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ABSTRACT

This booklet contains resource material on cold climate phenomena and their influences on humans. It is intended for use by teachers and students in college-level geography courses as a supplement to existing textbooks and as a means of filling the gap between significant resources in geography and readily accessible materials. The material is presented in six chapters. Chapter I introduces the scope of the document and defines important terms. Chapter II focuses on various climatic characteristics, including annual temperature ranges and classifications of periglacial climates. Chapter III examines permafrost, with emphasis on its thermal characteristics, distribution, depth, origin, and associated features. Chapter IV investigates geomorphic processes (landscape evolution) in periglacial environments. Information is presented on frost action, patterned ground and mass wasting. In Chapter V, biologic processes involving periglacial soil, vegetation, and wildlife are explored. In the final chapter, the limitations and potentials of periglacial environments with regard to human living, engineering, and land use are explored. The ecology of polar regions is also examined. (DB)

THE PERIGLACIAL ENVIRONMENT, PERMAFROST, AND MAN

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FOREWORD

The Resource Papers have been developed as expository documents for the use of both the student and instructor. They are experimental in that they are designed to supplement existing texts and to fill a gap between significant research in geography and readily accessible materials.

This Resource Paper is one of a series being developed by the Commission's Panel on Physical Geography, in cooperation with the Panel of Resource and Technical Papers. This series will be concerned with important concepts, viewpoints and relationships in physical geography.

The Resource Papers are designed as supplements to a variety of undergraduate college geography courses at the introductory and advanced levels. These Resource Papers are developed, printed, and distributed by the Commission on College Geography under the auspices of the Association of American Geographers with National Science Foundation support. The ideas presented in these papers do not necessarily imply endorsement by the AAG. Single copies are mailed free of charge to all AAG members.

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I am the land that listens, I am the land that broods;
Steeped in eternal beauty, crystalline waters and woods.
Long have I waited lonely, shunned as a thing accurst,
Monstrous, moody, pathetic, the last of the lands and the first.

Robert Service
The Law of the Yukon

THE PERIGLACIAL ENVIRONMENT, PERMAFROST, AND MAN

I. INTRODUCTION

The word "periglacial" (literally, *around the glacier*) was introduced by the Polish geographer, W. von Lozinski (1912, in Wright 1961, p. 938) to emphasize the concept of formerly more severe climates adjacent to the Pleistocene continental glaciers. The meaning of the term has been considerably expanded through time, however, so that in current usage the word commonly connotes the spectrum of cold climate phenomena, both past and present (Dylik 1964). Any high altitude or latitude area or feature may be considered periglacial regardless of its proximity to a glacier in space or time. In general, the term embodies the concept of a cold and rigorous environment, the processes operative in such a milieu, and the features resulting from such conditions.

In this paper the periglacial environment is approached primarily on the basis of present climatic areas where frost processes dominate. Very little shrift is given to former periglacial environments although it is recognized and stressed that an understanding of these past environments depends heavily upon a knowledge of present periglacial features and processes. A map showing the extent of the periglacial environment is not included because too little information exists (and much of it is controversial) on the nature and distribution of former climatic conditions around the margins of the continental glaciers.

There are no precise boundaries even for present periglacial environments although some attempts have been made to establish temperature and precipitation limits. Peltier (1950, Table 1, p. 215), in establishing his morphogenetic regions, estimated an average annual temperature range of −15° to −1° C (5° to 30° F) and an average annual rainfall of 125–1400 mm (5–55 inches). Permafrost and tundra vegetation have also been cited as requirements. Such conditions would certainly favor the full development of frost heaving and mass wasting, but periglacial environments may not be limited to these areas. For example, permafrost underlies parts of the boreal forest in Siberia and North America, and tundra occurs in many areas not underlain by permafrost, e.g., high mountain areas of middle latitudes. For our purposes, periglacial environments are simply those where frost processes dominate. This would include those parts of tropical and middle latitude mountains as well as subarctic areas subjected to intensive frost action, even in the absence of permafrost.

Periglacial environments are contrasted with glacial and nivation environments as illustrated in Figure 1. In the glacial system the ice itself serves as the mode of transport while in the periglacial system mass wasting is the principal method of transport. Nivation is the least important of the three since it is an intermediate process depending on snow patch erosion and snowmelt transport. Nivation processes dominate at snowline in the transition zone between glacial and periglacial environments (Davies 1969, pp. 15–16).

In this paper, the periglacial environment is characterized as being composed of a number of processes, and particular emphasis has been given to those that contrast with processes operative in middle latitude temperate environments. An understanding of these processes is vital to a rational development of the north since the entire history of man's exploitation of marginal environments—tropical rainforest, deserts, and tundra—has been to apply middle latitude technology and approaches to land utilization. The infamous British ground nut scheme in East Africa is an outstanding example of mid-latitude technology applied to a tropical problem (Richason 1951).

Due to the nature of this publication a great deal has been left unsaid. For this reason the paper has been fairly heavily documented, not to be pedantic, but to allow free passage to the literature to those with greater curiosity on certain subjects. For those interested in more general background reading, there are several excellent sources. Of particular value is a forthcoming book scheduled to be published in late 1972, entitled *Periglacial Processes and Environments* by A. L. Washburn, University of Washington. I gratefully acknowledge access to a precopy of this

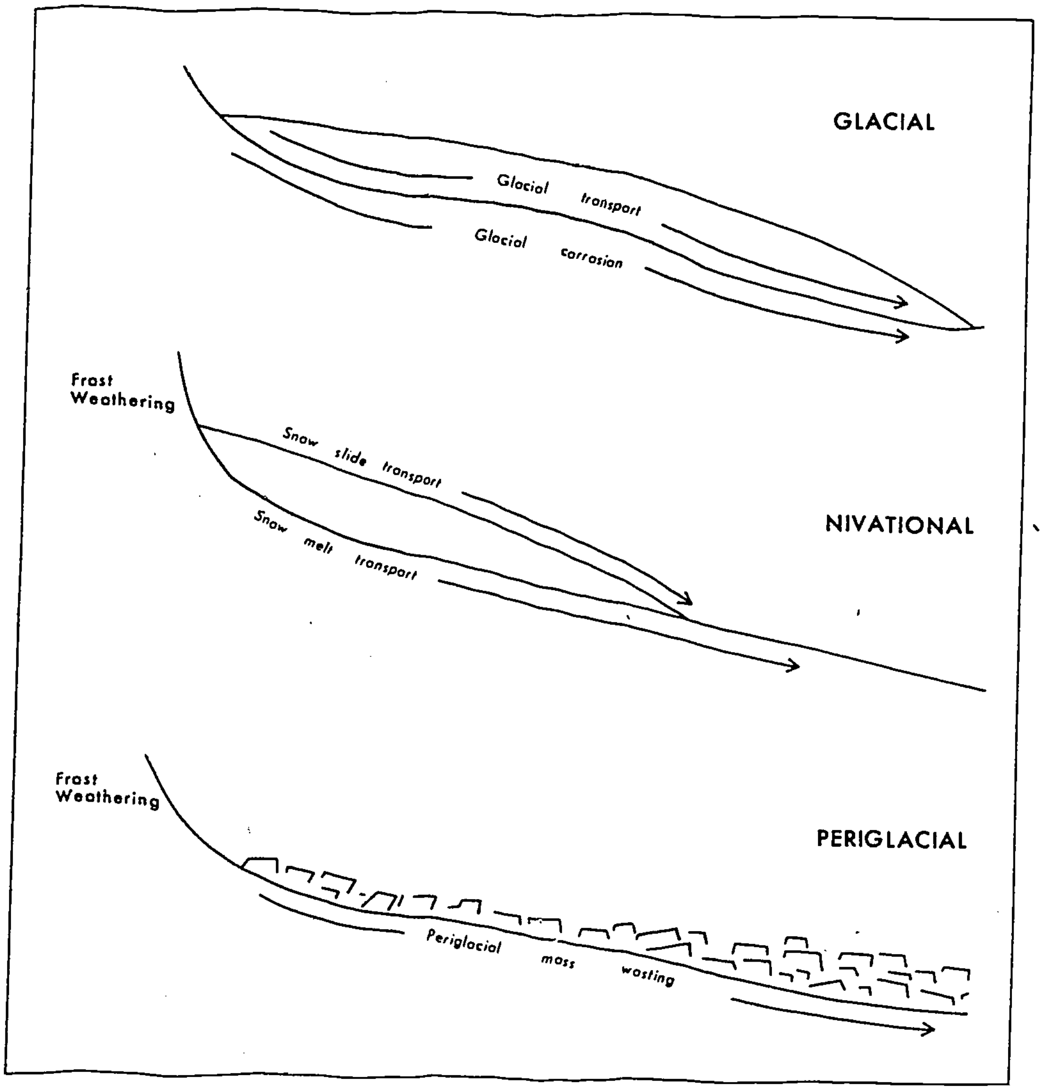

Figure 1. The three major process systems of cold climate landform evolution. The glacial system is dominated by glacial ice, while the periglacial system is dominated by frost action and mass wasting. Nivation is an intermediate process occurring at the snow line where snow patch erosion and snow melt transport are important. (After Davies 1969, Figure 9, p. 16.)

excellent monograph. There are in addition several other general works on the periglacial environment including: Bird 1967; Brown 1970; Davies 1969; Embleton and King 1969; Flint 1971; Péwé 1969; Tricart 1970; and Wright and Frey 1965, all listed in the bibliography. Major journals in English dealing with cold climate phenomena include *Arctic, Arctic and Alpine Research, Biuletyn Peryglacjalny, Geografiska Annaler*, and *Quaternary Research.* In addition, the activities of the International Quarternary Association (INQUA), the American Quaternary Association (AQA), and more informally, Friends of the Pleistocene (FOP) are highly recommended.

II. CLIMATE

Many people think of cold climates as simply being "cold," but there is perhaps as much difference between contrasting climates within the periglacial regime as those of middle latitudes. And as in middle latitudes, physical and biological processes vary in their importance under different climatic conditions. In 1944, Carl Troll published a monumental work (translated in 1958), *Structure Soils, Solifluction and Frost Climates of the Earth,* in which he synthesized much of the research up to that time and pointed out some of the major differences in cold climates. More recently, Tricart (1970, pp. 19–27) has published a useful classification of periglacial climates, based on the work of Troll (1944, 1958). Tricart's classification follows:

1. Dry climates with severe winters
2. Humid climates with severe winters
   (a) Arctic type
   (b) Mountain type
3. Climates with small annual temperature range
   (a) Island climates in high latitudes
   (b) Mountain climates of low latitudes

Dry Climates with Severe Winters

This is the continental arctic climate existing in central Siberia and northern Canada. Such areas are characterized by extremely low winter temperatures, very short summers (Figures 2a and 3a), low precipitation (average of 200 mm–8 inches), with a thin snow cover that is easily blown by strong winds. The climate is characterized by a morphogenetic system where permafrost is ever present and frost action is the dominant factor of denudation. Wind is next in importance, while running water is least important.

Humid Climates with Severe Winters

Arctic type

This climate is typical of Spitzbergen and the narrow coastal fringes of northern Siberia and Alaska where fog is often present. It is characterized by average temperatures similar to the previous climate, with a tendency towards a smaller annual range but with marked variations in weather conditions that tend to be masked by the averages (Figure 2b). Summers are short with a maximum of three to four months above 0° C (32° F), and permafrost is usually present. Precipitation is about (300 mm – 12 inches) and there is an appreciable snow cover that tends to protect the ground. This climate produces a morphogenetic system in which frost action dominates while wind action and running water are secondary.

Mountain type

This variation of humid climates with severe winters occurs in middle latitudes, and the lower temperatures are due to altitude. This periglacial climate coincides with the zone immediately below snowline. Monthly temperatures are similar to the arctic type, but winter temperatures are not as low and permafrost is usually lacking (Figure 2c). Precipitation is much higher (1000 mm – 39 inches) particularly in the form of snow. Aspect is of great importance; south facing slopes may have very different temperature regimes from north facing slopes. Valleys often experience a greater number of freeze and thaw cycles than higher elevations due to air drainage. Mountain climates of middle latitudes are characterized by frost action, although the greater snow cover prevents deep frost penetration, and permafrost is usually lacking. Running water is much more important here than in other periglacial climates because of high precipitation and slope, but wind action is relatively unimportant due to snow cover.

Climates with Small Annual Temperature Range

Island climates in high latitudes

These cold oceanic climates occur in the ice free seas of high latitudes. An example would be Kerguelen Island at 49°S. latitude (Figure 2d). The mean annual temperature of these climates is close to 0° C (32° F) and freezing may occur for short periods at all seasons although permafrost is lacking (Figure 2d). The mean annual temperature range is 10° C (50° F) but the weather is characterized by sudden changes with frequent cold waves. Fog and precipitation are persistent features and snow, when it falls, usually melts within a few days. This climate is dominated by frost action

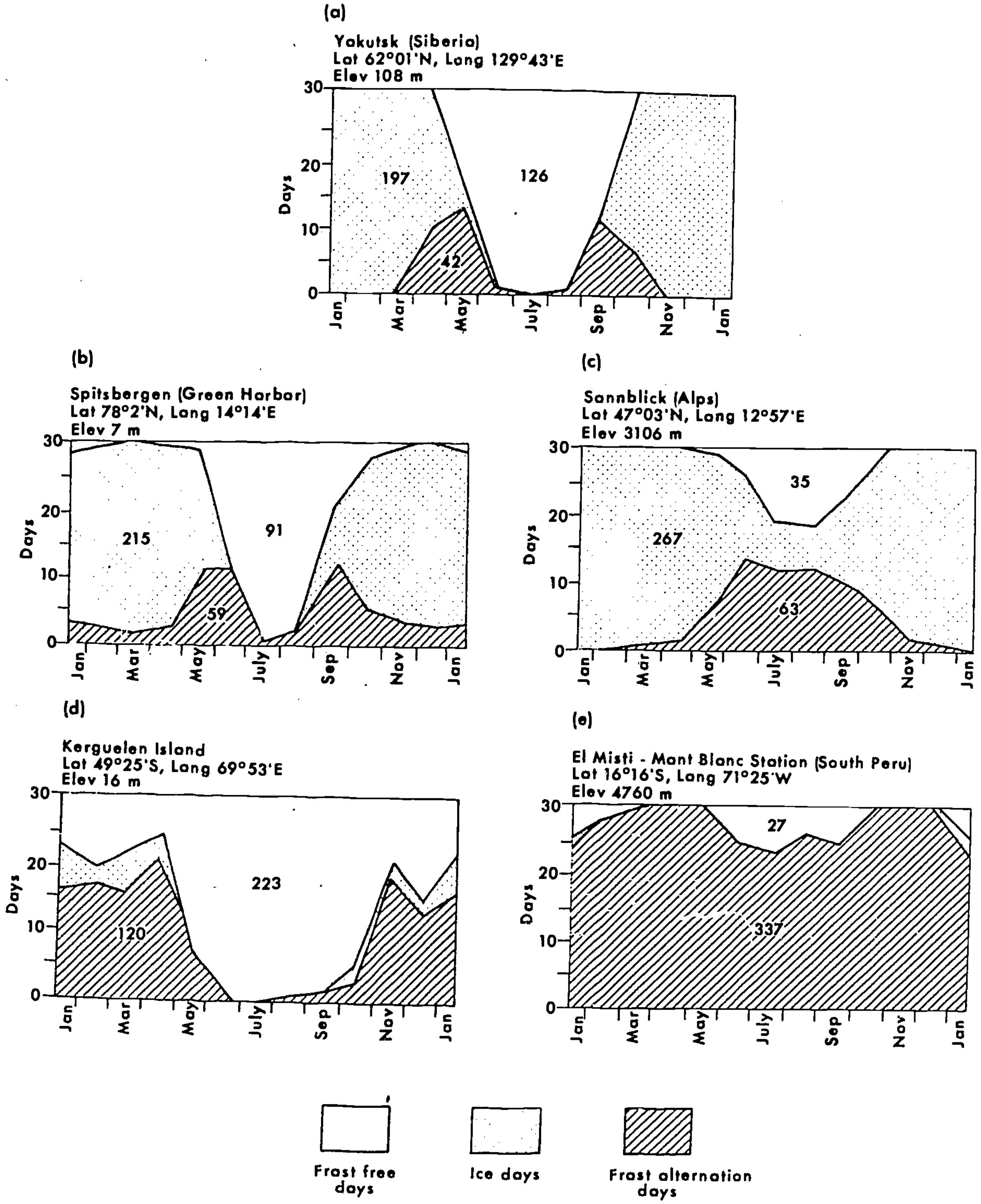

Figure 2. Graphic representation of frost alternation frequency at different climatic stations within the periglacial regime. *Frost free days* indicate the number of days when freezing did not occur, *ice days* indicate the number of days when the temperature was continually below freezing, and *frost alternation days* are the days when freezing and thawing occurred. Note that the least number of frost alternation days occurs in the most continental arctic climate (Figure 2a) while the greatest number of frost alternation days occurs in tropical mountains (Figure 2e). (Adapted from Troll 1958, Table 1, pp. 10–13.)

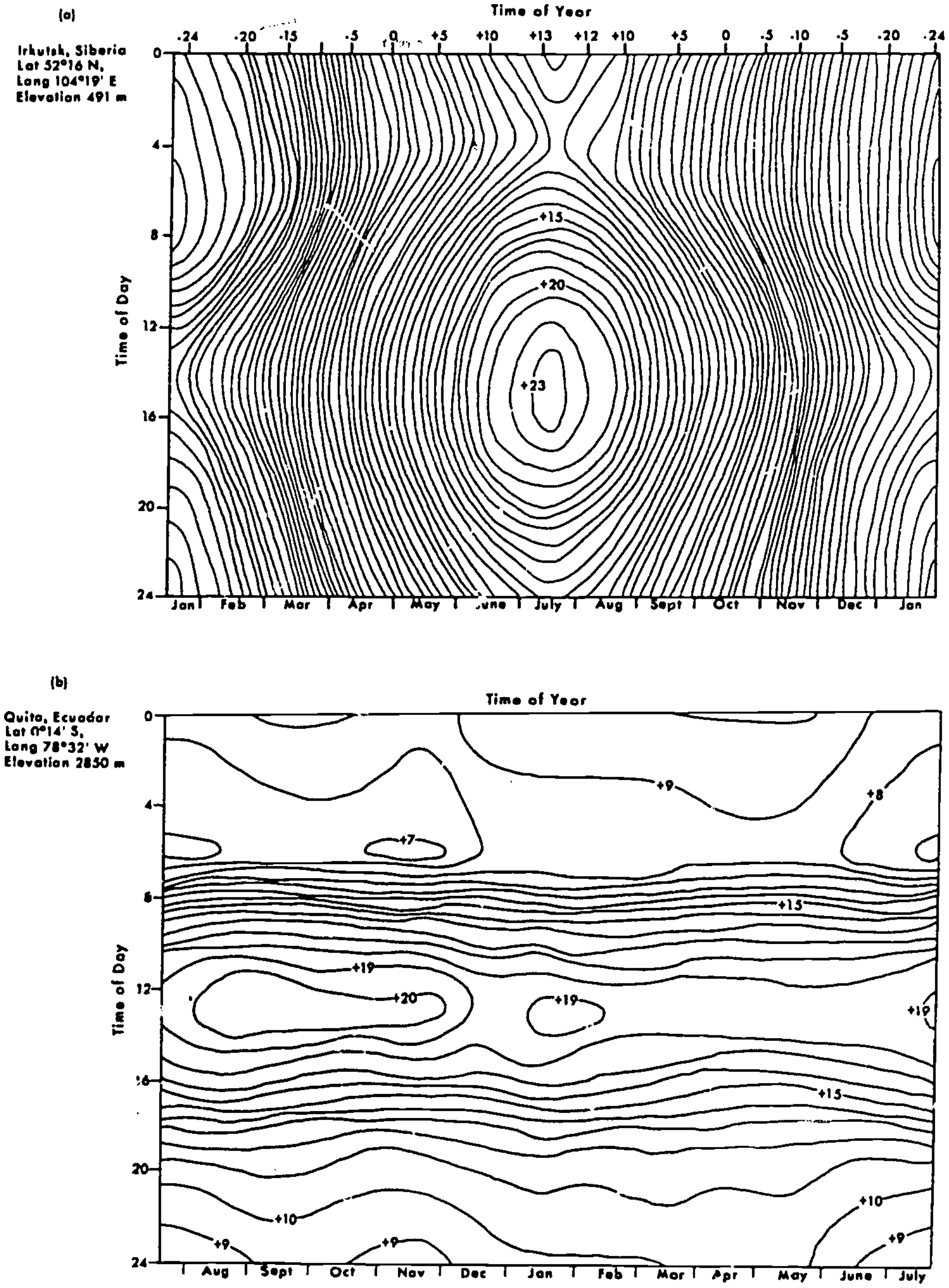

Figure 3. Daily and seasonal temperature distribution in a continental and alpine tropical periglacial climate. The opposite orientation of the isotherms reflects the fundamental differences in daily and seasonal temperature ranges in the two contrasting environments. The continental station (a) experiences a small daily temperature range (read vertically) but a large annual range (read horizontally). Conversely, the alpine tropical station (b) experiences a much greater daily temperature range than the annual range. (Adapted from Troll 1958, Figure 3, p. 11.)

in the form of freeze and thaw cycles of short duration and shallow penetration, while wind action and running water are of less importance.

Mountain climates of low latitudes

These climates are due to the effects of altitude in tropical regions. The temperature rhythm so characteristic of the tropics is maintained, i.e., small annual temperature range with no marked seasons and a daily range larger than the annual range (Figure 3b). The essential climatic feature of the higher elevations is lower temperatures resulting in diurnal frost cycles. These are of short duration and slight penetration into the ground, so permafrost is lacking, but more freeze and thaw cycles occur here than in any other area on earth (Figure 2e). As a result, frost wedging and needle ice formation (defined in Chapter IV) are very prevalent. Precipitation may be quite high and this tends to decrease the effectiveness of wind action, so mass wasting and running water are the major denudational agents.

When these climates are compared, some important contrasts emerge (Davies 1969, pp. 13–14). Permafrost is characteristic of the first type (dry climates with severe winters), is of irregular occurrence in the second (humid climates with severe winters), and absent in the third (climates with small annual temperature range). Parallel with this, type one experiences severe seasonal frost cycles penetrating to great depths, while type three experiences moderate frost cycles affecting only shallow depths, and type two is intermediate. Wind action is important in type one but running water is not, while in types two and three the reverse tends to be true. From a morphogenetic standpoint, mass wasting and frost action are important in all of these climates, but duration and intensity vary greatly.

Although permafrost is not a prerequisite for periglacial conditions, it is present in climatic types one and two and as such occupies the greatest percentage of land area under periglacial environments. In addition, many of the processes and features that characterize periglacial environments are best developed in areas underlain by permafrost. Many engineering and land use problems arise in these areas that are not important under seasonally frozen ground. For these reasons an understanding of permafrost is central to the study of periglacial environments.

III. PERMAFROST

General

Frozen ground may be divided into two major types – *seasonally frozen ground* and *permafrost*. Seasonally frozen ground is the zone at the earth's surface where annual freezing and thawing takes place, while permafrost is material permanently maintained at 0° C (32° F) or below. Both kinds of frozen ground are important with respect to periglacial environments especially as they reflect intensity of frost processes. Seasonally frozen ground varies in thickness from a few millimeters to 2–3 m (7–10 ft.) and is usually deepest in the subarctic decreasing in depth in either direction, equatorward because of less severe winters and poleward because of the decreasing depth of thawing above permafrost. Permafrost exists poleward of seasonally frozen ground and may be a few meters to several hundred meters thick (Figure 9). Although the processes that give rise to deep seasonally frozen ground and permafrost are similar in the transition zone, the effects may be very different. Engineering problems, for example, are greatly magnified in permafrost areas.

Permafrost is defined exclusively on the basis of temperature. It is soil, bedrock, or other material that has remained below 0° C (32° F) continually for two to tens of thousands of years (Muller 1947, p. 3). The term *permafrost* was first suggested by Muller (1947, p. 3) as an abbreviation for the more proper expression, *permanently frozen ground*. Although there is still some tendency to use the Scandinavian *tjaele* or the Russian *vechnaya merzlota*, permafrost has been widely accepted and is in common usage today. It has not escaped criticism, however. Kirk Bryan called the term "an etymological monstrosity. . . . It sounds like a trade name for a refrigerator and 'permaform' and 'permalift' actually exist as trade names of types of brassieres" (Bryan 1946, p. 635).

Permafrost displays a wide range of qualities, depending on water availability, from pure ice to dry ground with no ice. Ice is the essential ingredient, however, and may occur in many forms—as a coating around individual soil particles, or as more or less pure segregated masses called *ground ice* (Shumskii 1964). Ground ice exists in many forms but since ice usually develops at right angles to the cooling plane, horizontal accumulations (lenses) are most common, although vertical accumulations (veins, wedges) may be prevalent at cracks and other zones of discontinuity. The amount of ground ice normally controls the behavior of permafrost upon thawing while the orientation of ice segregations is indicative of their origin (Washburn 1972, Chapter 3).

