice up to several meters wide at the top and perhaps five or more meters tall. Each summer, warming causes expansion of the frozen soil adjacent to the wedge, and it undergoes plastic flow that bends it upward. In some places the wedges are so extensive that they no doubt have elevated the overall ground surface. Classic photographs of an initial crack and of a well-developed ice wedge appear in **Figures 4.1** and **4.2**, and **Figure 4.3A** shows a schematic drawing of how the wedges develop.

1. Brown (1967); Péwé (1975b).
2. Leffingwell (1919); Lachenbruch (1962).

Figure 4.1 A frost crack on the surface of a recently drained area on Flaxman Island. From Plate XXIX in Leffingwell (1919). Cracks such as this occur abruptly, generating loud noises and very small, localized earth tremors called cryoseisms by Lacroix (1980).

Spacing and orientation of contraction cracking

Polygonal cracking is a commonly observed phenomenon in materials that contract when cooled or desiccated.[3] Examples of cracking caused

3. Any process that causes the volume of a material to decrease in a way that creates internal tension may generate contraction-crack polygons, so phase changes and chemical reactions might also generate the cracks.

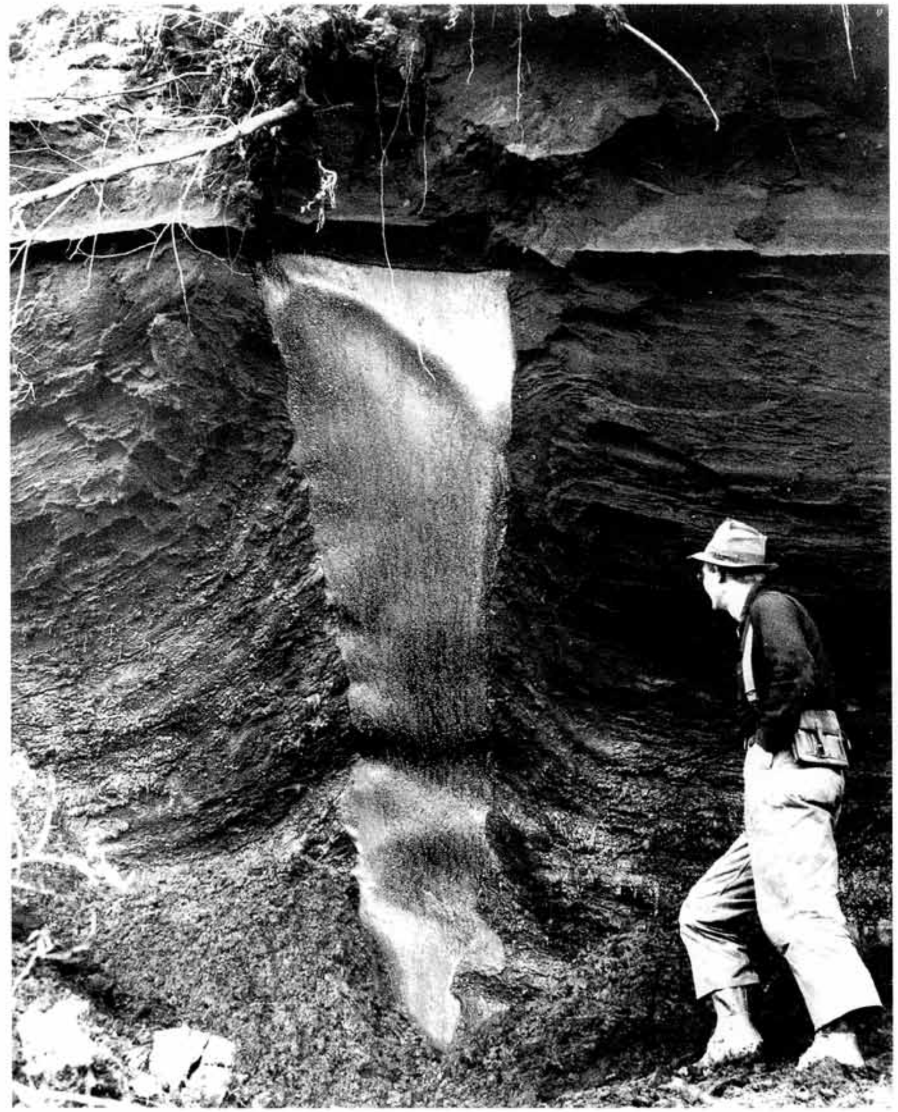


Figure 4.2 Foliated ice wedge in silt exposed by placer mining operations near Livengood, Alaska. Photograph No. 474 by Troy L. Péwé, September 1949.

by cooling are the crackling in paint on metal surfaces, the crackle finish on some pottery, and shrinkage cracking of concrete and of some basaltic rocks. Commonly seen examples of desiccation cracks are those appearing in mud when it dries. Since the cracks occur because the

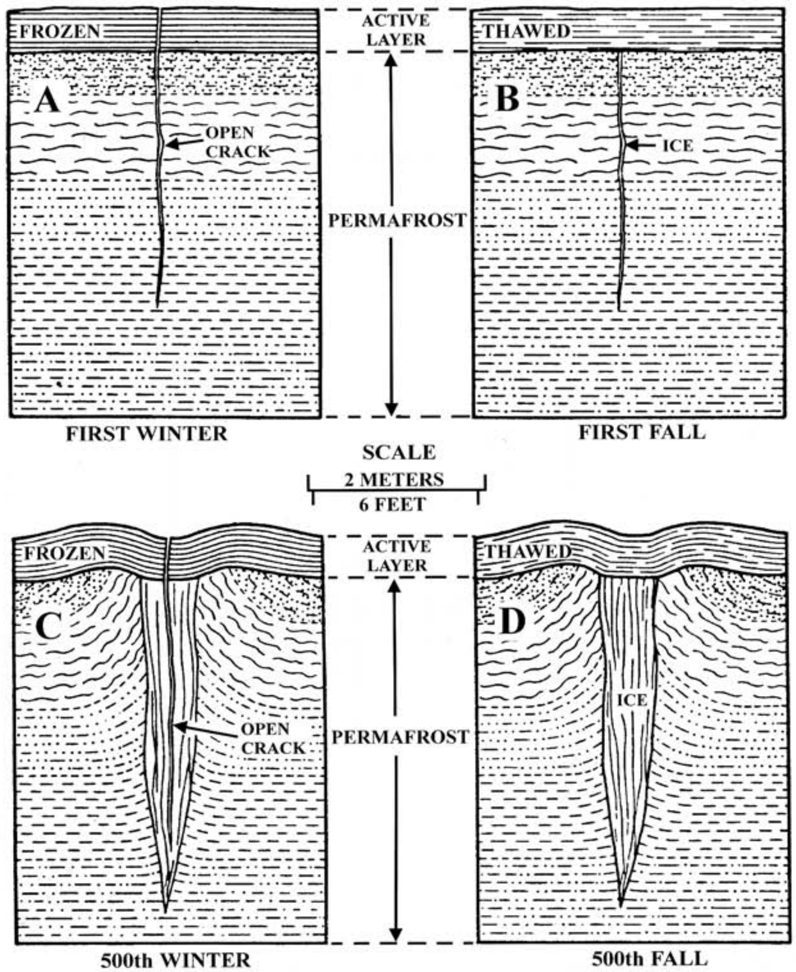


Figure 4.3A Schematic representation of the evolution of an ice wedge according to the contraction-crack theory. The crack is exaggerated for illustrative purposes. Diagram modified slightly from Figure 1 of Lachenbruch (1962).

material has failed under tension, the various kinds of cracking share common characteristics. The scale of the cracking differs because it depends on the tensile strength of the material involved, and the cracks are less uniform when the cracked material is not homogeneous. Certainly one of the least homogenous materials is soil, so it follows that when the ground undergoes cracking during cooling, the cracks are likely to be far from perfectly uniform.

Frozen ground gains tensile strength and becomes increasingly brittle as it grows colder. However, rapidly falling temperature causes differential shrinking in frozen ground and thereby generates high enough internal ***stress*** that exceeds the tensile strength of the frozen ground and causes it to crack. The cracking involved in the development of ice wedges typically occurs in midwinter when the near-surface ground temperature is –15°C or below and rapidly falling air temperature further cools the ground by another 10 or 20 degrees. Ice wedges become widespread where the mean annual temperature is lower than –7°C. The cracking happens abruptly, and people report hearing rifle-shot noises as the cracks break open to widths ranging from a few millimeters to 2 cm at the top and tapering down with depth in consequence of lowered stress there.

Geocryologists believe that the initial cracking that begins the development of a polygonal array of ice wedges starts at the ground surface and propagates downward into the active layer and permafrost below until compressive forces created by overburden help the frozen soil's inherent strength stop further cracking. In permafrost areas the final depth of cracking typically is 3 to 10 meters. That initial cracking relieves stress in the direction at right angles to the plane of the crack (by convention, called the normal direction). All the normal stress just beside the crack disappears, and the amount of normal direction stress release declines with distance out away from the crack. For cracks 3 to 10 meters deep the normal stress is down to about one-third the initial value at a horizontal distance of 3 meters, and it falls to 5% at distances of 10 to 20 meters. That distance—10 to 20 meters—is roughly equal to the diameters of ***polygon***s that develop when further cracking occurs. A factor determining the polygon size is how rapidly the ground cools while the cracks are forming; the more rapid the cooling, the smaller the polygon.

Contraction crack polygons generally fall into two main categories called orthogonal and nonorthogonal polygons. Orthogonal polygons tend to have four sides, since in orthogonal cracking the cracks tend to meet at right angles. The nonorthogonal polygons tend to have six sides since the responsible cracks tend to meet at angles of 120°, as shown in **Figure 4.3B**.

The Universal System Happiness Rule dictates that highly homogeneous materials should undergo nonorthogonal cracking because that form releases the most strain energy per unit crack area and therefore leads to a configuration of least free energy.[4] Because naturally occurring materials are rarely homogeneous, nonorthogonal cracking is rare, but a

4. Lachenbruch (1962) p 49.

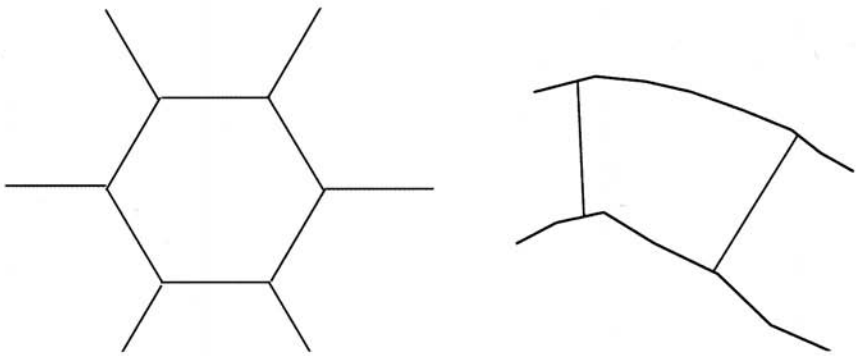


Figure 4.3B Schematic drawing showing the nonorthogonal cracking typical of homogeneous materials, and the orthogonal cracking typical of materials such as soil that have nonuniform characteristics.

familiar example is the formation of hexagonal columnar blocks in cooling lavas. Another seen on occasion is hexagonal cracking in thin layers of drying moss or other humus matter atop the ground. Orthogonal cracking predominates in nature because of the inhomogeneity of the materials involved. Desiccation cracks in drying mud typically are orthogonal, and most permafrost polygons are also.

Cracking commences in frozen ground where the material has flaws and also where horizontal temperature gradients exist. For the latter reason the first cracking is likely to occur parallel to the shores of lakes or streams. Secondary, typically orthogonal, cracks then develop until the eventual result is a polygonal array of cracks that can evolve into ice wedges if filled with water that freezes. If the initial cracking leading to a polygonal array is somewhat curved, favored sites for secondary orthogonal cracking are on the convex side of bends, such as those shown in **Figure 4.4**.

Growth of Ice Wedges

Although the first-year cracking that initiates the formation of ice wedges most likely begins at the ground surface, the cracking during subsequent years probably begins lower down, at the top of the permafrost.[5] Obviously,

5. Lachenbruch (1962).

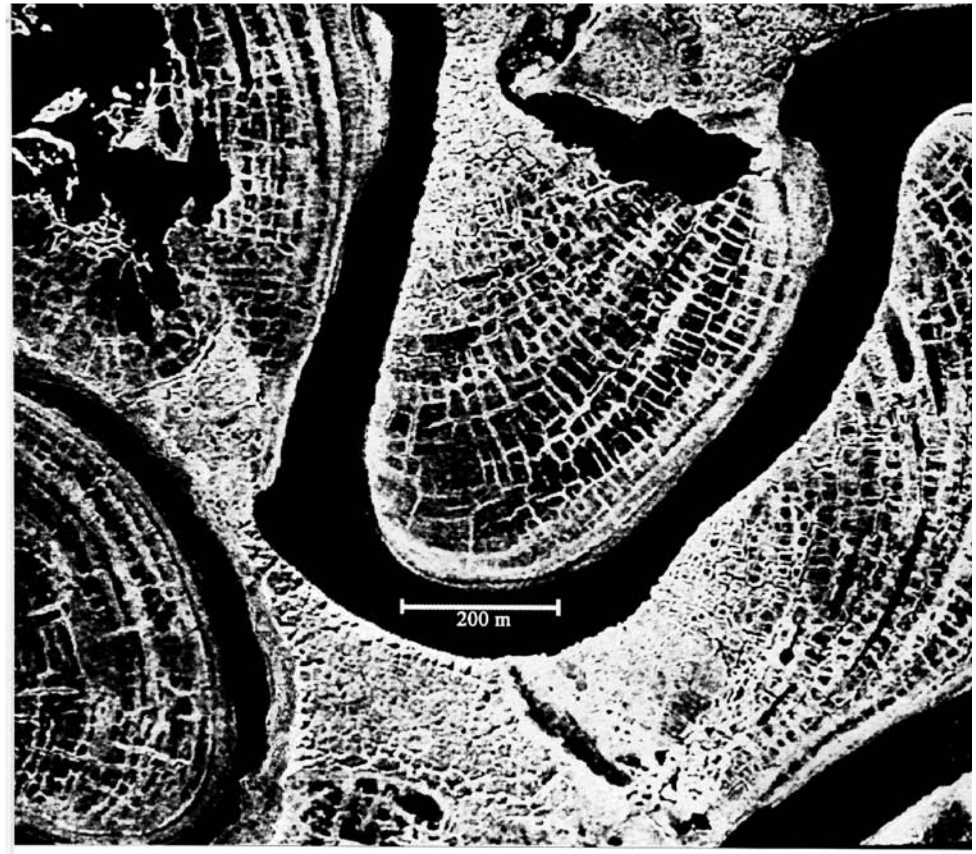


Figure 4.4 High-altitude infrared photograph (false color) of ice-wedge polygons on Alaska's North Slope. Courtesy Geophysical Institute, Fairbanks, Alaska. See also Plate 8.

any ice that might form in cracks within the active layer during early spring would melt in summer, allowing the cracks to slump or reseal through expansion of the warming soil. But essential to the continuing development of ice wedges is that the ice-filled cracks formed in the permafrost are sufficiently weak to break again before the soil cracks during the next strong cycle of thermal contraction. Renewed cracking at the center of each growing ice wedge and subsequent freezing of added water may occur on average only one out of two years, but after many years of repeated cracking an ice wedge can develop to a thickness exceeding 2 m.[6]

6. That a crack once formed will break again when the conditions are right would seem to be expected in view of the premelting phenomenon since it requires the existence of a water film at the interface whenever the temperature is warmer than approximately –27°C.

A distinguishing characteristic of ice-wedge ice is its foliated structure, the consequence of the method of formation. Each foliation layer represents one annual growth increment and is marked by air bubbles or other inclusions such as soil particles. The foliations show readily in Figures 4.2, 4.9, and 4.10, where the striated appearance is the two-dimensional manifestation of the three-dimensional foliation.

Most of the water coming into the central crack of an ice wedge undoubtedly runs down from the active layer above, but it is possible for water to move horizontally or upward through the wedge ice under the influence of a temperature gradient. At temperatures fractionally below 0°C both the thermal and hydraulic conductivities of ice exceed that of frozen silty soil, so an inward horizontal migration of water toward the center of the wedge can occur when the ground is cooling in the fall. Similarly, when the ground is warming, the migration could reverse to cause an outward transport of water through the ice. Such cryogenic transport raises the possibility of new ice forming near the boundaries of an ice wedge as well as in the core. However, the observed orientation of ice crystals—parallel to the boundary rather than normal to it as in the core of the wedge—does not hint that this horizontal transport contributes to the growth of ice wedges. Also, the observed tendency for ice crystals to increase in size outward from the center of ice wedges indicates that the outer ice is the oldest, because the size of individual crystals in an ice body typically increases with age. In ice wedges, the size of the crystals ranges from 0.1 mm to 10 cm.[7] Nevertheless, it seems unlikely that all the ice in any ice wedge arrived at its location strictly by the flow of water under the influence of gravity during summer, since gradients in temperature within the forming ice wedges and the adjacent frozen soil—as well as in the active layer above both—are normally present. The consequent gradients in free energy of liquid water (the cryosuction) are bound to move some water, and all directions are possible, sideways as well as up or down. Also, because of premelting, the central crack in each wedge contains a liquid layer along which water can move if under cryosuction.

Active and inactive ice wedges, ice-wedge casts, and sand wedges

Various events can terminate the growth of ice wedges or lead to their demise. A warming climate might elevate winter temperatures sufficiently

7. Black (1974, 1978); Washburn (1980) p 49.

to curtail growth by stopping further cracking. In the same vein, anything—including landslides and burial by loess—that increases the insulation over ice wedges will lessen the rapid temperature changes that foster repeated cracking within them. If the growth of ice wedges has pushed up soil on either side, the resulting relative depression of the ground surface over the wedges can collect snow which acts as a good insulator. Also, an increase in moss cover might slow or terminate further growth of the wedge. The relief of stresses by fracturing within nearby ice wedges may allow some wedges to grow at the expense of others, or perhaps cause all to slow their growth.

Actively growing ice wedges typically produce ***low-center polygons*** on the ground surface because summertime thermal expansion pushes up soil adjacent to each ice wedge. Between the resulting two upthrust ridges a slight furrow may be evident; it lies directly over the top of each wedge. Thus evolves a low-center polygon, one with a central region lower than its boundary area. If an ice-wedge array becomes inactive and its top portion melts due to warming climate or removal of overlying insulating material, the resulting depression directly over the ice wedges leads to ***high-center polygons***. Thus the topographic appearance of polygon arrays can indicate their degree of activity. As shown in **Figure 4.5**, the region where ice wedges are active in Alaska corresponds to the region of continuous permafrost (where mean annual temperature is about –7°C or lower, and the winter temperature at the top of the permafrost is –15°C or below). There, active ice wedges occur in silt, sand, and gravel, and low-center polygons are far more common than high-center ones. Farther south, in the colder part of the discontinuous permafrost region, the ice wedges are either weakly active or inactive, and it is usual to find more high-center polygons, especially in areas where the vegetative mantle has been removed. See **Figure 4.6**.

The shapes of ice wedges, their relation to each other and to the present location of the ground surface serve as indicators of past climate and past episodes of soil erosion or deposition. Climatic warming or soil erosion can lower the permafrost table from previous levels and thereby destroy or clip off the top of ice wedges previously formed (see **Figure 4.7**). Episodes of soil deposition can engender complex wedges similar to that illustrated in Figure 4.7C. Figure 4.7D illustrates a situation observed in a tunnel bored into permafrost at Fox, Alaska, just north of Fairbanks, (**Figures 4.8–4.10**) and in a nearby roadcut (**Figures 4.11–4.13**). In the tunnel one inactive array of wedges lies about 13 m below the present ground surface, and a second group of inactive wedges stands well above that, at depths of 2 to 10 m below the surface. Carbon-14 dating indicates that the lower array in the tunnel is about 32,000 years old, and

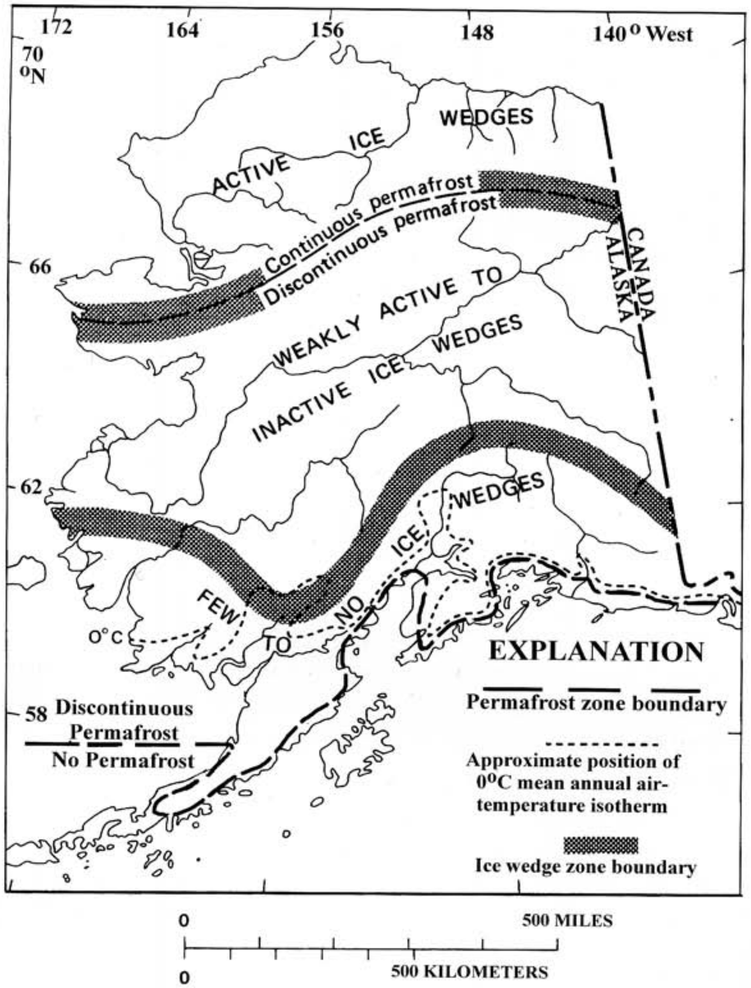


Figure 4.5 Distribution of ice wedges and permafrost in Alaska. Modified slightly from Figure 28 by Péwé (1975a)

that the upper and smaller wedges are 8,000 to 10,000 years old.[8] Evidently sometime between the formation of these two groups of ice wedges climatic warming and much new soil deposition occurred. The lower ice wedge array appears to have formed mostly during an epoch of minimal if

8. Sellmann (1967, 1972) cited by Péwé (1975a).

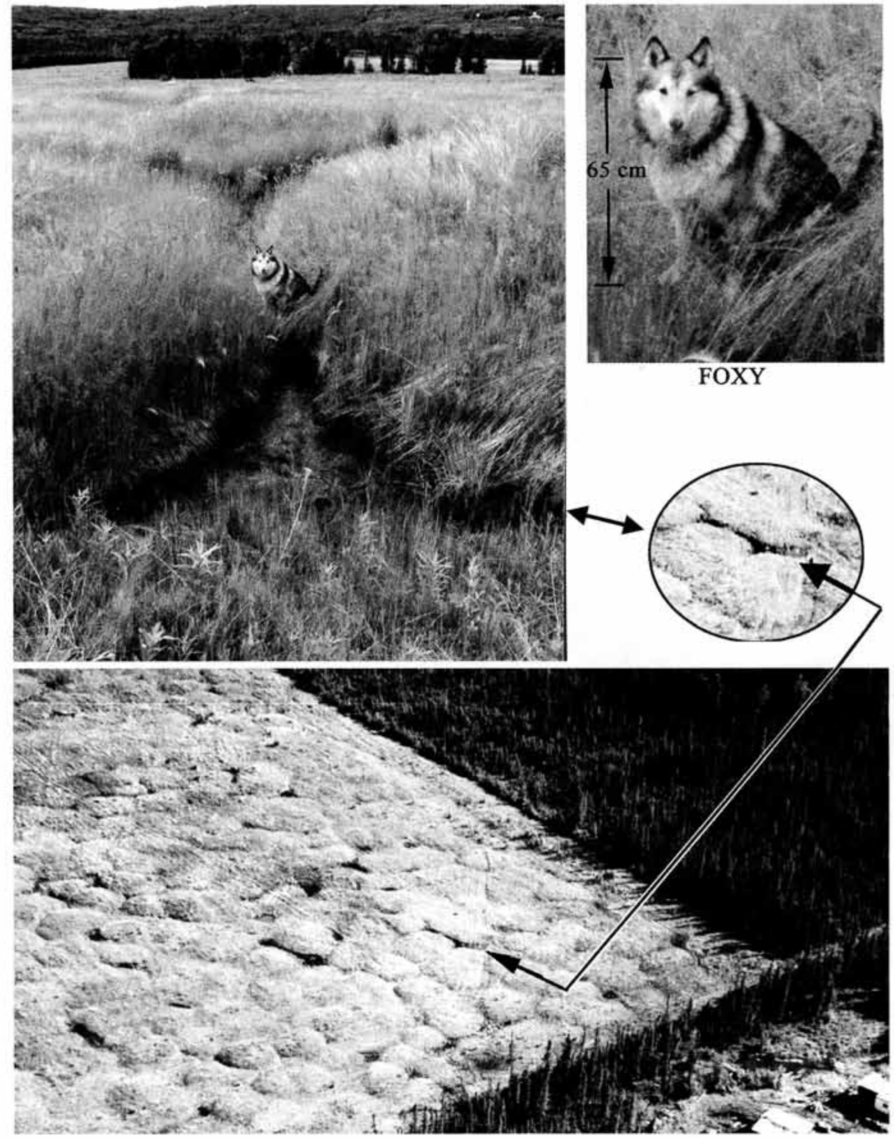


Figure 4.6A Top—Photo of thermokarst topography (high-center polygons) in an abandoned field taken in 1996, two days after the aerial photograph shown below. Microrelief in the thermokarst area is near 1 meter. On the higher ground such severe cracks parallel the depressions that it would be unwise to ride a horse across this field, located near the eastern end of the Farmers Loop permafrost area near Fairbanks. The scale dog seen in this and following illustrations is Foxy, a sheltie-husky cross 1 m long from tip of nose to base of tail. She stands 50 cm tall at the shoulder, and when sitting the top of her head is about 65 cm above ground. See also Plate 9.

