2004; Kaab et al., 1997; Kneisel, 2004; Lambiel and Delaloye, 2004). Rheological models are also being examined (Whalley and Azizi, 1995). Currently, the study of rock glaciers constitutes a major component of alpine (mountain) permafrost study.

6.5. FROST MOUNDS

Various types of frost mounds occur in permafrost regions. They can be distinguished on the basis of their structure and duration, and by the character of the ice contained in them. Figure 6.11 summarizes the different types in terms of their uplift source and ice type. Certain types of frost mounds are of special interest because they are uniquely permafrost features. They are also of Pleistocene significance because collapse structures, interpreted as frost-mound remnants, have been described from many non-permafrost areas of the world. The latter are discussed more fully in Chapter 12.

6.5.1. Perennial-Frost Mounds

Pingos are perennial, intrapermafrost, ice-cored hills, typically conical in shape, that can grow and persist only in a permafrost environment (Mackay, 1998). The word "pingo" is of Inuit origin, used to describe an ice-cored conical hill in the Mackenzie Delta, Canada. The Russian equivalent is bulganniakh.

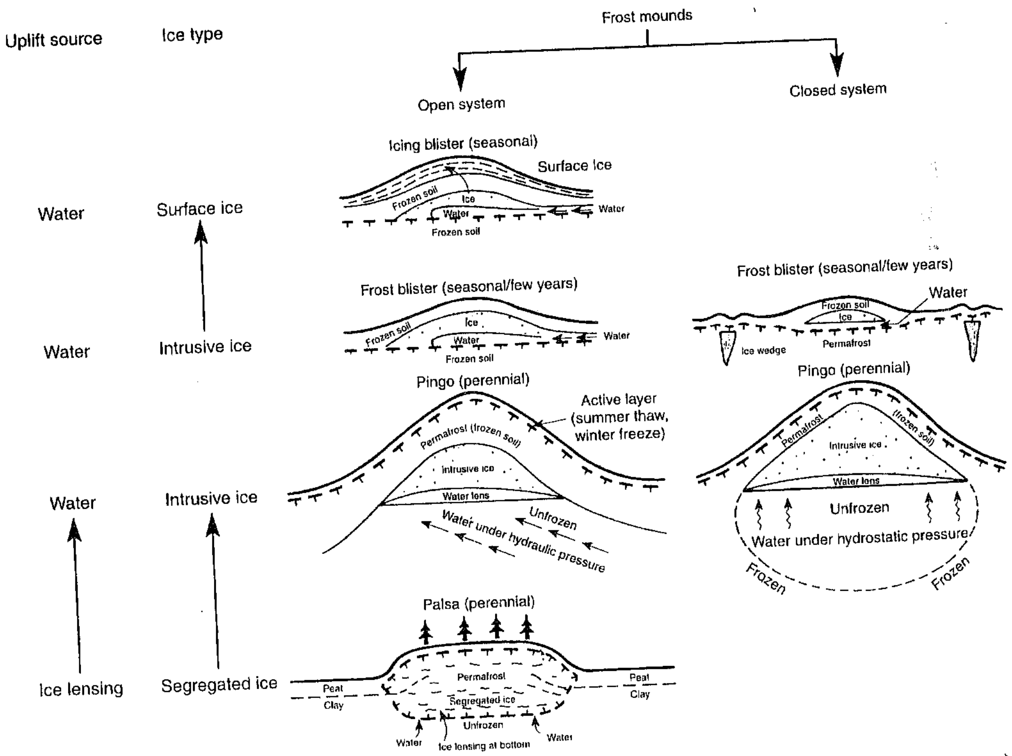

Figure 6.11. The various types of frost mounds and their origin. Modified from Mackay (1986c). Reproduced by permission of the Canadian Association of Geographers.

A well-developed pingo can be a striking geomorphic form (Figure 6.12). However, pingos are not common features and their existence is usually the result of a number of distinct and limiting geomorphic and hydrologic conditions. Pingos vary from a few meters to over 60m in height and up to 300m in diameter. They range in form from symmetric, to asymmetric, to elongate. Not all pingos have a typical conical form. Their one common characteristic, however, usually concealed by 1.0–10.0m of overburden, is a core of massive ice or icy sediments. The ice may be remarkably pure, sometimes with seasonal bubble-rich and bubble-poor banding, or it may consist of layers of icy sediments. Fractures and faults are sometimes seen within the pingo ice core. Frequently, pingos portray dilation cracks and are ruptured near the summit. This is the first stage in decay, melt of its ice core, collapse of the mound, and ultimate formation of a shallow-rimmed depression (Figure 6.13).