Moisture in permafrost is much more abundant in finely divided soils than in coarse soils, and it is normally frozen as either ground ice or as cementation in interstices of rock particles. There are some situations, however, where water may remain unfrozen several degrees below 0° C (32° F). Examples would be water containing salts or clayey material with abundant pore water allowing the depression of the freezing point by capillary forces. If water is lacking so that no cementation is present, it is known as *dry permafrost* (Muller 1947, p. 3). Dry permafrost is more desirable from an engineering standpoint since it is friable and easily excavated, while material with ice cementation is as hard as rock. The hardness of the material is a minor factor, however, compared to problems associated with thawing when permafrost has a high moisture content, i.e., slumping, collapse, or flow.

Thermal Characteristics

The essential feature for the occurrence of permafrost is an average annual temperature of 0° C (32° F) or below. Under these conditions the depth of winter freezing will exceed the amount of summer thawing and a layer of frozen ground will be added to the bottom of permafrost each year until the downward penetration is balanced by heat flowing upward from the earth's interior. This internal earth heat results in a normal temperature increase with depth on the order of 1° C (1.8° F) per 30 m (100 ft.) and is called the *geothermal gradient* (Lachenbruch, Brewer, Greene, and Marshall 1962, p. 791). Thus an equilibrium depth is eventually reached where heat from the earth's interior just offsets the negative temperatures filtering downward from the surface, and permafrost ends (Figure 4).

The greatest temperature fluctuations in permafrost areas take place immediately above the ground surface and in the *active layer*, which is the zone above permafrost that

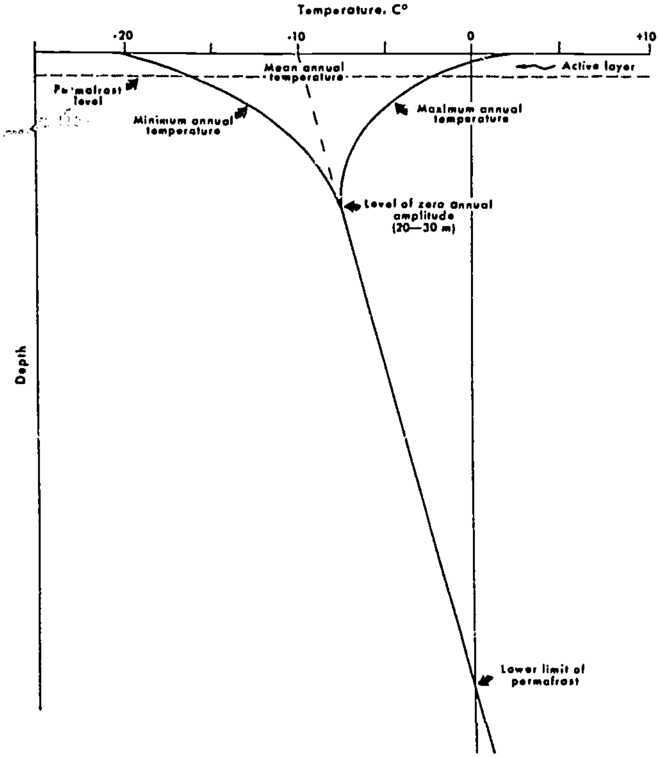

Figure 4. Idealized geothermal gradient in permafrost, indicating the fact that temperatures increase at a fairly steady rate with depth due to heat escaping from the earth's interior. Greatest temperature fluctuations occur at the surface and decrease with depth until *zero annual amplitude* is reached, below which seasonal changes do not occur. (Adapted from Lachenbruch, Brewer, Greene, and Marshall 1962, Figure 1, p. 792.)

thaws in summer and freezes in winter (Muller 1947, p. 6) (Figure 4). The average air temperature is usually lower than the average ground surface temperature, however, since the ground is often insulated by snow in winter but is bare during the summer. For example, at Barrow, Alaska the mean annual air temperature is −12.1° C (10.2° F) (Brewer 1958, p. 22). With increasing depth, temperature fluctuations decrease until a point is eventually reached where temperatures remain unchanged the year round. This level is called *zero annual amplitude* (Muller 1947, p. 11) (Figure 4). Zero annual amplitude varies from place to place but it is generally between 20–30 m (65–100 ft.)

Figure 5 gives the amplitude of seasonal temperature change of the air and different depths below the surface at Barrow, Alaska. In addition to showing decreasing temperature fluctuations with depth, the curves reflect a "lag" at each successive depth. For example, minimum temperatures at 4.6 m (15 ft.) occur in the spring while at 9.1 m (30 ft.) they take place in midsummer (Figure 5). It is this factor that is responsible for the occasional spring and summer freezing of wells and pipelines in periglacial areas.

Substantially different processes operate in the spring and fall in the zone above zero annual amplitude, giving rise to asymmetry in the annual temperature curves (Figure 5). In the spring the active layer is completely frozen so when air temperatures rise, heat penetrates into the ground and melting takes place from the surface downward, resulting in a relatively uniform temperature rise throughout. In the fall, however, lowering of the temperature in moist ground does not penetrate at a uniform rate. A sandwich of unfrozen material develops between the frozen surface and permafrost, and as freezing progresses considerable pressure is created, depressing the freezing point. The major factor in impeding the rate of freezing, however, is the heat released when water freezes (latent heat of fusion). This often causes the temperature to remain at or slightly above 0° C (32° F) for a considerable length of time and is known as the *zero curtain* effect (Muller 1947, p. 17). Many tundra areas are poorly drained due to the impermeable nature of

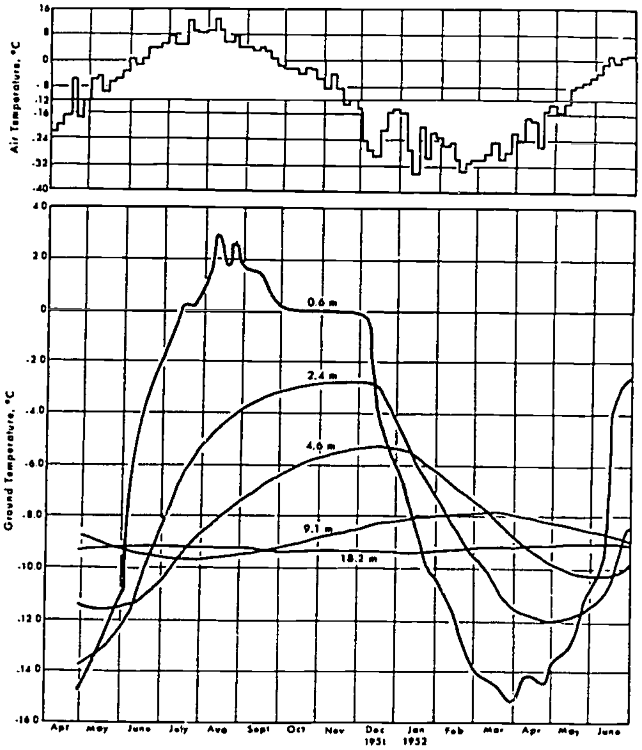

Figure 5. Typical air and ground temperatures at Barrow, Alaska. Note the basic asymmetry of the temperature curves and the decreasing amount of annual fluctuation with depth. Of particular interest is the "lag" at increasing depths in the spring (compare 0.6, 2.4 and 4.6 m depths from March through May). At 0.6 m (2 ft.) the temperature remains at 0° C (32° F) through October and November due to the *zero curtain* effect. (Adapted from Lachenbruch, Brewer, Greene, and Marshall 1962, Figure 6, p. 796.)

permafrost, and in the presence of abundant water the zero curtain may last for a month or so, and under extreme conditions for three to four months. This is well illustrated at a depth of 0.6 m (2 ft.) in Figure 5. Temperatures decrease in the autumn, but once they reach the freezing point they level off and stay essentially stationary through the months of October and November (Figure 5). The practical significance of the zero curtain is that it allows, to a certain extent, the artificial regulation of the heat balance in the ground. For example, a pipeline could be surrounded with a layer of permeable clay and a low heat conductive material such as peat moss or a commercial substitute, and the high water holding ability of this material would extend the zero curtain effect, possibly protecting the pipe from severe freezing.

A major factor affecting the thermal regime of permafrost is the presence of water bodies (Figure 6). Small lakes freeze completely in winter so they do not have a major effect on permafrost, but they thaw more quickly in the summer due to more efficient warming by water circulation and, as a result, permafrost is slightly thinned (Figure 6a, b). Lakes deeper than 1.5 m (5 ft.) normally do not freeze completely even in the high arctic, and the result is an underlying thawed basin and an upward indentation at the bottom of permafrost (Figure 6c, d, e). In large lakes (diameter at least twice as wide as the permafrost depth) there will be an unfrozen zone extending completely through permafrost beneath the lake (Figure 6f, g). Such features provide a year-round source of ground water in the continuous permafrost zone (Ferrians, Kachadoorian, and Greene 1969, p. 5). In terms of its thermal effect, a river behaves like a long thin lake and the ocean like a very large deep lake (Figure 6h, i). Permafrost probably does not exist beneath the ocean bottom more than a few hundred meters offshore (Lachenbruch 1957). In addition to the examples listed above, there is a general tendency for the top and bottom of permafrost to parallel the ground surface, rising over hills and lowering beneath valleys (Figure 6j, k) (Ferrians, Kachadoorian, and Greene 1969, p. 5).

One of the more recent and very fruitful phases of permafrost research has been the measurement of temperatures at great depths from bore holes. Figure 7 shows three such profiles from arctic Alaska. These follow expected geothermal gradients, revealing a temperature increase with depth on the order of 1° C (1.8° F) for 24–50 m (80–165 ft.). In addition, these profiles yield important information about past climatic change. For example, the temperature curves in the upper 100 m (330 ft.) of Figure 7 clearly represent a recent climatic warming. On the basis of theoretical reconstruction, the mean annual surface temper-

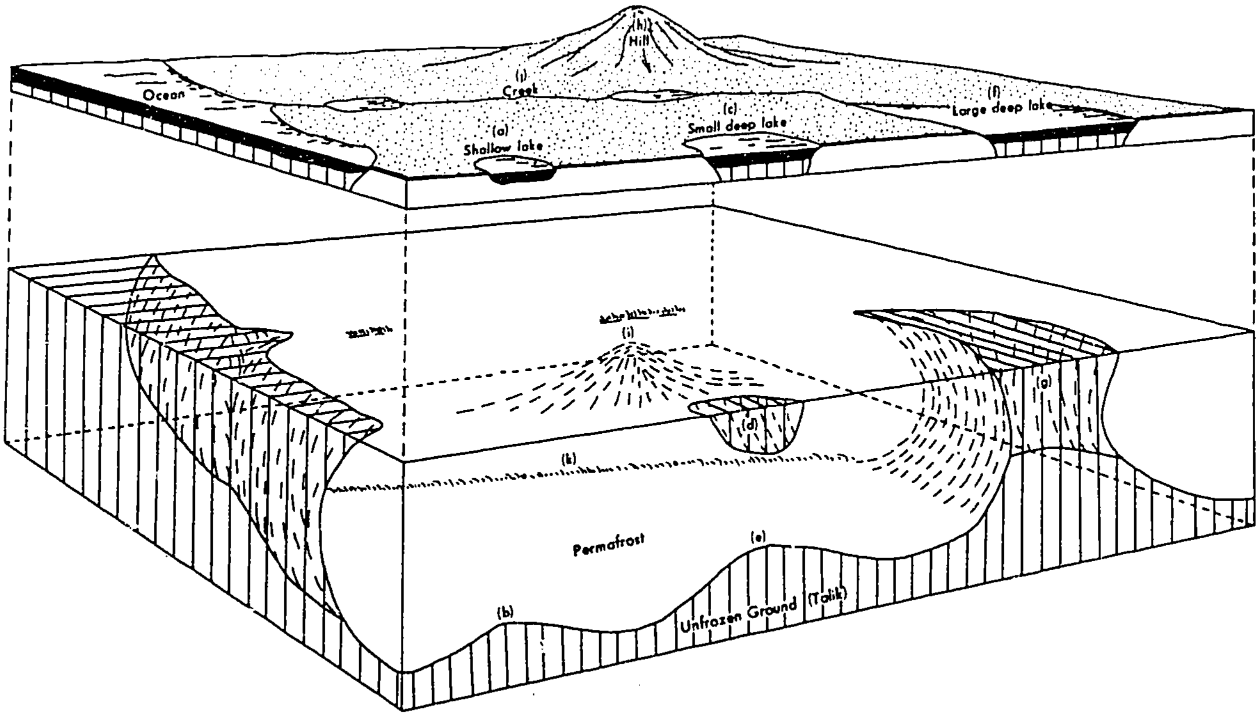

Figure 6. Schematic representation of the effect of water bodies on permafrost. Note that areas underlying large lakes are completely thawed. In general, the bottom topography of permafrost closely follows that of the ground surface. (After Lachenbruch, Brewer, Greene, and Marshall 1962, Figure 8, p. 798.)

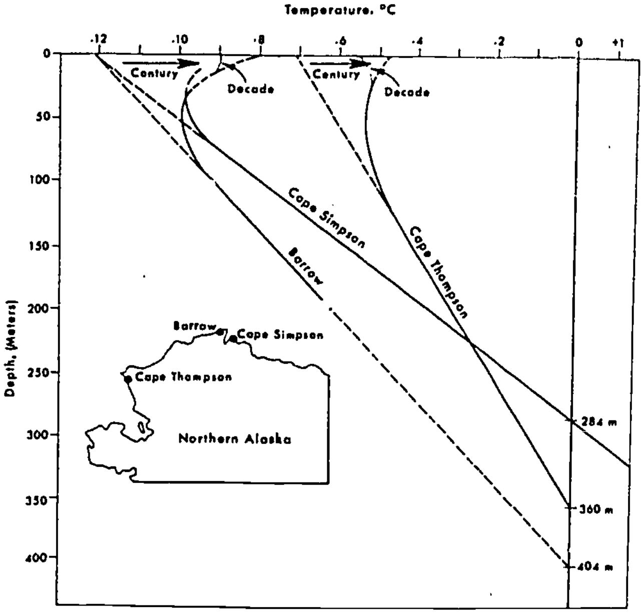

Figure 7. Temperatures with depth at three locations in arctic Alaska (solid lines). Dashed and dotted lines are theoretical extrapolations. By comparing the actual temperature near the surface to what it formerly was (extrapolated), one can identify climatic trends. These curves from northern Alaska indicate slightly higher temperatures for the last century but a cooling trend for the last decade. (After Lachenbruch and Marshall 1969, Figure 2, p. 302.)

ature at Barrow has increased about 4° C (7° F) since the middle of the 19th century. Moreover, present surface temperatures are lower, and this appears to represent a cooling trend for the last decade or so (Lachenbruch and Marshall 1969, pp. 302–304) (Figure 7).

Heat flow measurements are much simplified in permafrost since water is immobilized in the frozen state and temperatures are largely determined by conductive transfer. On the other hand, in middle latitudes complex heat transfer by moving fluids may dominate the geothermal field (Lachenbruch, Brewer, Greene, and Marshall 1962, p. 792). For this reason, simple heat conduction models (see p. 795 of previous reference) can be used with confidence in permafrost areas and, as illustrated, may yield tremendously valuable information (Figure 7).

Distribution

Permafrost underlies about 26% of the land surface of the earth, covering approximately 22.4 million km^2 (8.6 million mi.^{2}) in the northern hemisphere and 13.1 million km^2 (5.1 million mi.^{2}) in the southern hemisphere (Black 1954, Table 1, p. 840). The reason for the greater amount of permafrost in the northern hemisphere is the contrasting distribution of land and water in the respective hemispheres. Two major differences are at once apparent: (1) the north polar area is occupied by water and surrounded by land, while the south polar area is occupied by land and surrounded by water; (2) as a result, much of the circumpolar area of the southern hemisphere is occupied by water while the circumpolar area of the northern hemisphere is occupied by land. Although these basic geographic facts are patently obvious, they greatly affect the distribution of permafrost. Much of the circumpolar area of the northern hemisphere is underlain by permafrost, while Antarctica is the only major area of occurrence in the southern hemisphere and it is largely ice-covered, so permafrost conditions there are poorly known. It should come as no surprise, then, that our knowledge of permafrost has been gained largely from the northern hemisphere.

As can be seen from Figure 8, permafrost extends farthest south on the leeward and more continental areas of both North America and Eurasia and occurs on the eastern seaboard of both continents at about 55° N. latitude. The southernmost extension of contiguous permafrost is reached in the high plateau country of Mongolia south of Lake Baikal. This is due to the more rigorous continental climate and higher elevations in this region of Siberia as compared with eastern Canada.

Although many different schemes have been devised to classify and map permafrost, it is conveniently divided into two major zones – continuous and discontinuous (Figure 8). The former is underlain by deep permafrost everywhere while the latter is more shallow and has permafrost-free areas which increase in size and number southward until it occurs only as isolated patches (Figure 9). Unfrozen areas occurring in permafrost are called *taliks*, a Russian term meaning "thawed ground." A talik can appear as an island of unfrozen material at the surface, as a thawed layer within permafrost, or as unfrozen material beneath permafrost (Figure 9). The presence of taliks in continuous permafrost is fortunate since they serve as aquifers and are often the only source of water during the winter. An additional advantage is that the water is frequently under hydrostatic pressure, and pipes imbedded in taliks are not likely to freeze and break (Muller 1947, p. 10). Toward the southern margin of discontinuous permafrost, taliks become more prevalent (Figure 9) and increasingly reflect the influence of local factors such as slope, exposure, vegetation, drainage, snow cover, and ground water circulation. North facing slopes may be underlain with permafrost while south facing slopes may be permafrost-free. Also peatlands which occur throughout the southern margin of the discontinuous zone in Canada, are usually underlain by permafrost due to the excellent insulating ability of the mosses (Brown 1968).

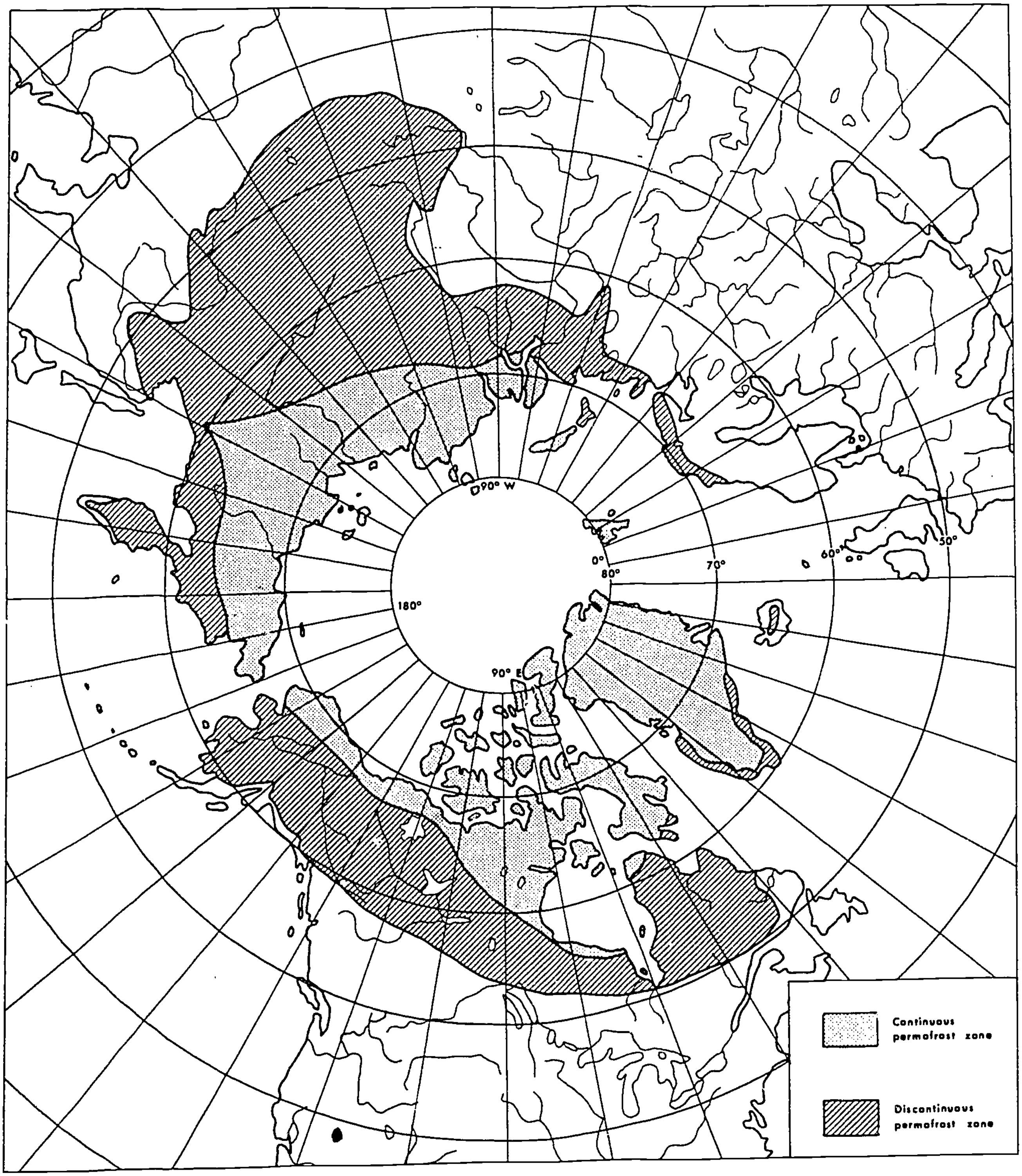

Figure 8. Distribution of permafrost in the Northern Hemisphere. The continuous permafrost zone is everywhere underlain by deep permafrost, while the discontinuous zone has occasional permafrost-free areas. Note the more southerly extent of permafrost on the leeward sides of the continents. (After Ferrians, Kachadoorian, and Greene 1969, Figure 1, p. 2.)

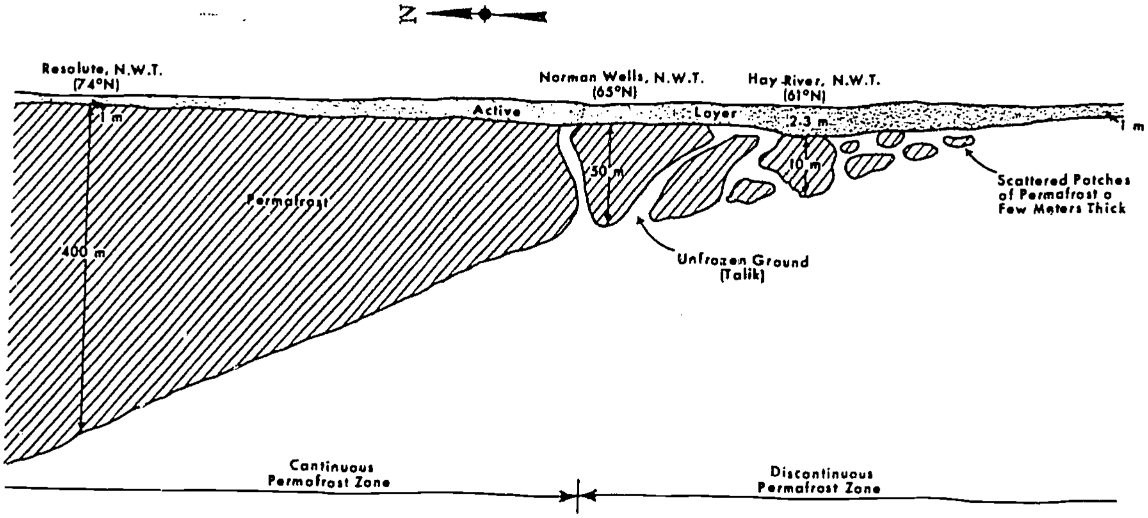

Figure 9. Idealized cross section of the continuous and discontinuous permafrost zone. Note that the active layer is deepest in the subarctic and decreases in depth both north and south. (Adapted from Brown 1970, Figure 4, p. 8.)

Climate is still the major controlling factor for permafrost, however, even though many factors can be important on the local level. The southern limit of discontinuous permafrost in Canada coincides closely with the −1° C (30° F) isotherm, and the continuous permafrost zone occurs at about the −6° C (21° F) isotherm although it is slightly south of it along Hudson Bay (Brown 1967, map). The same general temperature and permafrost conditions exist in Alaska (Ferrians 1965, map) and in Eurasia (Baranov 1964, Figure 24, p. 83).

Depth

The greatest depths of permafrost occur in the nonglaciated areas of the continuous zone since these were not protected by the ice and were subjected to the extreme cold. Russian scientists have long held that glaciation and permafrost are antagonistic—that glaciation develops in oceanic climates with abundant precipitation, while permafrost develops in continental climates (Gerasimov and Markov 1968). Although it is certain that permafrost does exist under some glaciers, it is uncertain whether the areas underlain by thick ice caps, such as Greenland and Antarctica, have permafrost.