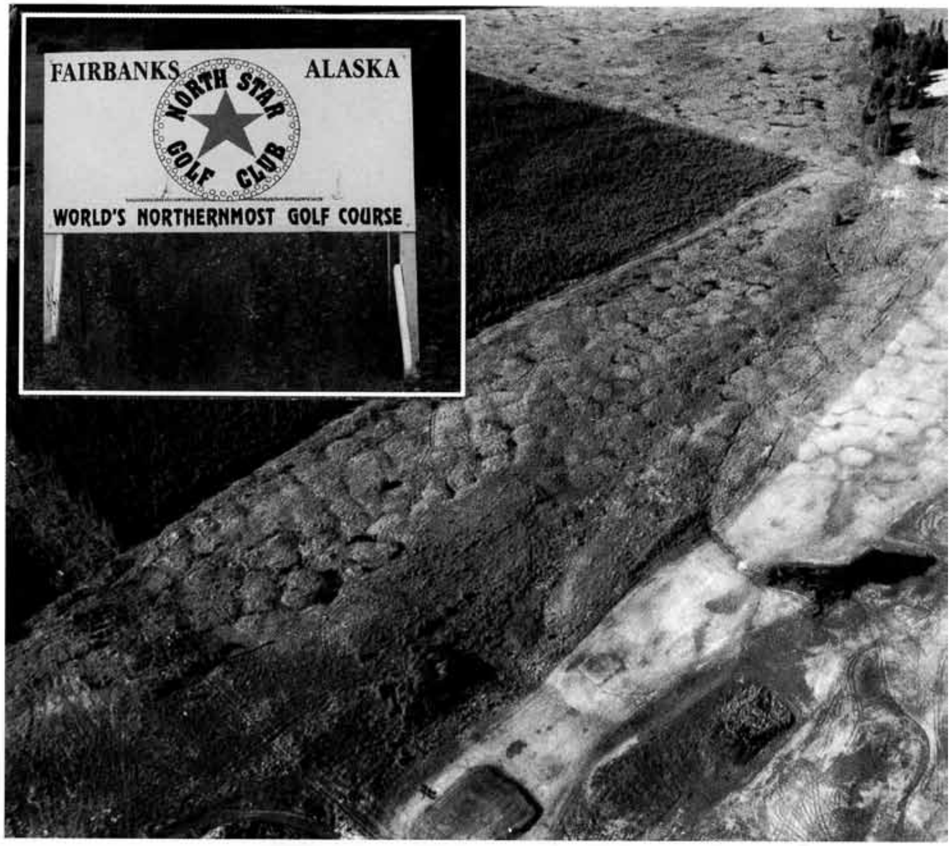


Figure 4.6B Players at the North Star Golf Club—self-billed as the world's northernmost golf course—have their ups and downs as they putt through the high-center polygons. The fairways cover the right-hand side of the aerial photo taken at the same time as that in Figure 4.6A. The group of trees surrounding the green at top is the same as shown in the top part of the upper photo in Figure 4.6A.

any deposition. Geocryologists term such wedges (and also permafrost) as ***epigenetic*** to distinguish them from the so-called ***syngenetic*** wedges (and permafrost) formed during epochs of deposition. The upper grouping of ice wedges in the Fox permafrost tunnel appear to be of the syngenetic type. Syngenetic wedges, especially, may be quite complex in form. An example of what is probably a complex syngenetic wedge is shown in part B of **Figure 4.14**. The exposure shown in part A results from recent mining operations near Ester, Alaska, that have provided an unusual opportunity to observe the three-dimensional configuration of an ice wedge array.

Even ice wedges completely destroyed by thawing can reveal information about the past because soil spilling down into the voids left by melting ice wedges can form ***ice-wedge casts*** that become, in a sense, fossil ice

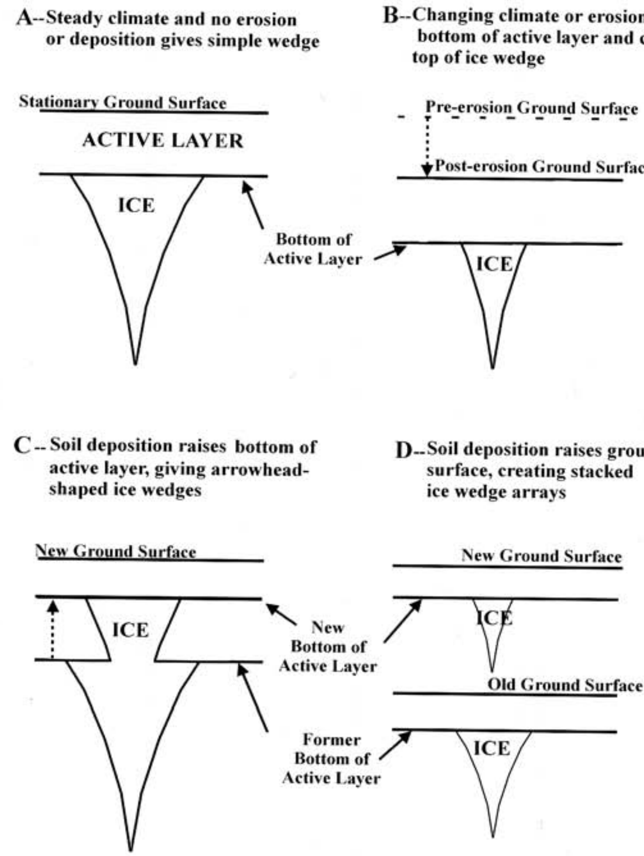


Figure 4.7 Schematic illustration of how: A) unchanging conditions can lead to classic-shaped ice wedges, B) erosion or warming can remove the upper parts of wedges, C) deposition can create syngenetic wedges with odd shapes, and D) extensive deposition after wedges form can lead to stacked arrays of wedges.

wedges.[9] However, not all soil-filled wedge shapes left by polygonal contraction cracking are ice-wedge casts because blowing sand or silt instead of water sometimes fills the contraction cracks. These similarly tapered deposits are called ***sand wedges*** to distinguish them from ice-wedge casts, and they differ also by having vertically oriented layers instead of primarily horizontal ones, as is depicted in **Figure 4.15**. Although moisture-rich, fine-grained soils are conducive to the formation of ice wedges in permafrost, those soils tend to flow so much that they inhibit the preservation of ice-wedge casts. Consequently most ice-wedge casts found are in gravel or other soil that can maintain steep faces when thawed.

9. Washburn (1980) pp 111–17.

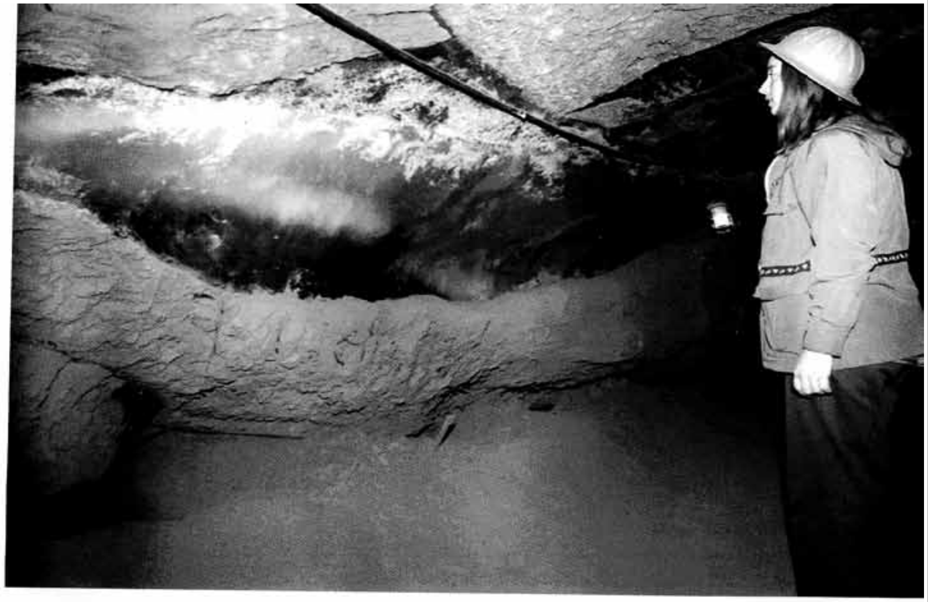


Figure 4.8 A thick layer of segregation ice or pond ice in the Fox permafrost tunnel. Its nonfoliated structure contrasts sharply with the foliated wedge ice shown in Figures 4.9 and 4.10. Photographed 1979; Fran Pedersen of the Geophysical Institute at right.

Figure 4.9A Foliated ice wedge cut by the Fox tunnel so that the remaining portion forms part of one wall and the ceiling of the tunnel. Some ablation of the surface has occurred subsequent to the boring of the tunnel in the early to mid-1960s. Photographed 1978; Rosemarie Davis at right.

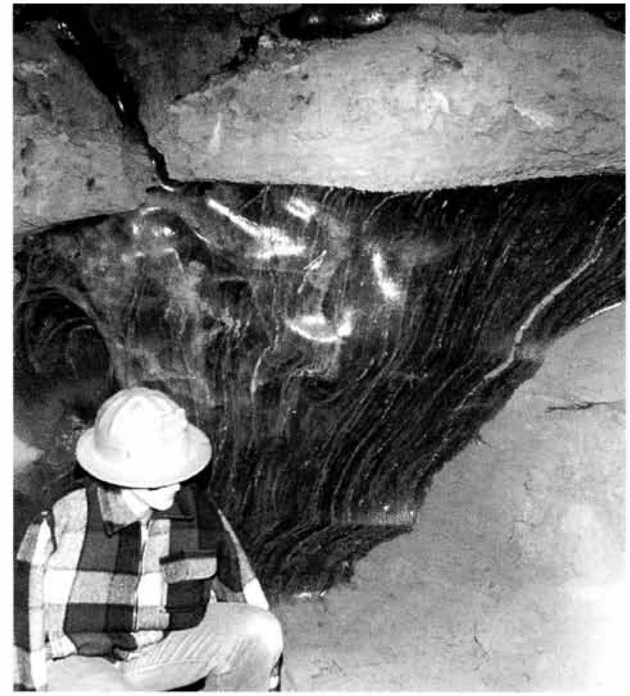


Figure 4.9B Top part of an ice wedge overlain by silt containing massive, irregular-shaped and interconnected masses of segregation ice. Photographed 1979.

Figure 4.10 Intersecting ice wedges in the roof and wall of the Fox permafrost tunnel. Paula Jones and Fran Pederson of the Geophysical Institute stand directly below the intersection. Photographed 1979.

Figure 4.11 Ice wedges interconnected by multiple sheets of segregation ice in a roadcut approximated 1 km south of the Fox permafrost tunnel; photographed in 1979.

Figure 4.12A Part of the same roadcut shown in Figure 4.11.

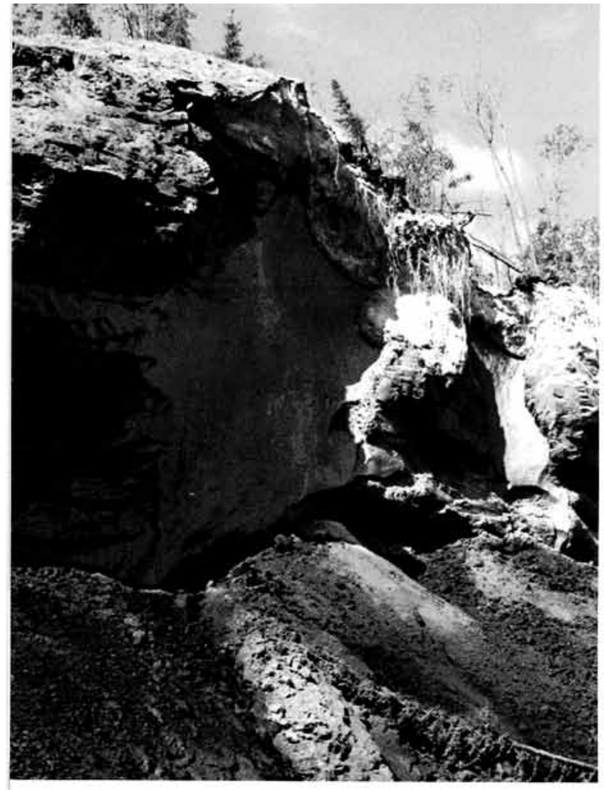


Figure 4.12B Detail view of the ice wedge and interconnected sheets of segregation ice appearing in Part A just above and to the front of the truck cab. The configuration suggests that this is a syngenetic ice wedge, its upper part likely to have grown thousands of years later than the lower part that joins the layers of segregation ice.

Figure 4.13 Another view of the roadcut near the Fox permafrost tunnel which portrays the extensive nature of the multiple segregation ice layers interconnecting with ice wedges.

Figure 4.14A A polygonal array of ice wedges partly excavated by mining activities near Ester, Alaska. A large tractor has removed the tops of the wedges shown in the foreground and exposed cross-sections of those in the background. The interconnected dots show observed or inferred centers of the ice wedges in the array.

Figure 4.14B Close-up view of the complex ice wedge at upper left in Part A. (Photographed 1996.)

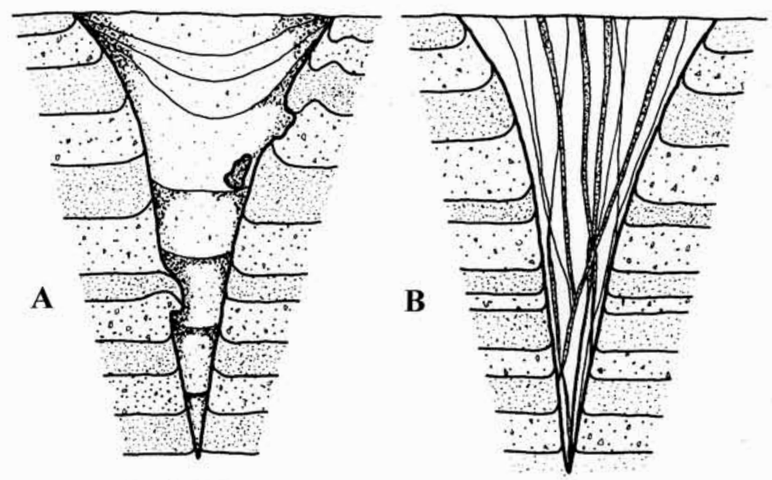


Figure 4.15 A) Schematic representation of a fossil ice wedge. It contains soil with slump structures but mainly displays a horizontal fabric. B) A sand wedge formed by sand falling into contraction cracks leads to a cast with vertical fabric. Reproduced from Figures 4.34 and 4.35 in Washburn (1980), originally drawn by R. F. Black.

Because ice wedges can form only in permafrost, their casts are one of the accepted indicators of former permafrost. Ice-wedge casts dating back more than 1 million years—to the earliest part of the ***Pleistocene epoch***—have been found in Alaska, and many of Wisconsinan age (10,000 to 100,000 years B.P.) are found in other parts of North America where permafrost no longer is present.[10]

Pingos, Palsas, and Other Protuberances

Pingos

"Pingo" is an Eskimo word for mound or hill, and, according to the teachings of former University of Alaska anthropologist Ivar Skarland, a much longer word starting with "pingo" means mound-that-blows-up. He said that the Eskimos gave this name to certain very strange large mounds that had broken tops and which therefore must have exploded. Skarland, suggesting it was merely legend, related a story he had heard about a man who, once, a long time ago, was standing on such a mound when it blew apart and threw him unhurt onto the nearby tundra. However, this event may actually have happened. Many of the ice-cored mounds now called pingos do have splits or depressions in their tops, caused either by melting of the top of the mound or a splitting open by dilatation (i.e., expansion) cracking in consequence of high hydraulic pressure within the pingo. Furthermore, two Russian scientists actually have observed the explosive dilatation rupturing of a pingo. It threw blocks of ice having volumes of 2 m^3 into the air and cast smaller blocks as far as 22 m. The pingo simultaneously spouted a jet of water that lasted 30 minutes.[11] In other instances scientists have observed the escape of both water and nonexplosive gases.[12]

Pingos are large circular or elongated mounds having massive ice cores that have grown from water transported to the site by hydrostatic pressure. As the cores formed they pushed overburden upward as much as 50 m to create the pingo mounds. Sometimes looking like small volcanoes, pingos are perhaps the most exotic landforms created by cryogenic processes. As would any prominence rising discordantly above an otherwise swampy countryside, a pingo attracts attention. They are favorite nesting sites for small mammals such as foxes, and people also find them

10. Hopkins (1972) cited by Péwé (1975a).
11. Bogomolov and Sklyarevskaya (1973) cited by Washburn (1980) p 186.
12. MacKay and Steger (1966) cited by Washburn (1980) p 186.

appealing. Residents of Tuktoyaktuk in northern Canada have used the ice core of one pingo as a cold-storage facility, and in the vicinity of Fairbanks, Alaska, several people have purposely built homes atop pingos, sometimes without realizing the problems they likely would soon encounter.

Pingos are of two kinds, ***closed-system*** and ***open-system***, referring to the nature of the water supply involved in the pingo formation. **Figure 4.16** illustrates the mechanisms believed responsible for the two pingo types. As is seen in **Figure 4.17**, the closed-system pingos in Alaska and northwestern

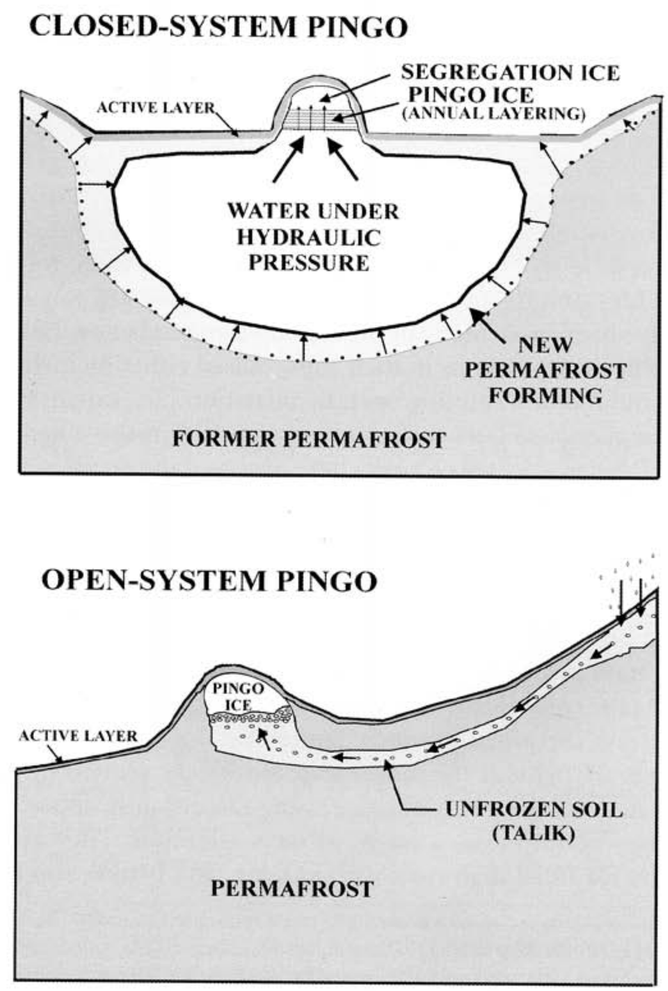


Figure 4.16 The mechanisms responsible for closed-system and open-system pingos.

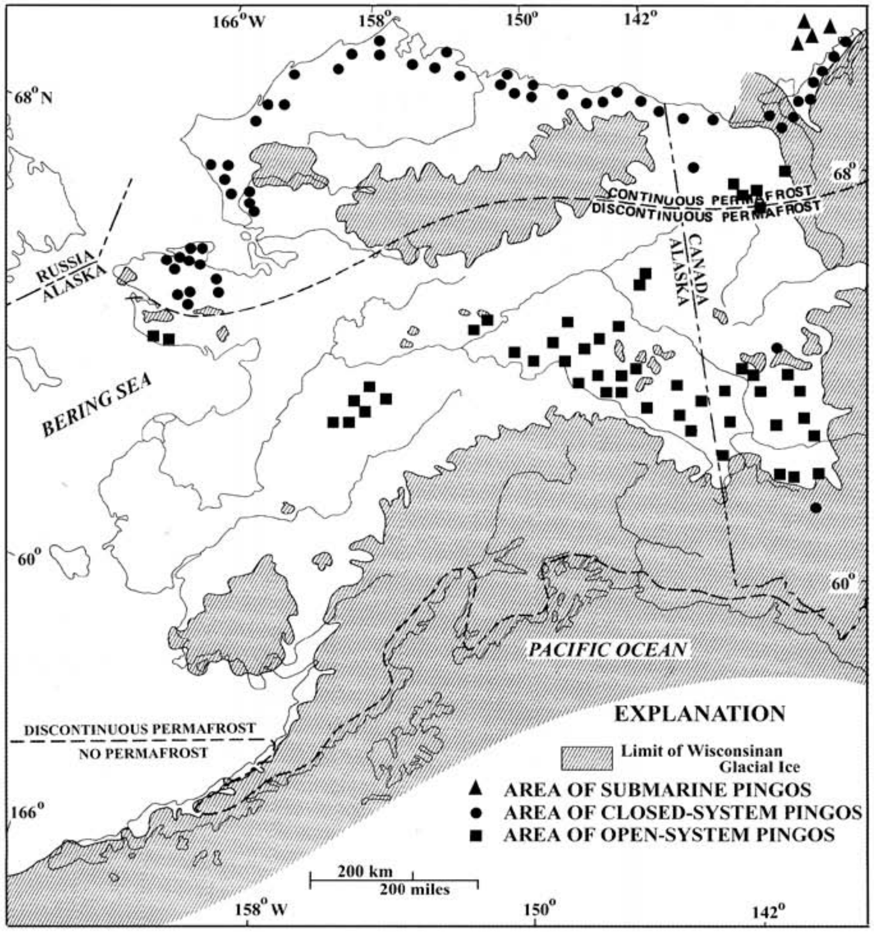


Figure 4.17 Distribution of open- and closed-system pingos in relation to permafrost zones and areas covered by Wisconsinan glacial ice in Alaska and western Canada. Modified from Figure 32 in Péwé (1975a).

Canada lie primarily in the low northern coastal plain. This is a region of continuous permafrost, where the mean annual temperature is –5°C or below. The open-system pingos are almost entirely in the warmer discontinuous permafrost region, and mostly in a zone of valley-cut upland within central Alaska that extends eastward into Canada. With a few exceptions, cold continuous permafrost is necessary if closed-system pingos are to form. Similarly, a warmer environment permitting discontinuous permafrost is required for the formation of open-system pingos.

Closed-system pingos

Closed-system pingos are formed on low ground primarily from water trapped when the boundaries of dying lakes freeze. Of nearly 1,400 closed-system pingos mapped in the Mackenzie Delta area of Canada, 98% were in or beside former lake beds.[13] The lakes once were deep enough to remain unfrozen, but vegetation growth, alteration of drainage, or other change allowed subsequent inward freezing from the sides and bottoms of the lakes as well as from the top. If a lake's freezing soil is sufficiently coarse-grained its volume remains essentially constant, but the freezing displaces water ahead of the freezing front. If the soil is fine-grained, the cryogenic suction $P_{ice} - P_{water}$ generated by the temperature falling below 0°C will draw water to and just behind the freezing front, thereby increasing the volume of the freezing material (frost heaving, in essence). In both situations, inward freezing creates a confining volume less than the volume of unfrozen water remaining so that this water is under increasing pressure. Part or all of the pressurized water may eventually freeze into what is termed ***injection ice*** or pingo ice, expanding by 9% as it does, to form a massive ice core that pushes the surface upward. However, the observed thickness of core ice formed in closed-system pingos and their overall height require pressures not attainable by hydrostatic pressure alone; thus at least a portion of the massive ice layers found in these pingos must be segregation ice formed from water pulled in by cryogenic suction. Since this suction depends on the grain size of soils as well as on subzero temperature, it follows that the fine-grained materials typical of many lake beds should foster the growth of large closed-system pingos.

As was observed by the Russian scientists who watched a pingo rupture, some of the water trapped within or below the pingo may escape by bursting out through cracks opened in the tops or sides of the pingo. Such loss of water probably is the explanation of the occasional observation of the periodic rise and fall of some pingo surfaces. Holes drilled by J. R. Mackay into one pingo on the Canadian Arctic Ocean coast released 30,000 to 40,000 cubic meters of water, and the top of the pingo sank by 60 cm.[14] Just as water may at times escape through dilitation cracking or unfrozen soil at the top of a closed-system pingo, surface water may at other times seep into a pingo from above. In fact, ice wedges have been observed on some pingos, although those wedges perhaps evolved before the pingos pushed upwards. **Figure 4.18** shows examples of closed-system pingos.

13. Stager (1956) cited by Washburn (1980) p 181.
14. Reported by Washburn (1980) p 185.

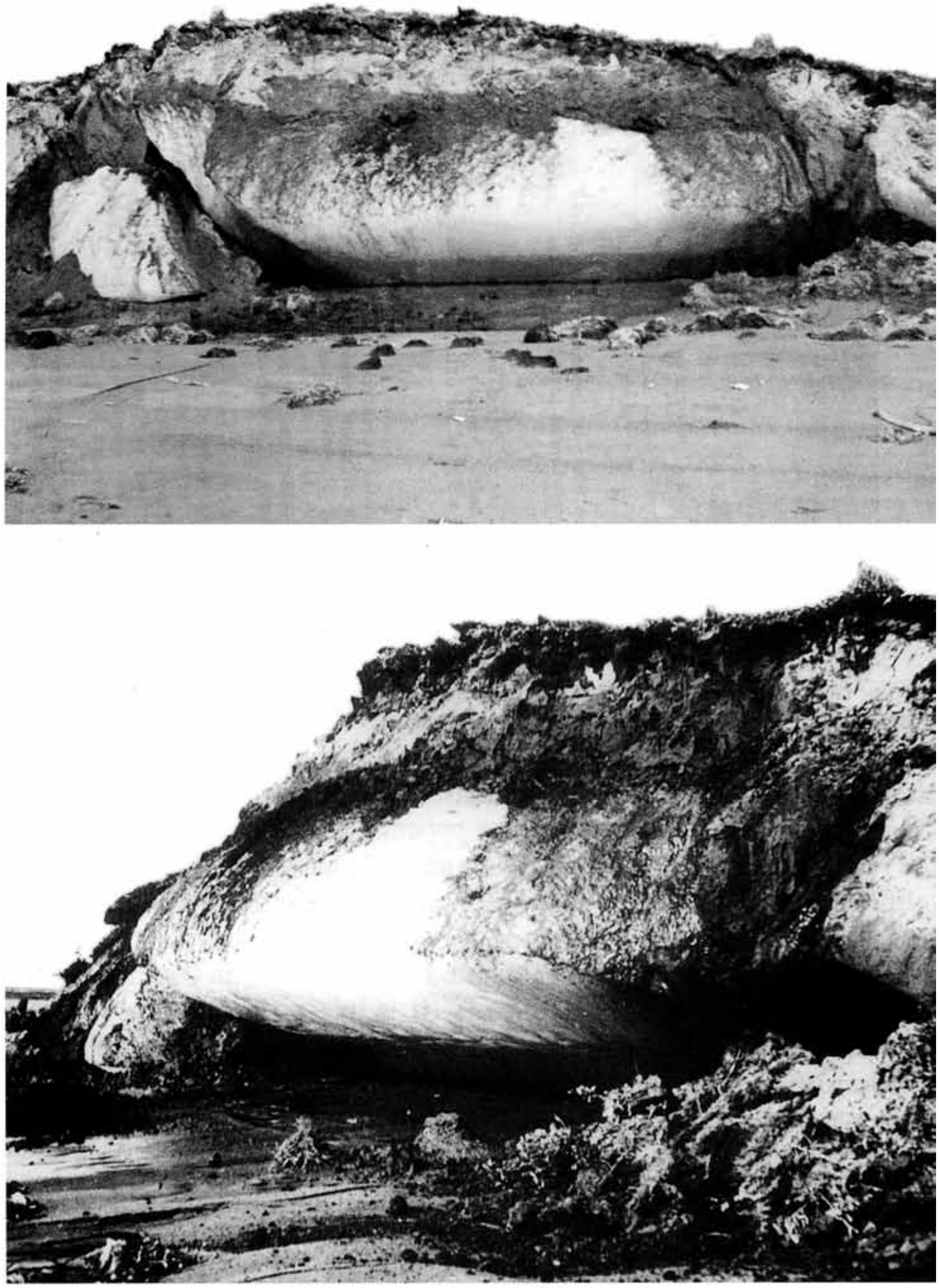


Figure 4.18A Two views of an egg-shaped ice core in a pingo cut away by wave action. Photographed by J. R. Mackay in 1955 on the Mackenzie Delta, near Point Atkinson, 100 km northeast of Tuktoyaktuk; see Figure 4.17. [One view is reproduced as Figure 79 in French and Heginbottom (1983) and the other is reproduced as Figure 4.11 in Pissart (1994).]