Pingos were first described from northern Canada by Dr John Richardson (1851). They were later described in more detail from northern Alaska (Leffingwell, 1919) and from Siberia (Tsytovich and Sumgin, 1937). A. Leffingwell (1919) was the first to suggest hydraulic pressure as the cause while the botanist, A. E. Porsild (1938) was the first to suggest freezing in a closed system. Although the terms "open-system" and "closed-system" explain pingo growth, the words "hydraulic" and "hydrostatic" better identify the source of the water pressure that initiates and sustains pingo growth (Mackay, 1979a). These terms are used here. Put simply, hydraulic-system pingos derive their water pressure from a topographic gradient and hydrostatic-system pingos derive their water pressure from pore-water expulsion beneath aggrading permafrost in saturated sand.

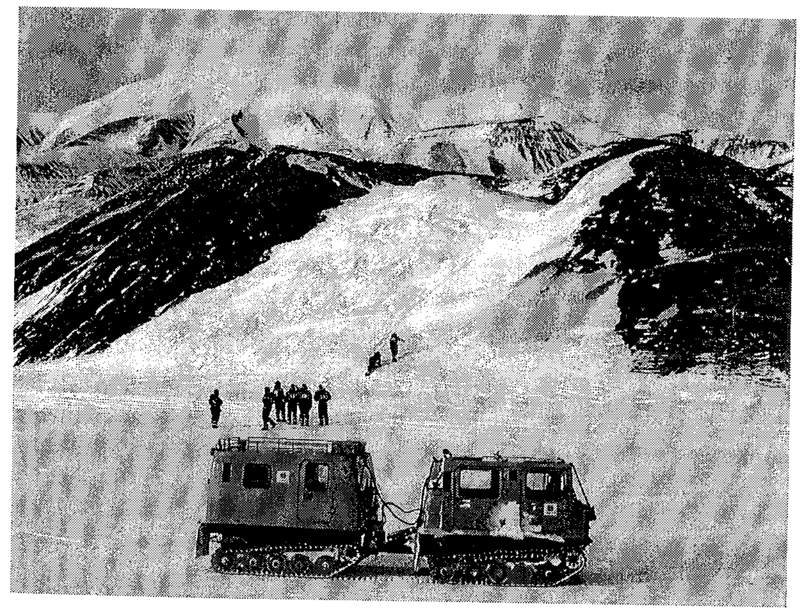

Figure 6.12. Large hydraulic (open) system pingo ("Inner Pingo") in Adventdalen, Svalbard. Water issuing from the summit crater has formed an icing which extends down the flank of the hill. The photo, taken April 2006, is supplied courtesy of Professor O. Humlum.

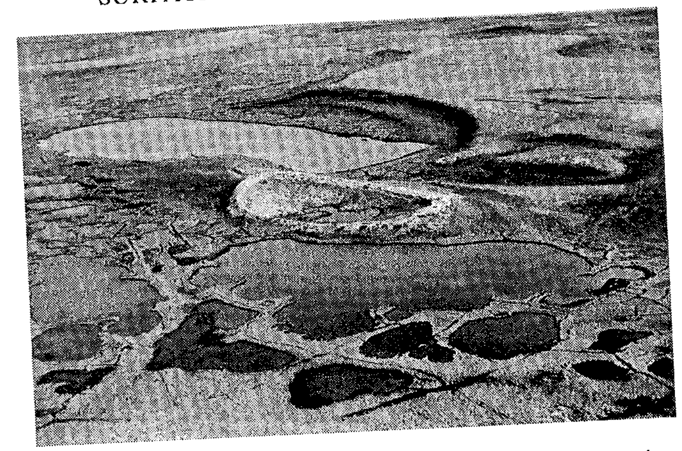

Figure 6.13. Collapsed hydrostatic (closed) system pingo, Sachs River lowlands, Banks Island, Canada.