There are some indications that Greenland may be underlain with permafrost, while Antarctica may not be. A recent bore hole drilled through the Antarctic ice to a depth of 2164 m (7,098 ft.) has revealed a layer of unfrozen water 0.3 m (1 ft.) thick underlying the ice and the temperature was estimated to be −1.6° C (29.1° F), the pressure melting point (Ueda and Garfield 1968, pp. 111–112). The maximum recorded permafrost thickness in Antarctica is 150 m (500 ft.) beneath a glacier-free area (Williams 1970, p.15) so it is very possible that permafrost extends only in the form of a belt around the periphery of Antarctica (Grave 1968, p. 6). If this holds true, it will cause a major revision in total permafrost estimates.

The average permafrost depth in the continuous zone of North America is 245–365 m (800–1,200 ft.) while it is 305–460 m (1,000–1,500 ft.) in Eurasia (Black 1954, p. 842). Permafrost depths decrease southward and are usually less than 60 m (200 ft.) in the discontinuous zone. The deepest known permafrost is 1500 m (4,920 ft.) in Siberia near the Arctic Circle on the upper Markha River, a left bank tributary of the Viliui (Grave 1968, pp. 3–4). This may be an anomaly, however, due to special geologic structure since the maximum known permafrost depth even much farther north is 650 m (2,130 ft.) (Table 1). The greatest known published depth in North America is 548 m (1,800 ft.) at Melville Island, Northwest Territories (Lachenbruch 1968, p. 835), although recent measurements through permafrost near Prudhoe Bay, Alaska indicate a depth of about 609 m (2,000 ft.) (Personal communication, Arthur Lachenbruch). Table 1 gives permafrost depths for selected sites in the northern hemisphere.

Origin

Permafrost is a reflection of both past and present climatic conditions. Its great depth in the unglaciated areas of Siberia and North America reflect the influence of past climates since it would have taken millenia for these thicknesses to have accumulated at normal rates of growth (a few centimeters per year). It can be calculated from simple conduction theory that the present depth of permafrost at Barrow, Alaska (Table 1) took at least 10,000

TABLE I

Selected Northern Hemisphere Permafrost Thicknesses

Location	Mean Annual Air Temperature	Thickness of Permafrost
ALASKA		
Prudhoe Bay (70°N, 148°W)	−7 to 0° C (20 to 32° F)	609 m (2,000 ft.)
Barrow (71°N, 157°W)	−12 to −7° C (10 to 20° F)	405 m* (1,330 ft.) 16 km (10 miles) inland
Umiat (69°N, 152°W)	−12 to −7° C (10 to 20° F)	322 m (1,055 ft.) 235 m (770 ft.) under Colville River
Cape Thompson (68°N, 166°W)	−12 to −7° C (10 to 20° F)	306 m* (1,000 ft.)
Bethel (60°N, 161°W)	−7 to 0° C (20 to 32° F)	184 m (603 ft.) 13 m (42 ft.) under Kuskokwim River
Ft. Yukon (66°N, 145°W)	−7 to 0° C (20 to 32° F)	119 m (390 ft.) 5.5 m (18 ft.) under Yukon River
Fairbanks (64°N, 147°W)	−7 to 0° C (20 to 32° F)	81 m (265 ft.)
Kotzebue (67°N, 162°W)	−7 to 0° C (20 to 32° F)	73 m (238 ft.)
Nome (64°N, 165°W)	−12 to −7° C (10 to 20° F)	37 m (120 ft.)
McKinley Natl. Park-East Side (64°N, 149°W)	extremely variable	30 m (100 ft.)
CANADA		
Melville Island, N.W.T (75°N, 111°W)	————	548 m (1,800 ft.) near coast, probably thicker interiorward
Resolute, N.W.T. (75°N, 95°W)	−16.2° C (2.8° F)	396 m (1,300 ft.)
Port Radium, N.W.T. (66°N, 118°W)	−7.1° C (19.2° F)	106 m (350 ft.)
Ft. Simpson, N.W.T. (61°N, 121°W)	−3.9° C (25.0° F)	91 m (300 ft.)
Yellowknife, N.W.T. (62°N, 114°W)	−5.4° C (22.2° F)	61-91 m (200-300 ft.)
Schefferville, P.Q. (54°N, 67°W)	−4.5°C (23.9° F)	76 m (250 ft.)
Dawson, Y.T. (64°N, 139°W)	−4.6° C (23.6° F)	61 m (200 ft.)
Norman Wells, N.W.T. (65°N, 127°W)	−6.2° C (20.8° F)	46-61 m (150-200 ft.)
Churchill, Man. (58°N, 94°W)	−7.1° C (19.2° F)	30-61 m (100-200 ft.)
U.S.S.R.		
Upper Reaches of Markha River (66°N, 111°E)	————	1500 m (4,920 ft.)
Udokan (57°N, 120°E)	−12° C (10.4° F)	900 m* (2,950 ft.)
Bakhynay (66°N, 124°E)	−12° C (10.4° F)	650 m (2,130 ft.)
Isksi (71°N, 129°E)	−14° C (6.8° F)	630 m (2,070 ft.)
Mirnyy (63°N, 114°E)	−9° C (15.8° F)	550 m (1,805 ft.)
Ust'-Port (69°N, 84°E)	−11° C (12.2° F)	425 m (1,395 ft.)
Salekhard (67°N, 67°E)	−7° C (19.4° F)	350 m (1,150 ft.)
Noril'sk (69°N, 88°E)	−8° C (17.6° F)	325 m (1,070 ft.)
Yakutsk (62°N, 129°E)	————	195-250 m (650-820 ft.)
Vorkuta (67°N, 64°E)	————	130 m (430 ft.)

*A calculated depth not actually measured.

Various sources, but chiefly the following: Brown 1967, map; Ferrians 1965, map; Yefimov and Dukhin 1968.

years to accumulate and it is probably much older than this. On the other hand, the southern boundary of permafrost closely coincides with the 0° C (32° F) isotherm and indicates that its present distribution reflects current climatic conditions. There are other kinds of evidence, too, for both the ancient and contemporary nature of permafrost.

One evidence in favor of the great age of permafrost is the discovery of wooly mammoths and other extinct mammals in Siberia and Alaska (largely in the unglaciated areas). Some of these beasts have been amazingly well preserved with flesh still intact and food in their stomachs (Figure 10). Carbon-14 dating indicates time of death to be from 15 to 30 thousand years ago (Farrand 1961, pp. 732–733; Péwé 1967, pp. 40–44). Permafrost must have existed at the time of death and continuously since to have maintained these carcasses in such good condition (Figure 10).

Another indicator of the antiquity of permafrost is its presence at considerable depths below the surface of unfrozen ground. In still other cases there is permafrost at the surface, a thawed zone, and then another layer of permafrost. These conditions occur in the discontinuous permafrost zone and reflect past climatic change (Grave 1968, pp. 6–10). There are also regions where temperatures decrease with depth rather than increase as is normally the case. This is thought to be due to residual cold preserved from a more severe climatic period (Gerasimov and Markov 1968, p. 12).

Figure 10. Extinct bison with partial flesh and hide still intact, discovered August 1951 in permafrost during placer gold mining operations near Fairbanks, Alaska. Radiocarbon dating of hide has established an age of 31,400 years (±2,000 years) for this creature. (Photo No. 600 by Troy L. Péwé, Arizona State University.)

The contemporary nature of permafrost is proven by the fact that it is being maintained under present climatic conditions. Although there are some areas where permafrost is slowly retreating, as along the southern margin of the discontinuous zone, there are other areas where permafrost is currently being formed. Examples are recently drained lakes, newly deposited sediments, and areas recently disturbed by man. A macabre example of the recency of permafrost is provided by Professor Troy Péwé (1967, p. 55). A research team from the University of Iowa was sent to Alaska to find a dormant flu virus responsible for the death of many Eskimos in the 1918 flu epidemic. Such an investigation was possible only because the bodies had been well preserved in permafrost.

Associated Features

A number of distinct landscape features are related to permafrost, particularly with respect to ground ice. Only the more important will be mentioned here—ice wedges and ice-wedge polygons, pingos, and thermokarst. These features are important in that they reflect special kinds of processes, but also in that they may be preserved as fossil forms in middle latitude environments and indicate the former presence of permafrost. Therefore, a knowledge of their characteristics is important to their recognition in the field. Unfortunately, there are other similar features not related to permafrost which are easily confused with them, so definite identification is not easy.

Ice wedges and ice-wedge polygons

Ice wedges are vertically oriented masses of relatively pure ice occurring in permafrost. They are usually wider at the top than at the bottom and range from 1 cm to 3 m (0.4 inch to 10 ft.) in width and from 1–10 m (3–33 ft.) in depth (Figure 11). The origin of ice wedges is generally accepted to be due to thermal contraction. This theory was first proposed by Leffingwell (1915), one of the early but major figures in permafrost research, and has more recently been given a sound theoretical basis by Lachenbruch (1962, 1966). The basic idea is that during the winter the tundra surface contracts due to very low temperatures, and tension cracks are created. These are reported to give off a sound like a rifle shot and to be accompanied by a shock "... of sufficient intensity to rattle dishes" (Leffingwell 1915, p. 638). The cracks that develop are usually only a few millimeters wide but may extend several meters in depth (Figure 12a). In the spring, water from melting snow freezes in these cracks and produces a vertical ice vein that penetrates permafrost (Figure 12b). As temperatures rise in

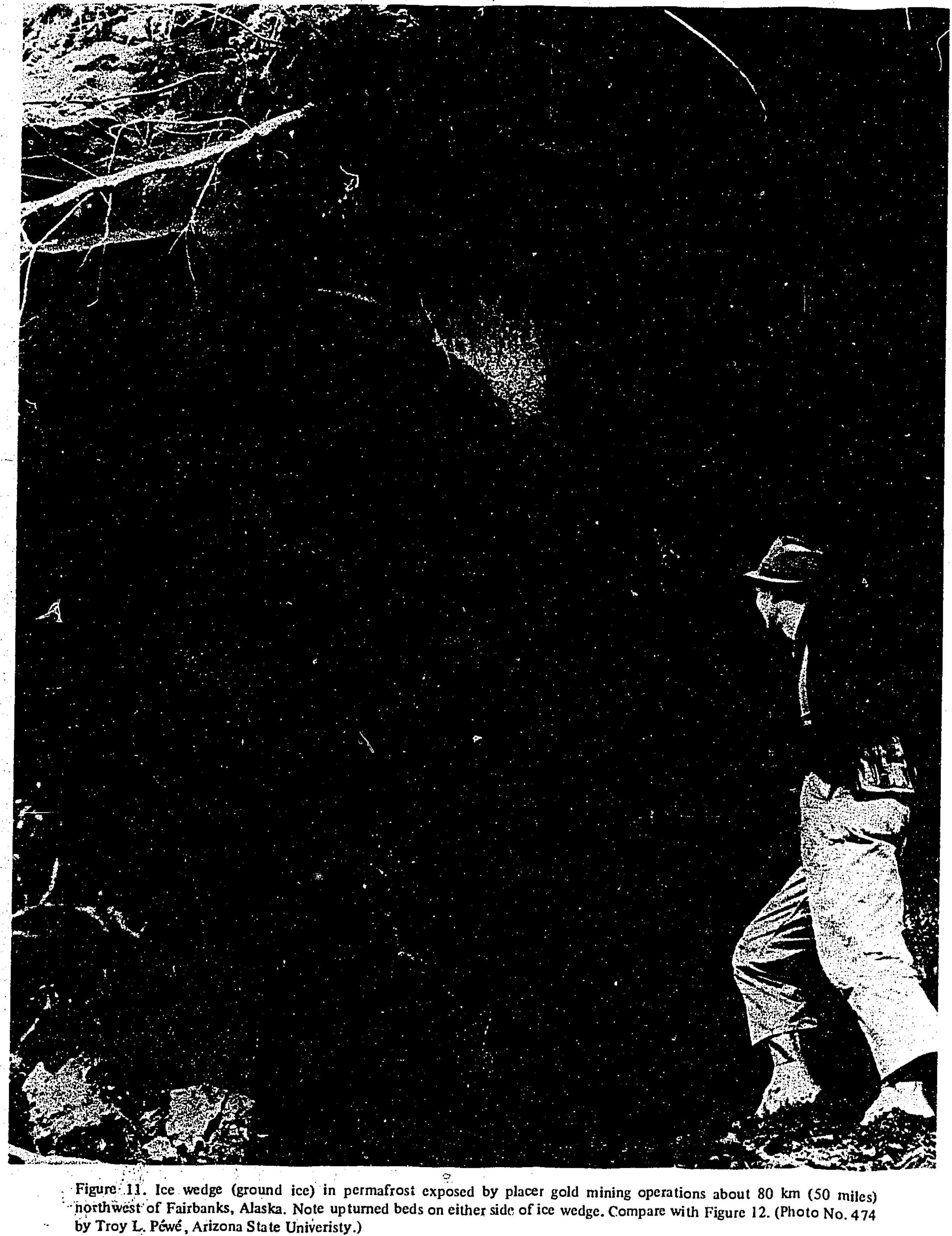

Figure 11. Ice wedge (ground ice) in permafrost exposed by placer gold mining operations about 80 km (50 miles) northwest of Fairbanks, Alaska. Note upturned beds on either side of ice wedge. Compare with Figure 12. (Photo No. 474 by Troy L. Péwé, Arizona State Univeristy.)

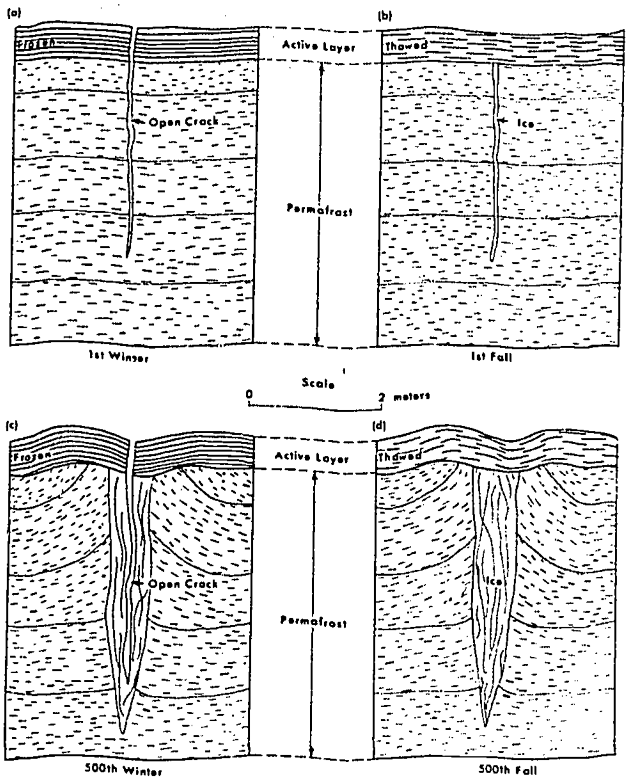

Figure 12. Schematic representation of ice-wedge evolution according to the thermal contraction theory. (After Lachenbruch 1966, Figure 6, p. 65.)

summer, the permafrost expands causing horizontal compression that results in upturning of the surrounding material by plastic deformation. In the following winter renewed thermal contraction reopens the crack since it is now a zone of weakness, and in the spring another increment of ice is added as meltwater enters the crack and freezes. Such a cycle operating for several hundred years creates an ice wedge (Figure 12c, d) (Lachenbruch 1966, p. 63).

Ice wedges may occur singly but they are most frequently connected at the surface in an extensive honeycomb system of *ice-wedge polygons* (Figure 13). These are among the most distinctive features of the tundra with a pattern similar to that formed by cracks in drying mud, a phenomenon to which they are fundamentally related, but on a much grander scale. The diameter of polygons, and therefore the spacing of ice wedges, ranges from a few meters to over 100 m (330 ft.) (Lachenbruch 1966, p. 63).

Polygons may be low centered or high centered depending on whether the margins of the polygons are higher or lower than the center. Ice wedge growth causes upturning of the strata within 3 m (10 ft.) of the wedge and this creates a ridge at the surface (Figure 11). If the ridge is prominent, as is often the case when the ice wedge is actively growing, the polygons are lower in the center and are called low-center polygons. If, on the other hand, thawing and erosion are more prevalent, small troughs or stream channels will form along the ice wedges and create high-centered polygons (Péwé 1966, p. 77) (Figure 13).

Most actively growing ice wedges and ice-wedge polygons are restricted to the continuous permafrost zone. In Alaska the mean annual temperature of this area ranges from –12° C (10.4° F) in the north to –6° C (21.2° F) in the south (Péwé 1966, p. 78). As temperatures increase in the discontinuous permafrost zone to the south, the ice wedges become inactive and eventually disappear (Figure 11). Once ice wedges become inactive and begin to melt, the space occupied by the ice is usually infilled with sediments creating a cast of the wedge. Such features are called fossil ice wedges and are among the few acceptable criteria of former permafrost (Washburn 1972, Chapter 4). Fossil ice wedges have been widely reported from the middle latitudes of Europe (Poser 1948; Johnsson 1959) as well as from the continental United States (Schafer 1949; Black 1965, 1969), but owing to the similarity of fossil ice wedges to features of various other origins, the presence of former permafrost in these areas has not yet been conclusively established.

Pingos

Pingo is an Eskimo word meaning "conical mound." It was first suggested by Porsild (1938, p. 46) for the large mounds found in the arctic, and it has since become a universally accepted term. Pingos vary from the barely perceptible to over 50 m (165 ft.) in height and up to 600 m (1,970 ft.) in diameter (Figure 14). They are ice-cored and relatively permanent features and as such should not be confused with the various types of small seasonal frost mounds, e.g., *palsas*, that also exist in the arctic. Pingos are restricted to permafrost and are best developed in the continuous zone but may also occur in the discontinuous zone (Holmes, Williams, Hopkins, and Foster 1968). A fundamental feature of pingos is that they are ice-cored and, as they increase in size, tension cracks develop at their summits allowing the development of small craters where lakes form due to melting of the exposed ice (Figure 14). Porsild (1938, p. 55) states that "The water of pingo lakes is fresh and sweet, never briny like the water of most of the lakes of the coastal plain. This fact is well known to the natives, who often walk long distances to get their drinking water from these lakes."

There are two main types of pingos–the Closed System type (Mackenzie type) and the Open System type (East Greenland type). The closed system type is best documented

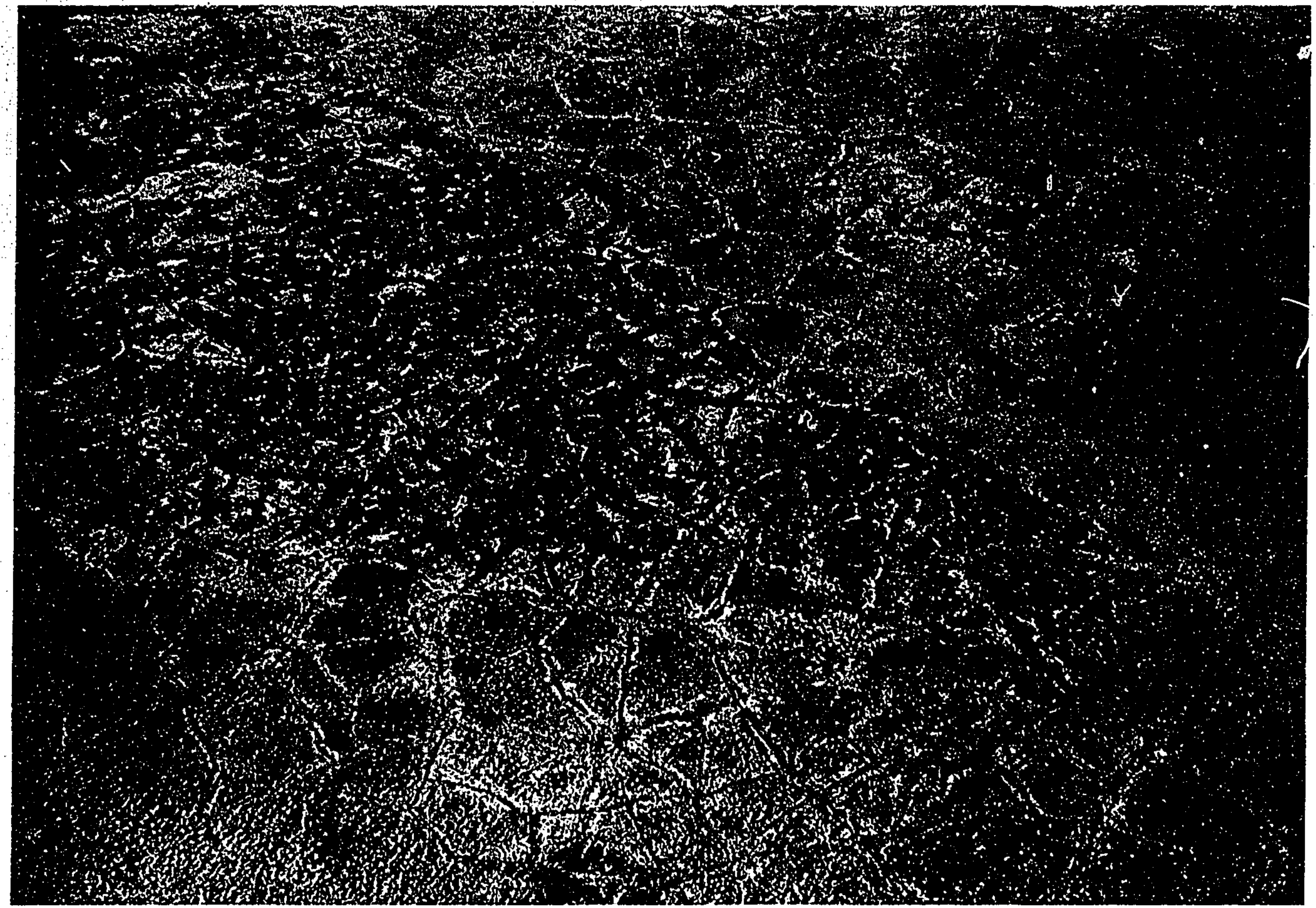

Figure 13. Aerial view of ice-wedge polygons in the Mackenzie River Delta area, N.W.T. To give perspective, the largest features are almost a city block across. An ice wedge similar to the one shown in Figure 11 occurs at each of the cracks. The darker polygons in center of photo are high-centered and indicate that ice wedges have become inactive and are melting. The lighter colored polygons in the upper right and lower part of photo are low-centered with ridges on either side of the cracks indicating that the ice wedges are active. (Photo by J. Ross Mackay, University of British Columbia.)

from the Mackenzie delta area of Canada where pingos occur in fairly level, poorly drained sites, especially shallow lake basins (Figure 14). A typical development would follow this sequence: The lake is drained by some process such as the changing water table. With the water gone, the heat balance is changed and permafrost can encroach on the lake bed as shown in Figure 15. If permafrost develops over the lake basin, a "closed system" may be created with the potential for producing considerable cryostatic pressure. The result is a mound forced up much the way the "...cork of a bottle filled with water is pushed up by the expansion of water when freezing" (Porsild, 1938, p. 55).

A major amount of work on the Mackenzie type pingo has been carried out by Professor J. Ross Mackay, University of British Columbia (Mackay 1962, 1966). Recently he has installed temperature cables to a depth of 30 m (100 ft.) along the shores of two lakes which he is going to drain artificially (Personal communication, J. Ross Mackay). Through this experiment he hopes to gain insight into the processes of pingo development. This is geomorphological field work at its best and is certainly the first time to my knowledge that anybody has attempted to "grow his own pingo."

The open system or East Greenland type pingo usually occurs on slopes rather than in level areas and is due to seeps or springs where artesian pressure develops in taliks (unfrozen areas) in the permafrost. As the water under pressure approaches the surface, it freezes and the continual supply of water allows the buildup of a considerable mass of ice which domes the surface upward. This type of pingo has been investigated in detail by Müller (1963).

There are, in addition, at least two more types of pingos

Figure 14. Closed-system pingos in the Mackenzie River Delta area, N.W.T. The far pingo is 43 m (140 ft.) high and the near one is 30 m (100 ft.) high. Note the tension cracks that have developed at their summits. (Photo by J. Ross Mackay, University of British Columbia.)

as reported by Pissart (1970) from Prince Patrick Island (76° N, 120° W). These belong to neither the East Greenland nor the Mackenzie type and suggest that the possible varieties of pingos are more numerous than previously thought, illustrating again the paucity of our knowledge of periglacial environments. Undoubtedly, many of the concepts and theories now held to be true will need to undergo major revision as future research is carried out.

Most indications are that pingos grow very slowly and that large ones are probably several hundred to several thousand years old. Radiocarbon dating has placed the age of two large pingos in the Mackenzie delta at 4,000 and 7,000–10,000 years old, respectively (Müller 1962, p. 284). The average growth rate for pingos is a few centimeters to a maximum of 0.6 m (2 ft.) per year (Müller 1963, p. 46). Although most large pingos are quite old, there is evidence that some may be currently growing. Porsild (1938, p. 52) mentions that the Eskimo names of some pingos suggest growth, such as "the one that is growing" or "the poor thing that is getting to be a pingo." Mackay has observed the development of several young pingos in the Mackenzie delta which have formed since 1950 when a coastal recession caused the drainage of a lake; they are now about 6 m (20 ft.) high (in Washburn 1972, Chapter 4).