Figure 4.18B Layered ice in a pingo. J. R. Mackay who photographed the layers suggested that they are annual accumulations and that they have been tipped over since deposition. Reproduced from Figure 6.1b in Williams and Smith (1989).

Open-system pingos

Whereas closed-system pingos form on flat areas that once were lake beds, open-system pingos typically lie in valley bottoms or on their slopes. They tend to be smaller than the closed-system pingos. The artesian water supplying the open-system pingos enters the ground on hilltops or hillsides, and as it flows downslope (perhaps carrying along fine-grained soil particles), it becomes trapped under permafrost so that it is under sufficient hydrostatic pressure to return to or near the surface through driven wells or natural channels. If the latter, the open water system may lead to the formation of one or more pingos, and they do tend to cluster. The interrelated association of pingos, permafrost and artesian well water is illustrated by an area a few miles north of Fairbanks, Alaska, where a road (Farmers Loop) runs generally east-west near the base of a southerly slope. Several wells adjacent to the road have yielded artesian water, and at least one pingo is nearby. Downslope from the road the permafrost layer is approximately 50 m thick, and part of the area contains extensive polygonal ice-wedge arrays. A few miles farther north, in a smaller valley, are a number of open-system pingos. Like the closed-system pingos, the open-system pingos often display split or depressed tops, but since they are mostly in areas of irregular topogra-

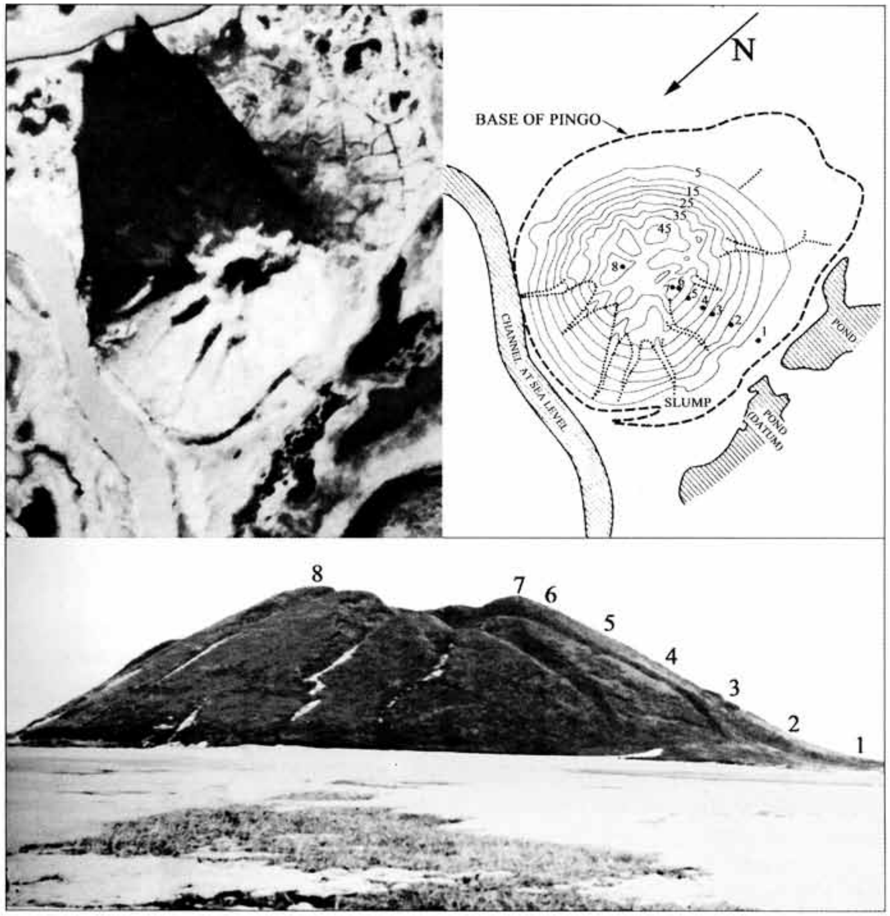


Figure 4.18C J. R. Mackay's ground photo and contour mapping of the Ibyuk pingo in the Mackenzie Delta near Tuktoyaktuk, along with a vertical aerial photo. Compiled from Figures 77 and 83 in French and Heginbottom (1983).

phy they do not stand out as dramatically from their surroundings as do the closed-system pingos. Shrubs and trees growing on the open-system pingos can hide them, but the vegetation on the mounds may differ enough from that nearby to attract attention, and thus help lead to their identification as pingos. Depressed tops or elongated depressions on the slopes of the mounds are identifying characteristics, but some might not be positively identified without drilling into their ice cores. **Figure 4.19** contains examples of open-system pingos.

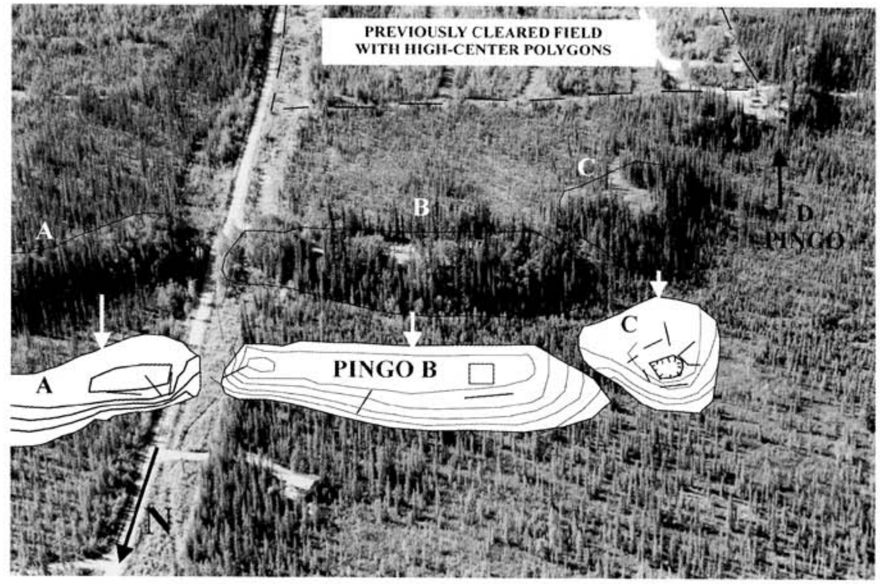


Figure 4.19 Open-system pingo complex on a 6-degree north slope in Goldstream Valley north of Fairbanks. On the offsets Labeled A, B, and C straight lines indicate ground cracks or wider collapse features. These also contain sketched-in contours at intervals of approximately 1 meter. The roadway (Miller Hill Extension) sloping downhill to the north cuts between pingos A and B, perhaps bisecting what was once a single pingo. A minor flow of water runs out of pingo B along the roadway. A house elevated on pilings sits atop pingo B, not far from where a previous structure had collapsed some years ago. The major collapse feature with numerous open fractures on pingo C resulted from clearing the vegetation several years ago. Houses sit atop the structure identified as pingo D. Uphill of the complex is an abandoned field now covered by brush and high-center polygons.

Pingo growth rates and life cycles

The available information on the ages of pingos and their growth rates comes mostly from observations of closed-system pingos. Many appear to be several thousand years old, but others are much younger, and some are so new that contemporary scientists have observed their birth and early growth. Carbon dating indicates that pingos at two widely separated localities on Banks Island in northern Canada grew during a cooling period occurring 4500 to 7000 years ago. It appears that many other such pingos are thousands of years old, but restricted to the Holocene epoch (the last 10,000 years).[15]

15. French (1977) cited by Washburn (1980) p 186.

Very young pingos also exist, and during the past 200 years observers have seen the initiation and early growth of a number of them. During the first year or so of pingo life the growth in height may exceed 50 cm per year, and the maximum reported is 150 cm per year. Based on his observations, the well-known Canadian geocryologist J. R. Mackay has suggested that, in early stages at least, pingo growth probably decreases with the square root of time. By 1972 he had seen pingos in the Mackenzie Delta that had formed after 1935 and that had grown to heights near 6 m, and also others birthed after 1950. Overall, the reports on growing closed-system pingos suggest rates typically near 10 cm per year and mostly within the range 0 to 50 cm per year.[16]

Inactive and fossil pingos (pingo scars)

When the entire volume of water available to build a closed-system pingo freezes or flows out through dilatation cracks, the pingo can no longer grow; even before that happens, dilatation cracking may expose the pingo's ice core to thawing that terminates the growth. Open-system pingos can suffer the same fate if the water supply is cut off or if dilatation cracking permits exposure to thawing. Climatic changes or lesser events such as forest fires that modify the vegetation can also stop pingo growth and foster eventual collapse.

Fossil pingos—the remains of formerly active pingos—may appear as pits not easily distinguished from other kinds of thermokarst depressions, but the pits often are surrounded by rampart-like rims that point to their pingo origin, as shown in **Figure 4.20**. Some fossil open-system pingos might long retain at least a part of their mound-like character owing to deposition in the pingo structure of fine-grained soil particles carried in with water through the supply conduits. At least one of the pingos shown in **Figure 4.21A** contains considerable clay in the upper meter or so of ice, as shown in **Figure 4.21B**, suggesting that these are open-system pingos. Some fossil open-system pingos are in the form of elongated, sometimes U-shaped rampart-like features that open uphill so as to enclose marshy areas. Some cross over each other, suggesting repeated episodes of pingo growth during favorable conditions.

Wherever fossil pingos can be identified in nonpermafrost areas they serve as proof of former cold climate. Extensive groups of fossil pingos of Pleistocene age have been found in the British Isles, Europe, and Asia. As many as 35 Pleistocene fossil pingos per km^2 have been identified in one

16. Based on discussion by Washburn (1980), pp 180–87.

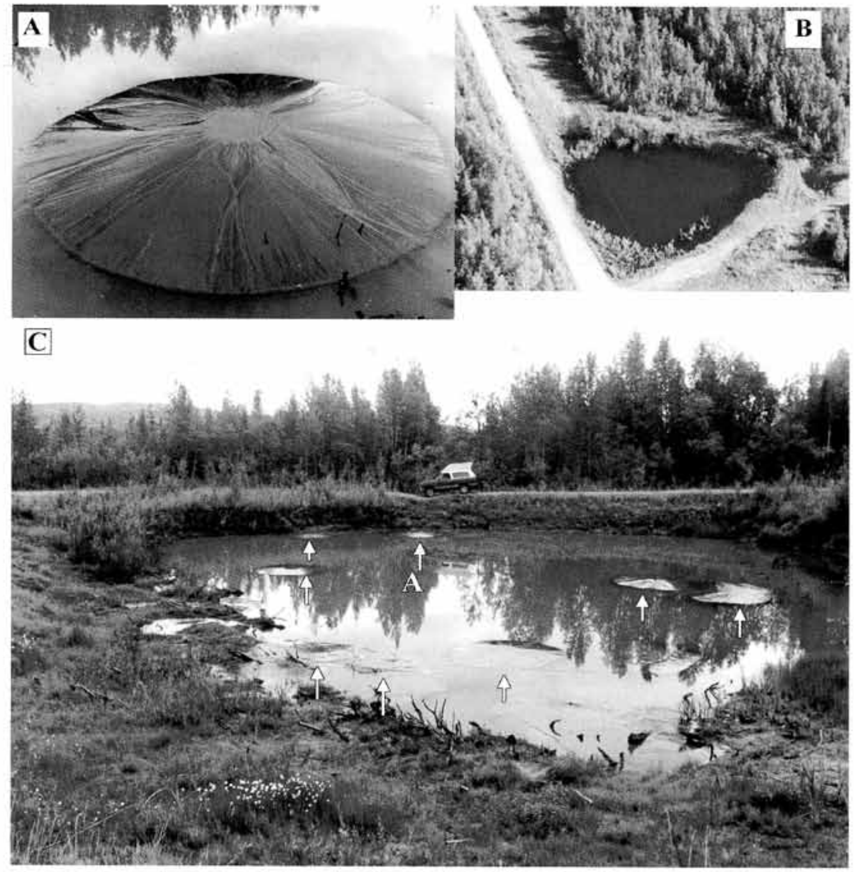


Figure 4.20 Collapsed open-system pingo in Goldstream Valley, just north of Fairbanks, Alaska. The pingo collapsed some years ago after being cleared of trees in an attempt to prepare the area for agriculture: A) Close-up view of one of the many mud cones formed by mud-charged springs in the lake of the collapsed pingo, the one labeled A in Part C; B) Aerial view of the collapsed pingo; C) View across the pingo lake with mud cones marked by arrows. These indicated water coming into the feature through numerous channels. New collapse around the perimeter in 1996 caused the dip in the road indicated by the tipped vehicle. See also Plate 10, bottom, showing two mud cones.

locality of northern France, but a density of one pingo per square kilometer is more typical.[17] The oldest reported fossil pingos are ones that developed in the Sahara during Ordovician times (500 million years ago).[18]

17. Cailleux (1976) cited by Washburn (1980) p 190.
18. Beuf, Bernard et al. (1971) cited by Washburn (1980) p 189.

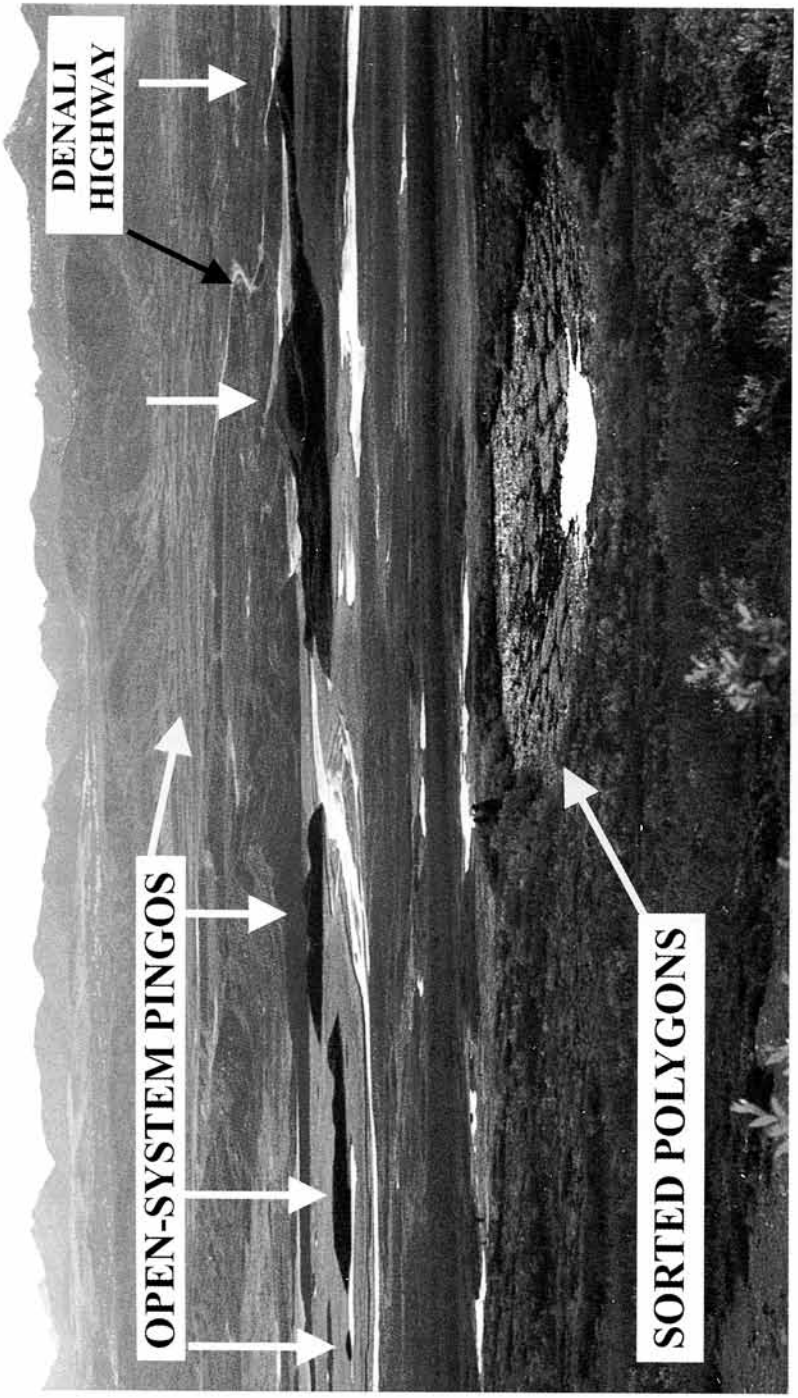


Figure 4.21A Described both as open-system pingos (Péwé, 1977) and palsas (Péwé, 1997), these large mounds stand adjacent to the Maclaren River in the Alaska Range at Mile 40.8 on the Denali Highway. An array of sorted polygons lies in the foreground. Photographed from the hill just to the east in 1996. The peat in contact with the ice in one mound is approximately 10,500 years old (Péwé, 1977).

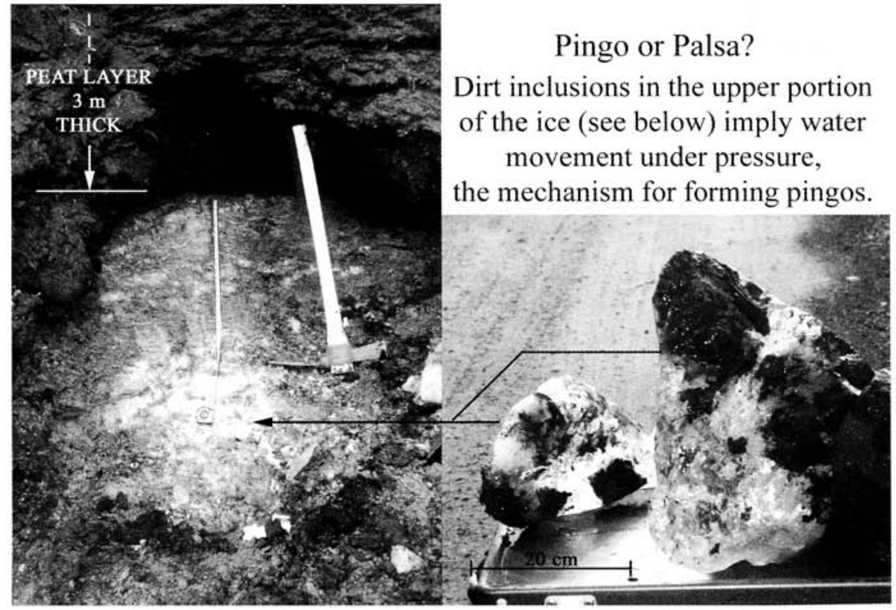


Figure 4.21B Beneath the 3-m-thick covering of peat, ice within the mound at the right-hand edge of Figure 4.21A, shows extensive thin layers of clay in the top meter of the ice. The amount of clay decreases with depth so that below depth 1 meter in the exposed cut, the ice contains only occasional thin lenses of clay. Photographed in August 1997.

Palsas

Like pingos, ***palsas*** are ice-cored mounds that bulge up above their surroundings. They tend to be smaller than pingos and more varied in shape. Palsas are from 1 to 12 m in height and range in shape from conical through hump-like and plateau-like to elongated ridges or esker-like dikes. The main difference between pingos and palsas is that palsas grow from water lifted by cryogenic suction instead of that transported by the pingo-forming combination of cryogenic suction and hydrostatic pressure.[19] Dilatation (doming), frost contraction or desiccation cracks typically develop on palsa surfaces and lead to their eventual demise.

Palsas form in wet boggy areas where a combination of mean annual temperature less than –1° or –2°C and low snowfall or high winds expose any projection above the ground surface to the winter cold. The result is a higher temperature gradient in the projection than in the surrounding

19. Seppälä (1988).

mossy area and thus a condition there that favors the formation of layers of segregation ice that frost-heaves the surface even higher. Contributing to the ongoing growth of palsas over the course of many years is the seasonal change in thermal conductivity of the covering of peat-like material (refer back to Table 2.1). Frozen peat is about five times as conductive as unfrozen water-saturated peat and nearly thirty times more conductive than dry peat.[20] Consequently, heat flows out far more rapidly through the top of a palsa in winter than it flows in during dry summer conditions.

When arrays of ice wedges become inactive and melt enough to form high-center polygons, the elevated center parts of the polygons may sometimes become the bases from which palsas grow. Other palsas emerge from the boggy areas typically formed from vegetation growth in shallow lakes and former lake areas. Vertical growth rates up to 15 cm per year have been observed, but average rates probably are somewhat lower. Observations of palsas in Finland indicate that their ages range from 100 to 2000 years,[21] and dating of the moss in a palsa complex in central Alaska (shown in **Figure 4.22**) indicates a possible maximum age of about 10,000 years.[22] Since the cores of most palsas are primarily ice—reportedly as much as 80 to 90%— palsas are like pingos in that they contain the seeds of their own destruction. The palsas grow until dilatation or other cracking, or perhaps disturbance from wildfire, breaks the surface enough to create melting and collapse, and then new palsas may grow at the same general location. Because of this cyclic growth behavior, palsas of various ages are found together. When they do collapse, palsas may leave little evidence of their former existence, but some leave minor rampart-like rims that may be quite difficult to distinguish from those of small fossil pingos. And even before they collapse, palsas may exhibit characteristics so similar to those of some open-system pingos that it is not easy to tell them apart.

Hummocks. Hummocks are small mounds to 50 cm diameter and to 1 m in height that form in uniform arrays on level or near-level ground in both permafrost and non-permafrost areas. They are of two main types: those called ***earth hummocks*** that contain cores of mineral soil, and those called ***turf hummocks*** that contain mainly organic material.[23]

20. Seppälä (1995).
21. Ibid.
22. Reger (1995).
23. The discussion here is based on material presented by Washburn (1980) pp 121–47; Williams and Smith (1989) pp 157–63; and Lundqvist (1969).

Figure 4.22A Palsas in an array at Mile 206.7 on the Parks Highway just south of Cantwell, Alaska. Dating of basal moss on the palsa gives an age of 9200 years (Richard Reger, private communication 1995).

Figure 4.22B Close view of nearly pure ice exposed within the palsa in foreground of Part A.

Figure 4.22C A symmetrical palsa mound in the complex; see also Plate 11.

Figure 4.22D An elongated palsa in the background with one that is collapsing in the foreground; see also Plate 12. Photographed fall 1995.

Earth hummocks (including ***thufur***, a form identified in Iceland and England) develop in fine-grained soils prone to frost heaving in environments where vegetation cover is light to moderate. The hummocks typically are dome shaped or sometimes elongate if on gentle slopes. They can occur singly but usually are in groups with spacings generally less than the diameter of the hummocks. That they can develop rather rapidly in nonpermafrost areas is indicated by reports of their forming within one or two decades in English and Icelandic pastures. Earth hummocks in permafrost areas indicate actively heaving surfaces (as shown sometimes by tilting trees growing on the hummocks) and those hummocks are associated with accumulations of segregation ice below the permafrost table. These hummocks may be thousands of years old; dating indicates that the period 2500 to 5000 years ago was a good time for hummock formation.[24]

Seasonal frost, adequate moisture, and heave-prone soil are necessary if earth hummocks are to form. What starts the hummock forming process is not clear, but recently reported theoretical work suggests that spatial differences in the amount of frost heave can be predicted and that the spacing between hummocks is likely related to the depth of frost penetration at the time when certain circumstances involving the rate of frost penetration and other factors are such that they promote rapid heaving.[25] This prediction is in keeping with observations that even artificially leveled soil that is fine-grained enough to be prone to frost heaving tends to develop an irregular surface. Once the surface is irregular, differential rates of freezing and accumulation of segregation ice—aided by differences in vegetation in the high and low areas—promote hummock growth. The tops of the embryonic hummocks are likely to be drier than the surrounding troughs during freezing, and the tops tend to develop a more insulating vegetative cover. Thus, initially, freezing should penetrate most rapidly in the troughs and the accumulation of pore and segregation ice there should squeeze the more slowly freezing soil beneath the hummock upward, thereby enlarging the mound. Later, at least in permafrost areas, a thicker vegetation layer grows in the troughs and then the active layer becomes thickest at the centers of the earth hummocks. There the greater depth of freeze and thaw each year creates bowls in the permafrost that may collect water during thaw periods. If thawing is rapid, high enough pressure may develop to help lift soil upward in the hummocks. However it occurs, the motion evidently is turbulent because

24. Zoltai et al. (1978).
25. Fowler and Noon (1997).

Figure 4.23 Top: A turf (bog) hummock; bottom: an earth hummock showing cryoturbated soil layers, both photographed along the Denali Highway between Miles 30 and 37 in 1997. See also Plate 13.

the hummocks often show irregular streaking of soils, and the carbon-dated ages of adjacent layers can vary wildly, by more than 1000 years.[26] This churning (cryoturbation, a process discussed more below) extends down only to depths of 30 to 60 cm in earth hummocks of nonpermafrost areas, but the churning reaches to the bottom of hummocks nested in permafrost. **Figure 4.23** shows an earth hummock, and also a turf hummock.

Turf hummocks (also called bog and peat hummocks) are of similar size or smaller than earth hummocks and often more columnar, but like them can develop in both permafrost and nonpermafrost settings. They are

26. Zoltai et al. (1978).

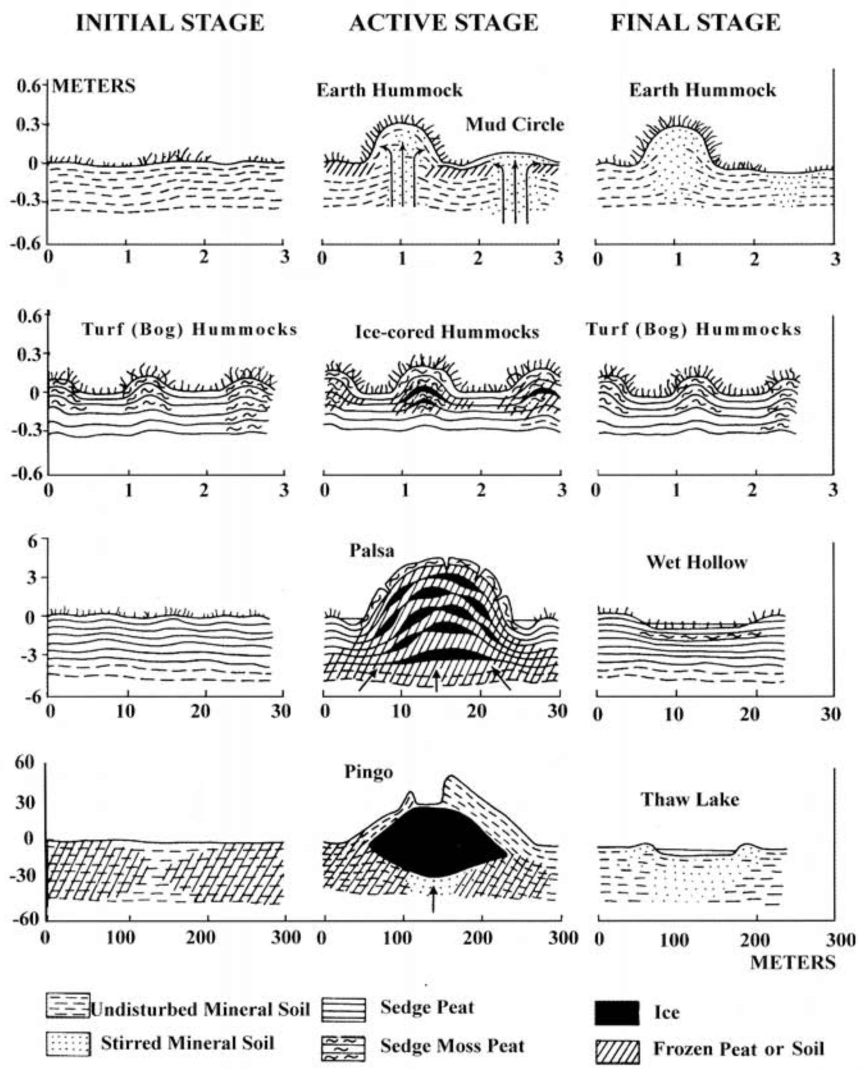


Figure 4.24 A schematic diagram depicting the differences among pingos, palsas, earth hummocks and mud circles. Modified slightly from Figure 1 in Lundqvist (1969).

widespread in boreal forest and tundra areas where they make walking difficult. The turf hummocks consist almost entirely of sedge (such as cotton grass) and sphagnum moss (also called peat moss), and are the consequence of differential vegetative growth rates rather than cryogenic transport of material. Some may at times contain cores or layers of segregation ice but when that ice melts the hummocks retain their upright form.