6.5.2. Hydraulic (Open) System Pingos

Hydraulic (open) system pingos are hydrological phenomena that develop at sites where intrapermafrost or subpermafrost groundwater, under artesian pressure, reaches the surface (Müller, 1959). In general, they occur as isolated features, or as small groups within the same locality. A few attain considerable dimensions (~20–50 m in height) (see Figure 6.12). In nearly all instances, hydraulic (open) system pingos form in areas with topographic relief, such as lower hillslopes, alluvial fans, or valley bottoms. The majority is clearly associated with groundwater seepage. Typically, springs and icings form on their flanks in winter (see Figure 6.12). In East Greenland, groundwater flow and discharge characteristics suggest that structural weaknesses control the taliks that are associated with the intra-permafrost hydrology (Worsley and Gurney, 1996). Likewise, on Svalbard, many of the larger pingos are related to geological faults or are fed by high artesian pressures that are constantly being recharged by the melt of ice from the temperate basal zones of glaciers (Liestol, 1976; Yoshikawa, 1993; Yoshikawa and Harada, 1995). In Tibet, the large pingo at the head of the Kunlun Shan Pass is thought to have formed by groundwater rising to the surface along a fault (Wang and French, 1995c).

Despite numerous descriptive studies, there are no known surveyed growth data for hydraulic (open) system pingos. It is sometimes assumed they grow solely by ice injection. However, the role of artesian pressure is not to force overlying sediment upwards but rather to ensure a steady and slow movement of groundwater towards the surface. Pingo growth solely from injection represents an unstable condition that requires an unlikely long-term balance between three independent variables: (i) water pressure, which is determined by conditions external to the pingo, (ii) overburden strength, which varies with time of year, and (iii) the rate of freezing, which depends upon temperature (Mackay, 1973a, p. 1000). Since all three may change independent of the others, this balance will rarely be maintained for the total growth period of a pingo. The implication is that hydraulic (open) system pingos probably require a certain amount of ice segregation in addition to ice formed by intrusion of free water. In Yakutia, for example, where both "flat" bulganniakhs (dome-like elevations 2–5 m high) and upstanding large bulganniakhs (hills 10–50 m high) exist in close juxtaposition, it is thought that the ice core is of several origins, produced both by injection from groundwater under pressure from below and by segregation (Soloviev, 1973b, p. 148–151). The flat bulganniakhs are primarily of a segregated

nature, composed of icy sediments, while the larger forms possess massive ice cores 5–10 m thick, formed through the repeated injection of water.

Approximately 500 hydraulic (open) system pingos occur in central Alaska and interior Yukon Territory (Holmes et al., 1968; Hughes, 1969). They are preferentially located on lower south- and southeast-facing valley-side slopes. Theoretical calculations by Holmes et al. (1968) suggest that the average pressure required to overcome the tensile strength of frozen ground and to subsequently maintain a 30 m high pingo is considerably higher than most artesian pressure measured in central Alaska. This probably explains why the majority of open-system pingos in Alaska and Yukon Territory never attain a fully-domed state but persist largely as doughnut-shaped, semi-circular, or circular ramparts. It may also explain why many of the hydraulic (open) system pingos on Svalbard and East Greenland are much larger because relative relief is greater and the hydraulic head, provided by adjacent sub-glacier melt water, is higher.

6.5.3. Hydrostatic (Closed) System Pingos

Hydrostatic (closed) system pingos result from pore-water expulsion caused by permafrost aggradation beneath the bottoms of drained lakes that are underlain by saturated sand (Mackay, 1962, 1985b, 1998). The highest concentration of this type of pingo occurs in the Tuktoyaktuk Peninsula area of the Pleistocene Mackenzie Delta region of Canada, but others occur elsewhere in northern Canada (Craig, 1959; French, 1975b; Pissart and French, 1976; St-Onge and Pissart, 1990; Tarnocai and Netterville, 1976; Zoltai, 1983), northern Alaska (Leffingwell, 1919; Walker et al., 1985), and central Siberia (Soloviev, 1973a).