The existence of fossil pingos indicates a formerly more severe environment since pingos are by definition closely related to permafrost. Fossil forms are recognized by their pattern and internal collapse form and are being reported increasingly from former periglacial environments (Mullenders and Gullentops 1969; Wayne 1967, p. 402).

Thermokarst

Thermokarst is a collective term for a variety of features resulting from the differential melting of ground ice in permafrost. As the name implies, it resembles true karst and includes such features as mounds, caverns, disappearing streams, funnel-shaped pits, elongated troughs, and large flat-floored valleys with steep sides. The fundamental

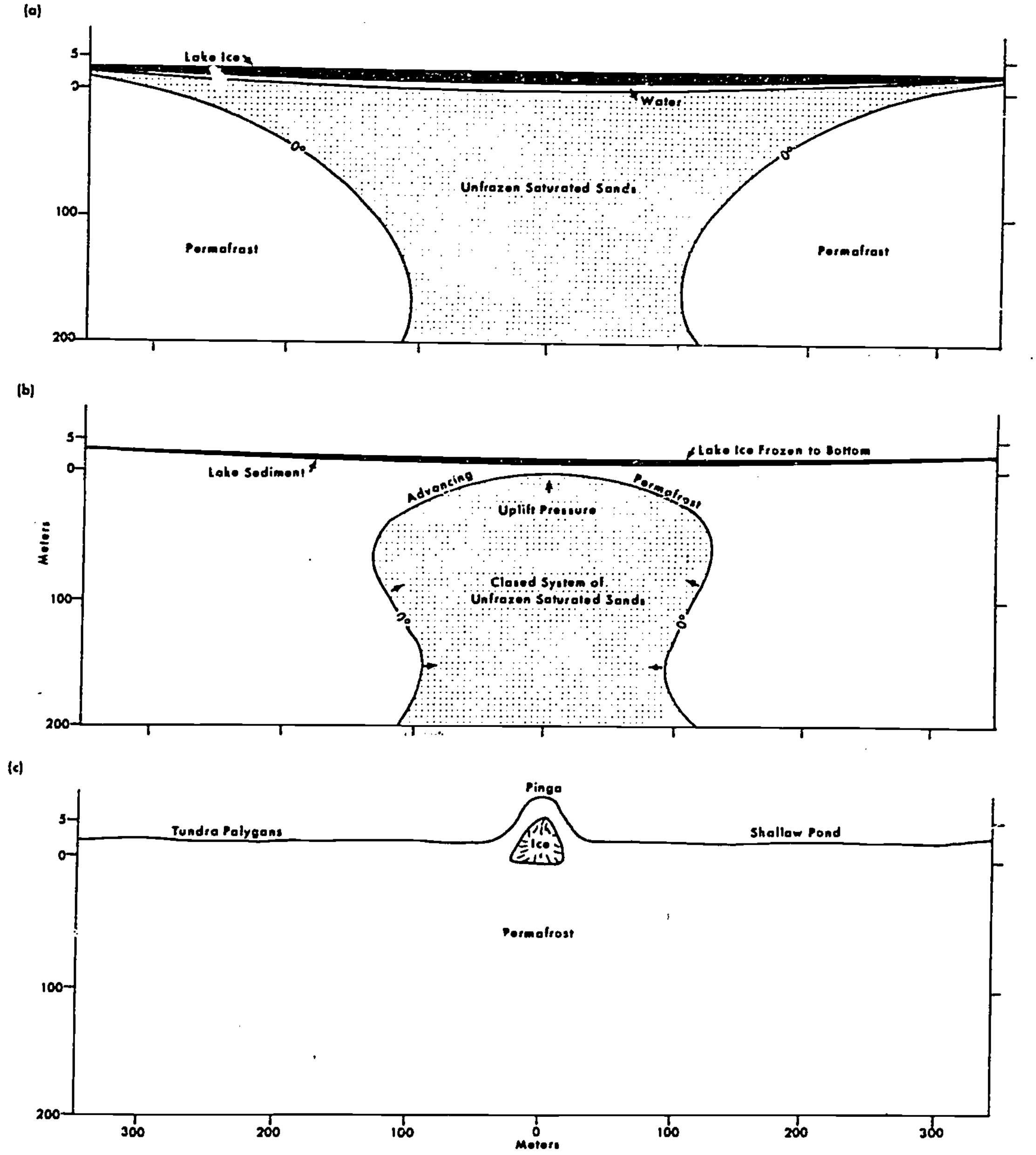

Figure 15. Schematic origin of the closed system (Mackenzie) type pingo. There is a vertical exaggeration of 5x in the height above zero in order to show the lake. (a) An unfrozen basin normally exists below lakes 1.5–2 m (5–7 ft.) deep in permafrost areas since they do not freeze completely to the bottom; (b) If a lake is shoaled, however, permafrost will encroach upon the unfrozen area and create a closed system of the unfrozen material; (c) The surface above the closed system is domed upward due to cryostatic pressure creating a pingo. (After Mackay 1962, Figure 15, p. 53.)

difference is that karst is formed through chemical processes in bedrock while thermokarst is formed by physical processes in permafrost.

Thermokarst is created when the thermal regime of permafrost is disrupted. This may be caused by broad-scale climatic changes or by local environmental changes. Climatically induced causes include a rise in the mean temperature or precipitation, or an increase in continentality leading to warmer summers (Kachurin 1962, pp. 29–30). Local changes favoring thermokarst development include cyclic changes in vegetation, shifting of stream channels, fire, and disruption of vegetation by man. Clearing of the forest for agricultural purposes near Fairbanks, Alaska in the early 1920's led to the development of an extensive pattern of thermokarst mounds varying from 3–15 m (10–50 ft.) in diameter and 0.3–2.4 m (1–8 ft.) in height (Rockie 1942). The area was underlain by ice-wedge polygons, and when the vegetation was removed the ice wedges began to thaw, causing the overlying soil to collapse in a polygonal pattern resulting in mounds in the intervening areas (Péwé 1954, pp. 331–333) (Figure 16). Similar features are well developed in Siberia, where they are called *baydjarakhs* (Czudek and Demek 1970, pp. 110–112). The famous "mima mounds" of southwestern Washington state are also theorized to have formed in a similar fashion (Péwé 1948; Ritchie 1953).

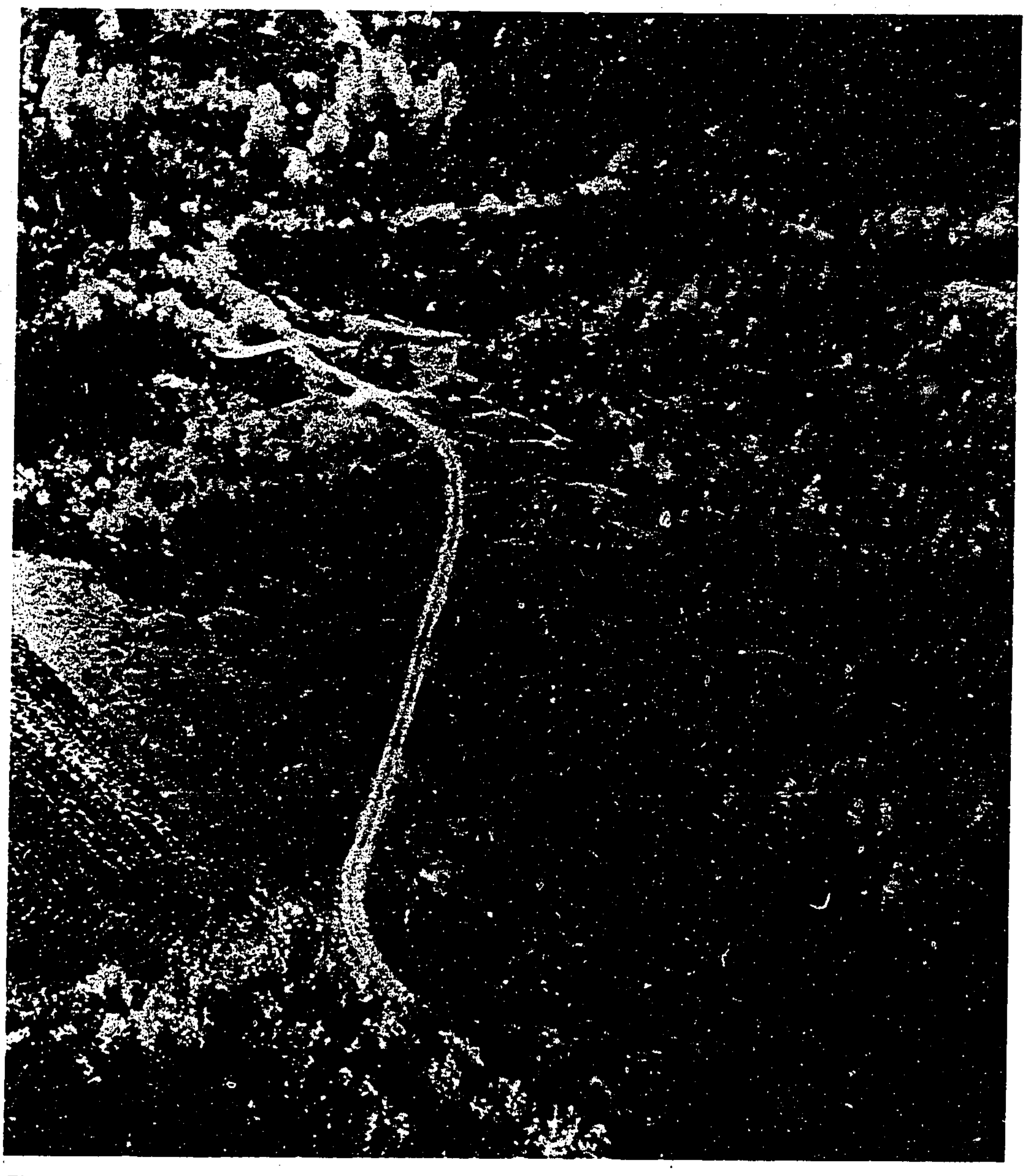

Figure 16. Low angle aerial view of thermokarst mounds near Fairbanks, Alaska. Mounds are 1–2 m (3–7 ft.) high and 3–9 m (10–30 ft.) in diameter and developed after the forest was cleared for cultivation. They were created by thawing of ice wedges and slumping of material inward at the depressions around the mounds. (Photo by Robert F. Black and Troy L. Péwé, September 1948.)

From a geomorphological point of view, the origin of thermokarst can be divided into two main groups—lateral permafrost degradation (backwearing) and permafrost degradation from above (downwearing) (Czudek and Demek 1970, p. 105). Backwearing is largely due to fluvial, lacustrine, or marine erosion. Rivers in permafrost areas undercut their banks during the spring melt and expose ice wedges or other kinds of ground ice which subsequently melt and collapse. If ice-wedge polygons are present, the conical mounds (baydjarakhs) may develop. Large ampitheater-like forms called *thermocirques* are also created in valley sides (Figure 17) as is well documented in Siberia (Czudek and Demek, 1970).

Perhaps the best example of backwearing in North America is the development of *thaw lakes* (Hopkins 1949). These lakes are characterized by undercutting along their margins due to thawing of permafrost and are dynamic features, constantly changing shape, coalescing, and often migrating across the tundra (Tedrow 1969). The well-documented *oriented lakes* in Alaska are a type of thaw lake (Figure 18). These range from small ponds to over 16 km (10 miles) in length and cover more than 65,000 km^2 (25,000 mi.^{2}) on the arctic slope. Their orientation is apparently due to prevailing wind directions although there is disagreement as to the exact process involved (Black and Barksdale 1949; Carson and Hussey 1962). They are consistently oriented to the north–northwest and are strikingly shown on topographic maps of the area (Figure 18). The enigmatic Carolina Bays of North Carolina have been interpreted as being periglacial features of similar origin (Brunnschweiler 1962) but this is not proved and is very controversial.

Permafrost degradation from above (downwearing) is largely restricted to fairly level areas. Specific features depend on the amount and kind of ground ice present, and where the amount is small the result is often flat and shallow depressions. Czudek and Demek (1970, p. 110) cite an example from the taiga in Siberia where a small forest fire occurred in 1953 and measurements in 1965 showed an increase in the active layer from 40 to 80 cm (16–31 inches) and the ground surface itself had settled 20 cm (8 inches). An example given by Mackay (1970) from the Canadian Arctic illustrates that even very small disturbances can create thermokarst. At a tundra research station where he was working, an Eskimo tied his dog to a stake with a 1.5 m (5 ft.) chain. It was summer time and after about 10 days the dog had badly trampled the vegetation cover so he was moved to another site. Within two years the site had subsided "like a pie plate" 18–23 cm (7–9 inches) and the depth to permafrost was 10–13 cm (4–5 inches) greater within the depression than in the surrounding undisturbed area (Mackay 1970, p. 425).

Thermokarst forms are more distinct in areas with large amounts of ground ice, particularly where ice wedges and ice-wedge polygons occur. Even in areas of actively forming ice wedges, as on the arctic slope of Alaska, the heat of water accumulating over ice wedges in the summer often causes thawing and creates troughs. The continuation of this process leads to the development of *beaded drainage*, which consists of a series of small pools connected by short straight watercourses. The pools range from 0.6–2.4 m (2–8 ft.) deep and up to 30 m (100 ft.) in diameter and usually form at the intersection of ice wedges. Viewed from the air these streams have the appearance of a string of beads (Hopkins, Karlstrom, and others 1955, p. 141).

Thermokarst development may also be very extensive

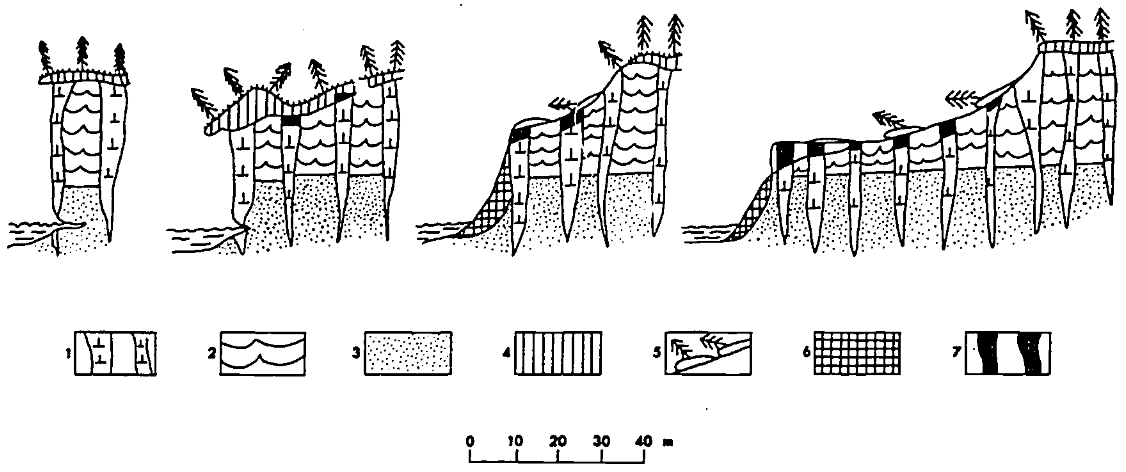

Figure 17. Thermocirque development along a river bank. 1. Ice wedges; 2. Frozen loams; 3. Frozen sand; 4. Active layer; 5. Mud flows; 6. Transported material; 7. Casts of ice wedges. (Adapted from Czudek and Demek 1970, Figure 3, p. 106.)

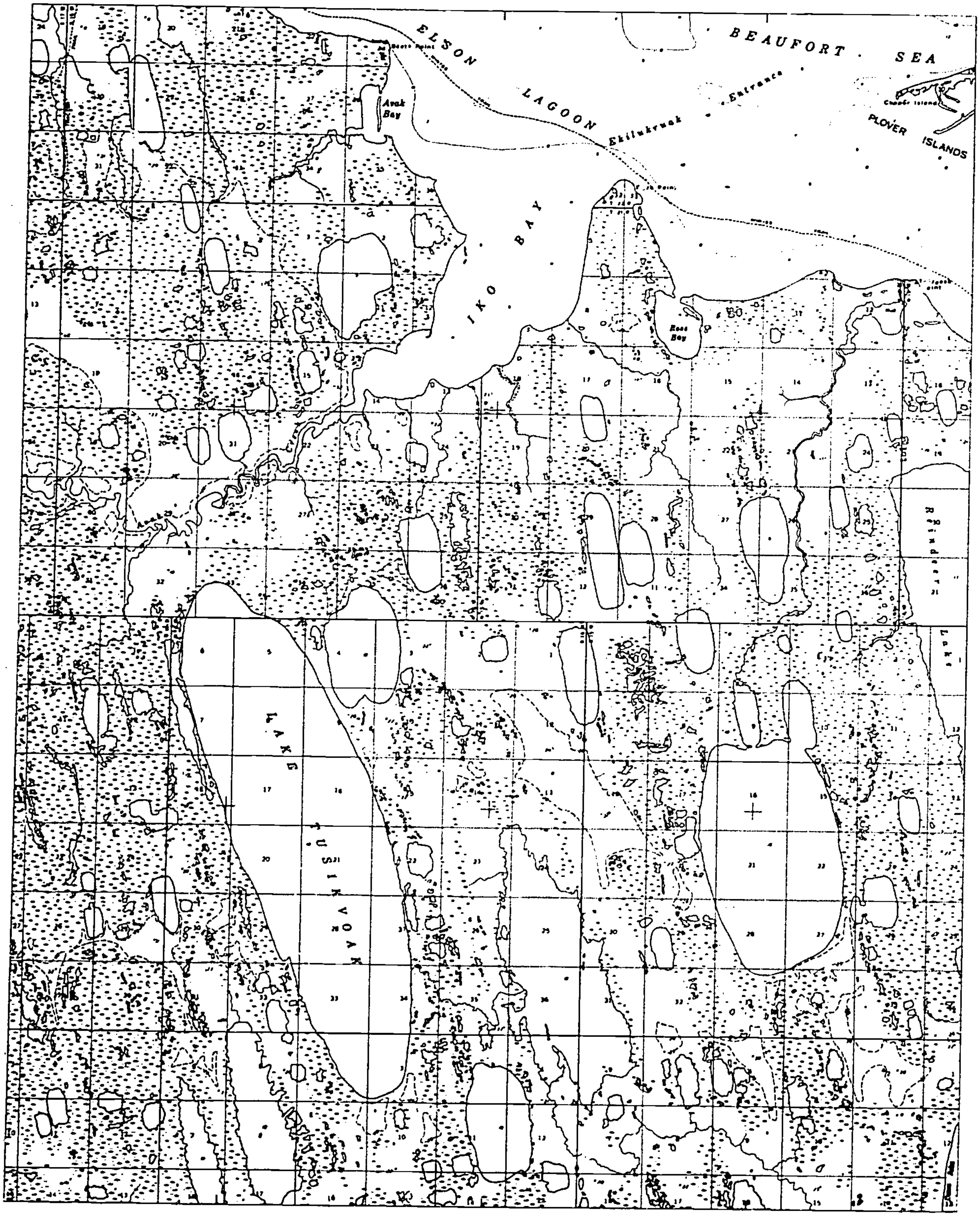

Figure 18. Topographic map showing a small area of oriented lakes on the arctic slope near Barrow, Alaska (71° N. Lat.). Such features cover over 65,000 km² (25,000 miles²) on the arctic slope and their elongation from NW to SE is apparently due to the prevailing southwesterly wind. The entire area of the map is below 15 m (50 ft.) and the dashed lines represent 7.5 m (25 ft.) contour intervals. The township and range system provides scale since each section is a square mile. The town of Barrow is located along the coast 22 km (14 miles) to the west. (Barrow (A-3) Quadrangle, Alaska, 1:63,360, U.S.G.S. Topographic Series.)

and give rise to large flat-floored basins called *alases*, a Yakutian term meaning "a circular or oval depression with steep sides and a flat floor overgrown with green grass around a thaw lake" (Czudek and Demek 1970, p. 111). Alases develop in several stages as illustrated in Figure 19. If the thermal equilibrium of the permafrost is disturbed, ice wedges begin to melt and high-center polygons develop (Figure 19a). As the ice wedges continue to melt, the surrounding earth material slumps into the depressions and conical mounds are created (Figures 16 and 19b). These eventually disintegrate and thaw lakes develop, considerably speeding the rate of permafrost melting since once a lake reaches a depth of 1.5 to 2 m (5–7 ft.) it does not freeze to the bottom (Figure 19c, d). Eventually, however, the lake is destroyed by infilling or by draining to a lower level and an alas is created (Figure 19e). The rate of alas development varies considerably; some are several thousand years old, while others are known to have formed in a human generation (Czudek and Demek 1970, p. 113).

The alases of Central Yakutia are 3–40 m (10–130 ft.) deep and 100 m to 15 km (330 ft. to 9 miles) in length. Occasionally they coalesce to form thermokarst valleys tens of kilometers long. In the Central Yakutian lowland, 40–50% of the initial surface has been destroyed by alas formation but, unlike other areas, e.g., mound development near Fairbanks, this has actually had a desirable effect. The flat-floored alases in Central Yakutia are the best agricultural areas available and in 1960 supplied more than 60% of the total hay production of the area (Czudek and Demek 1970, p. 117).

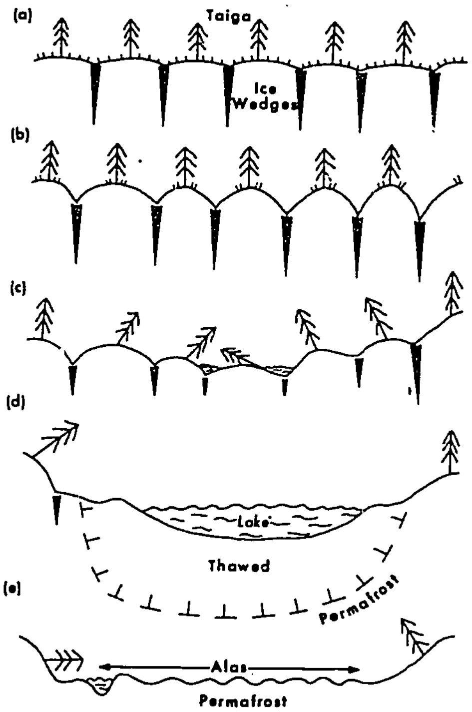

Figure 19. Schematic representation of alas development. (a) Original taiga lowland surface underlain with ice wedges; (b) The first stage after disturbance is the development of thermokarst mounds; (c) Continued thawing and slumping leads to a small central depression; (d) A lake forms in the depression and aids in increasing the size of the alas; (e) The final product is a flat-floored depression with steep sides (alas). Note that permafrost reestablishes itself near the surface of the alas in this final stage. (Adapted from Czudek and Demek 1970, Figure 9, p. 111.)

IV. GEOMORPHIC PROCESSES

General

There is nothing peculiar or unique about geomorphic (or for that matter biologic) processes in periglacial environments. They are the same processes that operate elsewhere; it is simply the combination and intensity that is different. The presence of permafrost, however, does provide a factor not present in temperate environments and there is no question that it has a great influence on physical and biological processes. Its primary importance is in providing an impermeable layer and thereby preventing the downward percolation of water. As a result, subarctic and arctic areas often display much more surface water than precipitation warrants. For example, most of the arctic slope of Alaska receives less than 200 mm (8 inches) annual precipitation, which is less than that received in some deserts, but if you were to visit this area in the summer it would certainly not resemble a desert. Due to low evaporation rates and poor drainage, water stands at the surface almost everywhere. You may be surprised to know that some arctic areas have a higher mosquito population than the tropics!

The dominant factors in landscape evolution in periglacial environments are frost action and mass wasting. The former is the chief process in preparing bedrock for erosion while the latter is the chief method of transport. Chemical weathering is relatively unimportant due to low temperatures and absence of water since it is frozen for much of the year. As a result much of the weathered detritus is angular and coarse—angular since it is physically broken apart, and coarse due to the inability of mechanical weathering to diminish particles beyond silt size.

Running water, the chief source of erosional transport in middle latitudes, is of considerably less importance in periglacial environments, except for some mountainous areas. The reason is twofold—low rates of precipitation and the presence of permafrost which hinders channel development. This is not to say that streams are not prevalent and that streams do not erode—they are and they do. It is simply that mass wasting is the dominant process. Consequently there is a tendency for valleys to become filled with detritus since streams are not sufficient to remove the material delivered to them by mass wasting. The ramifications of this in terms of landscape evolution will be discussed after the sections on frost action and mass wasting.

Frost Action

Frost action is a collective term including a number of related processes such as frost wedging, frost cracking, frost heaving and thrusting, and needle ice growth. The assemblage of these processes serves as the primary weathering agent in the initial breakdown of rocks as well as being important in mass wasting, i.e., frost creep. Frost action is also responsible for the selective sorting of surface materials and for the development of patterned ground.

The effects of frost have long been recognized. It was well known by the 17th century, for example, that frost was important in the disintegration of rocks, in the breaking of plant roots by heaving of the ground, and in the uplift of boulders in farmers' fields (Hiame 1644, in Beskow 1947, p. 1). Later as roads developed in cold countries, especially with stage coach traffic, problems arose with frost heaving of culverts and bridge piers, and from that time on frost action has become a matter of increasing practical concern.