Figure 4.24 provides a useful summary of the general characteristics of pingos, palsas, and hummocks. It is sometimes difficult to distinguish among

these various forms of ***frost mound*** and similar forms created by other mechanisms; part of the problem can be that transitional forms develop.[27] Hydrostatic pressure causes pingos, cryogenic suction generates palsas, and frost heaving is responsible for earth hummocks, but all of these mechanisms might operate simultaneously in certain circumstances, including the differential rates of vegetative growth that form turf hummocks.[28]

Weathering, Sorting, and Transport Processes in Cold Lands

Although many cryogenically produced landforms—pingos, palsas, polygons, and the like—occur in mossy or otherwise heavily vegetated lowlands, others are located in high alpine or arctic upland areas where trees are mostly absent and the ground vegetation is far from lush. There, cryogenic weathering and transport processes play a major role in shaping the land, and most important are those related to cyclic variations in temperature, mainly in the active layer. Less effective because of low temperature is weathering due to chemical reactions.

Chemical weathering

In warm, moist climates the most important cause of weathering is chemical. Chemical weathering involves several specific mechanisms that alter the rocks and cause their decomposition: 1) Dissolution, wherein water directly dissolves rocks or combines with other molecules to form rock-dissolving acids or other substances; 2) Oxidation, wherein oxygen combines with mineral ions contained in rocks to form insoluble but generally weak oxides; 3) Acidification, wherein acids derived from decomposing organic material decompose soil minerals; and 4) Hydrolysis, wherein water molecules combine with minerals and the H+ or OH- ions contained in water replace other ions in mineral structures to create fine-grained materials such as clay and also soluble compounds readily transported away by water. Heat and moisture foster chemical weathering, and living organisms assist by helping to expose rocks to weathering (specific processes include root growth by plants and soil churning by earthworms and other animal life). Granites, cherts, gneiss, and quartzite rocks resist chemical weathering; sandstones, basalts,

27. An example of the problem is the mound complex shown in Figure 4.21 which has been described both as open-system pingos [Péwé (1977)] and palsas [Péwé (1997)].
28. Nelson et al. (1992).

and schists are intermediate; and limestones and shales are least resistant. Chemical weathering tends to produce rounded rocks and landforms.

Cryogenic weathering

Cryogenic weathering, like chemical weathering, proceeds by several identifiable but interrelated processes, but each is of strictly mechanical nature. Cryogenic weathering pries rocks apart and mechanically chews them up into little pieces rather than chemically altering them, and it proceeds most rapidly where an ample supply of water is present and the temperature cycles frequently through the freezing point. Cryogenic weathering is commonly called ***frost wedging*** (and occasionally gelifraction, congelifraction, or gelivation, all words derived from the Latin *gelare*, meaning to freeze). The specific mechanisms are:

1. The freezing of water seeping into preexisting structural cracks, wedging rocks apart to create smaller fragments.
2. The freezing of water seeping into rocks along grain boundaries or other zones of weakness to form ice layers that pry splinters and thin sheets from the rock surfaces.
3. The freezing of water contained in the pore spaces of porous rock bodies, shattering their outer parts into fine-grained particles.
4. The damaging expansion and contraction of rocks caused by radical changes in the amount of adsorbed water on pore surfaces as the temperature varies. Called ***hydration shattering***, this mechanism can operate at temperatures above freezing, but because temperature fluctuations into the subzero range so radically affect the free energy of water in pore spaces, thereby affecting how many molecules get adsorbed onto the pore surfaces, hydration shattering may be particularly potent in this subzero range. Its effectiveness relative to the freezing of water in pore spaces is uncertain, perhaps since both mechanisms work to give the same result: the shattering of a rock body into small particles. In principle, hydration shattering should most affect fine-grained rocks such as shales and siltstones because of their high surface areas.[29]

29. In his excellent textbook *Geology* (1995) Stanley Chernicoff cites an experiment in which highly polished granite showed no effect when cycled through a temperature change of 38°C 89,500 times (equal to 244 years of daily cycle) but when the experiment was repeated using a fine spray of water to simulate nightly dews the surface of the granite became irregular and cracked.

5. The prying apart of rock by the formation of segregation ice from water transported into porous rock by cryogenic suction to produce splinters and rock fragments. Enormous pressures—up to 300 Atm—can develop according to the premelting model of segregation ice formation.

The susceptibility of rock to cryogenic weathering depends on a number of factors including the internal structure of the rock and its porosity, the availability of water, and the range, frequency, and speed of temperature fluctuations. Porous rock containing water typically grows stronger when the water freezes, and its strength increases with decreasing temperature. However, the internal pressure generated by the freezing of ice in rock pore spaces also increases with decreasing temperature, theoretically to a value roughly 10 times the tensile strength of rocks like sandstone and limestone (which have tensile strengths near 250 Atm). Thus, how cold it gets during a cycle of temperature fluctuation can help determine how much weathering occurs during that cycle. Various laboratory experiments indicate that the breakdown of rocks depends on the intensity and speed of freezing and also on the number of freeze-thaw cycles undergone. For example, when testing porous rocks, one experimenter found little cracking until the temperature was below –10°C, and the cracking occurred only when the rate of temperature decline was at least 6°C/hr.[30] Cryogenic weathering produces angular fragments ranging from house-size blocks down to those the size of sand, or even clay in certain circumstances.[31] Open-air settings (such as rock cliffs) and environments of extreme cold tend to produce a high proportion of large angular block debris, whereas situations involving rocks buried in debris (so that temperature fluctuations are not as rapid or severe) lead to a higher proportion of fines.[32]

Laboratory experiments in general also demonstrate that the availability of water is very important: rocks partially or fully immersed in water break up more rapidly than those coated only by films of water. Field observations show that rocks near patches of thawing snow or near shores are particularly prone to disintegration and fracturing when repeatedly frozen and thawed.[33]

30. Battle (1960) cited by Washburn (1980) p 75.
31. McDowall (1960) cited by Washburn (1980) p 76.
32. Tricart (1970) p 74.
33. Tricart (1970) pp 73–76.

The nature of the rock is a major factor as well. Crystalline (igneous) rocks such as granites tend to be the least permeable unless they contain the sheet-like muscovite and biotite micas that provide avenues along that water can enter and then wedge the rocks apart. Particularly susceptible to cryogenic weathering are fine-grained sedimentary rocks such as shale and siltstone that have a water-admitting layered structure or which contain plate-like clay or mica minerals. Individual minerals contained in rocks react differently to cryogenic weathering: quartz (SiO_2) is particularly susceptible, especially if heavily fissured, and biotite mica is more susceptible than muscovite mica.[34]

Those cryogenic weathering mechanisms that operate on a microscale—as contrasted with the large-scale prying apart of rocks into angular blocks—tend to produce particles of rather small size. They can split up chemically weathered clays into even smaller particles, but the end products of the weathering also depend much on the nature of the parent rock. Chemical weathering of quartz yields smaller particles than chemical weathering of feldspars, but cryogenic weathering of quartz produces larger particles than does cryogenic weather of feldspars. This difference seems to be a consequence of the repetition of freeze-thaw cycles, and this repetition is highly effective in splitting the feldspar-derived clay particles. The repeated freeze and thaw cycle also modifies soil, altering both soil particles and the size and shapes of pore spaces. Soil particles near layers of segregation ice tend to become more closely packed, and when the ice thaws the soil particles do not necessarily return to their prefrozen locations.[35]

Churning and sorting within the active layer

Cryogenic weathering typically leads to a soil layer containing products of various sizes, and if the size distribution and water availability are such that the soil heaves upon freezing, then a sorting of the material occurs quite naturally. **Figure 4.25** schematically illustrates the process, a shifting of objects that depends directly on their dimension in the direction of freezing, assuming that the freezing soil will grab tight to the object somewhere above its base and thereafter lift it as frost heave continues. Geocryologists generally refer to this as the ***frost pull*** mechanism. By the same means, any object such as a rock that has one end elevated above the other will tilt upward even more as freezing takes place. Since various

34. The discussion here is based primarily on material given by Lautridou (1988).
35. Williams (1999).

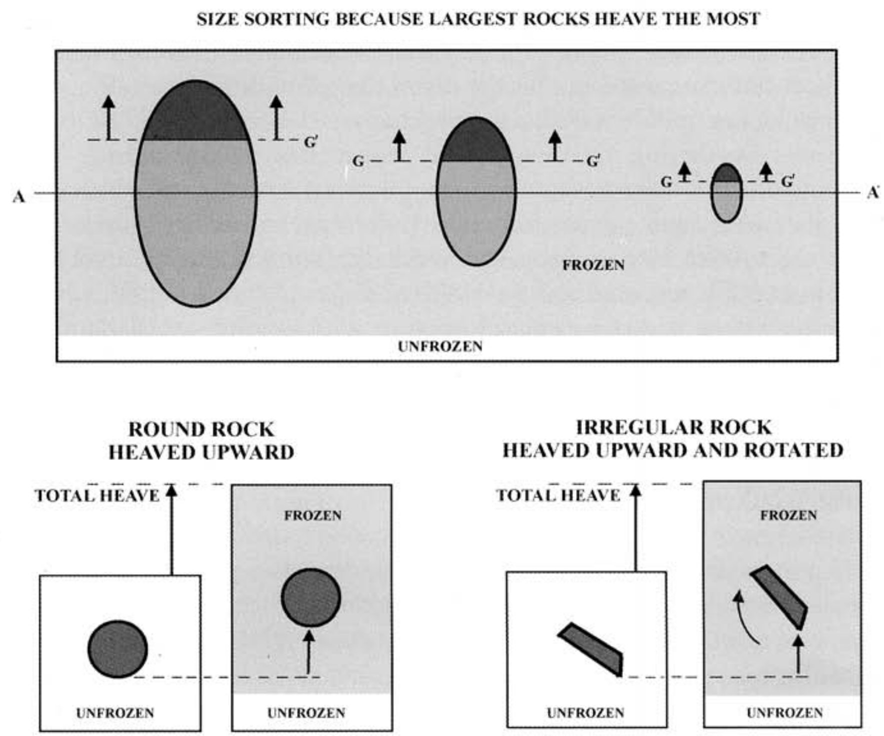


Figure 4.25 Schematic illustration of: top; how if similarly shaped rocks of various sizes lie at the same level in a soil profile, the frost pull mechanism of frost heaving can sort them by shifting them upward in proportion to their sizes because the soil that is heaved the most (the upper part of the profile) grasps the larger rocks, leaving the smaller ones to be lifted later by lesser amounts as the frost line penetrates the profile, and at bottom; that round stones merely heave upward (or perpendicular to the plane of the freezing front) but that heaving soil tilts irregular rocks by grasping their upper parts first, assuming the unfrozen soil below allows them to rotate.

observations show that frost heave does cause stones, fence posts, and other objects to rise out of the ground over the course of years, it is evident that at least part of the uplift occurring during freezing is preserved during subsequent annual thaws. Thus, vertically oriented rocks protruding from the ground are a common sight in certain cold land areas (see **Figure 4.26**). Dirt trickles down into the voids left below frost-heaved objects, and sometimes the friction between the objects and adjacent unfrozen material is sufficient to keep them elevated. Sometimes people

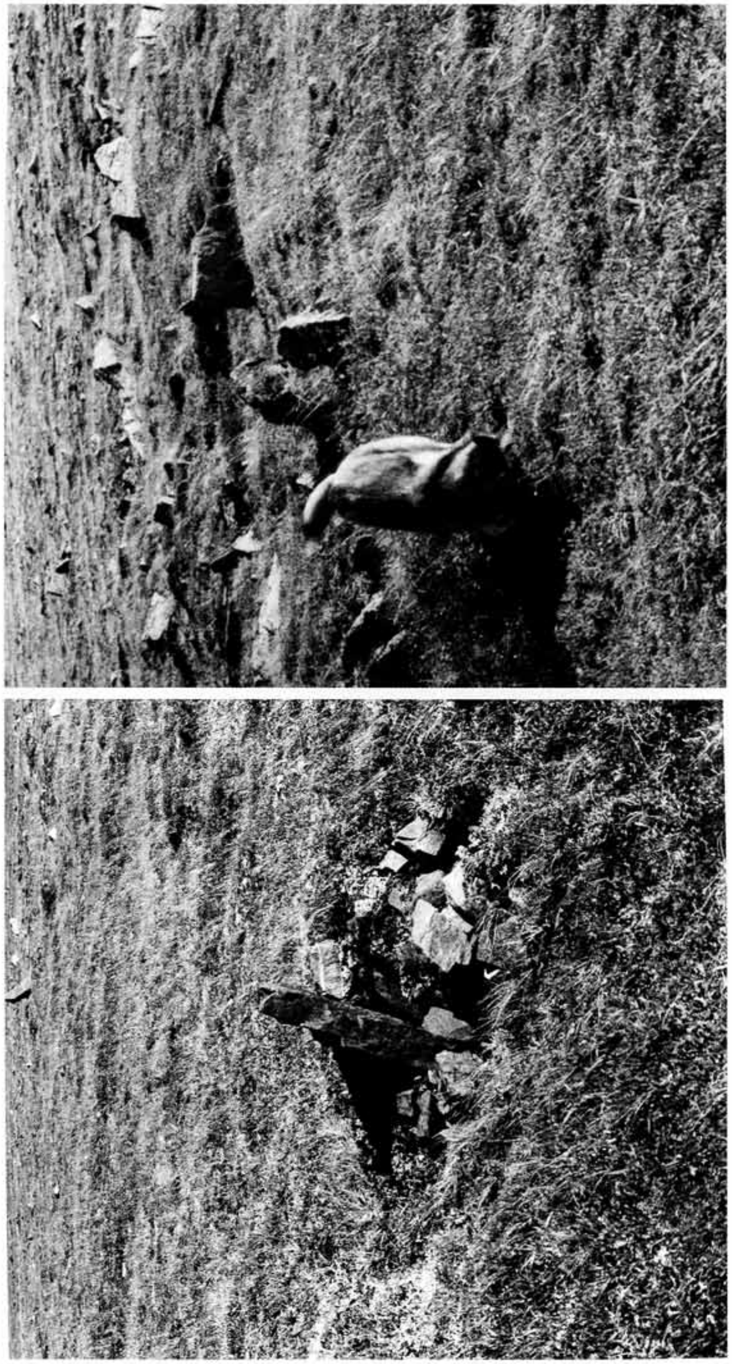


Figure 4.26 Uplifted rocks protrude through the thin moss cover of Eagle Summit, north of Fairbanks, Alaska, creating a moon-like landscape that provides a good habitat for rodents, which in turn titillate other animals like the 1-meter scale dog (nose to tail) in the right-hand picture.

have been able to hammer back into the ground posts elevated by frost heave, indicating that voids remained below.

As the freezing front progresses down across a rock or boulder embedded in soil, it may move faster through the rock than through the adjacent material simply because the rock has no latent heat of fusion to release, and perhaps also because the rock has relatively high thermal conductivity. The consequence then may be an accumulation of segregation ice below the rock that helps lift it. The overall effectiveness of this ***frost push*** mechanism is uncertain. Some of the water forming segregation ice beneath the rock may actually be migrating downward from wet soil beside the rock. If that soil is loose, some of it may be drawn downward with the water, thereby amplifying the sorting process, but another complicating effect may be desiccation and consequent volume decrease of the soil near the rock. Frost push appears to be important in lifting blocks of bedrock if that rock is porous, and if thermal conditions are such that the coldest part of the rock is well below the surface, perhaps resting on cold permafrost so that the freezing front is advancing upward within the block. Water can then move downward through the porous stone to form segregation ice that lifts the bedrock through the unfrozen soil. Experiments and field observations have shown that this mechanism can lift porous bedrock by approximately 5 cm annually.[36] In essence, the porous rock is acting like a fine-grained soil in permitting the accumulation of segregation ice.

Cryogenic sorting of soil and the upward displacement of rocks it contains can proceed even if the soil is generally texturally uniform throughout. If the soil is nonuniform, which is usually the case, differences in heat capacity and thermal and hydraulic conductivity are likely to lead to even more complex motions of water molecules, soil particles and contained rock fragments. The overall assemblage of churning and vertical uplift motions thereby taking place in the active layer goes by the name cryoturbation and, as the turbulent part of that name implies, the motions can be complicated. One part of the soil profile might expand by accumulating water and segregation ice while another contracts from loss of water or thawing. Further complication comes from the possibility of upward freezing from a permafrost layer as well as downward from the ground surface. The pressure within unfrozen pockets of wet fine-grained material caught between growing frozen layers may cause the material to squirt to a different place or break through to the ground surface. If the

36. Price (1970) [cited by Washburn (1980) p 91].

water contained in saturated fines cannot readily escape as they thaw, excess pore pressure can build up and the material may become so unstable that it cannot support the overlying load, causing slope failure or flow. Evidence of past cryoturbation includes deformed soil profiles ranging from wavy through regularly folded to highly complex, sometimes chaotic contortions, all of which fall under the generic name ***cryoturbations***, also ***involutions***.[37, 38] **Figure 4.27** contains schematic sketches showing some types of cryoturbations and also drawings of observed examples.

Cryogenic transport of weathered material

Water and wind operate worldwide to erode and transport weathered rock material, and in the process usually achieve some sorting. Wind, for example, carries fine particles farther than large ones from a source area, and water tends to do likewise. Both of these transport mechanisms abrade the moved material and in doing so round it into smoother forms. Deposits of rounded gravels and stones are sure signs of transport by fast-moving waters. By contrast, cryogenic transport processes tend to leave the material in angular shapes. Owing to low precipitation in most of the arctic and subarctic region, erosion by water is slow and episodic, so freeze and thaw processes are responsible for much of the transport of weathered material. The material thus transported remains angular, and the transport mechanisms also create landforms unique to cold lands. However, those landforms are influenced by eroding waters that flow across and beneath sloping surfaces (***slopewash***). Surface runoff from snowmelt and summer rains can transport fines carried in suspension and also remove soil by carrying it in solution. Subsurface waters can carry away dissolved soil, and also that held in suspension when the subsurface water is flowing down through voids in rocky deposits, a process called ***piping*** or ***stoping***.[39] The few measurements of rates of erosion by slopewash in cold areas indicate very slow transport that may lower surfaces by only a few millimeters in 1000 years.[40]

Cryogenic transport—the downslope movement of soil that is frozen or undergoing freeze and thaw—proceeds by three general processes: 1) very slow creep within the body of perennially frozen soil (***permafrost creep***), 2) slow ***solifluction*** flow, and 3) relatively rapid flows associated with slope failures of one sort or another. Solifluction proceeds by three different identifiable mechanisms: 1) ***frost creep***, 2) ***needle ice (pipkrake) creep***, and 3) ***gelifluction***. The rapid cryogenically caused mass movements may involve viscous-like flowing of unfrozen, often-saturated soil material, rapid en masse sliding along slippage planes, and falling away of blocks detached by freezing and thawing.

37. The term "periglacial involutions" also is used, and some geocryologists consider involutions to be a special form of cryoturbations [Washburn (1980)] p 170.
38. Vandenberghe (1988).
39. Péwé and Reger (1983) pp 125–27; Lewkowicz (1988) pp 354–57.
40. Lewkowicz (1988) pp 354–55.

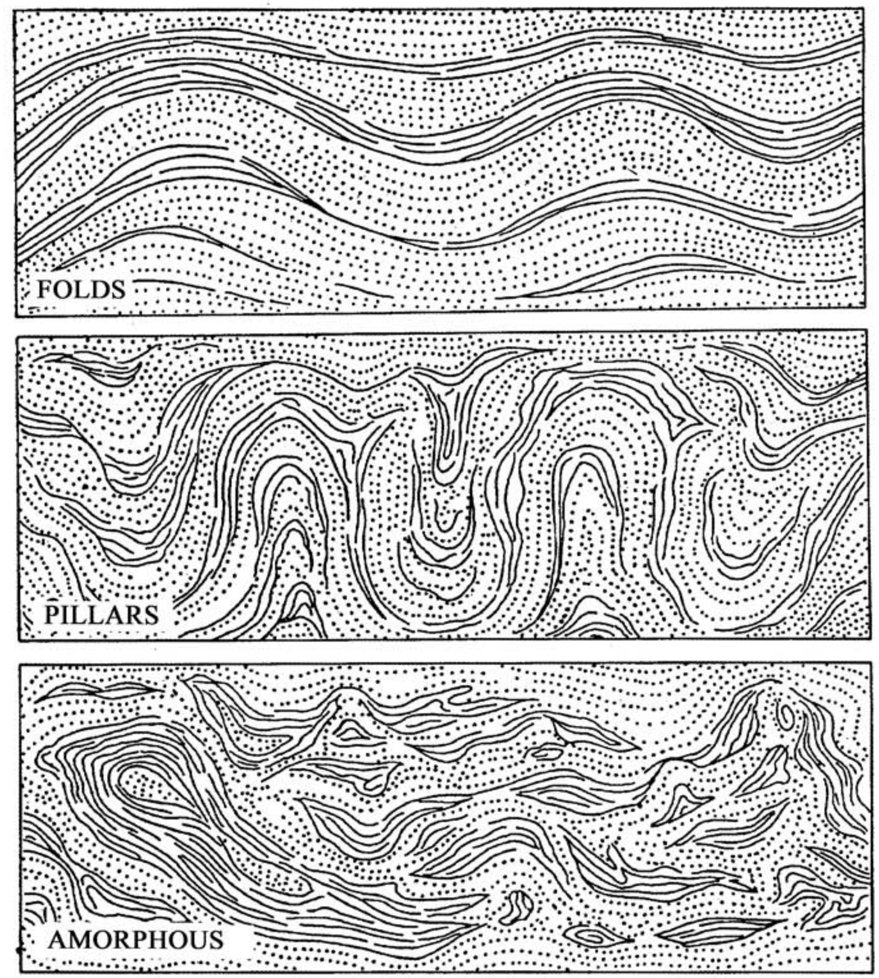


Figure 4.27A Schematic drawings of folded, pillar-like and amorphous cryoturbation structures.

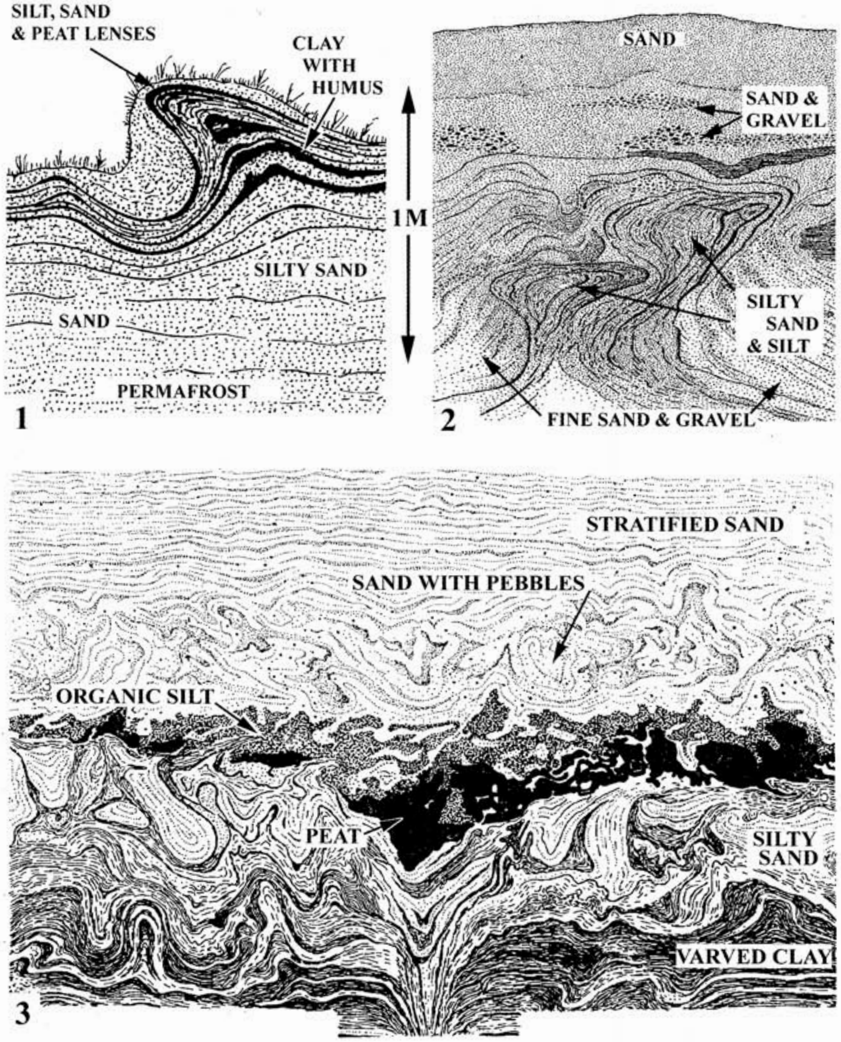


Figure 4.27B Drawings of actual cryoturbation structures observed within Pleistocene deposits in Poland: 1) a fold resulting from differential frost heaving; 2) pillar structures; 3) complex folded and pillar structures. Compiled from Figures 89, 92 and 93 of Jahn (1975).