The high concentration of hydrostatic-system pingos in the Tuktoyaktuk Peninsula area is the result of several favorable physical conditions. These include: (i) the occurrence of thick permafrost, (ii) large areas underlain by coarse-grained sediment, and (iii) numerous thermokarst lakes that drain frequently and easily, either by coastal erosion or by fluvio-thermal erosion along ice-wedge polygons (Mackay, 1998, p. 275). Typically, hydrostatic-system pingos occur within shallow lakes or former lake beds where both upward and downward permafrost growth occurs in the previously-unfrozen saturated sediment which comprises the sub-lake talik (Figure 6.14). They usually occur singly and not in groups, although at least one drained-lake basin is known to contain at least three actively-growing pingos (Mackay, 1973a, 1979a). On Banks Island, certain hydrostatic system pingos appear to have formed following the freezing of localized taliks that must have formed beneath the deeper sections of now-abandoned river channels (Pissart and French, 1976).

Detailed long-term field studies upon the growth of hydrostatic (closed) system pingos in the Tuktoyaktuk area have been undertaken by J. R. Mackay (1973a, 1979a, 1981c, 1986b, 1988b, 1990b, 1998).

The birth of a small pingo called Porsild Pingo (Mackay, 1988a) is typical of the early growth cycle. This pingo has grown in a lake which drained catastrophically about 1900. Birth probably took place between 1920 and 1930 when newly-aggrading permafrost ruptured and water was intruded into the unfrozen part of the active layer. A small mound, approximately 3.7 m high, was photographed by A. E. Porsild in May 1935 and subsequently described as part of a paper on "earth mounds" (Porsild, 1938, p. 53). Since then, Porsild Pingo grew steadily until 1976, at a growth rate approximately linear with height. After 1976, the growth rate has fallen. A similar pattern of rapid early growth (~1.5 m/yr) was monitored in a former lake bed that was drained by coastal erosion sometime between 1935 and 1950 (Mackay, 1973a, 1979a, pp. 14–18). Although quantitative observations on

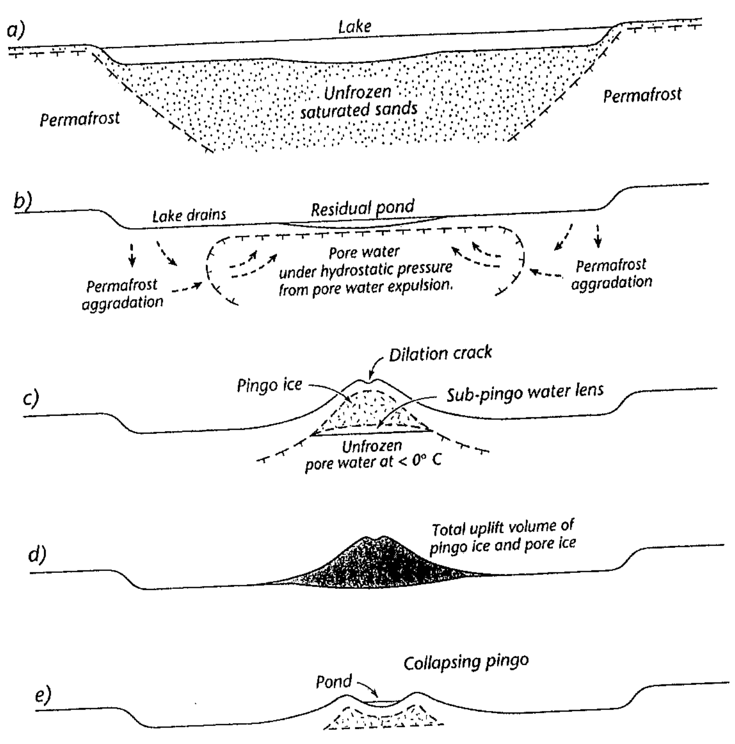

Figure 6.14. Genesis and growth of hydrostatic (closed) system pingos. (A) A large lake is underlain by unfrozen saturated sand. (B) Rapid lake drainage causes permafrost aggradation, pore-water expulsion, and development of hydrostatic pressure beneath a residual pond where permafrost is thin. (C) A growing pingo is underlain by a sub-pingo water lens whose downward freezing results in intrusive ice. (D) The total volume of ice required to grow a pingo is equal to the pingo volume above that of the bottom of the residual pond in which growth commenced. (E) Pingo collapse from partial thaw of pingo ice beneath the central pond that is surrounded by a pingo rampart. From Mackay (1998). Reproduced by permission of Les Presses de L'Universite de Montreal.

bulganniakh growth in Siberia are lacking, similar growth patterns are observed. For example, some hydraulic (open) system bulganniakhs have developed in recently-drained thermokarst (alas) depressions within the last 50 years. Eye-witness accounts indicate early growth rates of approximately 0.5–2.0 m/year (Soloviev, 1973a).