It was formerly believed that frost heave was due primarily to the volume changes that occur when water freezes (approximately 9% volume increase) but this was disproved by the classic experiments of Stephen Taber (1929, 1930) with open and closed systems. Taber found that freezing of soils in open systems, i.e., with free passage of water, as usually occurs in nature, often results in much greater heaving than can be attributed to the volume change of water alone. He concluded that the excessive heaving was due to ice crystal growth which involves additional water being drawn to the freezing plane by molecular cohesion. He also discovered that heave pressures are exerted in the direction of ice crystal growth, i.e., normal to the cooling surface, and not in the direction of least resistance as was formerly believed (Taber 1929, pp. 460–461). On the other hand, in closed systems, i.e., systems from which water cannot escape or enter, the amount of heave is limited just to the amount of water present (Taber 1930, pp. 303–304). The chief factors controlling ice segregation and excessive heaving are: particle size, water availability, amount of pore space, and rate and extent of cooling (Taber 1929, p. 428).

Frost wedging

Frost wedging is the prying apart by ice upon freezing (Washburn 1969, p. 33). Also known as frost splitting, frost riving, and frost shattering, this is one of the most intense forms of rock fragmentation on earth (Figure 20). Although many factors are important in its development, the primary ingredient, given sufficiently cold climate, is abundance of water. Many laboratory experiments have shown that wet rock disintegrates more quickly than dry rock (Potts 1970; Tricart 1956), and this is a readily observed fact in the field. For example, frost wedging is usually more intense at the base of rock cliffs where more water is available than at the top. The major weathering process on dry rock in periglacial environments is thermal contraction and expansion, a considerably slower process than frost wedging (Tricart 1970, p. 74).

Rock type is also very important to the rate and effectiveness of frost weathering. Sedimentary and other relatively soft porous rocks are generally more susceptible to frost wedging than igneous rocks due to the former's greater water holding ability. In addition to rock type, the rate and extent of freezing can produce vastly different results. For example, under varying conditions different rocks can reverse their susceptibility to breakdown. Rapid freezing of saturated solid rocks or rocks with cracks may enhance frost wedging by quickly freezing and sealing the surface, creating a closed system of unfrozen water within the rock. As freezing continues, pressures develop within the closed system and the rock is shattered. On the other hand, slow freezing of a porous rock sitting on wet soil may allow the migration of additional moisture toward the freezing plane and the growth of ice crystals would disrupt the rock, whereas rapid freezing would inhibit the flow of water (Washburn 1972, Chapter 4).

Figure 20. Frost wedging in a subarctic alpine environment, the Ruby Mountains, Yukon Territory (61°23′ N. Lat.). Moisture accumulates in cracks and joints of the bedrock (granodiorite) and upon freezing, expands and breaks the rock into large angular blocks. Continuation of this process, in combination with other weathering processes, will eventually diminish the individual blocks to smaller and smaller particles. (Photo by author.)

Frost wedging results in coarse angular debris which, if formed on a steep slope or headwall, accumulates at the base as talus. If bedrock is shattered in place on more level areas, blockfields result, as discussed later in this section. The size and shape of the angular debris depends upon rock type. For example, slate or schist usually produces flat slabs while granite or limestone shatter on a more random basis. The eventual size to which material may be reduced by frost wedging is commonly thought to be silt (Hopkins and Sigafoos 1951, p. 59; Taber 1953, p. 330) although there is some evidence that, depending on the rock type, clays may also be created (Washburn 1972, Chapter 4). Nevertheless, there is a general lack of clays in periglacial environments, and this is attributed to the relative unimportance of chemical weathering and the inability of frost wedging to reduce particles below silt size.

The great loess deposits of the world (composed principally of silt) located near the margins of the continental ice sheets have been interpreted as being products of intense frost wedging and wind action owing to a colder climate during the Pleistocene. Carl Troll states, "Only thus can we understand the distribution of the loess on the earth, especially the fact that it is found nowhere on the edge of the dry regions opposite the tropics. Without frost, no loess" (Troll 1958, p. 23)! It should be mentioned, however, that this view is not universally held and a great deal more work needs to be done before the significance of frost wedging in producing cold climate loess is fully understood.

Frost cracking

The term *frost cracking* is somewhat of a misnomer for this process because the cracking is actually due to thermal contraction at very low temperatures and not to the overt action of frost. Nevertheless, the term has become entrenched in the literature and we will follow that usage. Frozen ground has a thermal coefficient of contraction similar to ice, almost five times higher than that of steel, so cracks appear even with a slight frost. At temperatures of –30 to –40° C (–22 to –40° F) a network of frost (contraction) cracks develop similar to those in a dry lake bed (Tricart 1970, p. 78). The cracking is greatly dependent

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on the rate of temperature drop as well as the actual temperature at time of cracking (Lachenbruch 1966, pp. 65–66). Although this would vary with different conditions, a rapid temperature drop of 4° C (7° F) has been cited as sufficient to crack frozen ground while a temperature drop of about 10° C (18° F) would be required to crack rock (Black 1969, p. 228). Once cracks are created, conditions may be favorable for the development of ice-wedges and ice-wedge polygons, as discussed in the preceding chapter (Figures 11–13).

Frost heave and thrust

Frost heave and thrust are related processes with heave being the predominately vertical displacement while thrust is predominately horizontal (Eakin 1916, p. 76 in Washburn 1969, p. 50). The pressures responsible for heaving and thrusting are due to the 9% volume change from water to ice and to ice crystal growth when additional water is drawn to the freezing plane (Taber 1929, 1930; Beskow 1947). The latter is most important, however, with considerable pressures being exerted in the direction of crystal growth, i.e., the cooling surface. For this reason, heave is generally more important than thrust although there are some cases, owing to differing conductivities in heterogeneous material, where thrust may exceed heave.

Frost heave is responsible for a number of related phenomena. One of the most critical with respect to man's use of periglacial environments is differential heaving since this is a major devastative force for engineering structures. Frost heave is also the basic mechanism for forcing objects to the surface such as rocks or tree seedlings. Certainly objects placed in the ground such as fence posts or telephone poles are very susceptible to frost heave and may be completely ejected within a few years.

Differential heaving is unequal vertical displacement within adjacent surface areas. Its operation is largely dependent on microenvironmental conditions, especially abundance of water, soil particle size, and vegetation in its role as an insulating agent. For example, if a well-drained vegetation-free gravel area and a poorly drained sediment with sedge vegetation occurred side by side, the latter would obviously be much more susceptible to frost heaving. Differing terrain with commensurate potentials for frost heaving is one the basic reasons for problems with engineering structures such as roads and buildings in the subarctic. If the amount of heaving across surfaces was homogeneous there would be considerably fewer problems; it is differential heaving that causes the major disruption. This is discussed further in Chapter VI.

The other major result of frost heave and thrust is the upward displacement of objects in the ground. Perhaps the most common reflection of this is the upward movement of stones in farmers' fields. In periglacial environments more striking examples exist such as up-heaved blocks (Price 1970a). These are isolated blocks that protrude up to 1.5 m (5 ft.) above the surface in both bedrock and unconsolidated material and stand like lonely sentinels on the landscape.

The upheave of blocks in bedrock is generally thought to be due to water accumulating in cracks or bedding planes, and when freezing occurs the block is forced upward. Upon thawing, the block does not settle back to its original position due to detritus falling in the void and the fact that the rock may settle at a slightly different angle (Yardley 1951). The repetition of this process over several years can raise a block considerably above its surroundings and subject it to the full brunt of the harsh environment so it is more rapidly weathered.

The mechanisms responsible for ejection of stones in unconsolidated material are more complex than those confined to bedrock since the heterogeneity of unconsolidated material introduces several variables. There have been many theories suggested for the up-freezing of stones but the actual mechanics of this phenomenon are still poorly known. Laboratory research since World War II has greatly elucidated the problem (Corte 1961, 1962, 1966; Kaplar 1965, 1970; Bowley and Burghardt 1971), but much remains to be learned.

Washburn (1969, pp. 52–58) has summarized most of the basic theories into two groups which he calls the frost-pull and frost-push mechanisms. The frost-pull mechanism operates on the principle that when the ground expands during freezing it carries stones with it, but that in contracting during thawing the fines (silt, sand, clay) have greater cohesion for each other and are drawn back together, while the stones do not return completely to their original position owing to collapse of material about their bases. After many freeze and thaw cycles the stones would be ejected upward.

The frost-push hypothesis is based on the greater heat conductivity of stones than that of soil. Since stones heat and cool more quickly than the surrounding soil, ice would form at their bases during freezing and force them up. The seeping in of fines during thawing would prevent the complete return of the stones (Washburn 1969, pp. 55–56).

Although highly simplified, these are thought to be the two major processes operative in frost heave. In nature they work simultaneously so it is difficult to separate them, but the frost-pull mechanism is probably more important in the slow gradual ejection of stones and in the up-freezing of stakes and posts placed in the ground. The frost-push hypothesis would better explain the fairly rapid upward displacement (several centimeters per year) of large stones due to the potential for rapid buildup of ice at their bases (Washburn 1969, p. 58). The foregoing has assumed that at least part of the stone was buried below the surface. Once a stone reaches the surface it may be susceptible to an additional process, that of needle ice formation.

Needle ice

Needle ice, also widely known by the Swedish term *pipkrake,* consists of fine needle-like clusters of ice crystals occurring at or immediately beneath the ground surface (Figure 21). The needles usually stand perpendicular to the cooling surface and are characteristically 1–3 cm (.4–1.2 inches) high, although they have been known to grow as high as 40 cm (16 inches) (Troll 1958, p. 24). Needle ice development is usually a noctumal event and if melting does not occur the following day a second underlying layer may develop, separated from the first by a thin partition of soil. The repetition of this process for several days would lead to a series of such layers.

Needle ice development is most important in the higher middle latitudes, in polar oceanic areas, and in tropical mountains where frequent diurnal freeze and thaw cycles occur. It is probably least important in the high arctic since very few freeze and thaw cycles occur there (Troll 1958, pp. 27–28). Bare or sparsely vegetated soils with ample moisture are most favorable for needle ice development. The moisture is drawn from below the surface so loams and silts are more conducive for development than are tight clays, since moisture transfer is too slow in clays and needle ice growth is inhibited (Beskow 1947, p. 6).

The geomorphic significance of needle ice is primarily

Figure 21. Close up of needle ice taken at 9:00 A.M. in late October, Coast Range, Oregon. The individual needles are about 2.5 cm (1 inch) high and are beginning to melt and bend on left side of photo. Note the soil particles on upper surface of needle ice. (Photo by William G. Loy, University of Oregon.)

through creep because it has the ability to lift soil and stones several centimeters above the surface. If this occurs on a slope, there will be a small component of downslope movement since the soil and stones are lifted perpendicular to the surface but upon thawing will settle more nearly vertically (Figure 27). Needle ice development on level surfaces leads to a general stirring of the surface and often results in small lumps or "nubbins" (Washburn 1969, pp. 85–88). Needle ice is known to have a major disruptive effect on vegetation (Schramm 1958; Brink, Mackay, Freyman, and Pearce 1967) and it may also be important in the origin of certain kinds of patterned ground (Hay 1936).

Patterned Ground

One of the most striking features of periglacial environments is *patterned ground.* This is a collective term for the characteristic geometric patterning of the surface into such forms as polygons, circles, and stripes (Figure 22). These "surface markings," or "structure soils" as they were formerly called, were observed by early explorers (von Baer 1837; von Middendorf 1864, in Troll 1958, p. 1), but it wasn't until the beginning of the 20th century that patterned ground began to receive adequate attention. In fact, the literature is already so voluminous it is difficult to assimilate. As a colleague has said, "Seldom has so much been written about so little." This, of course, depends upon your point of view, but it is true that almost every scientist who has visited the polar regions has his own theory for the origin of these curiously arranged surface patterns. There are no less than 19 major theories for the origin of patterned ground (Washburn 1956, p. 823). However, before we discuss the processes responsible for these features, let us establish some of their characteristics.

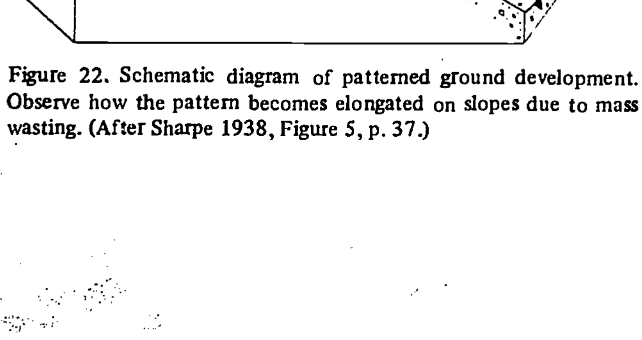

Figure 22. Schematic diagram of patterned ground development. Observe how the pattern becomes elongated on slopes due to mass wasting. (After Sharpe 1938, Figure 5, p. 37.)

Classification

In 1956, Professor A. L. Washburn published a major paper entitled "Classification of Patterned Ground and Review of Suggested Origins," in which he synthesized much of the literature and proposed a classification for patterned ground. There had been several earlier classifications but none was widely accepted due to confusion of terms and the inclusion of genetic aspects. Washburn's classification was completely descriptive and included a revised terminology that was orderly and consistent. Perhaps most importantly from our vantage point in time is that it has been widely accepted and is one of the most often-cited papers in the periglacial literature. Much of the following discussion is based on this classic paper.

Patterned ground can be divided on the basis of geometric form, i.e., circles, polygons, or stripes, and also on the presence or absence of sorting, i.e., separation of stones and fines. These two characteristics are combined to form the classification. The following are the principal forms encountered although there are obviously some that are gradational in both pattern and sorting: (1) circles—nonsorted, sorted; (2) polygons—nonsorted, sorted; (3) nets— nonsorted, sorted; (4) steps—nonsorted, sorted; and (5) stripes—nonsorted, sorted.

Only circles, polygons, and stripes will be discussed here since nets and steps are essentially transitional forms; the reader is directed to Washburn's paper for greater detail.

Circles

Nonsorted circles are bare circular areas margined by vegetation (Figure 23). There is no border of stones so the distinguishing feature is the vegetative border. Nonsorted circles are commonly 0.5 to 3 m (1.6–10 ft.) in diameter and may occur singly or in groups and are most often found on relatively level ground. More or less synonomous terms include frost scars, spot medallions, and mud circles.

Sorted circles are circular accumulations of stones around a center of finer material (Figure 24). Sorted circles vary in diameter from a few centimeters to over 3 m (0.1–10 ft.) and can extend to a depth of about 1 m (3 ft.). The size of stones in the border tends to increase with size of the circles; the stones are largest at the surface and decrease in size with depth. Sorted circles may occur singly or in groups and are most common on nearly horizontal surfaces since a gradient often causes elongation of the form into garlands or stripes. Synonyms for these features include stone rings and debris islands.

Polygons

Nonsorted polygons are polygonal-shaped features often delineated with a furrow or crack but without a border of

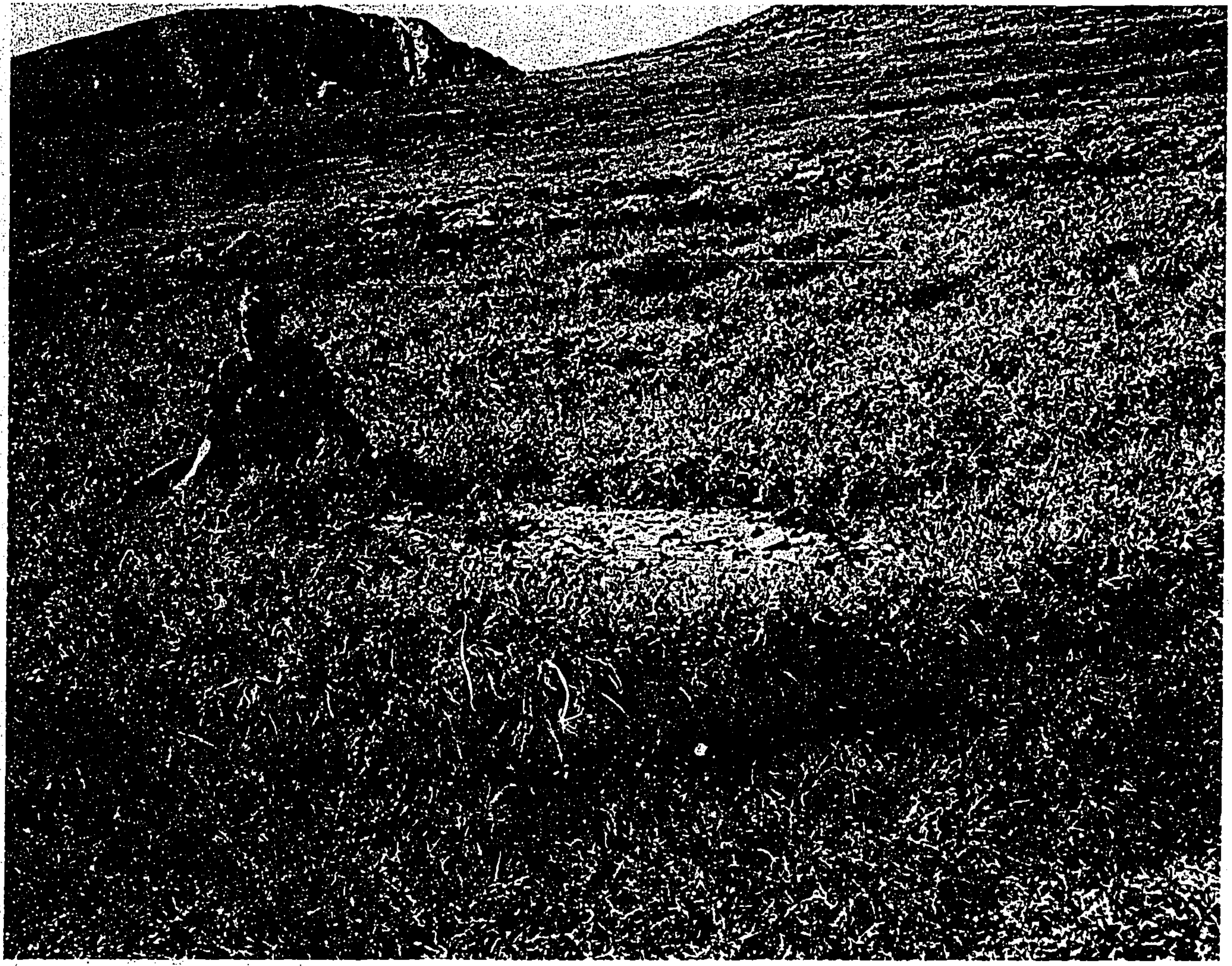

Figure 23. A nonsorted circle in the subarctic alpine tundra. Such features, also called frost boils, are bare areas bordered with vegetation and are initiated by differential frost heave. Once formed, frost action is more intense within the bare areas causing considerable instability, and vegetation is prevented from growing there. The furl around downslope part of bare area is 0.6 m (2 ft.) high and is caused by greater frost activity within the bare area. (Photo by author.)

stones. Vegetation is frequently concentrated in the furrow and helps to emphasize the pattern. Nonsorted polygons are best developed on nearly horizontal surfaces but they are also found on slopes. Unlike the circle variety of patterned ground, polygons never occur singly. Nonsorted polygons range from a few centimeters up to 100 m (330 ft.) in diameter and are not necessarily restricted to periglacial environments. Excellent examples occur in middle latitudes, especially deserts, where they are usually associated with dessication cracking. Small nonsorted polygons due to dessication are ubiquitous. You have doubtless observed these in the bottom of a pond or mud hole that has dried up.

The largest nonsorted polygons, however, occur in permafrost and are associated with ice wedges (Figure 13). The ice wedge forms the border which may be raised or depressed with respect to the central area depending upon the insulating vegetation and drainage. Although the very small nonsorted polygons are ephemeral and dependent on slight environmental changes, the large features may be very long lasting and preserved as fossil features indicating environmental change (Washburn 1972, Chapter 4). In very cold and dry environments such as parts of Antarctica, sand wedges often form the border, and nonsorted polygons have even been reported as occurring in solid bedrock (Berg and Black 1966, pp. 69–73). Synonyms for nonsorted

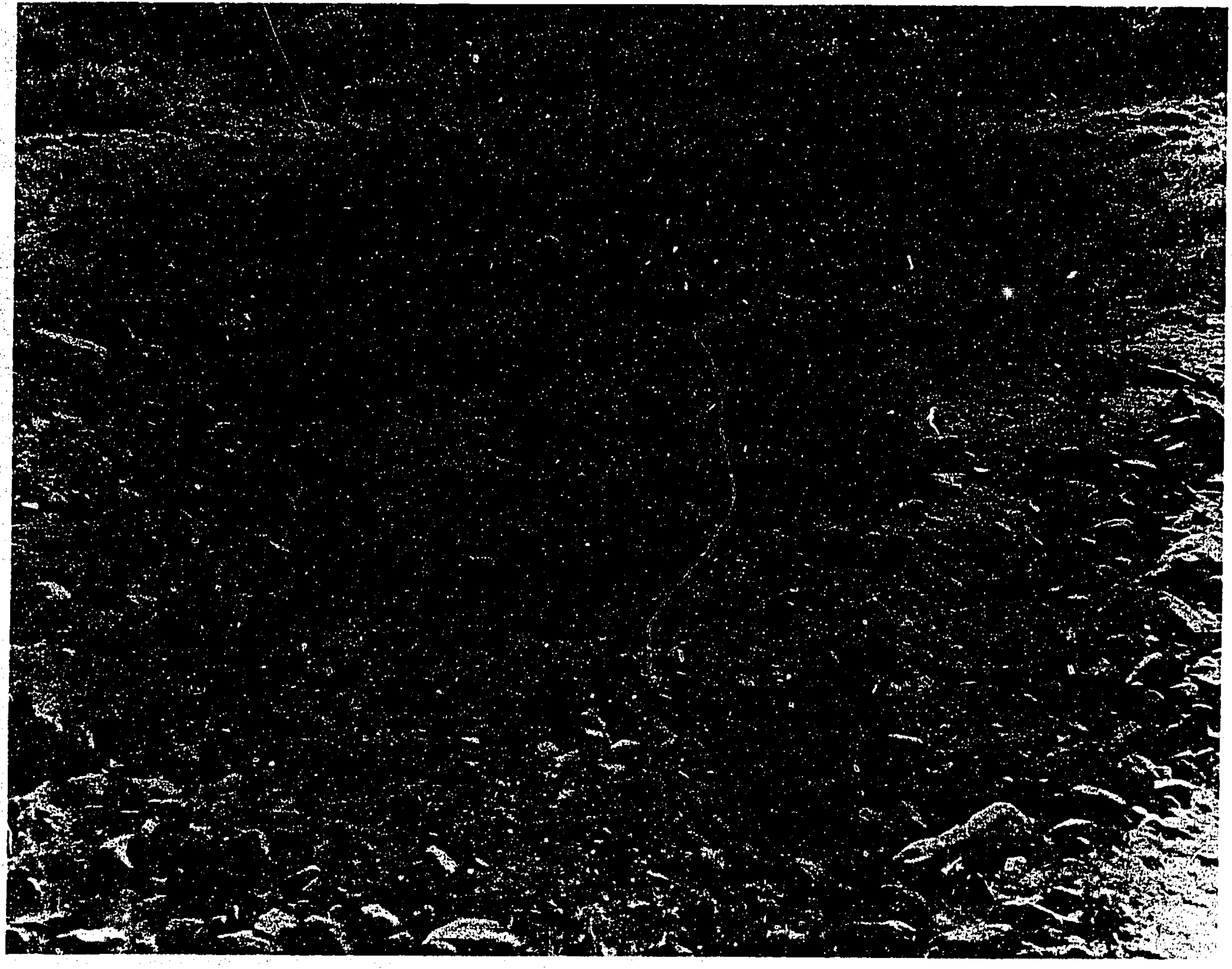

Figure 24. Sorted stone circles in bottom of small drained pond along Denali Highway near Mt. McKinley National Park, Alaska. (Photo No. 1764 by Troy L. Péwé, Arizona State University.)

polygons include fissure-polygons, mud-polygons, and contractual polygons.

Sorted polygons are polygonal features given definition by a border of stones surrounding a central area of finer material. More or less synonomous terms include stone-polygons and stone nets. Like nonsorted polygons, they are best developed on fairly level ground and occur as small and large forms. The minimum size is about 10 cm (4 inches) across while the maximum size is about 10 m (33 ft.). This is an order of magnitude smaller than the nonsorted polygon. Sorted polygons never occur singly, and like all forms of patterned ground, the size of the stones in the borders increases with the size of the feature and decreases with depth. The rocks in the border are often on edge and oriented parallel to the border which may or may not be coincident with crack patterns.

Small sorted polygons occur in many different environments, but most middle latitude occurrences (except for inactive or fossil) are in mountainous areas or deserts. Hunt and Washburn (1966, pp. B118–B120) report forms up to 3 m (10 ft.) in diameter occurring in Death Valley, California. Large polygons, however, are best developed in permafrost areas and the presence of similar inactive features in middle latitudes is often taken as reasonable evidence for the former existence of permafrost. Nevertheless, they cannot be accepted as indisputable proof.