Permafrost Creep

Given enough time, frozen ground, even if under light loading, will undergo creep. In warm permafrost, that at temperatures just below 0°C, enough unfrozen water may be present to enhance creep by reducing the friction

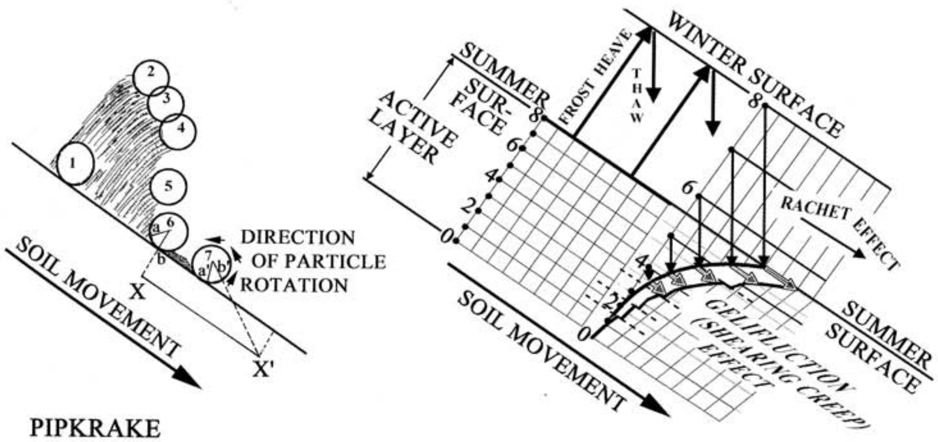
between soil particles, especially if the permafrost is ice rich. Observations in the Mackenzie River area over a period of several years on a steep slope (15 to 30°) containing both dry sand and ice-rich clay showed little creep in the sand and more in the clay, where it appeared that deformations were occurring in conjunction with ice layers. The creep was slow, 2.5 to 3.0 mm/yr, but fast enough to indicate that creep within warm permafrost may be an important process in helping to denude steep slopes of soil.[41]

Solifluction

About a century ago, the term solifluction was used as a name for slow downslope flow of soil saturated with water. Over the years the meaning has evolved to include slow downslope flow caused by or associated with cryogenic processes.[42] In the interest of fostering clarity, I here use the term ***cryogenic solifluction*** specifically to mean solifluction caused by or associated with cryogenic processes. The term cryogenic solifluction (or simply solifluction, if the meaning is clear) is useful for refering to the full gamut of specific physical mechanisms involved: frost creep, needle ice creep, and gelifluction.

Frost (active layer ratcheting) creep. Freezing of a sloping soil in the active layer causes it to push upward in the direction perpendicular to the slope. Then, as it thaws, the material tends to drop straight down. Thus, repeated freeze and thaw rachets soil downslope, as illustrated in **Figure 4.28**. Observations show that frozen material does not necessarily drop vertically, but instead falls back slightly toward its original position, thus executing a retrograde motion. That behavior is thought to be due to a cohesion between the soil particles that fosters maintenance of the original positioning of one soil particle above another, or perhaps a relative desiccation of the top part of the profile that causes it to contract to slightly smaller volume than the soil below.[43] The few measurements made on frost creep in the active layer indicate that it progresses about ten times faster than creep in permafrost, at rates up to approximately 2 cm/yr.

41. Much of the discussion here is based on Lewkowicz (1988).
42. Washburn (1980) pp 198–213; Lewkowicz (1988) pp 329–39; Williams and Smith (1989) pp 123–31.
43. Washburn (1980) p 199. Also, this cohesion and the resulting cracking may well be a major factor in determining the spacing of cryoturbation steps.



PIPKRAKE (NEEDLE ICE) SOIL TRANSPORT

FROST CREEP (FROST HEAVE RATCHETING) AND GELEFRACTION (SHEARING) CREEP

Figure 4.28 Processes causing solifluction. Left: downhill transport of soil by pipkrakes (needle ice) that also causes retrograde rotation of soil particles [reproduced with minor modification from Figure 95 of Jahns (1975)]. Right: Both frost creep (frost heave ratcheting) and gelifluction shearing in the active layer may act to cause the upper part of the active layer to override the lower part. Dashed lines suggest locations of segregation ice layers. In the diagram frost heaving and shearing are both exaggerated for purpose of illustration; not shown is the slight retrograde motion of soil involved in frost heave ratcheting.

Needle ice (pipkrake) creep. In climates where repeated freeze and thaw occurs and where soil permeability and adequate moisture combine to allow the growth of tall pipkrake crystals, they can be an important and rapidly acting agent for moving the very top of the soil layer. Needle ice creep moves surface material downslope at rates typically near 10 to 20 cm/yr, and in some instances more than 30 cm/yr. In cold-climate areas, needle ice creep probably is of less importance than the other cryogenic solifluction processes: frost creep and gelifluction.

Gelifluction (shearing creep). Gelifluction is cryogenic solifluction involving shearing within the active layer because of slow slippage, probably mainly along melting layers of annually formed segregation ice in consequence of particularly high pore pressures developed there. Within a thin layer at the thawing interface of an ice-rich soil, the pore pressure can become so high that the soil's strength is drastically reduced until downslope stresses exceed the soil's resistance to shear. Gelifluction can develop on

slopes as low as 1 or 2°; silty soils are particularly susceptible.[44] Contributing to gelifluction may be a variety of microscale differential motions related to expanding and contracting soils, reorienting of soil particles and to cavities formed in the soil by air coming out of solution during freezing. Some of these may progress during the freezing process or after the soil is frozen, so gelifluction is a process that can be underway much of the year.

Especially in situations where the active layer is in contact with continuous permafrost, the heaving associated with frost creep, like gelifluction, can occur in summer as well as winter, and then the distinction between the two forms of solifluction blurs so much that it perhaps becomes artificial.[45] Both kinds of solifluction typically lead to vertical velocity profiles that are concave downslope (as in Figure 4.28), so that the combination of the two kinds of solifluction causes material to override itself. The overall end result, notes Alaska geocryologist Richard Reger, is that the soliflucting material behaves much like the tread of a caterpillar tractor in that it rolls forward downhill over itself. In **Figure 4.29**, he points to some of the evidence for that suggestion.

Complexities in the gelifluction slippage along layers of melting segregation ice can modify the normal vertical velocity profile, causing it to be more irregular than illustrated in Figure 4.28, and even convert its concave-downslope shape to convex-downslope. This situation is most likely to occur when the active layer is in contact with permafrost, because then layers of segregation ice may form near the bottom of the active layer, especially in late summer.[46] The melting of these lower ice layers creates a shear zone that allows the overlying material to flow more or less as a unit, a process called ***plug flow***,[47] which perhaps should be included with the other cryogenic solifluction processes.[48]

Cryogenically caused rapid mass movement

Characterized by their episodic and spatially discontinuous nature, cryogenically caused mass movements are important transporters of soil, especially on steep slopes, those exceeding 15 or so degrees. Viscous-like flowing of soil material and en masse sliding along slippage planes can

44. Washburn (1980) pp 202–04.
45. Lewkowicz (1988) p 332.
46. Mackay (1981).
47. Rein and Burrous (1980).
48. Williams and Smith (1989) p 130.

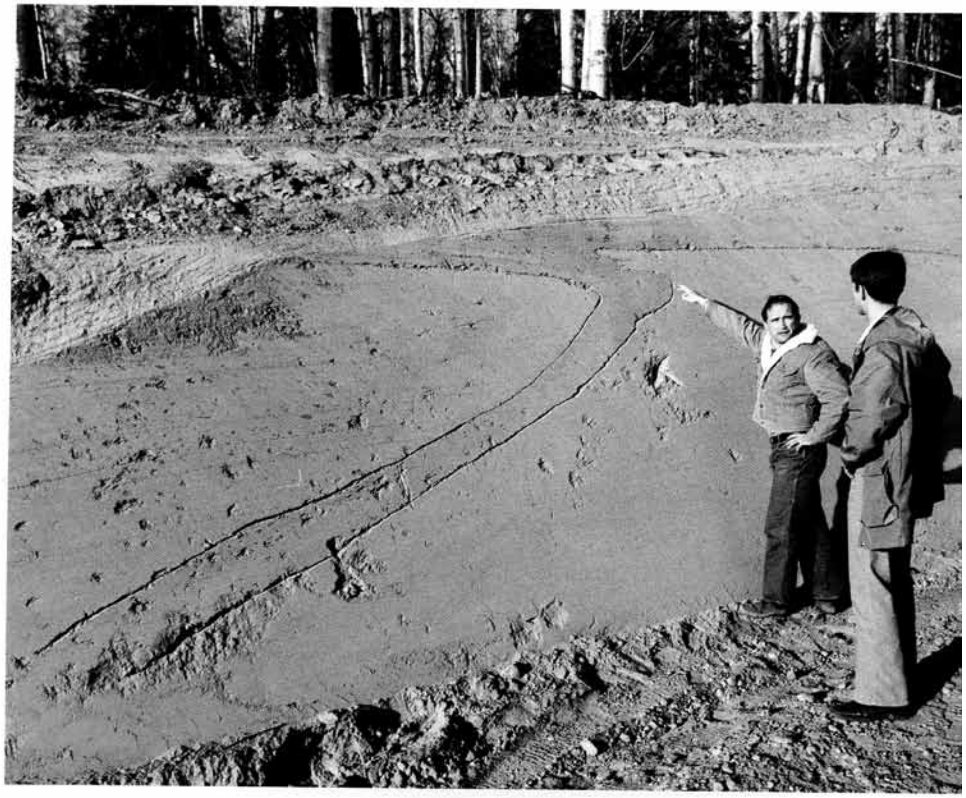


Figure 4.29 Geologists Richard Reger and Stu Rawlinson discuss the effects of solifluction, in this instance a deformed soil layer. Photographed 1978 in a roadcut on the campus of the University of Alaska Fairbanks.

occur simultaneously, although in any particular situation one process may dominate. The term ***active-layer failure*** has been used in a general way to refer to any type of failure occurring strictly within the active layer overlying permafrost, and also as a name for flow-dominated mass movements on steep slopes. Synonymous names for flow-dominated movements within the active layer are ***skin flow*** and ***earth flow***. These failures, typically ribbon-like, with a small slump scar compared to the movement track, may be only a few to several tens of meters wide and hundreds of meters long.[49] The one shown in **Figure 4.30** exceeds 500 m in length. Causes of the episodic flows include unusually rapid snowmelt or unusually heavy

49. Lewkowicz (1988) pp 342–42.

Figure 4.30 A ribbon-like active-layer failure (skin flow) originating high on a steep slope and flowing down a gentler slope almost to the Dalton Highway in Alaska's Brooks Range. Photographed in summer 1995.

summer rainfall that increases stress through saturation of organic material, ***thaw consolidation***, and melting of permafrost caused by natural or man-made disturbance to ground cover or climatic warming.[50]

Another widespread active-slope failure on steep (>10°) slopes in permafrost areas is ***active-layer glide*** (also sometimes called ***block slide***, ***detachment failure***, and active-layer detachment). It involves downhill sliding of the active layer as a unit, usually along the typically ice-rich per-

50. Lewkowicz (1988) p 342.

mafrost table. A large area of the active layer may slide as a unit, but most commonly a section near the base of the slope detaches and then, over the course of minutes to days, sections higher up successively detach to create an overall slide area usually with length greater than width. The cause of active-layer glide is excess pore-water pressure near the bottom of the active layer. Heavy summer rainfall can contribute by increasing the weight (and hence the shear stress), and other contributors are man's activities or forest fires that deepen the active layer enough to melt the ice-rich soil just beneath the former permafrost table.[51]

Another flow-dominated episodic transport phenomenon is the ***mudflow***, the downslope movement of saturated soil material. Mudflows are not necessarily created by cryogenic processes nor restricted to the active layer, so they exist wherever conditions foster saturation of soils on slopes. Cryogenic mudflows are usually small—only a few meters in extent—and so do not constitute an important transport process. In permafrost areas mudflows usually develop in consequence of thawing ground ice that has become exposed for one reason or another. They have been observed to emanate from mudboils, along eroding riverbanks, and on slopes with subsurface water derived from melting snow or summer rains.[52]

Still another flow-dominated failure of slopes in the discontinuous permafrost zone is ***multiple retrogressive flow***, wherein repeated slope failures occur in a way that exhibits flow (typically within silty clay) but which in the bowl of the flow creates arcuate ridges retaining some evidence of the former relief.[53]

Differing from the multiple retrogressive flow is the ***multiple retrogressive slide***, a large-scale repeated slumping that may develop in frozen and unfrozen sediments and along the permafrost table. The distinguishing characteristic is the production of a series of arcuate slumping blocks, concave downward and up to 60 m high, that step up toward the head of a scarp and tend to tilt over backwards, especially near the toe of the slide area.[54]

Another shear failure is ***thaw slump*** wherein blocks of frozen or unfrozen sediments break away along a concave slip face. Thaw slumps are common near rivers with undercut banks, particularly where sand or gravel overlies silt and clay. Contributory may be the development of high pore-water pressures in the fine-grained soils when the river banks freeze.[55]

51. Lewkowicz (1988) pp 344–45.
52. Lewkowicz (1988) pp 342–45.
53. McRoberts and Morgenstern (1974a; 1974b).
54. Lewkowicz (1988) p 345.
55. Lewkowicz (1988) p 345.

Rockfall, the free falling of rocks down steep slopes, is primarily a vertical transport process that operates in all climates, but it is a periglacial process in localities where freeze-thaw cycling is an important release process. Frost wedging, perhaps augmented by thawing of interstitial ice and stress increases created by avalanches or debris loading, is a significant cause of rockfall in cold-climate areas. The variation in frequency of periglacial rockfalls with season tends to follow variation in the number of freeze-thaw cycles; for example, rockfalls on south-facing slopes tend to occur earlier in spring than on north-facing slopes, and rockfalls tend to occur more frequently in spring and fall than in summer and winter. The rockfalls also tend to occur most frequently during the warmest part of the day. Although amounting to only a few millimeters per year at most, the combination of frost wedging and rockfall on near-vertical slopes results in substantial erosion—up to several tens of meters during the past 10,000 years (Holocene).[56]

Landforms Resulting from Weathering, Sorting, and Transport Processes

Talus slopes

Frost wedging of steep cliffs contributes to the development of apronlike deposits (also called scree) below with their surfaces lying at the angle of repose. The tendency for the largest falling rocks to roll leads to some sorting. Any type of weathering can create talus slopes, so they are not limited to cold environments. Long-lasting snowbanks accumulating at the bases of talus slopes sometimes provide platforms for material to scoot across. The resulting deposits, called ***protalus ramparts***, are thus isolated from the main talus slopes and may show up as separate ridgelike deposits best seen after climatic change reduces the accumulation of the perennial snowbanks.

Solifluction sheets and lobes

Cryogenic solifluction taking place on shallow (down to 1°) and steeper slopes creates various shapes of deposits: sheet-like, bench-like, and lobate. A characteristic of solifluction is that it tends to fill in low places, and so acts as a great leveler. Water erosion, by contrast, tends to deepen depressions and thereby acts to generate relief. Examples of the difference are widespread in the upland and mountainous areas of central Alaska where past or current cryogenic processes have created smooth, low relief slopes at high altitude,

56. Washburn (1980) pp 76–77; Lewkowicz (1988) pp 345–47.

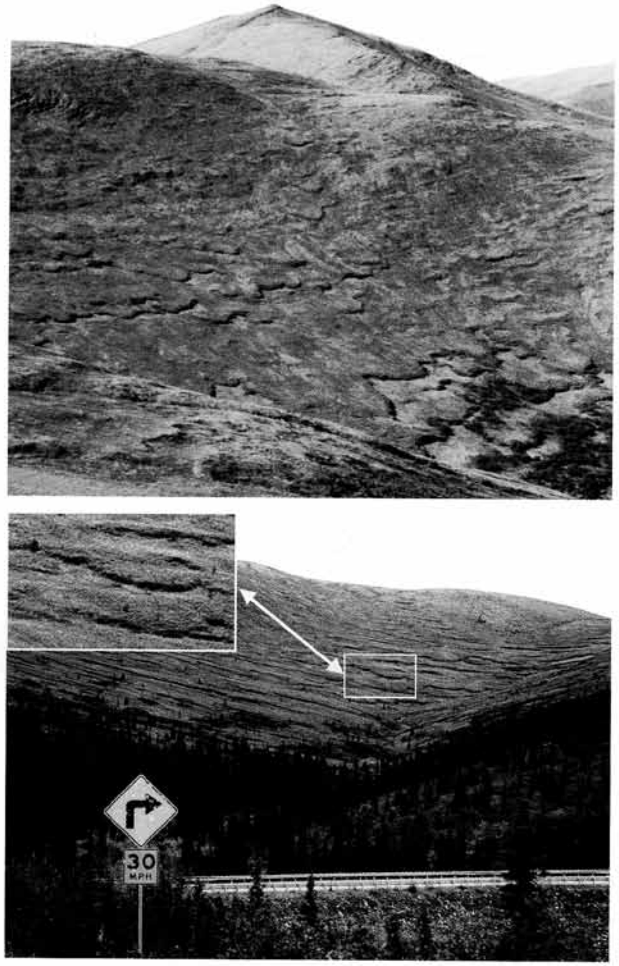


Figure 4.31A Top: Solifluction lobes seen when looking west from Eagle Summit on the Steese Highway north of Fairbanks, Alaska. Bottom: Others seen a few miles south of the summit.

and water erosion has incised the slopes lying at lower altitudes where past and current climate favors water transport over cryogenic transport.[57]

Among the more easily recognized sheet-like landforms created by solifluction are the turf-covered ***solifluction benches*** and lobes that spread out across upland slopes in north-central Alaska and elsewhere, the benches tending to develop more on the gentler slopes and the lobes on steeper ones. The general form and steep fronts of the benches and lobes make them look much like the folds in an elephant's skin; see **Figure 4.31**.

57. Wahrhaftig (1949).

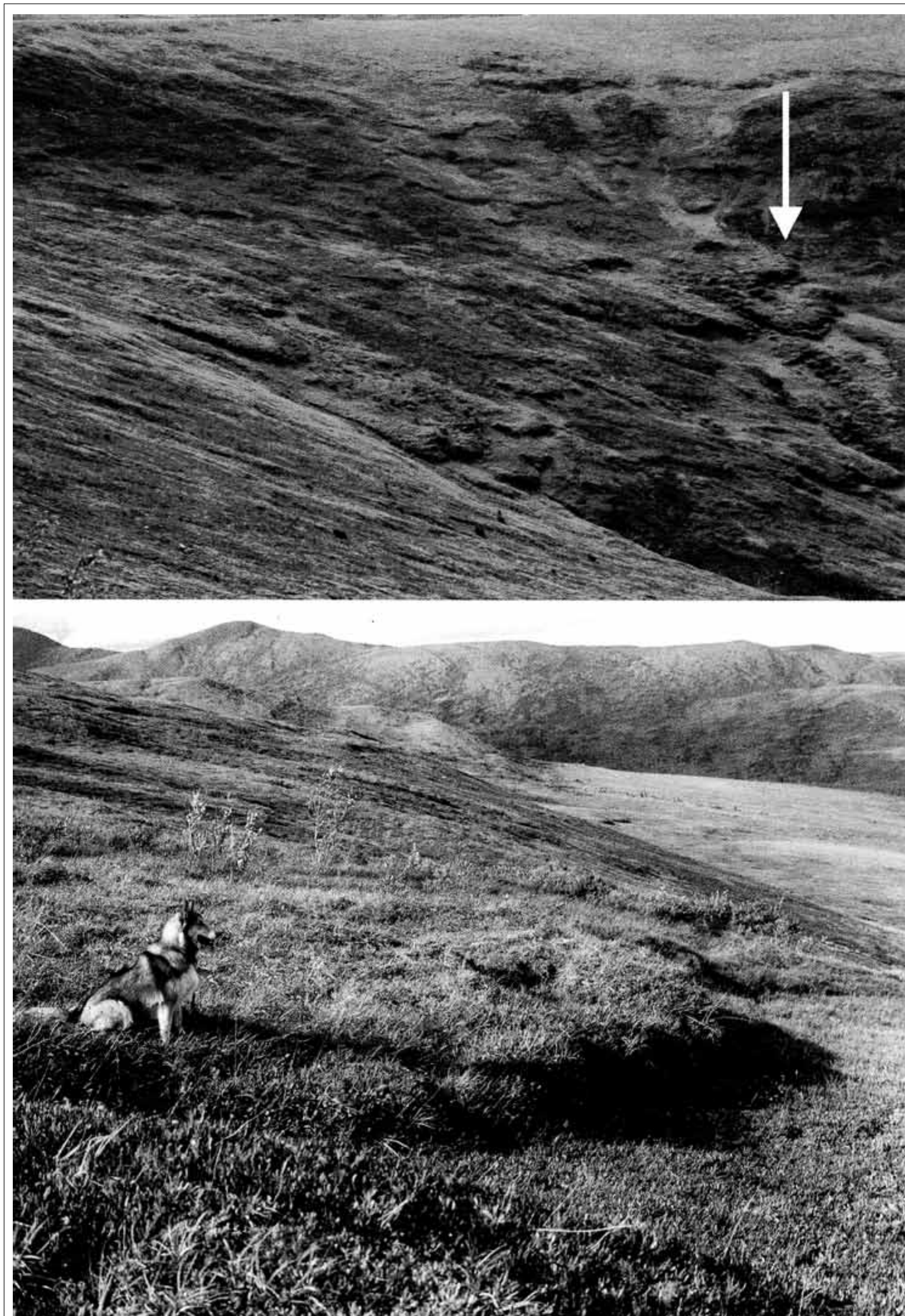


Figure 4.31B Top: The arrow in the photograph at upper right taken from the highway on Eagle Summit indicates the position of the bottom photograph and the photographs on the next page.

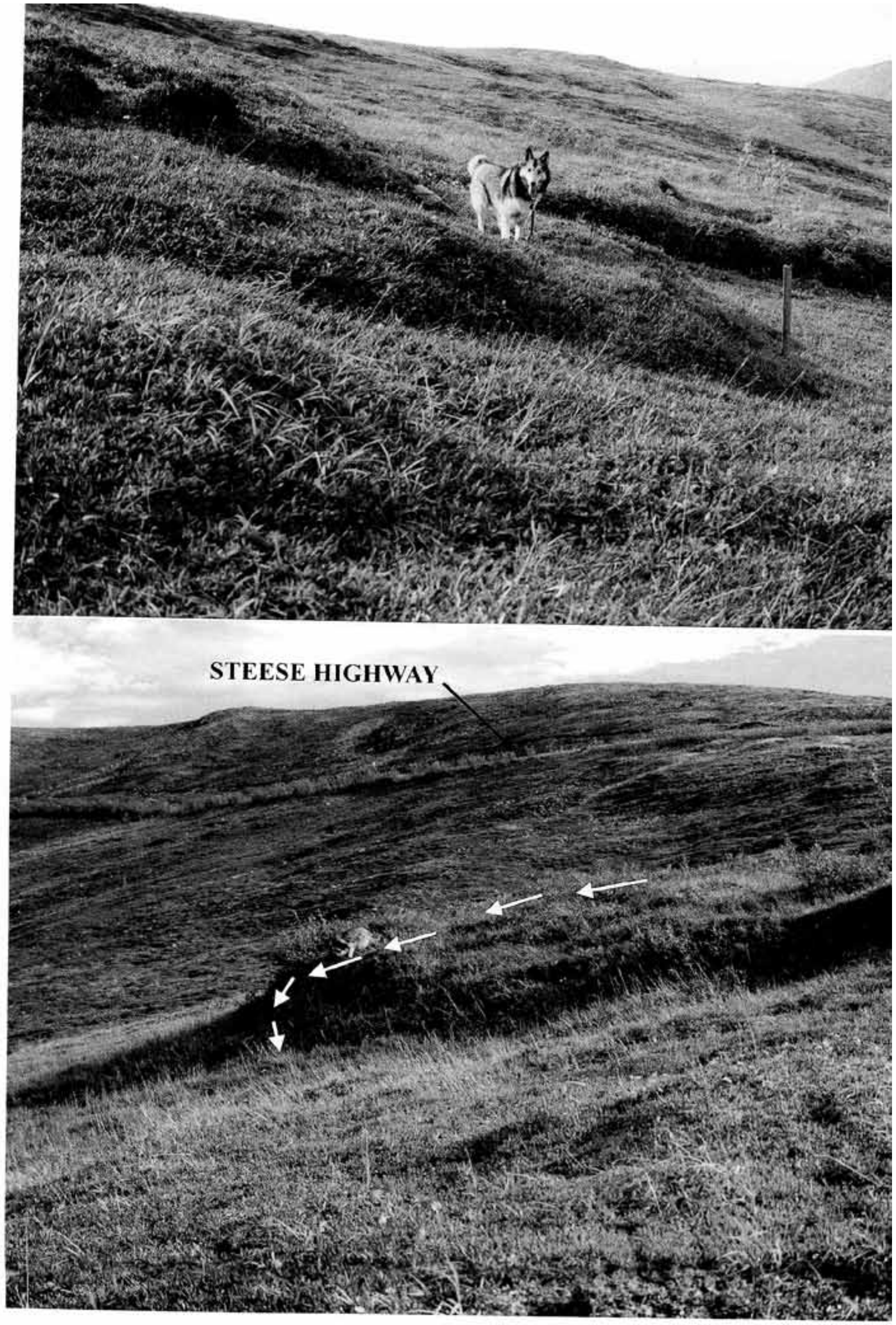


Figure 4.31C Top: Views to the west across the lobes. Bottom: View east toward the highway. In that photograph, the 1-meter scale dog digs for rodents resident in the toe of the lobe, and just below, arrows indicate the inferred solifluction motion.

The rates at which material soliflucts down a slope depend not only on the slope gradient but also on the availability of water, the distribution of grain sizes in the material, and perhaps the vegetation cover. Measurements on shallow to moderate slopes (5° to 20°) over a period of years indicate movements ranging from less than 1cm/yr in dry areas to a maximum of 6 cm/yr in wet areas, with speeds near 1 to 2 cm/yr most typical.[58] Silty soils are the most prone to solifluction flow, more so than clays and far more than sands and gravels. (Recall that silty soils also favor the formation of segregation ice, the melting of which is thought to be important in promoting solifluction.) The role of vegetation cover is less clear in that it may impede solifluction by anchoring soil and drying it through plant respiration, or, especially if it makes soil humus-rich, the vegetation might contribute to solifluction flow by helping to retain water in the soil.

Rock glaciers

An active ***rock glacier*** is a distinctive flowing landform, typically several tens to 100 meters thick that forms on mountain slopes having a mean annual temperature low enough that water percolating into blocky soil debris can freeze into a long-lasting ice matrix. The material in the rock glacier may derive from that in a talus slope or from the debris deposited by a normal ice glacier at its terminal moraine, which is the case in the example of a rock glacier shown in **Figure 4.32**. Whatever its source, when this material develops a sufficient ice matrix within its internal voids, it takes up a life of its own, flowing downhill through deformation of the interstitial ice.[59] The slope-dependent rate of flow is typically in the range of 1 to 100 cm/yr, and a few observations indicate speeds exceeding 1 m/yr.[60] Thus, rock glaciers typically flow at rates near the upper range of solifluction flow (a few cm/yr), but at rates far less than ice glaciers in the same environment. Cold ice glaciers flow only a few meters per year, while those in relatively warm alpine settings flow at speeds exceeding 100 m/yr.