As pingos become older, their growth rates decrease. Some of the largest pingos, such as Ibyuk Pingo, are over 1000 years old and growing at a rate of only 2–3 cm/year (Mackay, 1986b). As a rough estimate, Mackay suggests that, for the Mackenzie Delta region, possibly 15 pingos may commence growth in a century. Probably, only approximately 50 are actively growing today.

Hydrostatic (closed) system pingos often exhibit pulsating patterns of heave or growth (Mackay, 1977a). This is caused by the build-up of water lenses that develop under pressure beneath the growing pingo (Mackay, 1978b). These pressures are released when water escapes to the surface, usually towards the periphery of the pingo where overburden strength (i.e. permafrost thickness) is least. This may result in seasonal frost mounds forming on the flanks of growing pingos (Mackay, 1979a, pp. 18–24). If penetrated by drilling, these water lenses can cause temporary artesian flow and geysers several meters high.

All pingos contain pore ice and varying proportions of intrusive and segregated ice. According to Mackay (1985a), the majority of growth is by ice segregation. In the early stage of pingo growth, as the recently-drained lake bottom begins to freeze, pore ice forms and the entire lake bottom heaves upwards. This is what was observed at the Illisarvik drained-lake site during the first 6 years of observation (see Chapter 5). Then, as permafrost continues to aggrade in the coarse-grained water-saturated sediment that underlies the basin, pore-water expulsion occurs (see Chapter 4). Segregated ice forms when hydrostatic pressure equals or exceeds overburden pressure, and uplift of the pingo, senso stricto, commences. Intrusive ice is associated with the freezing of the sub-pingo water lens. At that stage, pore water in the unfrozen and unbonded sand beneath the water lens remains at or below 0 °C because of a freezing-point depression. Using the opportunity of a rare pingo-ice exposure, Mackay (1990b) has described how seasonal-growth bands, consisting of alternating clear and bubble-rich bands, form in the intrusive ice (Figure 6.15). These

(A)

(B)

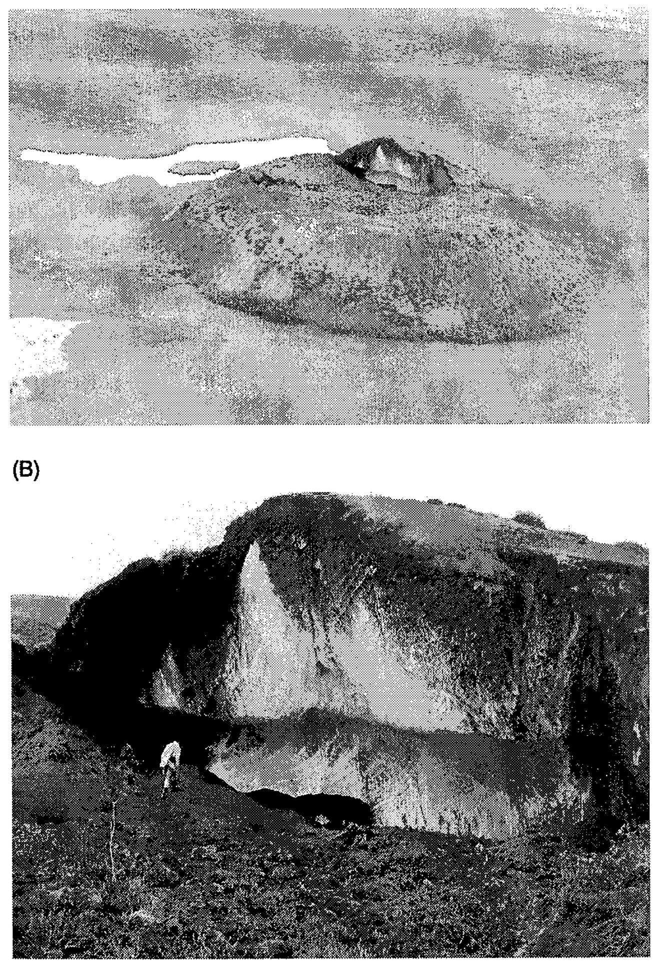

Figure 6.15. Seasonal-growth bands in pingo ice. (A) Oblique air view of pingo 20, Tuktoyaktuk Peninsula, Canada (see Mackay, 1990b, 1998), showing exposure of the ice core. (B) Seasonal banding in the ice core. Note the person for scale. Both photos were taken in August 1988.

result from the downward propagation of the cold and warm seasonal temperature waves. The gradual transition from clear to bubble-rich ice reflects the change from winter to summer, and the abrupt transition from bubble-rich to clear ice reflects the change from summer to winter.