Stripes

Nonsorted stripes are linear patterns of soil or vegetation on slopes without related lines of stones (Figure 25). They frequently consist of parallel lines of vegetation and intervening strips of relatively bare ground oriented down the steepest available slope. Synonomous terms include solifluction stripes and vegetation stripes. They range in size from a few centimeters to 1–2 m (3 to 7 ft.) in width and can extend downslope several tens of meters although they are often discontinuous. Nonsorted stripes are usually considered to be the slope analogue of nonsorted polygons.

Sorted stripes are elongated accumulations of stones with intervening areas of finer material. They are also known as soil stripes, stone-bordered stripes, striped ground, and stone stripes (Figure 26). Like sorted polygons, sorted stripes are not known to occur singly. They are usually restricted to slopes and are often derived from the downslope extension of sorted polygons. A typical situation is for sorted polygons to form on nearly level surfaces, while on gentle slopes the pattern becomes more elongated into sorted nets or steps, and with increasing slope they become elongated into sorted stripes (Figure 22). Some sorted stripes occur independently of these other forms, however.

Sorted stripes range in size from a few centimeters to 1.5 m (5 ft.) or more wide and the intervening finer

Figure 25. Nonsorted stripes occurring in the St. Elias Mountains, Yukon Territory (61° N. Lat.). These particular features consist of gravel-sized material elongated into furrows and ridges down the slope. There is no major difference in particle size from ridge to trough, and the [illegible]ation has apparently been due to differential mass wasting, e.g., frost creep and solifluction. (Photo by author.)

Figure 26. Sorted stripes occurring near Lonerock, a ghost town in north central Oregon. The stripes are 1–3 m (3–10 ft.) wide and up to 100 m (330 ft.) long (the two men provide scale). The slope has a gradient of 25° and the rock type is basalt. A wide range of patterned ground features occur throughout the Columbia Plateau, possibly due to former periglacial conditions, but a great deal more research is needed before this is proved or disproved. (Photo by John B. Pyrch, Portland State University.)

material is commonly several times wider. They can be over 100 m (330 ft.) long and tend to be straight on steep slopes but more sinuous on gentle slopes. As with other kinds of patterned ground, the size of the stones increases with the size of the feature. I have seen sorted stripes in the Ruby Range, Southwest Yukon Territory where the average stone size was about 1 m (3 ft.) in length. Stones usually decrease in size with depth and the stripe itself narrows in wedge fashion. The stones are commonly turned on edge and oriented parallel with the stripe.

Sorted stripes are a characteristic feature of periglacial landscapes but they are also found in deserts, e.g., Death Valley, California (Hunt and Washburn 1966, p. B125). Inactive and fossil forms occur in other mid-latitude areas. Many good examples occur on the Columbia Plateau of Idaho, Washington, and Oregon (Figure 26). These may or may not indicate a formerly more severe climate; there has not been enough research in these areas to determine their origin with certainty.

Origin

The origin of patterned ground is very controversial. In periglacial environments, frost action is certainly of major importance but just exactly what mechanisms are involved remains far from settled. Washburn reviews 19 major hypotheses for the origin of patterned ground and comes to the following general conclusions: "(1) the origin of most forms of patterned ground is uncertain; (2) patterned ground is polygenetic; (3) some forms may be combination products in a continuous system having different processes as end members; (4) climatic and terrain interpretation of patterned ground, both active and "fossil", is limited by lack of reliable data about formative processes" (Washburn 1956, p. 823).

Nevertheless, several general statements can be made with respect to the origin of periglacial patterned ground. Drying and/or frost cracking are probably most important as initiating processes in the creation of polygonal patterns while local differential heaving is probably most important in creating circular patterns. The sorting of materials is principally due to frost heaving and thrusting. This includes both the frost-push and frost-pull mechanisms as discussed in the preceding section. Basically the theory is that in heterogeneous material there will be some areas with a greater concentration of fines than in others. The accumulations of fines have a greater waterholding capacity and, upon freezing, greater expansion will occur within these nuclei. Upon contraction during thawing, the fines are drawn back together due to their greater cohesion, while the coarser material does not contract as far. After each period of freezing and thawing the nucleus of fines grows in size and the coarse material is forced farther outward and becomes more sharply segregated. This process continues until the individual nuclei begin to impinge upon each other forming either sorted circles or polygons. Although the above statements are mainly for horizontal surfaces, the same basic processes apply for slopes except that the features are generally elongated due to mass wasting.

Recently Washburn (1970) has attempted a classification based on the origin of patterned ground which serves to outline the major genetic factors and associated forms (Table 2). It is an all inclusive classification, not limited to cold-climate patterned ground, and combines in matrix form the existing terms for geometric patterns with existing terms for genetic processes. He recognizes that there are still too many unknowns to formulate a satisfactory classification based on origin, but his attempt does help to pinpoint critical problems and allows the orderly appraisal of complex variables (Table 2). The next steps in patterned ground research call for more laboratory and cold room experiments, more rigorous instrumentation and measurement in the field, and a more intensive investigation of middle latitude patterned ground. The latter is particularly important with respect to the intriguing question of whether these areas in fact did experience a periglacial environment.

Mass Wasting

Mass wasting is downslope movement of surficial material due to gravity. Mass wasting and frost action together form the chief agents of denudation in periglacial landscapes. Frost action is largely responsible for the initial breakdown of the surface in preparation for erosion, and mass wasting is the chief method of transport. Mass wasting may take many forms in periglacial environments, including mud flow, debris avalanche, slumping, rock glacier creep, and landslide, but the two primary processes are frost creep and solifluction.

Frost creep

Creep in general is defined by Sharpe (1938, p. 21) as "... the slow downslope movement of superficial soil or rock debris, usually imperceptible except to observations of long duration." This is a good definition for most circumstances but unfortunately Sharpe considered flow and solifluction as a kind of creep (1938, p. 22). This position has been criticized by Strahler (1952, p. 929) and Washburn (1967, p. 10) among others on the basis that creep and solifluction are distinct processes. In an effort to identify the specific processes more sharply, Washburn (1967, p. 10) defined *frost creep* as the "... ratchet-like downslope movement of particles as the result of frost heaving of the

TABLE 2

Genetic Classification of Patterned Ground

			Processes												
			Cracking Essential						Cracking Nonessential						
					Thermal Cracking										
						Frost Cracking									
			Desiccation Cracking	Dilation Cracking	Salt Cracking	Seasonal Frost Cracking	Permafrost Cracking	Frost Action Along Bedrock Joints	Primary Frost Sorting	Mass Displacement	Differential Frost Heaving	Salt Heaving	Differential Thawing and Eluviation	Differential Mass-Wasting	Rillwork
GEOMETRIC PATTERNS	CIRCLES	NONSORTED								Mass-displacement N circles	Frost-heave N circles	Salt-heave N circles			
		SORTED						Joint crack S circles (at crack intersections)	Primary frost-sorted circles, incl? Debris islands	Mass-displacement S circles, incl. Debris islands	Frost-heave S circles	Salt-heave S circles			
	POLYGON	NONSORTED	Desiccation N polygons	Dilation N polygons	Salt-crack N polygons	Seasonal frost-crack N polygons	Permafrost-crack N polygons, incl Ice-wedge polygons, sand-wedge polygons	Joint-crack N polygons?		Mass-displacement N polygons?	Frost-heave N polygons?	Salt-heave N polygons?			
		SORTED	Desiccation S polygons	Dilation S polygons	Salt-crack S polygons	Seasonal frost-crack S polygons	Permafrost-crack S polygons	Joint-crack S polygons	Primary frost-sorted polygons?	Mass-displacement S polygons?	Frost-heave S polygons?	Salt-heave S polygons?	Thaw S polygons?		
	NETS	NONSORTED	Desiccation N nets, incl? Earth hummocks	Dilation N nets		Seasonal frost-crack N nets, incl? Earth hummocks	Permafrost-crack N nets, incl Ice-wedge nets and sand-wedge nets?			Mass-displacement N nets, incl? Earth hummocks	Frost-heave N nets, incl. Earth hummocks	Salt-heave N nets			
		SORTED	Desiccation S nets	Dilation S nets		Seasonal frost-crack S nets	Permafrost-crack S nets?		Primary frost-sorted nets	Mass-displacement S nets	Frost-heave S nets	Salt-heave S nets	Thaw S nets		
	STEPS	NONSORTED								Mass-displacement N steps	Frost-heave N steps?	Salt-heave N steps?		Mass-wasting N steps?	
		SORTED							Primary frost-sorted steps?	Mass-displacement S steps	Frost-heave S steps	Salt-heave S steps	Thaw S steps?	Mass-wasting S steps	
	STRIPES	NONSORTED	Desiccation N stripes?	Dilation N stripes?		Seasonal frost-crack N stripes?	Permafrost-crack N stripes?	Joint-crack N stripes?		Mass-displacement N stripes	Frost-heave N stripes	Salt-heave N stripes		Mass-wasting N stripes?	Rillwork N stripes?
		SORTED	Desiccation S stripes	Dilation S stripes		Seasonal frost-crack S stripes?	Permafrost-crack S stripes?	Joint-crack S stripes	Primary frost-sorted stripes?	Mass-displacement S stripes	Frost-heave S stripes	Salt-heave S stripes	Thaw S stripes?	Mass-wasting S stripes	Rillwork S stripes

Source: Washburn 1970, pp. 440-441

ground and subsequent settling upon thawing, the heaving being predominantly normal to the slope and the settling more nearly vertical." The initial confusion is not the theoretical distinction between creep and flow, because creep had been clearly identified much earlier (Davison 1889); the problem arises at the practical level owing to the difficulty of distinguishing between the two processes in the field. Recently, however, they have been isolated and measured in two different field investigations (Washburn 1967; Benedict 1970).

One of the most striking things to come out of these investigations is the discovery and isolation of "retrograde movement" (Washburn 1967, pp. 109–115). Retrograde movement is an actual backward or upslope movement due to the tendency for the soil to settle back against the slope rather than vertically as is usually depicted in beginning texts (Figure 27). The reason that the soil does not settle vertically upon thawing after being frost heaved, but at an intermediate position, is the cohesion of the soil particles for each other. This was recognized by Davison (1889, pp. 256–257) but was largely ignored until Washburn recently revived the concept by his carefully controlled field measurements. Working in Northeast Greenland, he installed small wooden pegs in the ground and measured the amount of movement with a theodolite at different times of the year. He found that during freeze up in the fall the soil is lifted at right angles to the slope due to frost heave (Figure 27). Upon thawing in the spring some flow (solifluction) may occur if the material is saturated. As the surface continues to thaw, the soil settles and often moves

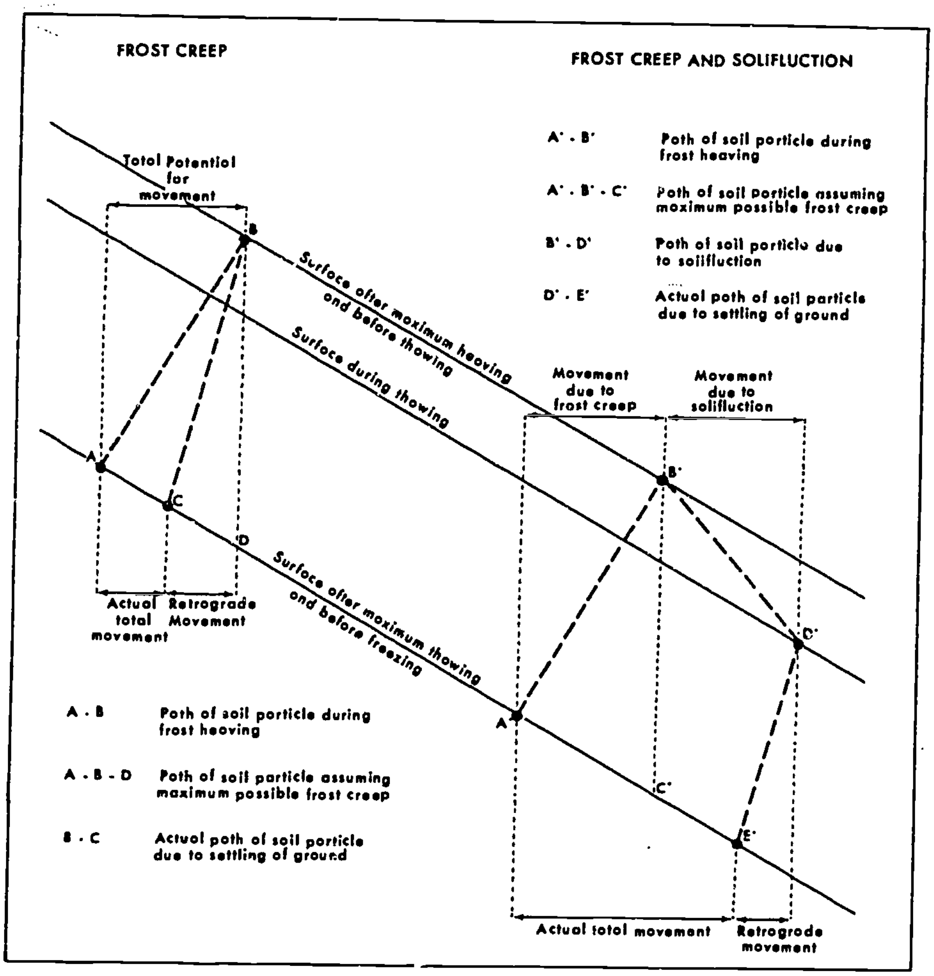

Figure 27. Diagram showing relationship between frost creep, solifluction, and retrograde movement. Note that in the case of frost creep the particle does not settle vertically but rather settles at an intermediate position due to cohesion. Therefore, if measurements were made at the time of maximum heaving and immediately after thawing, there would tend to be a slight upslope or backward movement. (Adapted from Washburn 1967, Figure 5, p. 20.)

upslope with respect to the position it formerly occupied. This intriguing phenomenon is graphically illustrated in Figure 27.

The total role of frost creep in the denudation of periglacial landscapes is unknown since very few measurements have been made of it alone, but it is probably one of the most important processes. Washburn (1967, p. 118) found that on a silty 10–14° slope in Northeast Greenland, frost creep tended to exceed other forms of mass wasting (mainly solifluction) by a factor of three to one, but either process could dominate in any given year. The efficacy of frost creep at any particular place, like that of frost action in general, depends upon soil texture, abundance of moisture, vegetational development, and the number and extent of freeze and thaw cycles. Owing to the latter factor, frost creep is probably more important in the subarctic and higher middle latitudes, while solifluction would be relatively more important in the high arctic.

Solifluction

The term *solifluction* was first proposed by Andersson (1906, pp. 95–96), "This process, the slow flowing from higher to lower ground of masses saturated with water (this may come from snow melting or rain) I propose to name solifluction (derived from *Solum*, 'soil' and *Fluere*, 'to flow')." Andersson did not specifically limit solifluction to cold climates, although his discussions were largely limited to these areas. General usage of the term since has also been restricted largely to cold climates, but some have maintained that solifluction occurs in all latitudes including the tropics, while others have attempted to restrict its use to areas underlain with permafrost. Because of this confusion several new terms have been suggested for soil flow in cold climates (Dylik 1967). The most notable of these is ***gelifluction,*** which is solifluction associated with frozen ground (Baulig 1957). Since permafrost is not a prerequisite for periglacial conditions as defined in the first chapter, solifluction will continue to be used here, although gelifluction is recognized as being more appropriate in some cases.

No matter what the definition, the process of soil flow itself is unquestionably best developed in areas underlain by permafrost owing to its impermeable nature which helps to maintain a high water table. The moisture comes primarily from melting snow and frozen ground but precipitation may also contribute, particularly in alpine areas. When soil becomes saturated, the friction between soil particles is reduced, and without adequate cohesion the mass takes on the characteristics of a viscous fluid and begins to flow. Solifluction may occur on slopes as low as 2–3° but it is best developed on slopes of 5–20°. In steeper areas, water is quickly lost as runoff and fines are eroded, so solifluction plays a diminished role.

A number of factors are important to the development of solifluction, including moisture, gradient, orientation, soil texture, rock type, vegetation, and in areas underlain by permafrost, the depth of the active layer. Of these, moisture appears to be the overriding prerequisite, but all of these factors are inter-related so it is difficult to isolate any single factor as primary. For instance, the slope gradient will govern rapidity of runoff, the retention of soil, and the development of vegetation. The slope orientation controls the amount of sunlight and accumulation of snow drifts. A north facing slope in the subarctic receives less sunlight than a south facing slope, and there are corollary micro-climatic and vegetational differences. Orientation with respect to the wind may be even more important to the occurrence of solifluction than sunlight, owing to the accumulation of snow which is frequently a key factor in providing the necessary moisture for solifluctional development. As a result, east, southeast, and south facing slopes are favored for solifluction in the northern hemisphere, while east, northeast, and north facing slopes are favored in the southern hemisphere.

Soil texture is a key factor in the development of solifluction since the finer the soil the greater its water holding ability, its frost susceptibility, and its potential for flowage. A point of diminishing returns is eventually reached, however, since silt is more frost susceptible, i.e., it undergoes greater frost heave, than clay because moisture can migrate more freely to the freezing plane. Also silt is more subject to flow than clay since it lacks the cohesion of clays and slakes readily (Taylor 1948, in Washburn 1967, p. 103). This may in part explain the pervasive development of frost creep and solifluction in periglacial environments since silt is more abundant than clay owing to the dominance of mechanical over chemical weathering.

Some investigators have maintained that rock type is the single most important factor in solifluctional development. Jahn (1967, p. 216 and 224), working in Spitzbergen, states, "The view that water is a major positive factor in the action of polar solifluction, however widespread, still reamins doubtful." And, ". . . the size of solifluction tongues, the rate of their movement as well as successsion depend on type of material." In some instances there may be a clear relationship between rock type and solifluction, but to suggest that rock type is a major determinant of solifluctional development on a global scale is overstating its significance. This has been demonstrated by many other studies (Johnson and Billings 1962, p. 129; Sigafoos and Hopkins 1952, p. 182; Washburn 1967, p. 105). In my own research in southwest Yukon Territory, I found that solifluction occurred across many rock types as long as other factors, particularly soil moisture, were sufficient (Price 1970b, p. 276). Rock type is simply another environmental parameter to be considered.

Vegetational development is important to solifluction in two main respects: (1) It insulates the surface and reduces the depth of the active layer above permafrost which results in raising the water table to very near the surface. (2) It acts as a retarding or binding agent helping to stabilize areas and prevent movement. The first factor is probably more important than the second because vegetation and solifluction are frequently best developed in the same sites–the wetter areas. Vegetation itself increases the moisture content of the soil by reducing the soil temperature, evaporation, and the depth of the active layer. Although some have maintained that vegetation may be sufficient to stop solifluction (Wilson 1952, pp. 262–263), it is probable that the additional moisture contributed by the vegetation more than compensates for its binding effect. In general, solifluction and vegetation are both better developed in the wetter areas than in the barer but drier sites (Washburn 1967, pp. 104–105; Price 1970b, pp. 275–276).

Associated features

A number of characteristic features develop in periglacial nvironments due to frost action and mass wasting, and mong the most distinctive are: talus accumulations, lockfields, rock glaciers, and solifluction lobes.

Talus

Talus is an accumulation of rock debris at the base of a liff or headwall, consisting of coarse and angular stones hat have broken away from the rock face and tumbled ownslope. Talus formation is not restricted to periglacial nvironments although it is probably best developed here wing to rapid frost wedging and nivational processes. igure 28 shows a series of coalesced talus cones on a laciated valley slope in southwest Yukon Territory. The alley has been free of ice for only 200–500 years so the nount of talus gives a crude estimate of the rate of talus cumulation in such an environment.

Talus has been reported to be currently forming in irginia (Hack 1960), and it is a common feature in arid vironments, so a periglacial interpretation for talus would ve to be based on more information than merely its esence. Actively forming talus slopes are usually vegetaon free with very few interstitial fines, but inactive talus on becomes stabilized and supports vegetation. There ve been numerous studies on rates of talus succession, ainly from mountainous areas (Fisher 1952).

Blockfields

Blockfields are accumulations of angular blocks formed *in situ* from weathering of the underlying bedrock. They are also known by the German term *Felsenmeer* which means "sea of rocks." Blockfields usually occur on fairly level areas although they may also occur on slopes (Figure 29). The size and angularity of blocks vary greatly with the rock type and severity of weathering, but the blocks are usually good sized, varying from 0.5 to 2 m (1.6 to 7 ft.) in diameter with essentially no matrix of fine material. In periglacial environments the primary originating force is frost wedging, and a highly jointed bedrock surface where water could accumulate and freeze in the cracks would be particularly susceptible to blockfield development. Active blockfields are characterized by freshly broken rock surfaces, absence of fines, absence of vegetation, and general instability. If you have ever walked on a blockfield you know that it is much safer to stay on the more heavily lichen-covered areas than freshly disturbed areas where the blocks are less stable and frequently tilt or dislodge when stepped on.

The presence of blockfields in middle latitudes is widely taken as evidence for the former existence of a colder climate. There are numerous examples from northeastern United States, particularly in Pennsylvania (Smith 1953; Potter and Moss 1968). If such features consist of very angular blocks and it can be proven that they are no longer forming in the area, they may be reasonable evidence of a formerly more severe climate, but this interpretation must be made with great caution since other processes may give rise to similar forms.

Rock glaciers

Rock glaciers are similar to true glaciers except that they are composed of coarse angular rock debris (Figure 30). They are usually restricted to areas above tree line in mountains and head in cirques or high steep cliffs where sufficient rock debris is available. Rock glaciers are commonly narrowest at their head and widest at the terminus, especially when they reach a lower valley and spread laterally. They vary from a few hundred meters to over a kilometer in length and average from 15–45 m (50–150 ft.) in thickness with active rock glaciers being considerably thicker than inactive features (Wahrhaftig and Cox 1959, p. 383). Ice is usually present 1–2 m (3–7 ft.) below the surface of active rock glaciers, where it occurs as cementation in the interstices of the coarse blocky debris. Rock glaciers have many microtopographic features similar to true glaciers, including longitudinal and horizontal furrows, transverse ridges, crevasses, conical pits, and lobes (Figure 30). The fronts of active rock glaciers are generally

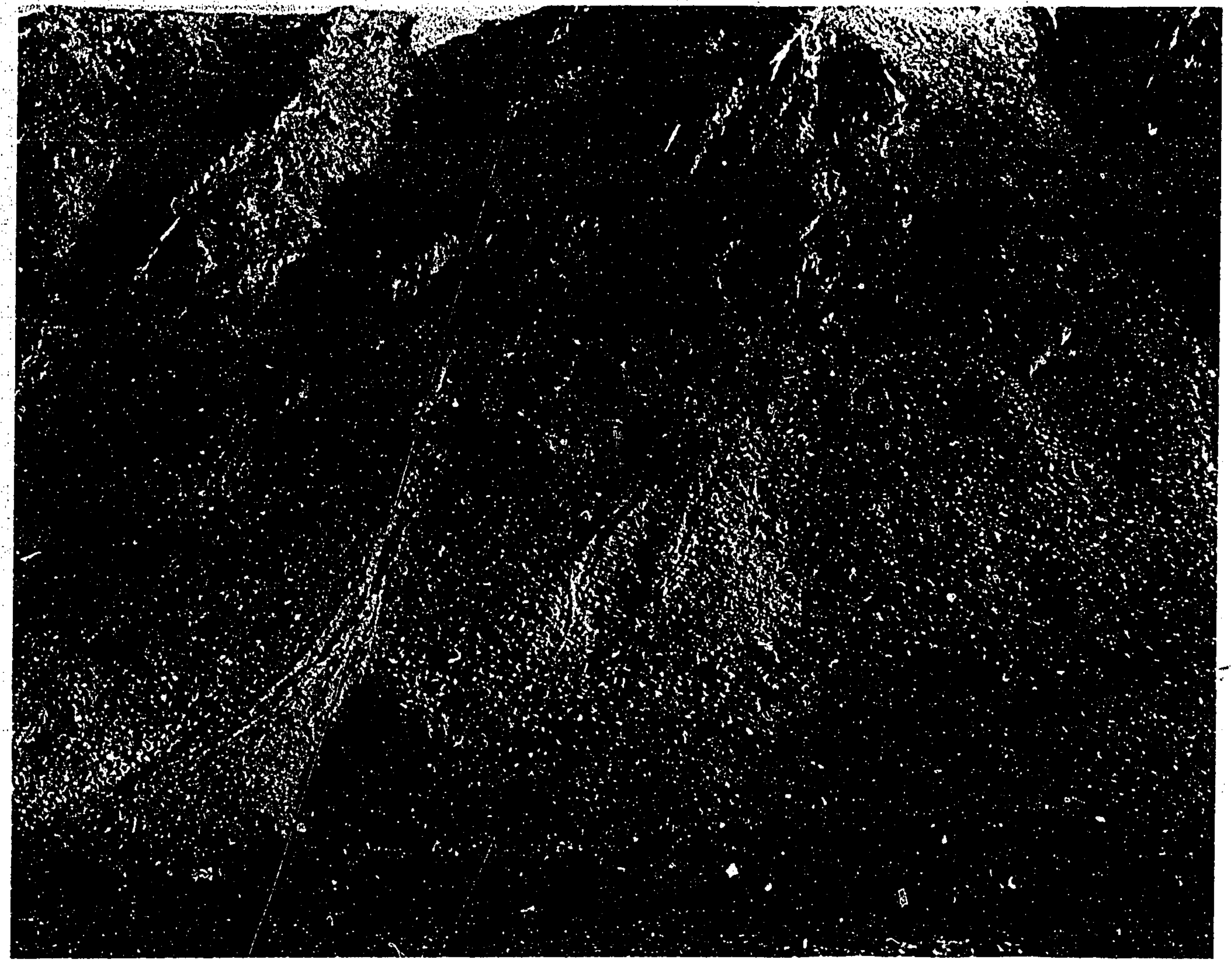

Figure 28. A talus accumulation in the Ruby Mountains, Yukon Territory (61°23′ N. Lat.). Such features are formed by rocks being weathered and broken from the bedrock above and tumbling downslope. The largest rocks are usually found at the base since they can roll the farthest. Largest white rock in foreground is about 1.5 m (5 ft.) high. The elongated depressions in the talus are mud flow channels caused by melt water released from late-remaining snow patches upslope. (Photo by author.)

free of vegetation and quite steep, at or near the angle of repose, while inactive fronts are often vegetated and more gentle.