The top two or so meters of a rock glacier is essentially all rock fragments and perhaps some soil, but below this rind (essentially the active layer), ice makes up approximately one-half of the rock glacier's volume. It is down here that the flow occurs through deformation of this ice. The flow occurs mainly in summer and is faster the warmer the ice, so the

58. Washburn (1980) p 204.
59. Wahrhaftig and Cox (1959).
60. Vitek and Giardino (1987) p 16 (Table 1.1).

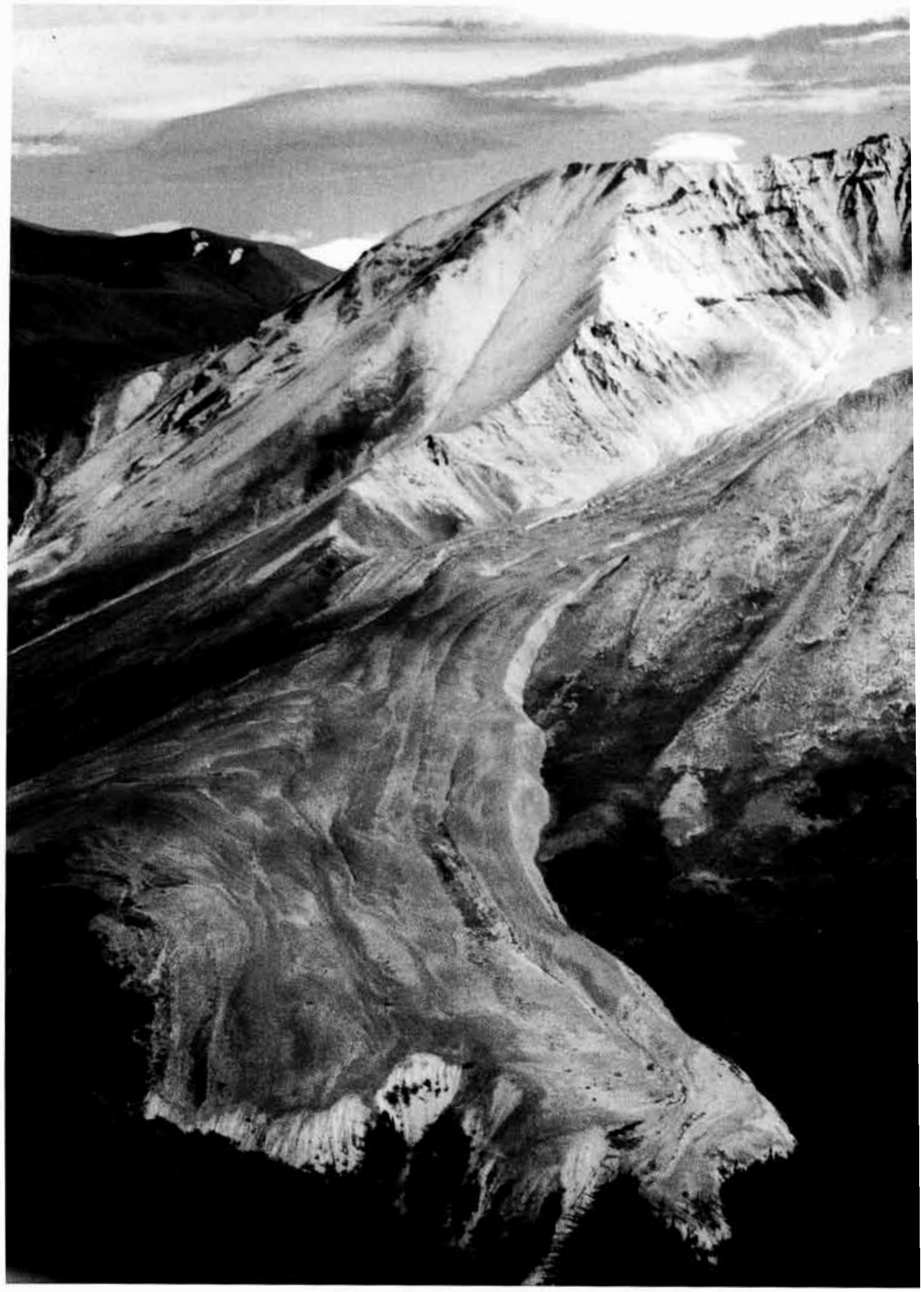


Figure 4.32 A large rock glacier fed by debris from a cirque glacier near McCarthy in Alaska's Wrangell Mountains. Photographed in 1979.

faster motion is in the upper part of the ice-rich body of a rock glacier. This motion carries along the topmost few meters. The material in that top layer generally tends to be more blocky than at depth; the rocks are angular and, depending on the nature of the source material, they may be mixed with a poorly sorted sandy or shaley matrix.[61]

The differential flow—faster near the top than at depth—creates the key distinguishing feature that allows easy identification of an active rock glacier: it has a steep frontal ramp breaking sharply away from the top surface of the rock glacier and inclined at the angle of repose of the material in the core of the rock glacier. The ramp of the rock glacier shown in **Figure 4.33** is a 32-degree slope, and the top surface of the glacier is roughly parallel to the ~20-degree mountain slope on which the rock glacier rests. Active rock glaciers maintain their steep frontal ramps because the faster downslope movement of the surface portion of the glacier delivers a steady supply of new material to the terminus where it cascades down over the slower-moving material beneath.

Figure 4.33A A small rock glacier photographed from the Richardson Highway at Mile 208 in 1996. The black dots mark the approximate upper boundary of the glacier, and the white arrow marks the location of the photographs in Part B.

61. Calkin et al. (1987) p 69; Barsh (1988) p 74.

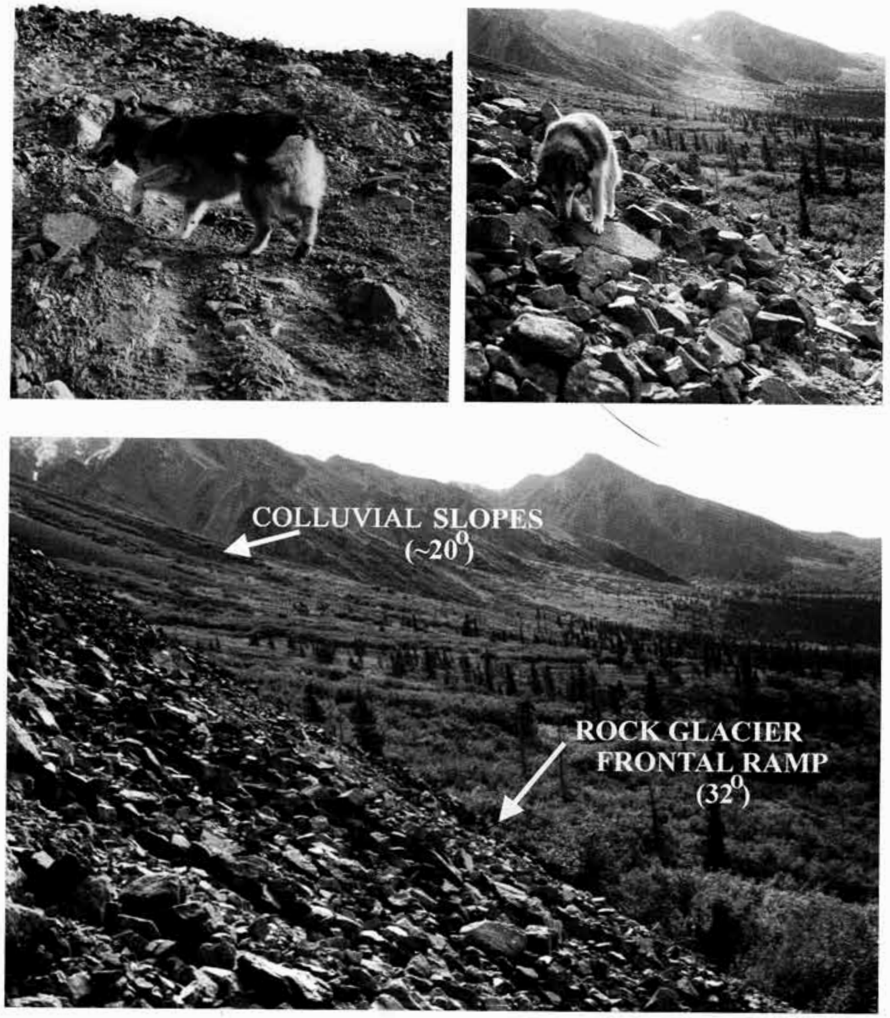


Figure 4.33B At top left the 1-meter scale dog Foxy scrambles directly up the frontal ramp and, at right, slinks unhappily across it because she has discovered that every footstep can start a slide of the loose rock and soil lying at its angle of repose. Bottom, a view directly across the frontal ramp toward the less steep colluvial slopes beyond. See also Plates 14A and 14B.

The top surfaces of rock glaciers exhibit the same signs of flow seen in ice glaciers and in other bodies of viscously flowing material: lobate structures and transverse and longitudinal ridges and furrows, such as easily seen in Figure 4.32. Variations in topography, supply of material to its upper reaches and perhaps other changes can cause a part or all of a rock glacier to

become inactive. Signs of that happening are the development of vegetation on the frontal ramp and substantial furrowing of the ramp by water erosion, as is evident on parts of the rock glaciers shown in Figures 4.32 and 4.33. Also, the surfaces of rock glaciers may show evidence of changing flow patterns that cause some parts of a rock glacier to override others that have slowed down or become inactive.

Rock glaciers are found in the near-glacial parts of all major mountain systems, from the Andes to the Alps (which alone contain more than 900) and from the Antarctic to the Arctic. Two hundred have been identified in relatively small parts of the Alaska Range.[62] Although rock glaciers do not transport material very far nor very fast, they are an important means of moving rock downslope, accounting for 15 to 20% of the periglacial transport in the Swiss Alps.[63]

Rubble sheets (block fields and block slopes) and rubble streams (block streams)

In situations where frost wedging of massively jointed bedrock produces blocky angular rocks, these may stand up out of an array of finer material that undergoes solifluction and transport by water or wind erosion.[64] Geocryologists generally give the name ***block field*** to ***rubble sheets*** on level or near-level ground, and ***block slope*** to those on slopes of 10° or more. They apply the terms ***rubble stream*** and ***block stream*** to linear arrays moving down the steepest slopes available or confined to narrow valleys. To qualify as a rubble sheet or stream, the deposit must have more than half of its surface (typically one to three meters in thickness) composed of blocky material ranging in size upward from 10 cm.[65]

Rubble sheets and streams differ from talus slopes in usually not having a cliff or steep angled source of rock at their heads. Instead, they derive their rubble through the wedging of blocks from bedrock by frost action, or in some instances they may lie downslope from till bodies that supply their blocks. The developmental history of many rubble deposits begins with cryogenic weathering and sorting of bedrock by frost action followed by solifluction flow downslope and removal of the finer-grained material

62. Wahrhaftig and Cox (1959).
63. Barsh (1988) p 85.
64. Most cryologists consider solifluction to be the primary transport mechanism but studies by Thorn (1988) indicate that erosion performed by flowing of snow meltwater can be appreciable.
65. Washburn (1980) p 219; Péwé and Reger (1983) p 125.

largely by water and wind erosion. On shallow slopes gelifluction and frost creep appear to be the primary transport processes, and on steeper slopes water runoff and rapid mass wasting (mudflows) become more important.

Some rubble sheets may be of fairly recent origin—one in Finland appears to be less than 6000 years old[66]—but ones in the Alaska Range are much older, forming during colder parts of the Wisconsin (75,000 to 10,000 years ago). In fact, in one Alaska Range locality, Jumbo Dome, a sequence of five rubble sheets has formed, each sheet probably representing a separate glacial substage of the Wisconsin.[67]

Ploughing blocks and braking blocks

Seen on slopes undergoing solifluction, ***ploughing blocks*** are large rocks that move 2 to 10 times faster than the surrounding soil because of enhanced gelifluction beneath the blocks.[68] They tend to turn so their long axis is aligned along the slope. Helping to identify them is the furrow each leaves behind, and perhaps a slight mound in front. A bit harder to recognize are ***braking blocks***, large rocks that move slower than the surrounding solifluction, tending to impede the flow. Both ploughing blocks and braking blocks are widespread in alpine environments, more curiosities than anything else, but they do help mark slopes as undergoing or having undergone solifluction.

Cryoplanation surfaces

The shapes of eroded landforms seen in upland areas reflect the weathering and transport processes that created them: chemical weathering smoothes sharp edges and so tends to produce rounded hills; flowing water incises the hills to carve between them V-shaped valleys, and glaciers—like giant ice cream scoops—gouge out rounded cirques and U-shaped valleys. In cold rocky upland areas, the combination of cryogenic weathering and cryogenic transport can produce yet another characteristic shape, the gently inclined plane known as a ***cryoplanation surface***. Cryoplanation surfaces are of two main kinds that share in common the basic planar shape but differ enough in size, location, and origin to deserve separate names: ***cryoplanation terrace*** and ***cryopediment***. **Table 4.1** summarizes the main characteristics of these two erosion features.

66. Washburn (1980) p 222.
67. Wahrhaftig (1949); Péwé and Reger (1983) p 60, pp 125–27.
68. Washburn (1980) pp 223–24.

Table 4.1 Characteristics of cryoplanation surfaces, a slightly simplified version of a table given by Priesnitz (1988) and incorporating some results of Reger and Péwé (1976)

Attribute	Cryoplanation Terrace			Cryopediment		
Location and relation to other topography	On hilltops or interrupting upper or middle slopes at several levels			At foot of mountain or valley slope, usually at one level only		
Morphology:	low	common	high	low	common	high
downslope width	5 m	100 m	>1 km	100 m	1 km	>10 km
alongslope length	30 m	400 m	> 10 km	1 km	10 km	>100 km
tread gradient	1°	6°	14°	1°	3°	12°
riser gradient	9°	30°	90°	7°	25°	35°
riser height	1 m	6 m	50 m	10 m	100 m	>300m
Original slope	25° or less			No restriction		
Original slope lithology	Generally in hard rocks producing coarse debris			Hard and soft mainly sedimentary rocks		
Tread material	Bedrock surfaces mantled by <1–3 m solifluction and outwash debris			Bedrock surfaces mantled by <1–3 m solifluction and outwash debris, fluvial gravel		
Riser material	Frost-shattered cliff, blocks and bedrock			Frost-shattered slope, talus mantle rock		
Structural control	Apparent in many cases			None, cuts across original structure		
Observed processes in upper part of tread	Frost wedging and shattering, solifluction, meltwater washing, piping			Frost wedging, sheetwash, solifluction, piping		
Observed processes in lower part of tread				Sheetwash, stream transport, cryoturbation, frost sorting		
Observed processes in the riser	Transverse wearing by nivation enhanced frost wedging and shattering, solifluction, meltwater washing, piping			Frost weathering, gravitational transport, rillwash. Mainly transverse wearing but also down wearing in soft rocks		
Origin of water at upper end of tread	Snowbank melting, seepage water			Runoff from upper slope, meltwater, seepage water		
Permafrost dependence	Yes (but controversial)			Yes		
Estimated formation time	10,000 years			100,000 years		

Except for some cryoplanation terraces that sit atop hills, the planar portions (treads) of cryoplanation terraces and cryopediments abut steeper slopes (risers) at their upper ends. These abrupt junctures are a distinguishing characteristic of all but the hilltop cryoplanation terraces. (They too had them once, but now the risers are cut away.) Structural irregularities in the parent slopes probably initiate cryoplanation terraces. Like a pothole in a road, an irregularity in a cold upland slope tends to grow, and the physical processes involved—frost action, solifluction, piping, and wind deflation, especially in a permafrost setting—cause the growth to be primarily transverse, that is, essentially horizontally into the slope. The growing notch makes a fine setting for catching windblown snow, and when the snow melts it provides a plentiful and continuing supply of water to augment the erosion and transport processes. ***Nivation*** is the name applied to relatively rapid erosion taking place at the edges and underneath a lingering snow bank, and the cavity it cuts is sometimes referred to as a ***nivation hollow***. Thus, a nivation hollow can be thought of as the cutting edge of a cryoplanation terrace. The supply of moisture is critical to both the effectiveness of frost wedging and solifluction, and both surface and subsurface runoff help transport debris across the tread of the terrace. Because it forms a floor for the erosion and transport processes, permafrost is crucial to the growth of both cryoplanation terraces and cryopediments.[69]

Whereas cryoplanation terraces sit on hilltops or in bench-like arrays on the upper and middle portions of slopes, the much larger cryopediments lie in the bottoms of valleys or at the feet of mountain slopes. The supply of water crucial to continued widening of a cryopediment comes more from seepage and runoff from the upper slope of the riser than from the melting snowbanks that feed terrace erosion. Cryopediments tend to have slightly less gradient than cryoplanation terraces, and since they are observed to cut across topographic features their location depends little on structural control. Their risers are high, they undergo cryogenic weathering, and they readily shed the weathering debris downslope to the cryopediment where solifluction and water transport carry it large distances across the tread. The upper parts of the cryopediment treads look like treads of cryoplanation terraces, but the lower portions generally show more evidence of water transport across the surface, repeating ground patterns and more vegetation cover.

69. Reger and Péwé (1976); Péwé and Reger (1983) p 125.

The observed angularity of cryoplanation surface junctures with their risers testifies to high effectiveness of cryoplanation erosion processes relative to those (chemical and fluvial) that tend to round and incise topographic features. A cold, dry climate and a shallow permafrost table favor cryoplanation, whereas climate amelioration favors the rounding and incising processes. It follows that cryoplanation has been more active in the past, and in fact many if not most cryoplanation surfaces are now inactive.

Cryoplanation is a slow process, so most cryoplanation surfaces seen now (**Figures 4.34** and **4.35**) are the product of cryogenic erosion active for millennia, near 10,000 years for terraces and 100,000 years for cryopediments. By relating cryoplanation surfaces to sediments and river terraces of known age, or to known glaciations, it is possible to determine when the surfaces were formed and active. Some cryoplanation terraces studied in the Alaska Range are known to be less than 75,000 years of age,[70] and in the Richardson Mountains of Yukon Territory dating of moss on terrace treads indicates that active cryoplanation probably continued up to a few hundred years ago.[71]

Tors

As they near the end of their work, the processes that create cryoplanation surfaces sometimes leave monuments of their achievements in the form of ***tors***, spires standing up on all sides above the surrounding slopes. Tors are the products of differential weathering, and they owe their existence mainly to differences in bedrock joint spacing. The weathering and debris removal processes are not necessarily cryogenic, and although tors are more common in polar and subpolar climates, they also are found in warm moist and tropical climates where deep chemical weathering and fluvial transport of debris are the key processes. However, frost wedging and cryogenic mass transport probably dominate over other erosion processes in producing the cold-climate tors. Shown in **Figure 4.36** is a group of tors accessible to hikers in the Fairbanks area of Alaska. These stand starkly above sloping terrain that probably is not a true cryoplanation terrace.[72]

70. Péwé and Reger (1983) p 126.
71. Priesnitz (1988).
72. Richard D. Reger, personal communication, January 1998.

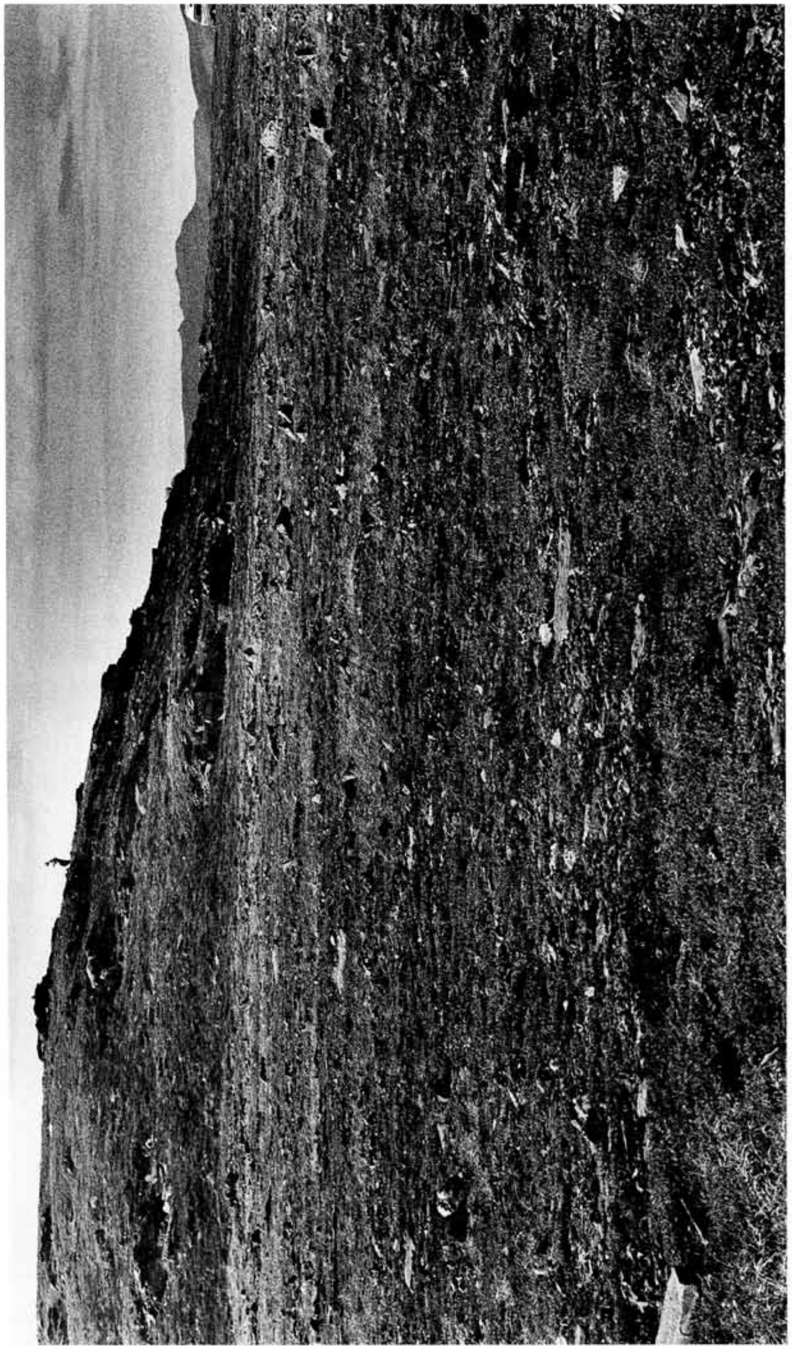


Figure 4.34 A cryoplanation terrace on the north side of the top of Eagle Summit, Alaska. Notice the angular uplifted rocks on the terrace and the sharp intersection with the steeper slope above.

Figure 4.35 A cryopediment about 4 km wide and with inclination 2° to 4° in the Little Keel River Valley in northern Canada's Mackenzie Mountains. Notice the sharp juncture with the mountain slopes. Reproduced from Figure 3.3 of Priesnitz (1988).

Figure 4.36 Granite tors standing above a gentle slope in the foreground that shows evidence of sorted polygons. Photographed northeast of Fairbanks, Alaska, by A. F. Weber.

Patterned Ground

Among the interesting things to look for and ponder over when traveling in any area are striking landforms and repeating patterns that reflect ongoing or past physical processes. A person cannot help but marvel over the power of the forces that have acted to create the repetitively folded rock strata seen on a rugged mountain slope nor, when viewing multiple, regularly spaced beds of coal sandwiched in between thick layers of sandstone, avoid asking just what curious set of circumstances could have caused this succession.

The contorted rock strata and the alternating coal and sandstone beds are the products of large-scale geologic processes initiated millions of years ago and which may still be acting. Also producing repeating patterns in the landscape are cryogenic processes—those involved in freezing and thawing—and they too may have operated only in the past or perhaps be still ongoing. However, the time scale is shorter—days to hundreds of thousands of years instead of millions of years—and the spatial scale is also much less, ranging from a few centimeters to upwards of a few meters.

The term patterned ground generally refers to a land surface that exhibits repeating geometric shapes generated by processes acting within a few meters of the surface. In the context here, "patterned ground" refers to a land surface with patterns created by or at least influenced by cryogenic processes. Some of these patterns may be identical to or similar to others observed in warm climates but which are not cryogenically caused.

Observed patterns on the ground surface are there either because they show up as topographic features or as spatial differences in composition of the ground surface, and perhaps in vegetation cover. Thus the patterns either are the products of processes that move soil in nonuniform ways or sort it according to size and thereby juxtapose small- and large-size particles in certain geometric arrays. In general, closed patterns—circular or polygonal shapes—develop on level ground, whereas open patterns—parallel or quasi-parallel banding or topographic irregularities—develop on slopes. Some of the closed and open patterns exhibit sorting, and some do not.

Examples of closed, nonsorted patterned ground created by cryogenic processes are the widespread arrays of high- and low-center polygons previously discussed and which are generated within perennially frozen ground. These polygonal forms are large, ten to several tens of meters across, and each has taken hundreds of years to develop. Many of the ice wedges forming the skeletons of these arrays are relics of past times when the climate was colder; many are no longer growing but remain perfectly

preserved within the permafrost, and yet others—those associated with high-center polygons—are now melting away because of lowering of the permafrost table for one reason or another.

Most other cryogenically generated ground patterns are due to processes within the active layer, but they may be influenced by what lies below. Patterned ground developed in a setting where the active layer is in contact with the permafrost table may differ much from that generated where no permafrost lies below, or where a layer of thawed soil (talik) separates the bottom of the active layer and the permafrost table. If in contact with the active layer, the permafrost table in cold areas such as northern Alaska and Canada can have a temperature well below 0°C during part of each summer. In this situation, upfreezing can proceed near the bottom of the active layer simultaneous with thawing of its upper part, and in fine-grained soils the associated suction can draw water down from above and generate frost heaving near the base of the active layer.[73] During the upfreezing, any horizontal irregularities that affect thermal conductivity or water flow are likely to produce differential heaving and discontinuous deposits of segregation ice deep within the active layer, in the same fashion as downfreezing produces them in the upper part of the active layer. Owing to its relative impermeability, the permafrost table also acts as barrier to downward flow of water, and it, compared to a wet talik layer, is a poor source of moisture which downward freezing might try to draw up into the active layer.

Local climate also is an important determinant of patterned ground. A temperate climate that allows frequent cycling of temperature through the freezing point fosters near-surface cryogenic processes such as pipkrake growth, a process believed important to the generation of some of the open patterns that develop on slopes. In a colder climate the more extreme annual temperature variation fosters deeper cryogenic processes such as frost heaving, ground cracking, frost wedging, and thaw consolidation, all of which can influence ground patterns. Vegetation plays a role as well by stabilizing soils on slopes, altering the thermal conductivity of the top layer, affecting the supply of water at the surface, and interacting with surface irregularities in ways that affect both the plant distributions and the irregularities. Thus the distribution of related plants can become an important part of whatever ground pattern develops, perhaps even its most visible component.

73. Mackay (1980).

Insight into the processes creating patterned ground comes largely from examination of the patterns in the field, field experiments, and laboratory experiments. It is a complex matter, so interpretations differ and in some cases the conclusions are more aptly described as conjectures. One widely accepted idea is that thermal or desiccation cracking initiates some kinds of patterned ground, and determines the spacings and mesh sizes of the elements in a soil pattern. Thermal contraction cracking is the accepted explanation for the origination and configuration of ice wedge polygon arrays. More widespread, especially in fine-grained soils, desiccation contraction cracking occurs when water leaves a soil through evaporation, gravity drainage or the cryogenic suction that develops during freezing. Both the thermal environment and the strength of soil involved are likely to be important in determining the space and depth of contraction cracking, regardless of cause. The cracks then constitute structural and thermal irregularities in the soil structure that affect other processes involved in creating patterned ground. Apparently playing a major role in the generation of patterned ground is differential frost heave, the uneven displacements of frozen ground in consequence of differing grain size, temperature distribution and moisture content. Differential frost heave appears to be the main cause of cryoturbation (see earlier discussion), and it can separate out soils of differing heaving abilities horizontally as well as vertically, thereby causing them to lie side by side.[74] Contributing also to small-scale sorting and circulatory motions may be cryostatic pressure created within the thawed parts of the active layer sandwiched in between the frozen parts above and below. Thaw consolidation due to loss of water drawn away by the suction accompanying freezing of adjacent soil layers also can contribute to the uneven motions that develop patterned ground.