In summary, hydrostatic (closed) system pingo growth is an example, albeit dramatic, of lake-bottom heave and aggrading permafrost.

6.5.4. Other Perennial-Frost Mounds

Pingo-like mounds occur in other geomorphic settings. For example, groups of pingo-like mounds have been described from the Canadian Arctic islands (Balkwill et al., 1974; Pissart, 1967a). On Prince Patrick Island, shallow mounds, between 1 m and 13 m in height and with average dimensions of about 60 m, are formed within thick sand formations of Tertiary age that rest discordantly upon impervious Paleozoic-age rocks. None appears to be growing today. Their location appears to coincide with deep-seated geological discontinuities that suggest the mounds are related to ancient groundwater movement along faults in underlying bedrock. The pingos probably developed when permafrost first began to form sometime during the early or middle Pleistocene. Those on Amund Ringnes Island are equally problematic.

A second geomorphic setting is provided by elongate and partially-collapsed mounds of varying sizes and shapes that occur in river valleys and on low fluvial terraces of Banks Island (French, 1975b, 1976c; French and Dutkiewicz, 1976). Most are less than 3 m in height and all appear relict. Especially puzzling are remnants of small, mutually-interfering mounds that occur on the broad fluvial surfaces of Central Banks Island. It is hypothesized that these may be seasonal-frost-mound remnants of Late-Pleistocene age that formed in shallow sections of braided channel systems.

6.5.5. Seasonal-Frost Mounds

Where freezing of the active layer restricts perennial discharge from intrapermafrost or subpermafrost aquifers, a variety of seasonal-frost mounds (frost blisters, icing blisters) may develop at the site of groundwater discharge. These have been described from northern Canada, Alaska, northern Scandinavia, Tibet, and Siberia. Typically, seasonal-frost mounds range between 1.0 m and 4.0 m in height. They form by the upheaval of seasonally-frozen ground brought about by the subsurface accumulation of water under high hydraulic potential. This occurs during progressive freezing of the active layer. Figure 6.16 illustrates the formation of frost blisters, one of the most common types of seasonal-frost mounds.

Seasonal-frost mounds are sometimes confused with palsas. The basic difference is that the former result from ice injection while the latter result from ice segregation. Thus, the interior of a frost blister, for example, is usually characterized by a core of pure ice with ice crystals aligned in a vertical columnar fashion that reflects the freezing of free water (Pollard and French, 1983, 1984, 1985).

Most seasonal-frost mounds are destroyed completely by thawing and collapse during the first summer after their formation. However, others may be preserved through one or more summers, depending on the insulating quality of their soil cover. As a result, they may assume the morphology and time duration of a palsa. It is also possible that some mounds combine both palsa and seasonal-frost-mound growth mechanisms. For example, palsa-like mounds have been described from a number of damp valley-bottom