The origin of rock glaciers is very controversial. Although they have been attributed to landslides (Howe 1909), this is not well accepted since measurements of current rock glacier movement indicate a fairly steady rate, usually less than 1 m (3 ft.) per year (Wahrhaftig and Cox 1959, pp. 392–395). The major controversy centers around whether rock glaciers are the remains of true glaciers that have been subsequently buried by weathering debris (Kesseli 1941) or whether rock glaciers can form independently of pre-existing glaciers (Capps 1910; Outcalt and Benedict 1965). There is increasing evidence to support the latter view.

Perhaps the most comprehensive study of rock glaciers yet to appear is that by Wahrhaftig and Cox (1959) on approximately 200 rock glaciers in the Alaska Range. The results of this investigation indicate that, "... rock glaciers move as a result of the flow of interstitial ice and that they require for their formation steep cliffs, a near-glacial climate cold enough for the ground to be perennially

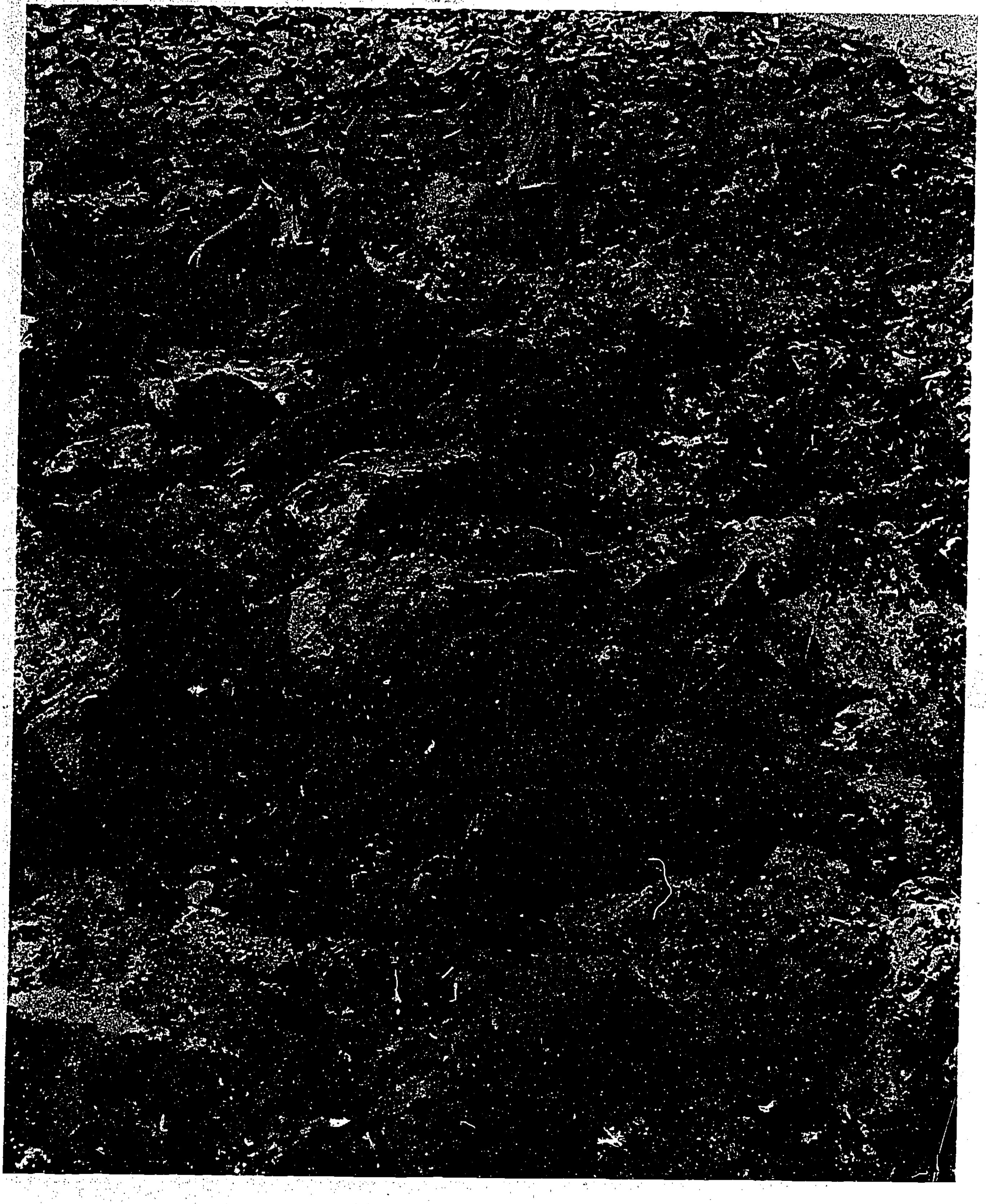

Figure 29. A blockfield occurring on a 20° slope at an elevation of 1675 m (5,500 ft.) in the Ruby Mountains, Yukon Territory (61°23' N. Lat.). This area is above tree line, and the evergreen shrubs are junipers growing in sheltered depressions between the rocks where there is soil. This fact, plus the heavy lichen growth and slight rounding of the rocks, suggests that the blockfield is currently inactive and was probably formed during a more rigorous past climatic period. (Photo by author.)

Figure 30. Rock glacier in St. Elias Mountains, Yukon Territory (61° N. Lat.). The various surface ridges and depressions suggest areas of movement. Note the way the rock glacier spreads laterally after passing through the narrow valley. An earlier advance is now vegetated and is being encroached upon by the present advance. A number of such rock glaciers can be seen along the highway from Haines, Alaska to Haines Junction, Yukon Territory. (Photo by author.)

frozen, and bedrock that is broken by frost action into coarse blocky debris with large interconnected voids" (Wahrhaftig and Cox 1959, p. 383).

Rock glaciers occur in arctic, subarctic, and middle latitude mountainous areas, and may be active and/or inactive in any of these environments. Rates of movement in middle latitudes vary from 5–10 cm/year (2–4 inches/year) in the Colorado Front Range (White 1971, p. 43) to 1–83 cm/year (0.4–33 inches/year) in the Absaroka Mountains of Wyoming (Potter 1969, in Washburn 1972, Chapter 5). Subarctic measurements which have been made include 70 cm (28 inches) per year in the Alaska Range (Wahrhaftig and Cox 1959, p. 383), and about 50 cm (20 inches) per year in southwest Yukon Territory (Personal communication, J. Peter Johnson, Jr.). Although restricted in distribution, rock glaciers can be a significant form of erosion in periglacial environments. It is estimated that in the Alaska Range they represent a denudation rate of 0.4–1 m (1–3 ft.) per century on bedrock walls (Wahrhaftig and Cox 1959, p. 434).

Solifluction lobes

Solifluction lobes are distinctive landscape features in arctic and alpine tundra, resembling huge soil tongues slowly flowing downslope (Figure 31). Frost creep also

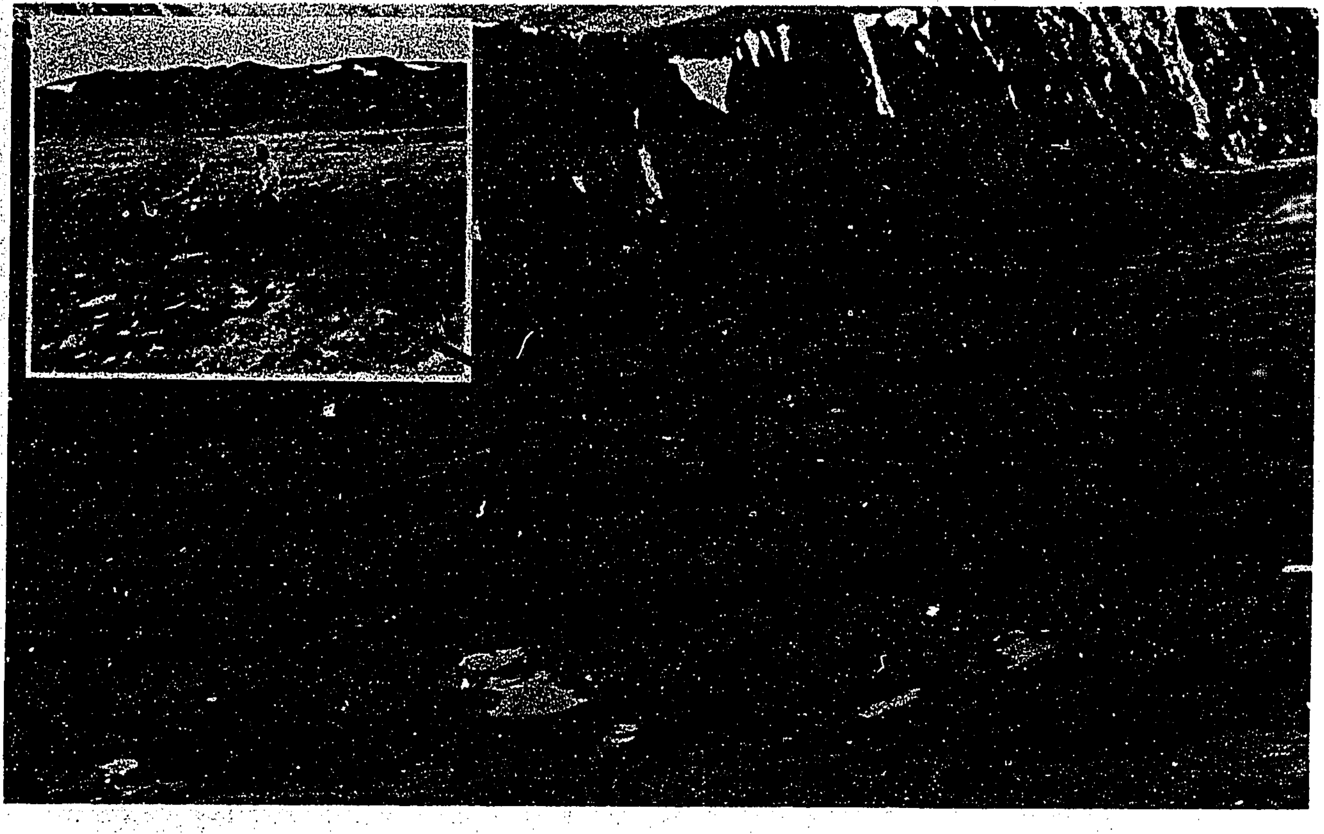

Figure 31. Solifluction lobes in the Ruby Mountains, Yukon Territory (61°23′ N. Lat.). This is a southeast facing slope with a gradient of 14° and an elevation of 1830 m (6,000 ft.). Note the way the individual lobes have coalesced to form the broadly crenulate pattern at the front. The close up of the lobe in the inset provides greater detail and also shows the ridge in the background where snow accumulates and melts slowly through the summer, providing moisture so necessary for the occurrence of solifluction. Although these features give the impression of great movement, measurements on this slope reveal an average surface movement of only 16 mm (5/8 inch) per year. (Photos by author.)

contributes substantially to their movement but, owing to the difficulty of separating the two processes in the field, it is generally assumed that solifluction is the major process. This illustrates nicely one of the difficulties in giving landform features genetic names. Solifluction lobes may form singly or as a series of crenulate necklace-like horizontal bands stretching a few tens of meters to a kilometer (0.6 mile) or more along the slope. These often occur one above the other like treads and risers in stair-like arrangement. Solifluction deposits consist of unconsolidated and unsorted material from silt-size to boulders over 1 m (3 ft.) in diameter. The material is usually fairly angular, and stones are largely oriented in direction of flow. Solifluction lobes vary in height from the barely discernable to more than 6 m (20 ft.) at the front, but average height is between 1–2 m (3–7 ft.). Horizontal distances across individual lobes average 30–50 m (100–165 ft.) (Figure 31).

Solifluction lobes begin as an initial bulge or furl as the saturated surface commences to flow and encounters some agent of retardation, usually vegetation, rocks, or simply a slower moving area. Once this occurs, other conditions being favorable, vegetation takes advantage of the microhabitat at the miniature lobe front and helps maintain the lobe intact. Lobes may also form in bare areas, however, so vegetation is not a prerequisite. The actual mechanism of movement in solifluction lobes is not well known, but it is quite certain that the entire lobe does not move. The greatest movement occurs at the surface, and substantial movement does not occur below a depth of about 25 cm (10 inches). The lobe's forward progression, then, is frequently caterpillar-like with a thin surface layer moving forward over the lobe front. The surface on which the lobe itself is moving is slowly buried, and if vegetated, a thin layer of organic material may be preserved as the lobe advances. This material can be radiocarbon dated and provide valuable information on the age and past rates of movement (Benedict 1966, pp. 24–31; Price 1970b, pp. 219–243).

Although early estimates of solifluction were about 1 m (3 ft.) per year (Högbom 1914, p. 369), measurements in recent years have revealed a much less spectacular rate of 1–3 cm (0.4–1.2 inches) per year (Price 1970b, pp. 157–164). Radiocarbon dating of lobes indicates an average movement of about 3–5 mm (0.2 inches) per year for the last 3,000 years (Price 1970b, p. 230). It becomes clear, then, that solifluction is not nearly as rapid as it was once thought to be but that it is nevertheless the major form of mass wasting in most periglacial environments and is certainly much more rapid than mass wasting in temperate environments.

Periglacial Landscape Evolution

In periglacial environments, as in other regions, the tendency for geomorphic processes is to wear down the land and destroy inequalities with the theoretical possibility of eventually creating a plain. Although it is questionable whether this process proceeds in definable stages, the tendency for this development in humid temperate regions is called *peneplanation* (Davis 1899). In peneplanation the major erosional process is downcutting through stream action which depends upon ultimate marine base level. Mass wasting, although not as important as in periglacial environments, does take place and delivers material to valleys where it is more or less effectively removed by streams.

In periglacial environments, however, frost action and mass wasting are the major geomorphic agents, and slope retreat through backcutting is more important than downcutting. Streams are not well developed due to low precipitation and the presence of permafrost, so material delivered to the valleys is not removed very effectively by streams. As a result there is a tendency for valleys to become filled with detritus. In this system, called *cryoplanation* (Bryan 1946), there is no major loss of material but simply a redistribution within the landscape.

Although the idea that periglacial landscapes are primarily molded by frost action and mass wasting is valid, it should be recognized that vast differences exist within the system. Compare, for example, the arid Arctic Islands of Northern Canada, where the active layer is rarely more than 10 cm (4 inches) deep, to the maritime areas of Iceland or Kerguelen Island, where permafrost is lacking. Such major differences, even though both are dominated by frost processes, must certainly be reflected in landscape development. There are, in addition, many other variables which complicate the picture such as rock type, tectonic activity, and age of surfaces. Taking just the latter factor, consider the importance of glaciation to the age of surfaces. There is considerable evidence that middle latitude areas may have undergone cryoplanation around the margins of the continental ice for varying time lengths during the Pleistocene (Raup 1951; Smith 1949; Wright 1961). Likewise, many subarctic areas were glaciated and not subjected to cryoplanation until free of ice. Therefore, many periglacial areas reflect a composite history of climate and age, and result in no clearly definable landscape pattern (Bird 1967, pp. 251–253). A great deal more research in the diverse areas of the arctic and subarctic needs to be done before the total picture of periglacial landform development comes into focus.

V. BIOLOGIC PROCESSES

General

The overriding factor for life in periglacial environments is low temperature and it is within this framework that all organisms must exist. It is not surprising, therefore, to find a great many adaptations or characteristics which reflect the influence of temperature, e.g., low growth form or low rates of biological activity. It should be mentioned, however, that the pervasive influence of temperature has been strongly questioned. Dunbar (1968, p. 71) maintains that high environmental oscillation, low nutrient status, and the very young age of periglacial landscapes have not allowed evolutionary processes to fully develop so that many of the characteristics attributed to low temperature, such as decrease in species, may be more a reflection of immaturity than low temperature. This contention is largely theoretical, however, and awaits a great deal more research before it is proved or disproved. For our immediate purposes, temperature will be considered as the most important limiting factor for life in periglacial environments (Billings and Mooney 1968; Bliss 1962).

It is difficult to think of any characteristic of periglacial environments which is not at least indirectly associated with low temperatures. Two of the most important aspects of the environment illustrate this point—frost action and permafrost. The combined processes of frost action, as discussed in the preceding chapter, give rise to considerable instability due to the constant mixing and stirring of the surface. Consider briefly some of the implications of this to life. Soil forming processes are greatly complicated due to the physical displacement of mineral and organic matter. This fact combined with the presence of poor drainage hinders the normal development of the soil profile. Vegetation is constantly disrupted since roots and stems are stretched and broken. This is a very important form of environmental stress and has been suggested as one of the major factors limiting the poleward extension of treeline since trees cannot withstand such instability (Griggs 1934a). On slopes, frost creep and solifluction create a very mobile surface, and plants must be able to withstand this considerable state of flux. There are also circumstances, as at the base of solifluction lobes, where the vegetation is continually being buried and it must keep pace with the rate of burial to survive. Animals, too, are affected, particularly those with burrows since considerable effort is required to maintain their homes under these conditions (Price 1971a).

It can be seen that all forms of life in periglacial environments are greatly affected by the constant instability of the surface due to frost action. This is a phenomenon largely lacking in temperate environments and has caused some investigators to question the entire concept of vegetative succession and climax for the tundra (Raup 1951; Sigafoos 1951). Others have maintained that the instability of the tundra is simply another environmental factor to which organisms must adapt (Bliss 1962, p. 119). Both sides of this very complex question have been reviewed by Churchill and Hanson (1958).

Permafrost is also a factor not present in temperate environments but one that has important implications to biological activities. Its major effect is in creating poor drainage through its impermeability. This changes water relations so that surfaces remain saturated for much of the summer even though precipitation is minimal. For the tundra as a whole, drainage is probably more important to the local development of soil and vegetation than are minor differences in climate (Tedrow and Cantlon 1958, p. 172) (Figure 32). On a larger scale, permafrost essentially limits the depth of biological activity. Roots cannot penetrate it and neither can burrowing animals. In addition, permafrost serves as a reservoir of cold and helps maintain the soil at low temperatures throughout the summer. It can be seen, therefore, that local variations in depths to permafrost may have a profound effect on life patterns.

Soils

The soils of periglacial environments are in general poorly developed and much less productive than those of temperate environments. They are shallow, coarse and rocky, acidic, poor in nutrients (especially nitrogen), and predominately poorly drained. Nevertheless they support a substantial amount of biomass which is to their tribute under such harsh environmental conditions. The periglacial regime spans two major vegetation types—the tundra and the northern part of the boreal forest. Emphasis will be given here to the tundra but, as will be shown, the soil

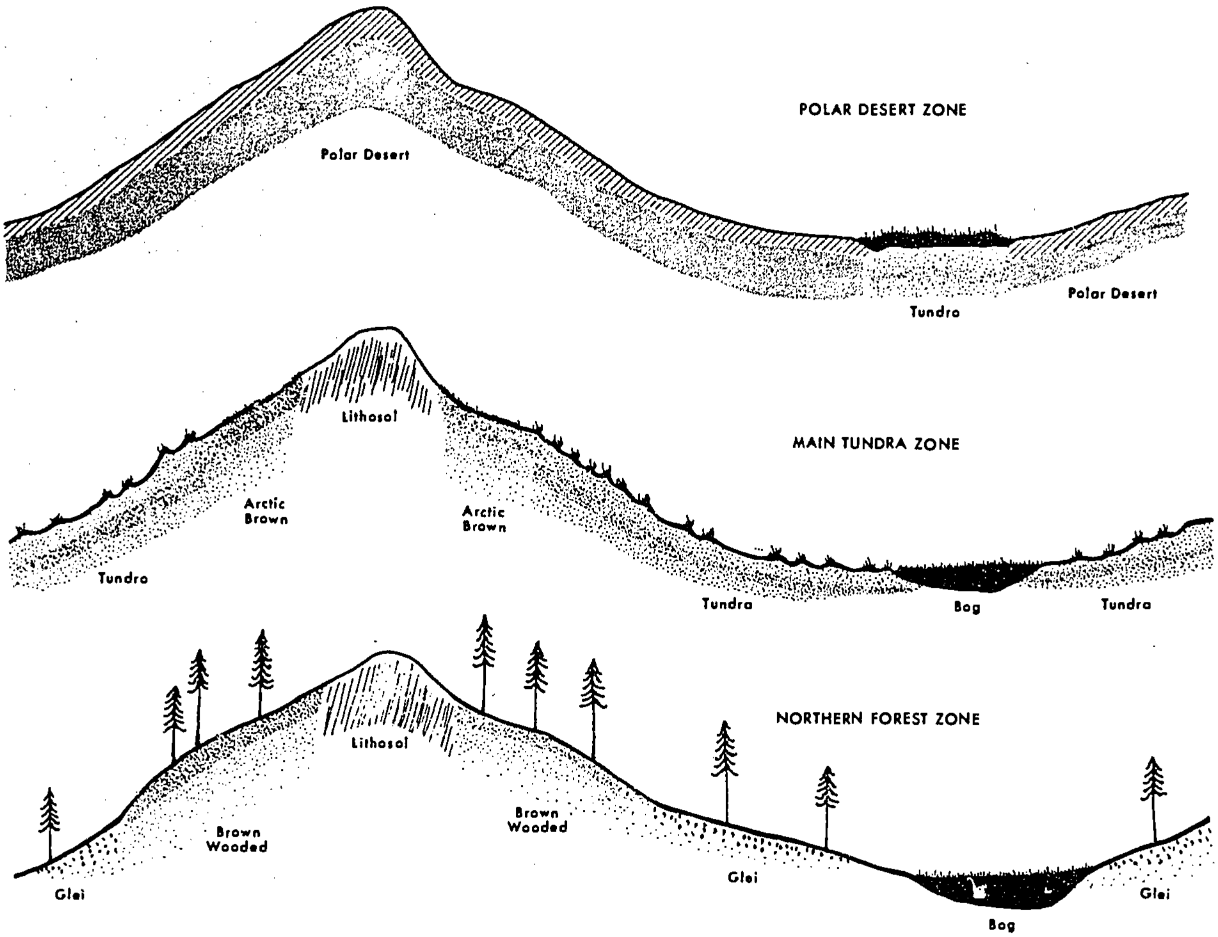

Figure 32. Diagram of soil patterns in northern areas. Note the importance of drainage to the type of soil that develops. (After Tedrow 1966a, Figure 3, p. 53.)

forming processes throughout the periglacial environment are similar.

Owing to their remoteness and relative unimportance, tundra soils are still poorly understood. In fact, much of what we know about them has come as secondary information from investigations with primary focus on other subjects such as geomorphology, botany, and engineering, rather than soil science. The first major pedologic research on tundra soils in North America was begun less than 20 years ago by J. C. F. Tedrow and his associates (1955, 1958, 1960, 1966). It should come as no surprise, then, to learn that several misconceptions have developed with respect to tundra soils. Most of these are related to the classification and mapping into Great Soil Groups on a global basis (Glinka 1928). This classification is the soil counterpart of climax vegetation types and is based largely on the world distribution of climate, the assumption being that given enough time in any climatic region, under a particular vegetation type, a mature soil would develop. The tropical rainforest would produce a Laterite, the middle latitude steppe a Chernozem, and the northern coniferous forest a Podzol. All of these zonal soils develop, by definition, under good drainage, and poorly drained areas within these larger areas would produce an immature soil type. It is therefore a curious extension of logic that can consider the tundra a zonal soil since it is almost universally poorly drained. As Tedrow and Cantlon (1958, p. 166) have said, "Although soil scientists point out that a zonal or mature soil can form only under conditions of free drainage, they nevertheless state that tundra soil is a zonal soil. This direct contradiction that originated over a quarter of a century ago should be done away with."