Nonsorted circles (also called mud circles, mudboils, earth circles, medallions)

Nonsorted circles are bare soil patches 0.5 to 3 m across that contain mainly silt and clay (see **Figure 4.37**). They are widespread in alpine, subpolar, and polar environments, in both permafrost and nonpermafrost settings.[75] The surface of a nonsorted circle is either flat or slightly domed, often dry and surrounded by lichens, but the fine-grained material at depth may contain enough water to be nearly at the ***liquid limit***, the point

74. Williams and Smith (1989) p 162.
75. Williams and Smith (1989) p 163.

Figure 4.37 Nonsorted circles (mud circles) near the Denali Highway near Mile 40 (top), and near Mile 11 (bottom). Photographed 1996.

at which the soil contains so much water it begins to behave as a liquid. In late summer rainwater or water released from melting in the active layer may increase internal pore pressures enough to cause liquefaction and a boiling up of the fines through the surface simply because of the stress from weight of overlying material. The names ***mud circle*** or ***mud boil*** then become quite properly descriptive. During spring breakup, vehicles rolling along roadbeds containing silts and clays similarly will cause mud to boil up through breaks in the road surface.

At depth, the fine-grained material forming the body of the material in a nonsorted circle may extend beyond the area of the circle itself, and excavations have in at least one instance shown interconnections with other nearby circles. In this case gravelly sand surrounded the silty clay body below the circles,[76] so here there seems to be evidence of horizontal sorting by differential frost heave and related processes.

Examples of a somewhat different pattern lacking sorting, the ***non-sorted polygon*** appear in **Figure 4.38**. This pattern, currently developing in a water-saturated, uniformly fine-grained river delta deposit, illustrates the major role that thermal or desiccation cracking can play in the development of patterned ground, and perhaps in the formation of hummocks as well, since these are forming in the driest parts of this deposit; see Figure 4.38E.

Sorted (stone) circles, sorted (stone) polygons, debris islands, and stripes

Cryogenic sorting of soils creates ***sorted circles*** and ***sorted polygons*** consisting of a central area of fines grading out to coarser rocky material; these are characteristic of level ground in permafrost areas. They are also present in subpolar highlands with a thick active layer. They range in size from as little as 10 cm up to about 5 m, the larger circles and polygons tending toward larger stones contained in their outer parts. If tabular, those stones tend to sit on edge and be aligned with their long axis parallel to the boundary of the circle or polygon.

The sorted arrays shown in **Figures 4.39** and **4.40** contain examples of both sorted circles and sorted polygons juxtaposed in such a way that it is fairly obvious that the arrays began as polygons, and then as their development ensued the trend is toward becoming more circular. Thus age

76. Washburn (1973) pp 103–06.

Figure 4.38 Thermal and desiccation cracking creating polygonal patterns in saturated, fine-grained soil deposited by Slims River where it empties into Kluane Lake at Mile 1028 on the Alaska Highway. Parts A and B show large parallel cracks spaced approximately 2 m apart with an inner array of polygonal cracks of spacing approximately 0.7 m, as shown in Parts C and D. The photo in Part E shows what appears to be a group of earth hummocks beginning to form. These are approximately 20 cm in height. Photographs taken August 1996.

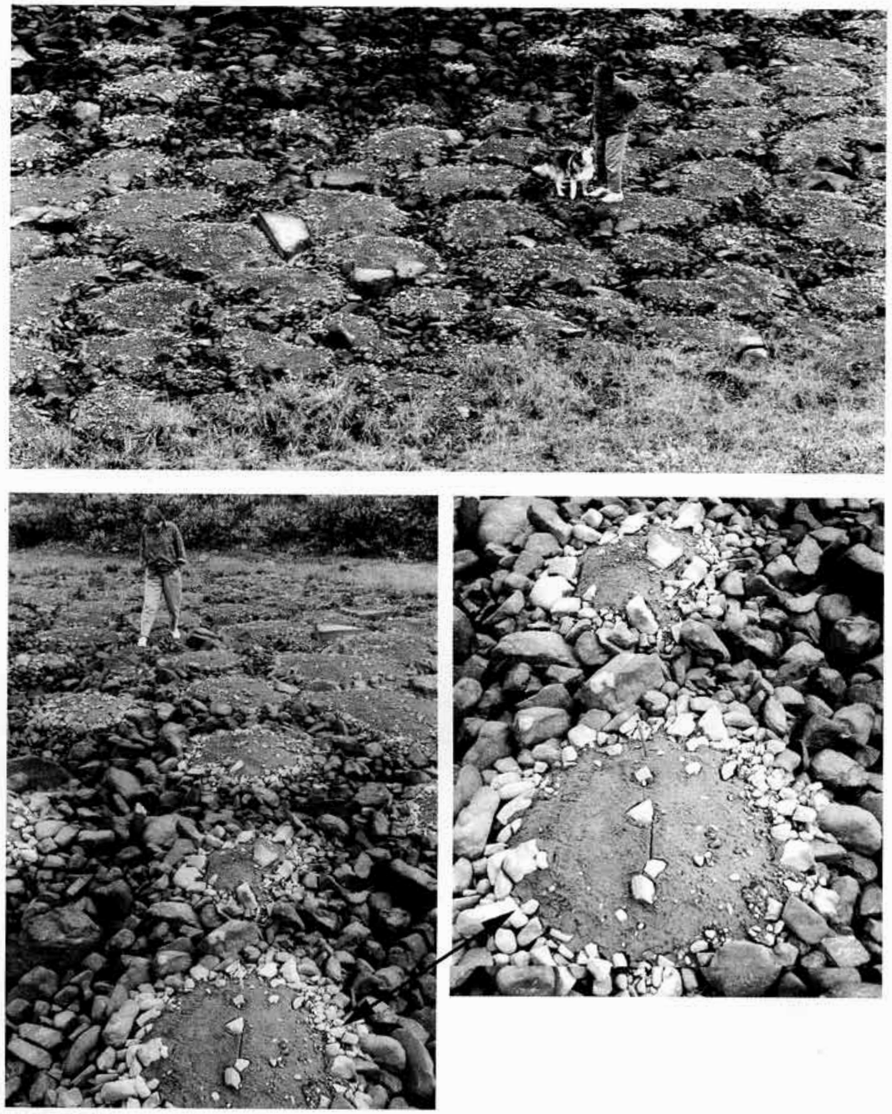


Figure 4.39 Sorted polygons at Mile 31.8 on the Denali Highway, Alaska. Top: Lightly vegetated soil showing thermal or desiccation cracks at lower-right corner grades into the sorted polygons at center, and these grade into the rock pavement beyond, the sequence illustrating the transition with time. The close-up views at bottom show newly exposed white rocks in the central part of polygons. (The two shown in the right-hand picture are the two nearest the camera in the left-hand picture.) Notice that the rocks grow darker the longer they are exposed, and that the boundaries between the inner fines and the outer rocks are trending toward circular. Photographed August 1996. See also Plate 15.

Figure 4.40 Sorted polygons at Mile 37 on the Denali Highway. This array appears in the foreground of Figure 4.21 Here the individual polygons are up to 5 m in diameter. Photographed in August 1996.

more than mechanism would appear to determine if a sorted array is polygonal or circular.

Excavations into sorted polygons and sorted circles indicate that the size of the stones in the outermost parts often but not always decreases downward.[77] Sorted circles and sorted polygons develop on slopes up to 30° where they tend to be more irregular and hence have received the name ***debris islands***.[78] **Figure 4.41** shows a spectacular array of sorted circles, and it is obvious that these are quite different from the sorted polygons depicted in the previous two figures, and perhaps the mechanisms involved differ.

77. Washburn (1973) p 123.
78. Washburn (1980) pp 129–30.

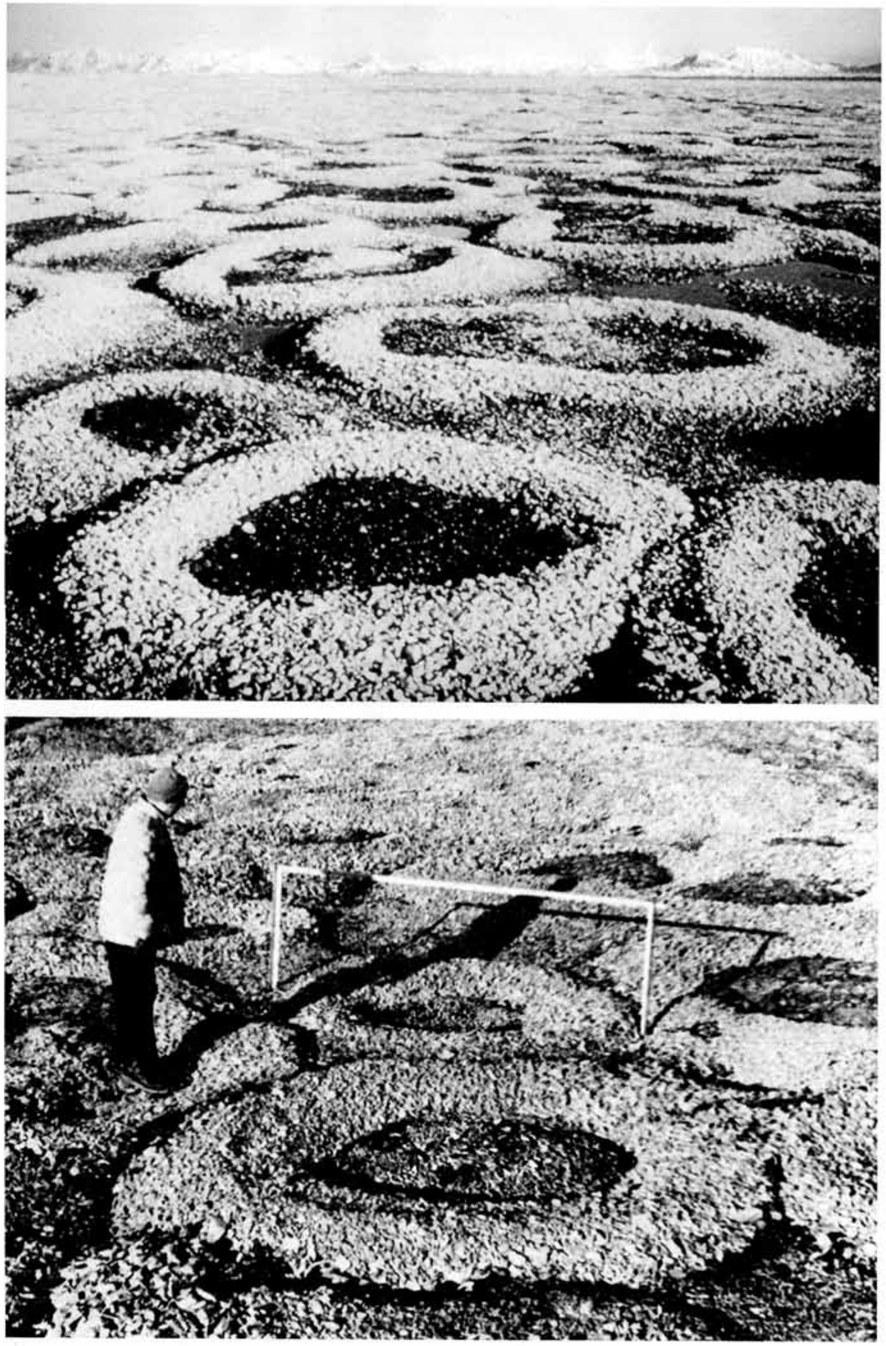


Figure 4.41 Dramatic examples of sorted stone circles photographed in Spitzbergen by Bernard Hallet (upper photo) and Alfred Jahn (lower photo).

Observations of sorted circles and sorted polygons formed in glaciated areas and exposed in recent decades or centuries coupled with results of experiments involving removal of surface vegetation indicate that sorting by differential frost heave plays the major role in forming these geometric patterns, and that desiccation and thermal cracking contribute significantly.[79] Observations made for several years after intentional stripping of vegetation from the surface of an unsorted soil, show that the larger rocks move rapidly toward the surface.[80] If any desiccation or thermally induced cracks appear at the ground surface, they create additional transverse temperature gradients that cause rocks to migrate toward them. The frost heaving also orients the rocks as they move outward, leaving the smaller particles near the center. In addition to thermal or desiccation cracking, processes triggering the sequence ultimately leading to a sorted polygon and then later a sorted circle might be initiated by any irregularity in the ground surface that affects the supply of water or fosters creation of horizontal temperature gradients. The falling over of frost-wedged stones, alteration of vegetation by browsing caribou and small rodents or erosion by water or wind are among the possibilities that may augment desiccation or thermally induced cracking. Once the sorted polygon-building sequence starts, it seems to perpetuate itself as long as conditions are favorable or until the growth itself modifies the situation enough to terminate further growth. One geocryologist has suggested that only those regions with mean annual air temperatures less than –4°C and having ice-rich soils produce well-developed sorted circles and sorted polygons of size greater than 2 m.[81]

Circular or polygonal patterns obviously resulting from cryogenic processes include small (decimeter-scale) configurations involving arrays of small stones surrounded by fines—just the opposite of stone circles—and networks of small arrays within larger ones. Considering the variability in soils and climatic conditions, it is not surprising that the observed variety in cryogenically caused microrelief seems endless.

79. Desiccation or thermal cracking obviously is the origination of the stone polygon nets shown in Figures 4.38 and 4.39 since it is easy to see the progression from the beginnings of thermal or desiccation cracking on one boundary of each array to the final product on the other, a block pavement containing no fines at all. These net arrays formed in a small drying lake bed in a glacial moraine. Observations of them and other net arrays in September 1996 and August 1997 showed much difference in water levels: some were completely exposed in 1996 but under several centimeters of water in 1997. In nearby shallow lakes some nets could be seen a meter or more below the water surface.
80. Pissart (1974) cited by Williams and Smith (1989) p 167.
81. Goldthwait (1976); Washburn (1980) p 145.

Closed sorted-microrelief patterns are restricted to level or near-level ground. On even rather slight slopes, those of only 3° or 4°, the closed patterns may become elongated parallel to the slope and develop into ***sorted stripes*** ranging in width from as little as 10 cm to more than 1 m. Sorted stripes consisting of alternating bands of fines and coarse materials propagate themselves downslope at least in part through differing rates of movement dependent on the size of the particles involved. Observations indicate slow movements ranging from a fraction of a cm/yr to more than 10 cm/yr; sometimes the coarse bands move faster than the fines, but usually the bands containing the fines move the fastest.[82] The long axis of stones in the sorted strips tends to be in the vertical plane and oriented parallel to the slope, and the size of stones usually decreases rapidly with depth. The faster transport of fines by water in summer may be part of the cause of differential speed, the tendency of larger stones to inhibit solifluction another, and the ratcheting by pipkrakes (needle ice) of the top layer above buried stones yet another part of the cause. The tendency for pipkrakes to occur in soil already loosened by former pipkrakes and to draw water and perhaps fines horizontally as the ice needles form may also contribute to the sorting that originates the stripes.

Nonsorted stripes also exist, consisting of alternating vegetated and nonvegetated bands or merely alternating bands of contrasting-colored exposed surface material. The stripes shown in **Figure 4.42**. appear to be of this type. Again, differences in rates of downslope movement caused by density differences, water retention, and vegetative binding of soil probably perpetuate these stripes as well.

Cryoturbation steps (terracettes) and sorted steps (stone garlands)

Cryoturbation steps, also called terracettes, are remarkably regular arrays of small benches 30 to 80 cm wide with risers between them of approximately the same size. **Figures 4.43A-E** show examples; see also Figures 3.3A and B. They can be seen on steep, lightly vegetated slopes in many parts of the northern half of the United States and in Canada. The steps are poorly sorted or nonsorted features that develop only on lightly vegetated hillsides with slopes in the range of 20° to 38°, the risers tending to be vegetated and the treads bare. Pipkrake formation is thought to play the primary role in generating the cryoturbation steps by lifting the smaller soil material up away from buried pebbles or rocks, or by lifting fully exposed rocks and shunting them

82. Washburn (1980) pp 151–54.

Figure 4.42 Stripes on hills composed of glacial till near Mile 40 of the Denali Highway. Brushy vegetation anchors the soil between the lighter colored strips. Photographed August 1996.

downhill, thereby creating some sorting.[83] The snow lying on the treads of the steps shown in Figure 4.43D suggests also that nivation (enhanced erosion at the edge of a snow deposit) on a microscale might play a part in enlarging the steps, and perhaps even provide an explanation of why the

83. Tricart (1970) pp 94–95; Washburn (1980) pp 147–51.

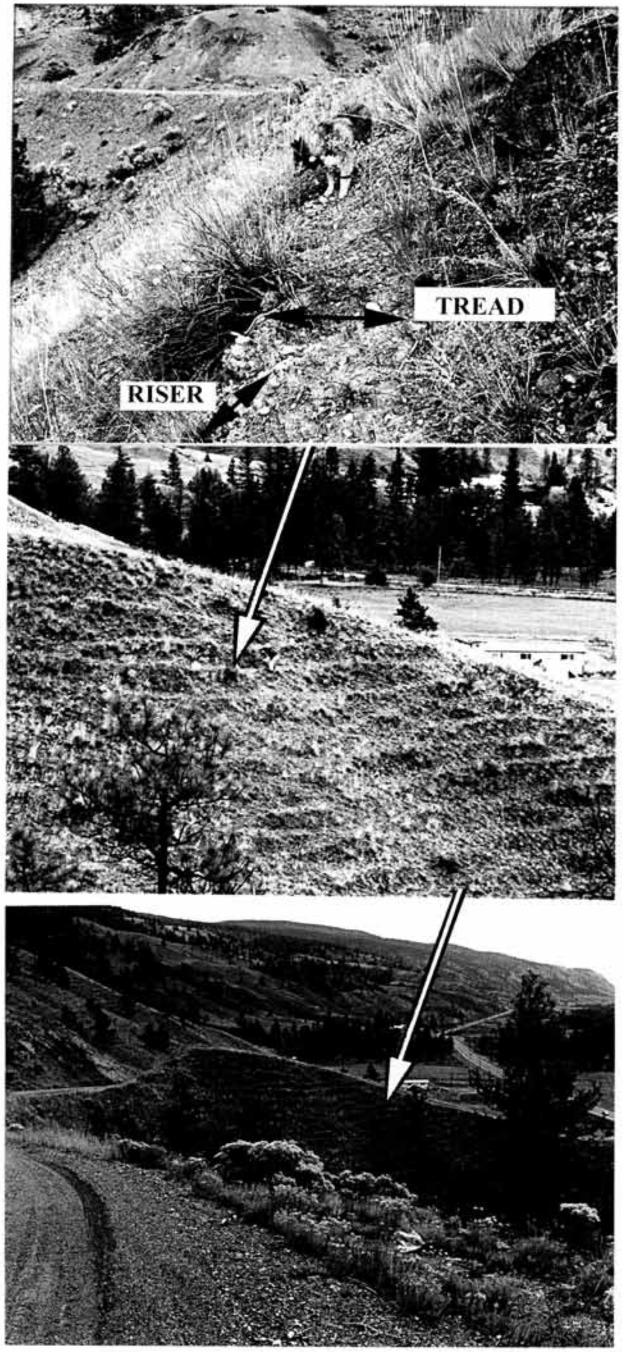


Figure 4.43A Cryoturbation steps approximately 10 km north of Cache Creek, B.C., on Highway 97. Top: view along the cryoturbation step identified by the arrow in the middle photograph (taken simultaneously by Rosemarie Davis), and at bottom, a more distant view of the array, looking south. Photographed in 1996. See also Plate 16.

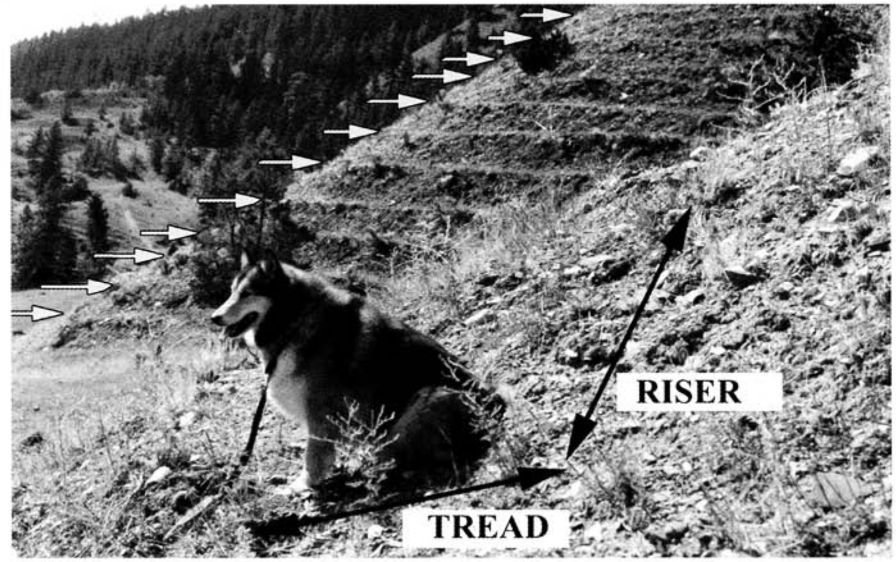


Figure 4.43B Large cryoturbation steps approximately 1 m wide on south-facing hillsides 13.6 km north of Cache Creek, B.C., on Highway 97. Photographed in 1998.

steps typically are horizontal or nearly so: once nivation starts in a snow-filled depression, it could enlarge the depression horizontally along the hillside as well as into the slope. Also, in a wind-blown area the steps would tend to catch snow, and the melting of the snow should add water to the soil on the step treads, perhaps fostering the growth of pipkrake ice during periods of freezing. Wind may have a role here too, helping to remove fines brought to the surfaces of step treads by pipkrake action. All this is conjectural, and it does not seem to give a reasonable explanation for the sizes of the steps and why they are so regular. Seemingly possible causes of the spacing between steps are local depth of freezing, soil depth, and layering within the soil or other characteristics that might affect how far cryosuction on the treads can move water horizontally from beneath the risers. Steps occur only on generally north-facing slopes in the more southerly areas where they appear, evidence that microclimate surely enters much into it too. Like the ripples on sand dunes, cryoturbation steps seem to be another example of self-organizing forms that start out as small bumps or hollows and evolve into larger forms having regular patterns as they migrate downslope.[84]

84. Werner (1999).

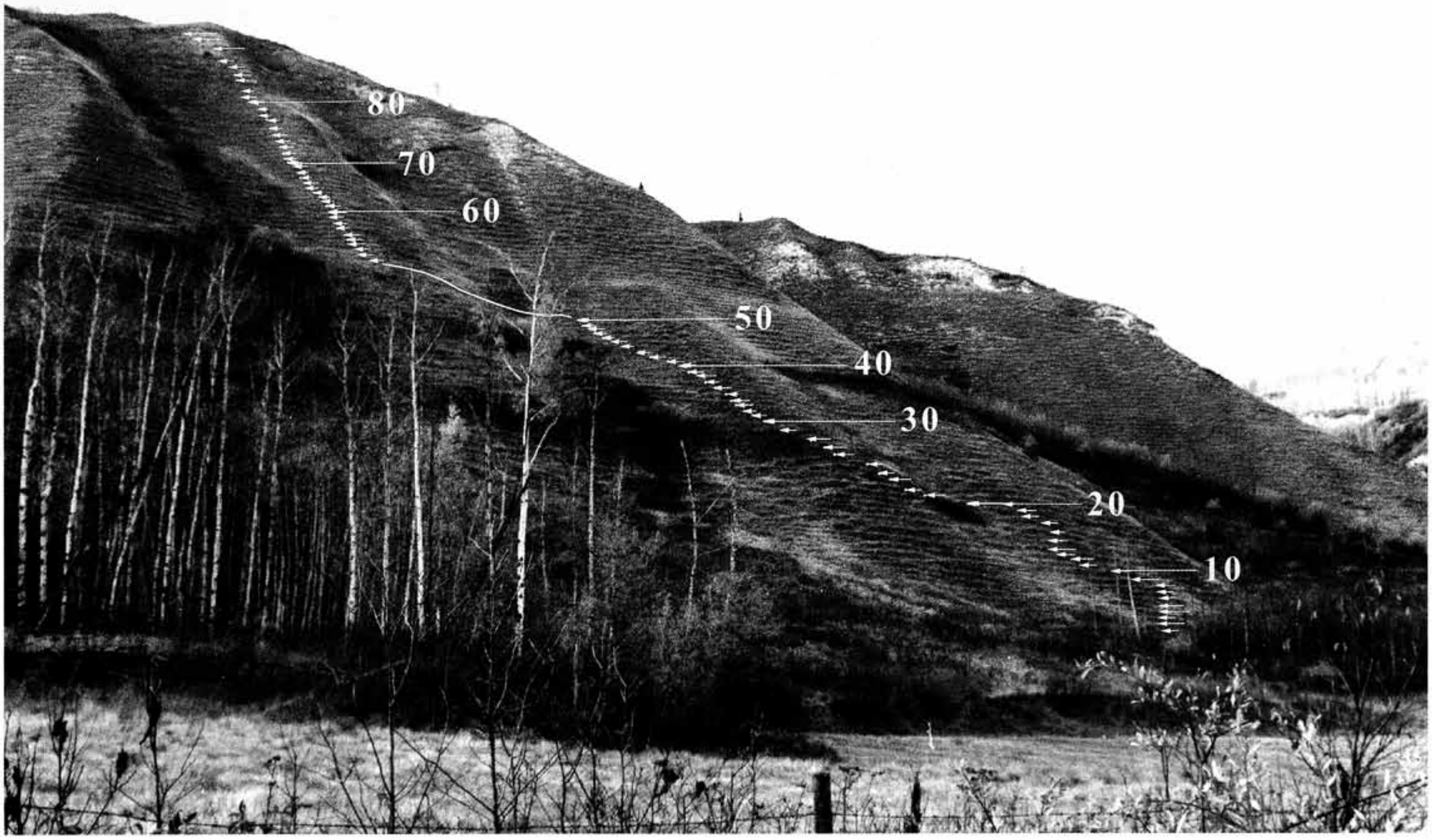


Figure 4.43C Approximately 90 cryoturbation steps on an east-facing hillside approximately 10 km north of Hudson Hope, B.C., on Highway 29. Photographed in 1998.

Figure 4.43D Horizontal cryoturbation steps photographed in March 1999 when snow was melting, with an off-road vehicle track cutting across them from center toward upper left. These steps are located 2 km east of those shown in Figure 3.3A. The approximately 100 in the array extend from the base to the top of the north-facing hillside.

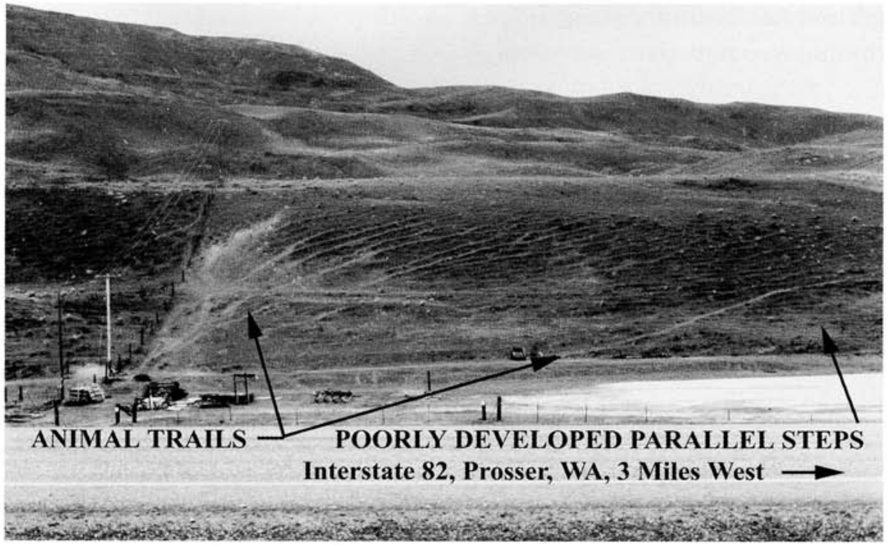


Figure 4.43E Animal trails radiate from a watering tank up across an array of weakly developed cryoturbation steps that are more fully developed on the hillside to the right of the photograph taken looking south in March 1999.