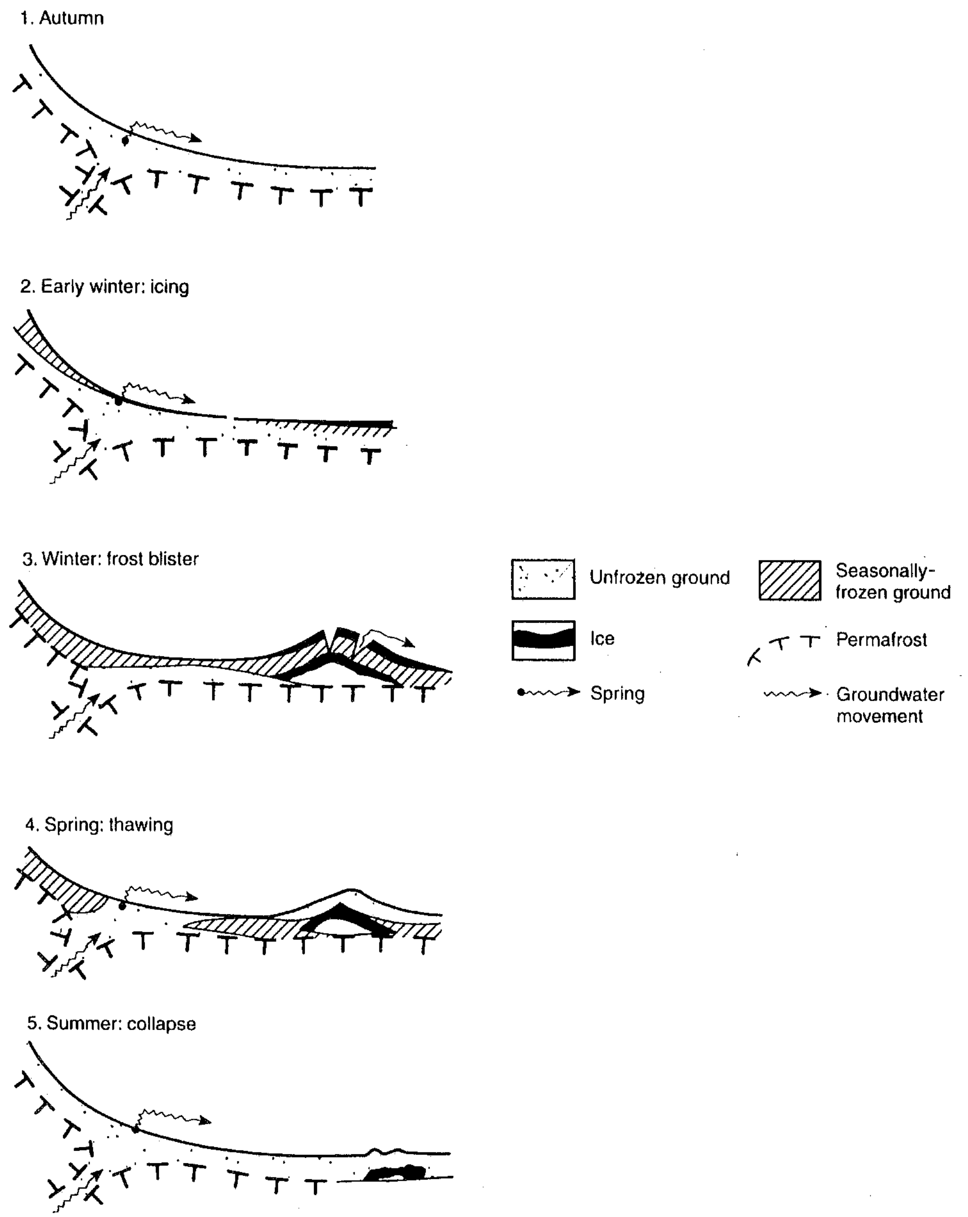

Figure 6.16. Sequence of events in formation and decay of a frost blister. Modified from van Everdingen (1978).

locations in the Mackenzie Mountains and southern Yukon Territory, Canada (Coultish and Lewkowicz, 2003; Kershaw and Gill, 1979; Lewkowicz and Coultish, 2004). Because high hydraulic potentials must exist in such hilly topography, the possibility exists that ice injection, rather than ice segregation, is the primary cause of uplift.

6.5.6. Hydrolaccoliths and Other Frost-Induced Mounds

A feature of many tundra landscapes is the presence of small mounds, many with either ice cores or ice lenses within them (Figure 6.17). These mounds are not regarded as pingos, mainly on account of their size and their location primarily within the active layer. They are also not usually regarded as a form of patterned ground since they are larger than the earth hummocks or non-sorted circles normally associated with patterned ground. Many function as owl perches and stand out as relatively dry sites. Their peaty soil frequently promotes the development of ice lenses immediately beneath the vegetation mat.

The variety of features suggests that they are not all of the same origin. In the Russian literature, the term "bugor" has been used to describe these small, gently-rising, and oval-shaped mounds (Dostovalov and Kudryavtsev, 1967). The North American literature (Sigafoos, 1951; Sharp, 1942a; Bird, 1967, p. 203; Porsild, 1955; French, 1971a; Washburn, 1983b) describes low circular mounds, rarely exceeding 2 m in height, and usually between 15 m and 50 m in diameter. The origin of these features is not clear. Some are probably the result of localized ice segregation that has occurred in response to subtle thermal differences in soil and vegetation cover.