At first glance a person might attribute the cryoturbation steps to the action of grazing animals, but that is not a viable explanation. It is true that once the cryoturbation steps have formed, grazing animals sometimes do tend to follow along them, so the animals may contribute secondarily to the growth of certain of the steps. That is most noticeable near fences where the frequent passage of cattle or other animals along the steps tends to widen the treads and leave enough fertilizer to create lush vegetation on the risers, making those selected steps stand out from others nearby. Animal trails sometimes cut across the steps, as shown in Figure 4.43E. This photograph helps show the distinction between cryoturbation steps and animal trails: the trails tend to diverge irregularly from a feed lot or watering place, whereas the steps parallel one another in very regular fashion.

Another step-like configuration, ***sorted steps*** (also called stone garlands), appears only on shallower slopes (5° to 15°) and has fines in the tread areas and stones on the risers. Sorted steps typically look less regular than cryoturbation steps and may be elongated downhill with steps wider than risers. They may be intermediate forms between closed patterned

ground configurations and stripes, and thus be more related to solifluction than to pipkrake formation.

Thermokarst Landforms

The term thermokarst refers to topographic depressions created by thawing of ground ice. Climatic warming is one reason thermokarst topography develops, and another is localized disturbance to the ground's thermal regime that promotes thawing of permafrost. Forest fires, shifting stream channels, and the activities of man are primary causes of rapidly developing thermokarst topography. Then too, as part of their normal life cycle some cryogenic landforms—such as palsas and pingos—develop thermokarst collapse features. High-center polygon arrays constitute another form of thermokarst topography, be they the result of climatic warming or localized disturbance such as occurs from the clearing of ground cover for construction and agricultural purposes.

Thermokarst lakes and beaded streams

Lakes and streams are always in transition. Streams continuously erode some parts of their beds and deposit material in other parts, and most lakes, especially those in formerly glaciated areas, grow smaller as they fill with sediments and encroaching vegetation. Exceptions to that general trend are ***thermokarst lakes*** (also called thaw lakes) which grow because of ice melting beneath and around them. That melting occurs because some change has taken place to alter a preexisting situation wherein permafrost was on the increase or stable. At nearby locations similar changes might or might not have occurred. Examples of changes likely to cause highly localized thawing of ice-rich permafrost are the normally continuous shifting of meandering streams in their beds, increasing inflows of water to lakes because of changes in streams that feed them, and slumping or settling caused by earthquakes or slower tectonic changes. In areas where permafrost thawing is widespread, the most likely change is a warming in regional or global climate.

One characteristic indicator of change in areas containing polygonal arrays of ice wedges is the development of ***beaded stream*** patterns consisting of sharply defined pools of water interconnected with short drainage channels that usually are straight or composed of straight segments connected by sharp angles. Several examples appear in **Figure 4.44**. The pools, typically 1 to 3 m deep and up to 30 m across, form mainly at the intersections of melting ice wedges, and the connecting channels tend to follow ice wedges. Beaded streams are distributed over widespread parts of northern Alaska, and are often found in conjunction with pingos and thaw lakes.

Steep collapsing banks creating treacherous shores and, in forested areas, inward-leaning trees signal thermokarst lakes. They are so common in the discontinuous permafrost zone of Alaska and Canada that most ponds and small waterbodies there are likely to show these thermokarst lake features. Examples appear in Figures 1.4 and **4.45**.

Oriented lakes

On Alaska's arctic coastal plain, near Point Barrow, groups of oriented thermokarst lakes create a spectacular scene when viewed from the air. Other groups of oriented lakes—those that tend to be elliptical or subrectangular and having parallel alignments—occur elsewhere, to the east of the Mackenzie Delta, on the Old Crow plain of northern Yukon Territory, and on Baffin Island, but the Point Barrow group is the most striking.

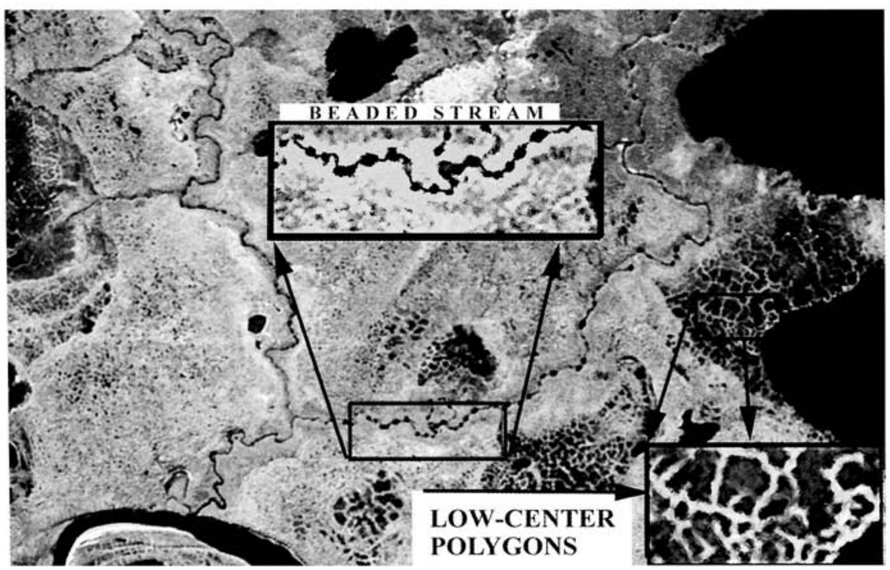


Figure 4.44 Beaded stream drainage and low-center polygons in a high-altitude infrared photograph of Alaska's North Slope. See also Plate 17.

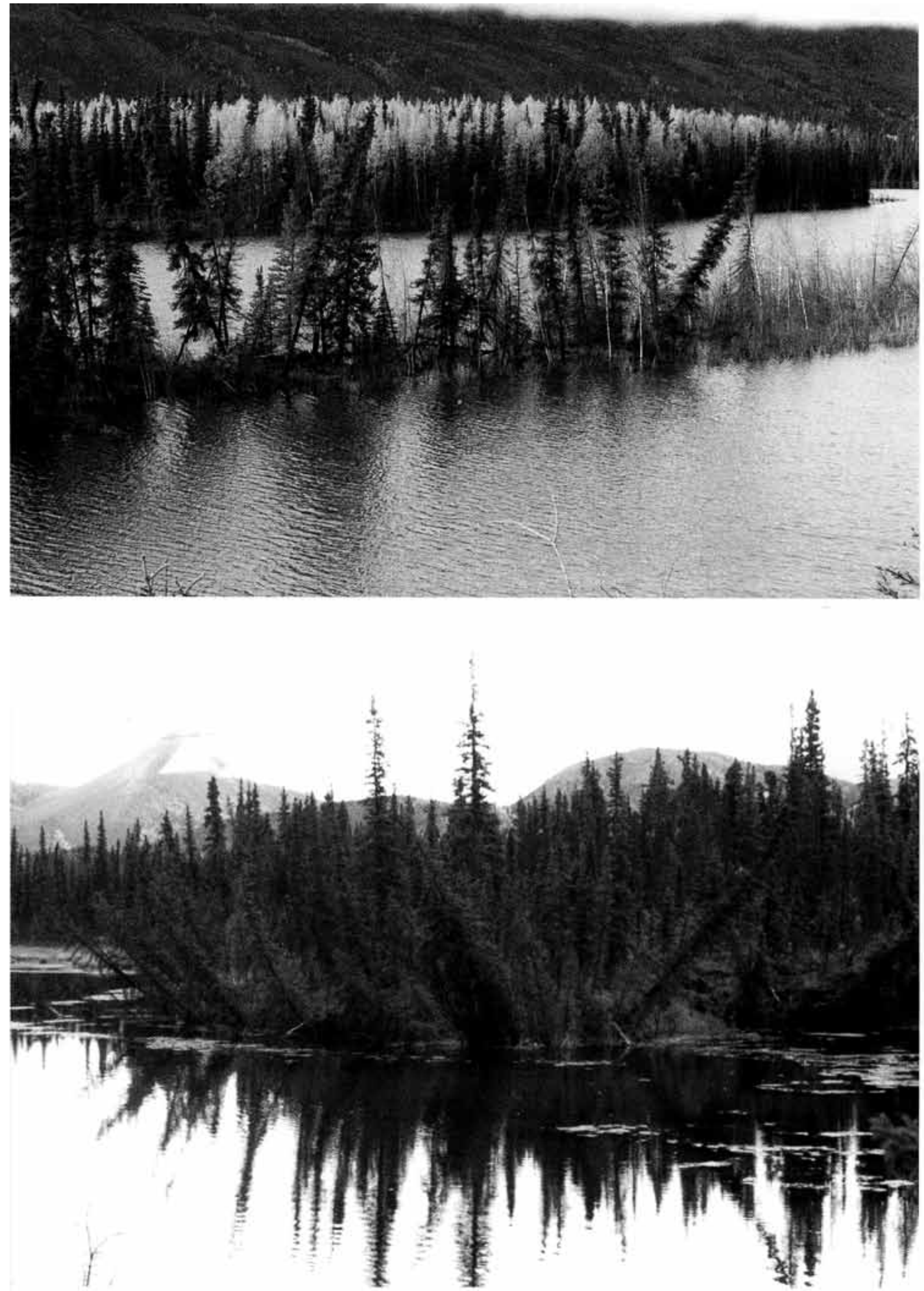


Figure 4.45 Two views of thaw lakes bordered by tilting and submerging trees, signaling that the lakes are undergoing rapid enlargement. The upper photograph was taken in September 1996 at Mile 1125.5 on the Alaska Highway and the lower along the highway some miles to the north, also in September 1996. See also Plate 18.

The oriented lakes near Point Barrow are elongated in the direction 10°–15° west of true north, essentially at right angles to the prevailing wind. Intuitively, a person would expect that if the wind had anything to do with the elongation and orientation of the lakes, that elongation would be parallel to the wind. Thus the first speculations on the cause of the oriented lakes were either that the wind was not the cause or that the prevailing winds must have shifted by 90° some time ago. Careful investigations carried out on the Point Barrow oriented lakes seem to have dispelled these earlier thoughts and also counter more recent suggestions that the orientation might be determined by geologic structures rather than wind-related processes.[85]

The oriented lakes are shallow, never exceeding 3 m. Those less than 2 m deep freeze to the bottom each year, but deeper ones do not, and those modify the depth to the top of the permafrost layer below. Beneath one lake 3 m deep, the depth of the permafrost table was found to be 60 m, whereas elsewhere in the area it is 0.3 to 0.6 m (the bottom of the permafrost in this area is at depth approximately 400 m).[86] Since many oriented thermokarst (thaw) lakes occur in association with polygonal ground patterns, they are thought likely to originate much like beaded drainage ponds, but in locations without comparable drainage. Many of the oriented lakes lie partly or wholly within the confines of former lakes reclaimed by sediments and vegetation.

Once initiated, the lakes grow preferentially at right angles to the wind because wind-driven wave and current patterns cause the fastest thawing and mechanical erosion at the cross-wind ends of the lakes. In the Point Barrow area the prevailing summer wind is from the east-northeast; at other times a second lesser prevalence is from the opposite direction, south-southwest. In the early stage of a lake's development, the wind-driven wave action tears sunken mossy vegetation from the lake floor and carries it toward the west and east shores. That action removes insulation from the floor of the lake, allowing deeper thawing and subsidence there, and deposits it in near-shore shelves and bars where it inhibits wave erosion and thawing. This transport of bottom material parallel to the wind is only part of the story. The rest has to do with subsurface current patterns set up by the prevailing winds. The key feature of these patterns, shown in **Figure 4.46**, is a fast flow of surface and subsurface water at the crosswind ends of the lake, at speeds typically several

85. Carson and Hussey (1962); Britton (1967); Sellman et al. (1975).
86. Brewer (1958).

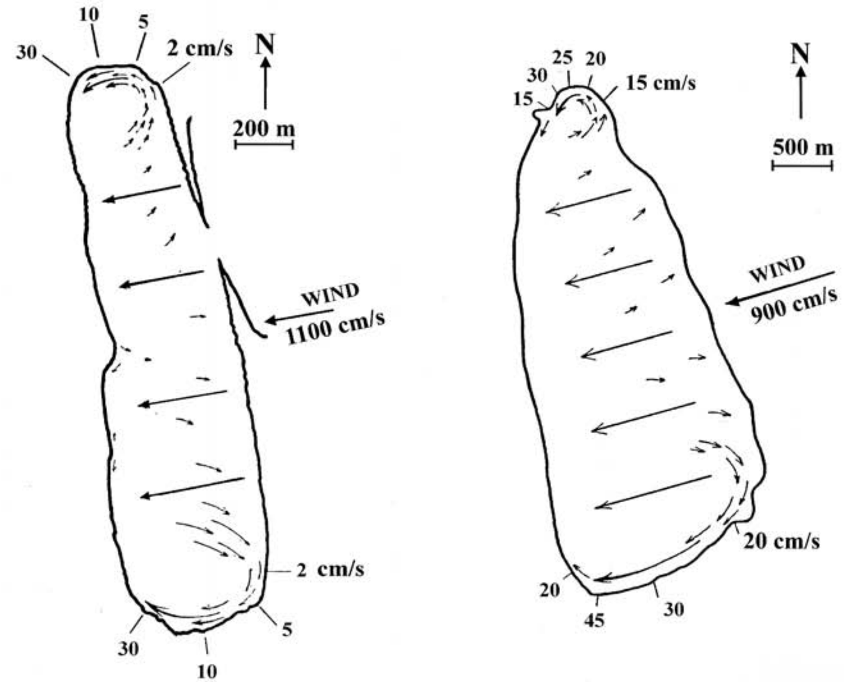


Figure 4.46 Wind and current patterns observed in two aligned lakes near Point Barrow. The diagram is compiled from parts of Figures 3, 9 and 10 in Carson and Hussey (1962).

times the subsurface flow elsewhere. With a 32-km/hr (20-mi/hr) wind, the currents at the north and south ends of the larger lakes reach speeds near 1km/hr (2/3 mi/hr) and that is fast enough to move even pea-size gravel along the beaches at speeds approaching 100 m/hr. This ability to transport material away from the ends, coupled with the ability of the faster moving water to deliver heat energy for thawing, evidently combines to foster erosion of the north and south shores.

High-altitude photographs of the oriented thermokarst lakes near Point Barrow reveal a striking pattern of sublittoral (nearshore) plant growth in those lakes now growing smaller, and the photographs show that this growth can accentuate the elongation of each lake as its area contracts. Tentatively identified as primarily *Arctophylla fulva*—a grass that grows in water up to depths of 1.5 m in arctic regions[87]—the vegetation grows outward

87. Viereck, Les A., personal communication, 1997. Britton (1967) gives information on this and related grasses that grow in shallow arctic waters.

from the shore in pronounced circular patterns that eventually coalesce to create a new shoreline subparallel to the former one. The photographs in **Figures 4.47** and **4.48** indicate that the new shores extend as far as or even farther out on the west and east shores of the lakes than on the north and south shores, and so the lakes become more linear as time progresses.

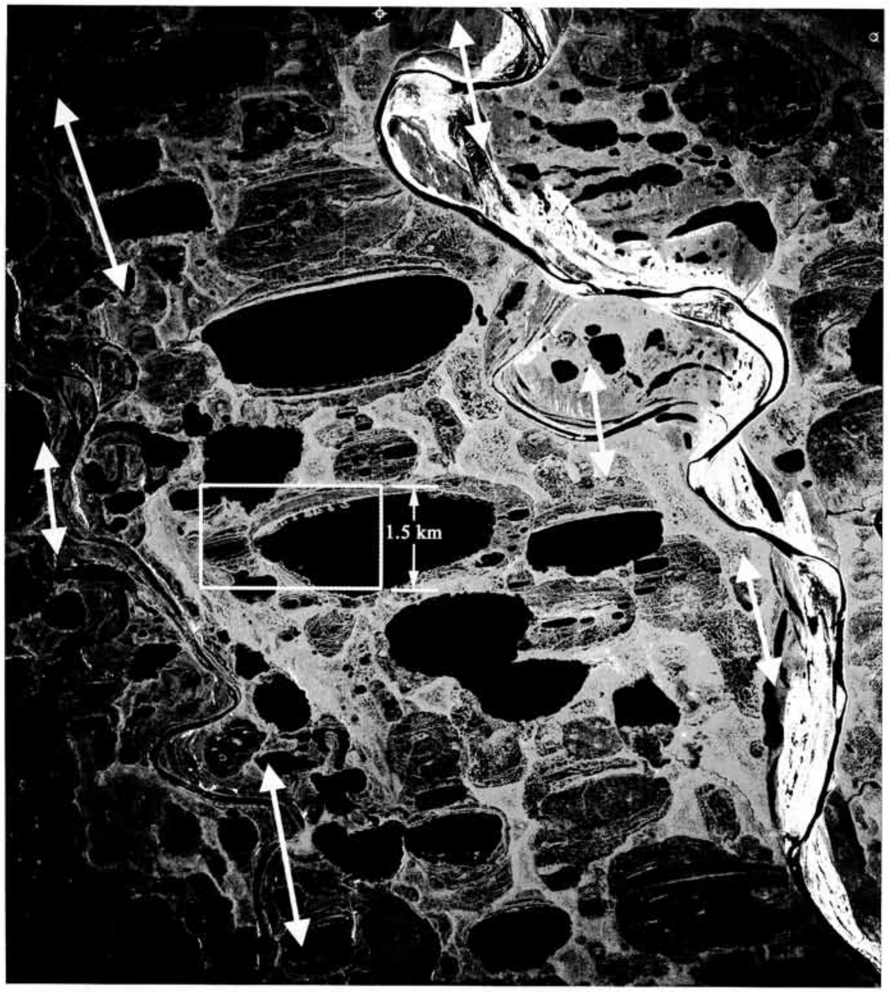


Figure 4.47 High-altitude infrared photograph of aligned lakes on Alaska's North Slope near Point Barrow. White arrows indicate approximate alignments of nearby snowdrifts, seen in the photograph. The portion within the white box is enlarged as Figure 4.48. See also Plate 19.

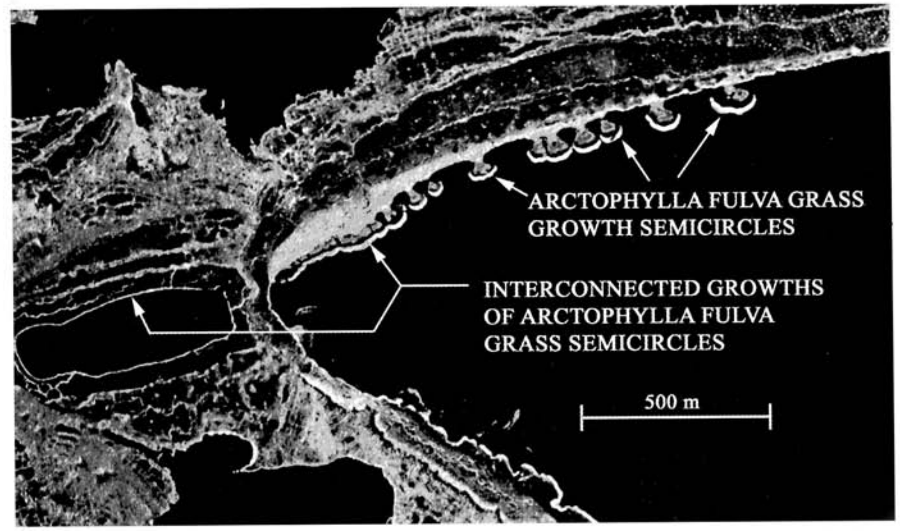


Figure 4.48 An enlarged view of the area shown in the white box of Figure 4.47. Around the small lake at left former shorelines are evident, each apparently created by joined semicircular growths of vegetation (Arctophylla [also Arctophila] fulva grass). See also Plate 20.

Earthquake Effects in Permafrost Areas

During earthquakes, the intensity of motion of the ground surface generally is much greater in areas of unconsolidated sediments than in areas of rock. Because freezing bonds unconsolidated sediments, it is likely that those frozen sediments in areas of thick continuous permafrost will behave like rock and therefore undergo less motion than unfrozen sediments when earthquakes occur. In an area of discontinuous permafrost, however, the major differences in behavior of frozen and unfrozen bodies of soil can create ground motions of unusual sorts, generating spectacular earthquake effects not seen elsewhere. **Figures 4.49** to **4.53** present examples generated by a series of earthquakes in northwest Alaska on April 7, 1958; the largest event of this series was Richter magnitude 7.[88] Occurring when the active layer was frozen, these earthquakes produced visible secondary ground fractures, massive flows of sand and water, and significant ground surface collapses in a 15- by 60-km area of the Koyukuk River valley near Huslia. The sloshing

88. Davis (1960).

Figure 4.49 Mud thrown up by an earthquake darkens lake ice fractured by severe ground motion and sloshing of water below. Many lakes in the earthquake area showed such effects.

of water in the many small lakes in the area caused fracturing of the surface ice, piling it up on the shores and pumping portions of the lake bottoms up through the ice fractures, as shown in Figure 4.49. Similar effects occurred on old lake beds having thick moss covers or in swampy areas, where the ground was frozen on top but unfrozen below. The frozen surface broke into rigid blocks that slid across the unfrozen soil beneath and then piled up near the lake or swamp boundaries (Figure 4.50). Occasionally, unfrozen material below squirted up through the fractures between the blocks, as shown in Figure 4.51. However, the most spectacular consequence of severe

Figure 4.50 Water sloshing under the moss cover of old lakes during the earthquakes has cast these moss blocks up on the edges of the former lake beds. This and following photographs taken in April and early May 1958.

and prolonged ground shaking in this region of discontinuous permafrost was the ejection of many massive flows of water and sand onto the ground surface, much of this material having been transported through unfrozen subsurface channels prior to ejection. Accompanying the ejection of sand and water was the formation of surface collapse pits. One of the largest is shown in Figure 4.52; it was associated with a flow of sand with estimated

Figure 4.51 Rosemarie Davis, the author's wife and field assistant on a 160-kilometer investigative trek through the roadless epicentral area, trusty .30–30 strapped to her back to fend off any bears that might appear (none did), stands with one foot on a slab of mud forced up through a crack in the mossy active layer covering a swampy area affected by the earthquake.

volume 100,000 cubic meters. Figure 4.53 shows both the surface of one of the mud flows and trees pushed over by the sliding of portions of the frozen surface layer over unfrozen material below. These secondary earthquake effects stemming from the presence of partially frozen soils all were located in a totally uninhabited area; had they not been, the monetary damage could have been substantial.

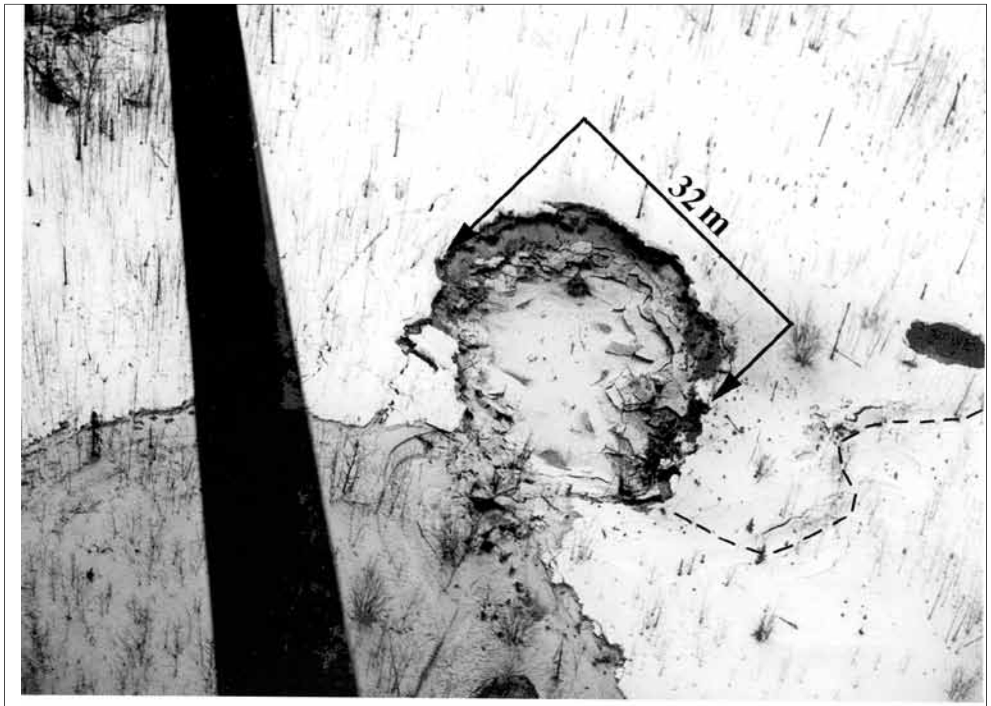


Figure 4.52 A collapse pit 32 m across and 4 m deep associated with a mud flow having estimated volume 100,000 cubic meters. A smaller collapse pit is at the right-hand edge of the photograph. Notice the linear collapse feature marked by a dashed line that suggests underground flow of material from the small pit to the edge of the large pit where the huge amounts of water and soil flowed out onto the ground surface.

Chapter Summary

In those parts of the world where the ground freezes annually and perhaps contains perennially frozen ground, cryogenic action causes weathering and generates certain geomorphic features. Some of these are similar to features produced in warmer climes by other processes, and some are unique to cold lands. The largest and most spectacular cryogenically caused landforms are open- and closed-system pingos, mounds up to 50 m tall created by the transport and freezing of water under hydrostatic pressure. Tending to be somewhat smaller are palsas that form where strong winter winds help generate strong thermal gradients conducive to the formation of thick layers of segregation ice which lift the ground surface. Cryogenic action also creates a variety of lesser mound forms ranging down to a few centimeters in size, and an almost bewildering variety of visible ground patterns. Of these, the most widespread and important in cold lands are polygonal ice-wedge arrays formed over long periods and which,

Figure 4.53 Rosemarie Davis, now carrying her ever-present bear gun on her shoulder, sashays over mud that has flowed up onto the ground surface near where shifting blocks of the frozen active layer have piled up and pushed over black spruce trees.

when melted, generate thermokarst topography. Other patterns involve sorting and short-distance transport of soil through cryogenic action. In some cold areas, cryogenic action's ability to break rock and soil down into smaller pieces and to move soil down even very gentle slopes (the solifluction process) helps make it the most important weathering and transport process. Repeated freezing and thawing of soil tends to sort particles by

size, and to modify the shape, size, and packing of soil particles. Because of spatial inhomogeneities in the soil and in the thermal regime, repeated freezing and thawing tends to churn the soil as well, destroying the uniform layering usually seen in a soil profile generated by noncryogenic processes. Because frozen soil is brittle relative to unfrozen soil, strong ground motions can produce unusual effects directly attributable to differences between the motions of frozen and unfrozen ground. The earthquake effects include abnormal fracturing of the frozen active layer, sliding of frozen portions of the ground over unfrozen portions, and ground collapses associated with the ejection onto the surface of soil and water owing to differential motions between frozen and unfrozen soils.