6.6. ACTIVE-LAYER PHENOMENA

The active layer (see Chapter 5) gives rise to a number of small-scale features of the permafrost landscape. These include disrupted bedrock and soil, and various patterned-ground phenomena. These are described below.

Figure 6.17. Small hydrolaccolith associated with poorly-drained low-centered ice-wedge polygons, Masik Valley, southern Banks Island, Canada. The mound consists of a body of pure ice immediately beneath the organic mat. The raised rims of the polygons create a closed system during annual freezing.

6.6.1. Bedrock Heave

The interaction between bedrock and groundwater controls the nature of bedrock heave (Figure 6.18). Usually, upward displacement is the result of excess water pressures created in the zone between the permafrost table and the downward-advancing freezing front. Where the saturated zone in the active layer becomes confined, the attempted expulsion of water supplies the heaving force. This is usually relieved along joints and bedding planes. Bedrock heave is particularly favored where the water table lies close to the surface in jointed granite, gneiss, quartzite, and other hard bedrock (Dredge, 1992; A. S. Dyke, 1978; L. S. Dyke, 1984). In such terrain, it is not uncommon for the active layer to be several meters in thickness.

Depending upon pre-existing fracture characteristics, bedrock heave varies from single ejected blocks to dome-shaped accumulations up to several meters in diameter. According to L. S. Dyke (1984) yearly movements may be as much as 5 cm, horizontally and vertically. As such, even compact sedimentary strata or igneous bedrock may experience deformation sufficient to damage man-made structures preferentially located upon these (assumed) firm foundations.

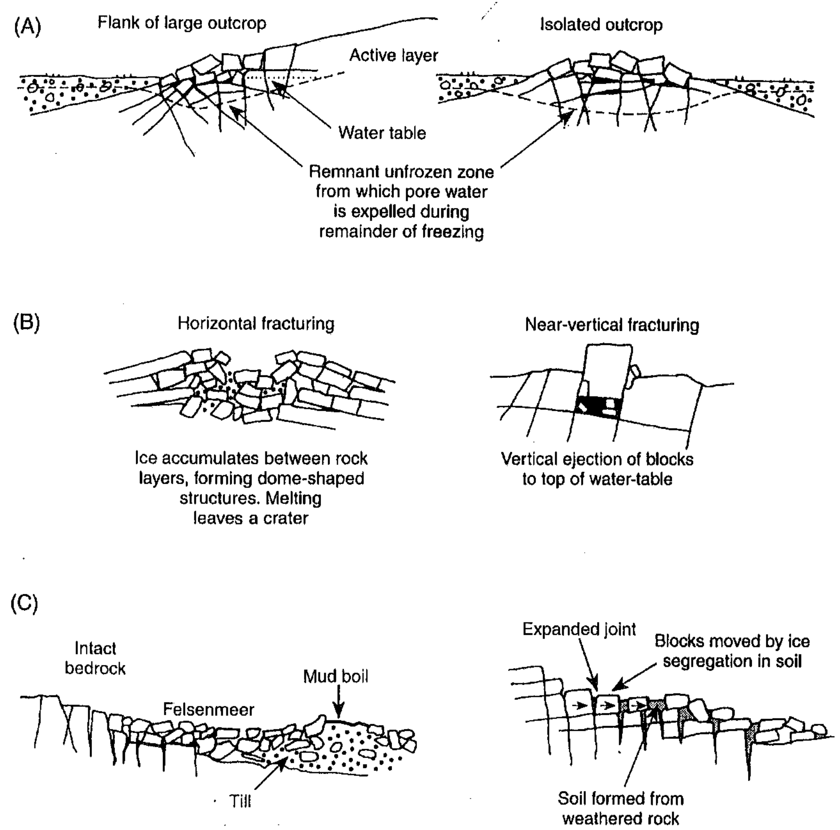

Figure 6.18. Different types of bedrock heave. (A) Water-expulsion mechanism in well-indurated rock with relatively-thick active layer (mainland, Canadian Shield). (B) Influence of fracture fabric on heaving style. (C) Ice-segregation mechanism displaces rock either by freeze–thaw creep of rock transported to a soil surface or by direct application of pressure applied by ice segregation in weathering products. Modified from Dyke (1984).