Another misconception, partially a result of the one just mentioned, is that a special or unique soil forming process operates in the tundra. The classification of soils into Great Soil Groups was largely inferred on the basis of vegetation and this same reasoning was applied to the tundra, so a soil boundary was drawn at the forest-tundra transition. Recent field studies, however, indicate that this boundary has very little if any significance in a pedologic sense and does not necessarily indicate a change in soil forming processes (Tedrow and Harries 1960, p. 245). Podzolization, the major soil forming process of the boreal forest, continues to operate on well drained sites in the tundra although it becomes noticeably weaker farther north (Tedrow, Drew, Hill, and Douglas 1958, p. 33). The major process, since much of the tundra is poorly drained, is gleization. This is no different from glei forming processes under poor drainage in the boreal forest, or any other area for that matter, except for the presence of low temperatures which has a tendency to weaken the process. Tundra soil forming processes therefore are qualitatively no different from those operating in the boreal forest; the only difference is one of degree (Tedrow, Drew, Hill, and Douglas 1958, p. 42).

Soils of the periglacial regime can be divided into four main categories—Lithosols, Arctic Brown (or Brown Wooded), Tundra (or Glei), and Bog soils (Figure 32).

Lithosols

Lithosols form on dry and windswept rocky areas where a dry brown soil may develop to a depth of 2–15 cm (1–6 inches). Vegetation is very sparse, consisting of a few crustose lichens, and there is much bare surface. The Lithosol is characteristic of subarctic and arctic mountains and also of the high arctic where they merge with Polar Desert Soils (Tedrow 1966b) (Figure 32).

Arctic brown soils

The Arctic Brown and Brown Wooded soils (Figure 32) are found in well drained sites and represent the highest development of soils in periglacial areas. In the tundra the Arctic Brown is the only soil that can be considered as forming a mature or zonal profile. Sites with these soils would be best for engineering purposes since they have a good strength-bearing capacity. Unfortunately they exist only in limited areas such as ridges, moraines, and dunes where the active layer is deeper and good drainage occurs (Tedrow 1966a, p. 52).

Arctic Brown soils average 38–50 cm (15–20 inches) in depth and are usually coarse textured with sandy loams predominating. The surface organic layer is 2–3 cm (1 inch) thick and the surface is usually quite acidic with pH values increasing with depth. Morphologically these brown colored soils are very similar to those of the boreal forest. Podzolization weakens farther north so that the bleached layer becomes progressively thinner until it is no longer visible. "The low summer temperatures coupled with small quantities of effective percolation are nearly always insufficient to produce a Podzol. Detailed chemical and mineral analyses show, however, that an embryonic form of podzoliation exists. Leaching is confined primarily to the surface horizon. The low pH of the surface horizon is sufficient to solubilize some iron compounds, deplete the A horizon of bases, dissolve the finer fragments of carbonate rock and translocate small quantities of Fe, Al, and Mn. The Fe which is released probably combines with organic matter to give the solum the strong brown color" (Tedrow and Harries 1960, p. 246).

Tundra soils

Tundra (or Glei) soils are associated with poor drainage due to permafrost and are the most extensive soils of the periglacial environment (Figure 32). They have a surface layer 2–15 cm (1–6 inches) thick consisting of partially decomposed organic matter, and below this the soil is silty. The surface is moderately acid with pH increasing with depth. Seasonal thawing occurs only to 30–60 cm (1–2 ft.) and soil profile development depends on relative wetness, parent material, plant cover, organic matter, and topography. Soil colors range from yellows and browns in drier areas to dark grays in wetter sites (Tedrow, Drew, Hill, and Douglas 1958, p. 36). The primary soil forming process of the tundra profile is gleization at low temperatures. Coupled with this, however, is frost action which keeps the soil in a constant state of flux and tends to retard horizon development. "At any time and place tundra soil morphology reflects two processes: One process relates to soil formation and involves organic matter production and a mildly acid-glei process; the other is a destructive, physical process—that is, frost action including solifluction" (Tedrow 1966a, p. 52).

One of the most striking features of the Tundra soil type is the presence of a fairly ubiquitous organic layer 5–15 cm (2–6 inches) thick at a depth of 60–90 cm (2–3 ft.) below the surface. The origin of this layer is not known, but since it is presently encased in permafrost it is assumed to have originated during a warmer climatic period (Mackay 1958). Radiocarbon dating of the material indicates an age of 8,000 to 10,000 years (Tedrow 1966a, p. 52), and there is increasing evidence for a considerably warmer period in the northern hemisphere at about his time (Broecker, Ewing, and Heezen 1960). In fact, much of the arctic tundra may have been forested during this period (Ritchie and Hare 1971). The exact process of origin is still problematic, however. The two most likely possibilities are that (1) the organic material was displaced by frost action downward during a warmer period or that (2) the organic layer may represent a former surface that has been buried by aeolian processes (although field evidence argues against the latter suggestion) (Tedrow 1966a, p. 52).

Bog soils

Bog soils are associated with Tundra soils and occur in the poorest drained sites, usually in valleys and where permafrost is very near the surface (Figure 32). Bog soils are extensive on the coastal plain of northern Alaska occupying 25% to 50% of the land (Tedrow 1966a, p. 52). Bog soils are always saturated during the summer months and frequently have standing water to a depth of 0.3 m (1 ft.). This water-logged condition essentially prevents organic matter decomposition; it instead favors the accumulations of peat mosses. The vegetation of Bog soils consists of sedges, grasses, and *Sphagnum* mosses. Peat thicknesses average 0.6–1.2 m (2–4 ft.) but in extreme cases may accumulate to over 9 m (30 ft.) (Tedrow, 1966a, p. 52).

Vegetation

The periglacial regime spans two major vegetation types: (1) subarctic and subalpine forests, and (2) arctic and alpine tundra. To simplify the discussion, we will limit our coverage to subarctic and arctic areas, although subalpine and alpine environments share many similarities. The subarctic forest, also known as taiga or boreal forest, is composed mainly of evergreen conifers, particularly spruce. It constitutes the largest contiguous forest on earth and stretches as a belt around the circumpolar land areas of North America and Eurasia (Polunin 1960, Plate I) (Figure 33). It coincides closely with Koeppen's Dfc climate and is basically a continental climate. Since there are no major land masses in the subantarctic to provide a similar continental environment, the boreal forest is essentially absent from the southern hemisphere.

Boreal forest

The *boreal forest* is remarkably similar in structure throughout its distribution. It consists of trees 6–12 m (20–40 ft.) tall with short limbs and tight crowns (Figure 34). The trunks taper quickly from the base upward, and spiraling cracks are often visible in the trunk where the sap has frozen and burst the wood fiber. The boreal forest does not provide very good timber for construction purposes; its main use is for pulp and it is questionable if it should be used for this since it may take a century or more for regeneration to take place.

For the boreal forest as a whole perhaps the greatest structural changes occur on a north-south basis. In the south the forest forms a continuous stand of closely spaced trees while in the north the forest-tundra transition consists of open stands of trees with a thick ground cover of *Cladonia* lichens. Merging into the tundra, the trees become more widely spaced and stunted until they disappear altogether. All gradations exist in between, depending on local conditions, with *muskeg* being characteristic of the more poorly drained sites. Muskeg, also known as "peatland" or "organic terrain," consists of bogs with accumulations of *Sphagnum* moss up to 12 m (40 ft.) thick, and scattered trees occur on slightly better drained sites (Figure 34). Muskeg is present throughout much of the boreal forest and is of considerable ecologic and practical interest since it has excellent insulating abilities and is usually underlain with permafrost (Brown 1968).

Although the boreal forests of both the old and new worlds are remarkably similar in appearance, and if viewed from the air might strike one as being monotonous, there are marked differences in species from east to west in both North America and Eurasia. This is actually somewhat surprising because the farther north one travels the greater the percentage of circumpolar species in the flora, but not a single tree species of the boreal forest has a truly circumpolar distribution (Hustich 1953, p. 161). In North America two major species of spruce dominate—Black spruce (*Picea mariana*) in the west and White spruce (*Picea glauca*) in the east. Where both species occur in the same area the Black spruce normally occupies the poorly drained sites and the White spruce occurs on the better drained sites. Associated species in western North America include Lodgepole pine (*Pinus contorta*) and Tamarack (*Larix laricina*), while in the east the associated species are Balsam fir (*Abies balsamea*) and Jack pine (*Pinus banksiana*) (Eyre 1968, p. 49).

In Eurasia there is also a species difference between east and west, with the dividing line occurring at the Urals. To the west Scotch pine (*Pinus sylvestris*) and European spruce (*Picea sylvestris*) dominate with the spruce occupying the more poorly drained sites. East of the Urals other species become dominant such as the Siberian fir (*Abies siberica*), Siberian larch (*Larix siberica*), and Siberian spruce (*Picea obovata*). In northeast Siberia a major anomaly exists; this area is dominated by a deciduous conifer—the Dahurian larch (*Larix dahurica*), which is the northernmost occurrence of forest in the world extending 72° 50′N., almost 650 km (400 miles) north of the Arctic Circle (Figure 33)!

The evergreen conifer as a growth form is well adapted to areas of long cold winters and short summers since its needle leaves with reduced surface area allow very little moisture loss due to transpiration. This is particularly important during the winter when the roots are encased in frozen ground. The evergreen conifer can also begin photosynthesis in the spring as soon as conditions permit since it does not have to spend energy and time growing

Figure 33. Boreal forest and tundra vegetation. Note that treeline occurs farthest south on the eastern sides of continents where the climate is more severe. (Adapted from Polunin 1960, Plate I, and Lambert's Azimuthal Equal Area Projection, *Goode's World Atlas*, 1970, 13th Edition, p. 57.)

new leaves as do broadleaf deciduous trees, a decided advantage when the growing season is short (Eyre 1968, p. 47). The situation may be reversed, however, when conditions become too severe. The very fact that a tree is evergreen may eliminate it from extreme environments.

The occurrence of the Dahurian larch in eastern Siberia is interpreted as such a case. This area has one of the coldest winters on earth. An often cited climatic station, Verkhoyansk, USSR, has an average January temperature of –50° C (–58° F) and has experienced temperatures as low as –84° C (–93° F)! Much of this area is underlain with permafrost (Figure 8) and is perhaps the most severe environment of all forested areas. The Dahurian larch grows very slowly and is normally quite stunted but in the

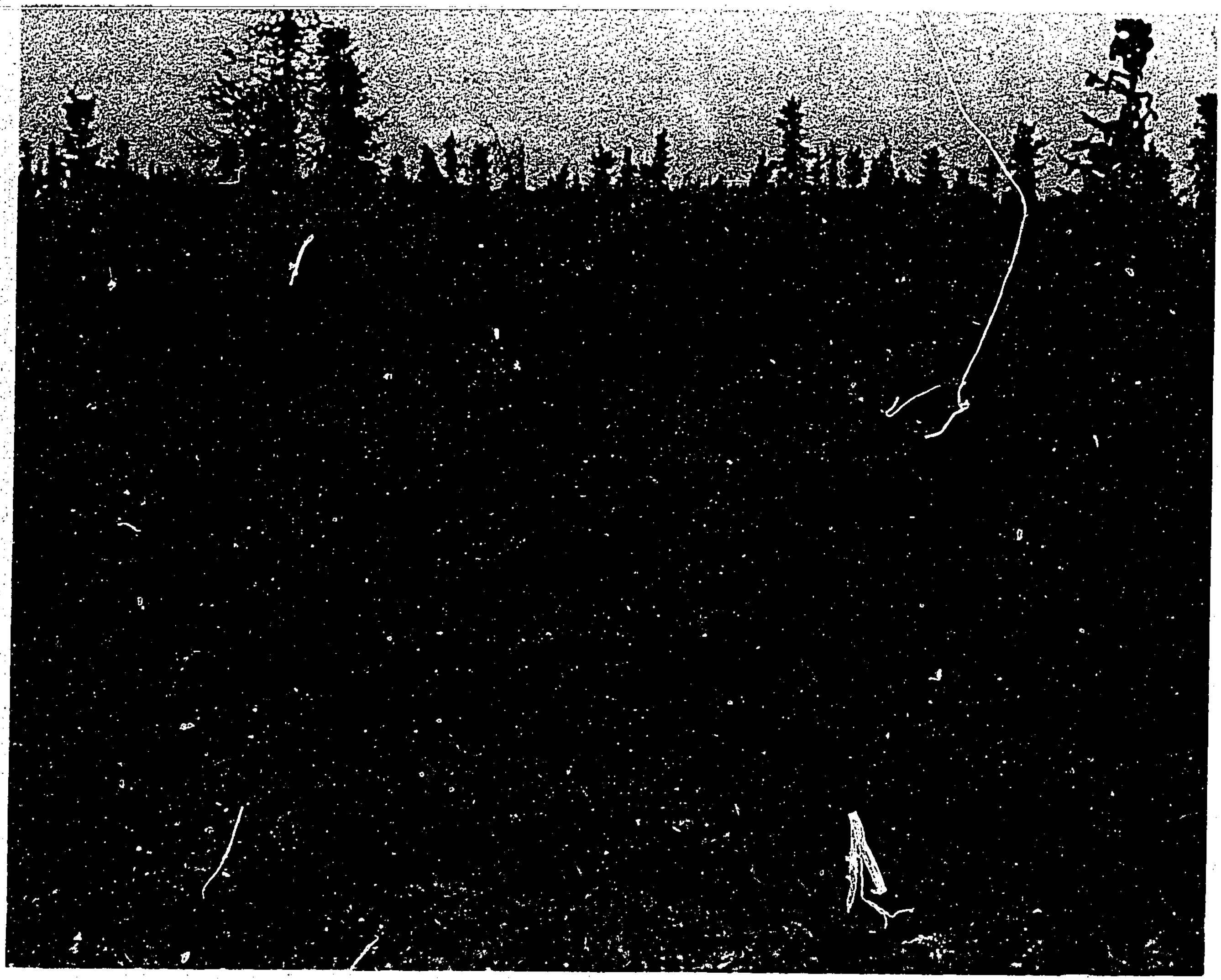

Figure 34. The boreal forest near Inuvik, N.W.T. (68° N. Lat.). This is near the poleward limits of the boreal forest and the trees are more stunted and widely spaced than farther south. Nevertheless, the general appearance is characteristic for this vegetation type. The forest is underlain by permafrost and the open areas are occupied by mossy "muskeg" terrain. (Photo by Lawrence C. Bliss, University of Alberta.)

absence of any real competition it easily maintains dominance. As Eyre (1968, p. 49) has said, "It is doubtful if these areas would be 'forested' at all were it not for the great climatic and edaphic tolerance of this tree."

It is worthy of note at this juncture that although the boreal forest is dominated by conifers, broadleaf deciduous trees do occur and frequently extend even farther north than conifers. Birches, alders, aspen, and poplars are associated species in the boreal forest but very seldom dominate except during the initial stages of succession. They are the first to occupy sites after fire or other disturbance, but since they need sunlight to reproduce, they are eventually overtopped and replaced by conifers. The important point here is that the reason the broadleaf deciduous tree as a growth form does not dominate in the subarctic is not the harshness of the environment but the interspecies competition (Eyre 1968, p. 51).

Treeline

The transition from forest to tundra, be it arctic or alpine, is one of the major ecological zones in the world. Consider, for example, the implications of treeline to a single type of organism such as birds. In the tundra they can no longer build a nest in the relative safety of a tree limb but must build it on the ground. In the forest they have a definite song perch, but in the tundra they must give their songs high in the air to announce the possession of territory and to solicit mates (Kendeigh 1961, p. 321). This is just one of the countless examples that could be given to illustrate the ecological impact of this major vegetational boundary. Before moving on to the tundra, it is worthwhile to discuss the treeline as a feature in its own right and some of the factors responsible for its location.

The reasons for the cessation of tree growth in high latitude and altitude areas are still poorly understood, but treeline is generally considered to be a climatic boundary (Hare 1952). Both arctic and alpine treelines generally parallel the 10° C (50° F) isotherm for the warmest month, and temperature is probably the major limiting factor although various combinations of wind, frost action, snow cover, permafrost, and cloudiness may be important in explaining local situations. Daubenmire (1954, p. 121) observed that alpine treelines in North America decrease in elevation at a rate of approximately 110 m (360 ft.) per degree of latitude. Alpine treelines are much more distinct than are arctic treelines since the transition zone is relatively narrow, usually occupying less than a few hundred meters. In the arctic the transition zone from forest to tundra may cover a distance of over 100 kilometers (62 miles) (Hustich 1953, p. 150). This has caused some observers to maintain that since the forest-tundra "transition" occupies as much area as the unique formations it lies between, it probably should be recognized as a distinct type on a par with the other two (Britton 1967, p. 71).

The actual location of arctic treeline is still imperfectly known due to the paucity of detailed investigations in some areas. The boundary on older maps appears as a fairly straight line but has become increasingly ragged as more information is available (Raup 1941, p. 221). One of the real problems in mapping treeline is deciding "when is a tree not a tree?" Various criteria have been used by different investigators and considerable confusion exists on this point. Hustich (1953, pp. 149–150) has listed four different definitions: (1) "economic limit of forest ... the limit beyond which commercial cutting of trees endangers natural afforestation, (2) biological limit of forest ... the limit of continuous forest, (3) tree-line ... the absolute polar, maritime, or vertical limit of a given species in tree-form (at least 2 m high), and (4) limit of species ... the line of most advanced outposts attained by a species northward, seaward, or in a vertical direction, irrespective whether growth is prostrate, ascending, or tree-like." The distance between the "limit of species" and the "biological limit of forest" may exceed 100 km (62 miles) so the range of difference between these criteria is substantial. Hustich (1953, p. 150) maintains that the most easily mapped feature is the "limit of species" since many observers have noted the outposts of tree species in the arctic. His map of the arctic treeline is probably the best available and has been used in the compilation of Figure 33.

An additional problem when discussing the location of treeline is that it is seldom static but is either advancing or receding depending on a complex of environmental factors, particularly climate. Griggs (1934a, 1946) presents rather convincing evidence that the treeline in Alaska is moving into the tundra. Farther east the picutre changes so that in western Canada the treeline is approximately stable while in Eastern Canada it is retreating (Raup 1941, pp. 221–227). The significance of these migrational trends must be interpreted with caution since a great many factors are involved. Nevertheless, they do seem to indicate a general amelioration of climate in Alaska while the opposite is true farther east in Canada.

Tundra

Tundra is the treeless expanse of sedges, grasses, herbs, mosses, and lichens existing beyond treeline in arctic and alpine areas. This is one of the most extreme environments on earth where above freezing temperatures occur for only one or two months in the summer. Permafrost is ever present, frost action is dominant, and the soils are poorly developed. Owing to low temperatures, the humidity is constantly high but the arctic tundra receives less precipitation than some deserts. There are strong and persistent winds, and great extremes occur in photoperiod from winter to summer. Nevertheless, tundra vegetation is well adapted to the environment; if this were not so it would have been eliminated long ago.

One of the characteristic and striking features of the tundra is its relatively small flora. There are over 225,000 species of flowering plants on earth today, but Polunin (1959) lists only 892 species in his *Circumpolar Arctic Flora.* The decrease in species with latitude is nicely shown from a tropical area like Brazil with 40,000 vascular species to southeast United States with 5,000, to southern Canada with 4,400, to the Canadian Arctic Archipelago with only 340 species (Billings 1970, p. 52). A similar reduction of species takes place within the tundra itself. The flora of the Alaskan tundra consists of approximately 440 species (Spetzman 1959) and decreases from 250 species along the southern edge of the tundra to 150 in the north near the coast to only about 100 species in the immediate vicinity of the coast at Point Barrow (Britton 1967, p. 87). Shrubs show a steady decline in number to the north and reach their poleward extent along streams and other sheltered areas. This reduction of species with increasing latitude is largely a reflection of increasing severity of the environment but other factors such as age since glaciation or emergence from the sea may also be important.

The flora of the arctic tundra is truly circumpolar with many species having a continuous distribution around the globe. For this reason the tundra is strikingly similar in appearance on a latitudinal basis and is conveniently divided into three belts, low, middle, and high arctic (Polunin 1960, p. 383) (Figure 33). Low tundra occurs immediately north of the boreal forest and is the most luxuriant type with a complete vegetative cover of shrubs, grasses, sedges, and herbaceous species (Figure 35a). Poorly drained and marshy areas are characteristically occupied by mossy hummocks or tussocks which range from 5–50 cm (2–20 inches) in height surrounded by depressions where water stands throughout much of the summer (Raup 1965). This is very similar to the "muskeg" of the boreal forest except there are no trees. Walking on these hummocks is like walking on a treadmill because they are spongy and very difficult to negotiate.

The middle tundra is poorer in species and less luxuriant than the low tundra (Figure 35b). Some of the plants important in the low arctic are absent although most of the dominants are still present. Site preferences remain the same but many species become more selective about where they occur. Shrubs become noticeably fewer and there are more bare areas. The last belt, high tundra, exists poleward of 70° N. latitude and is very poorly vegetated (Figure 35c). Species diversity is greatly reduced and vegetation is largely restricted to the favorable sites—usually the more moist ones. Lichen-dominated "fell field" areas become more and more dominant with increasing amounts of bare surface. This area is often called "the polar desert" (Tedrow 1966b).

If you were to fly over the arctic tundra, your impression would probably be one of a vast sameness, but an inspection on the ground would quickly convince you otherwise. Great environmental differences exist within small areas and these are reflected in patterns of life. An 11° C (20° F) difference may exist between the sunny and shaded side of a boulder; likewise, a snow-covered soil surface may be several times warmer in winter than an adjacent bare and exposed surface. Such differences constitute microhabitats and greatly influence the local distribution of tundra species. An excellent example of this is provided by the vegetational relationships across the solifluction lobes in Figure 36. These occur on a southeast facing slope in subarctic alpine tundra located at 62° N. in the Ruby Mountains of southwest Yukon Territory.

Several important facts are illustrated here: (1) the areas immediately below the solifluction lobes serve as favorable

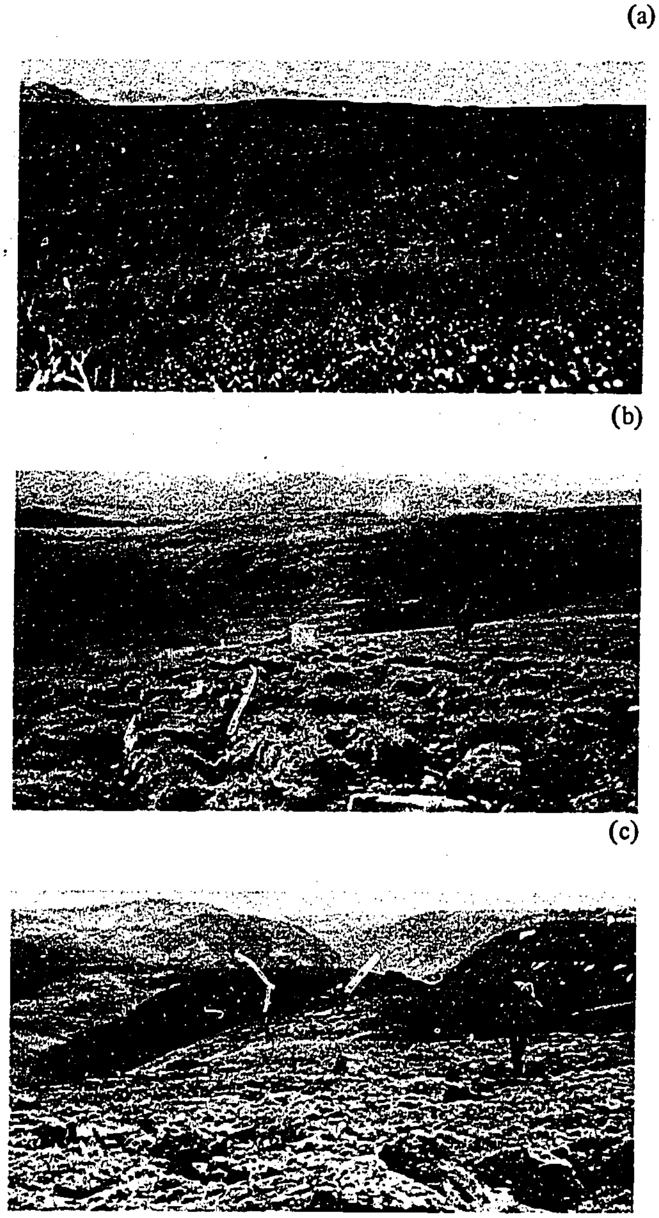

Figure 35. Views of typical plant cover in the (a) low, (b) middle, and (c) high tundra, as delimited in Figure 33:

(a) The low tundra is usually completely vegetated with shrubs, grasses and sedges;

(b) Shrubs largely disappear in the middle tundra and poorly drained mossy hummocks such as shown here become dominant;

(c) Plant cover is sparse in the high tundra with considerable bare area. The vegetation consists primarily of mosses, lichens, and low lying cushion plants. (Photos by author in (a) Alaska and (b and c) Yukon Territory.)

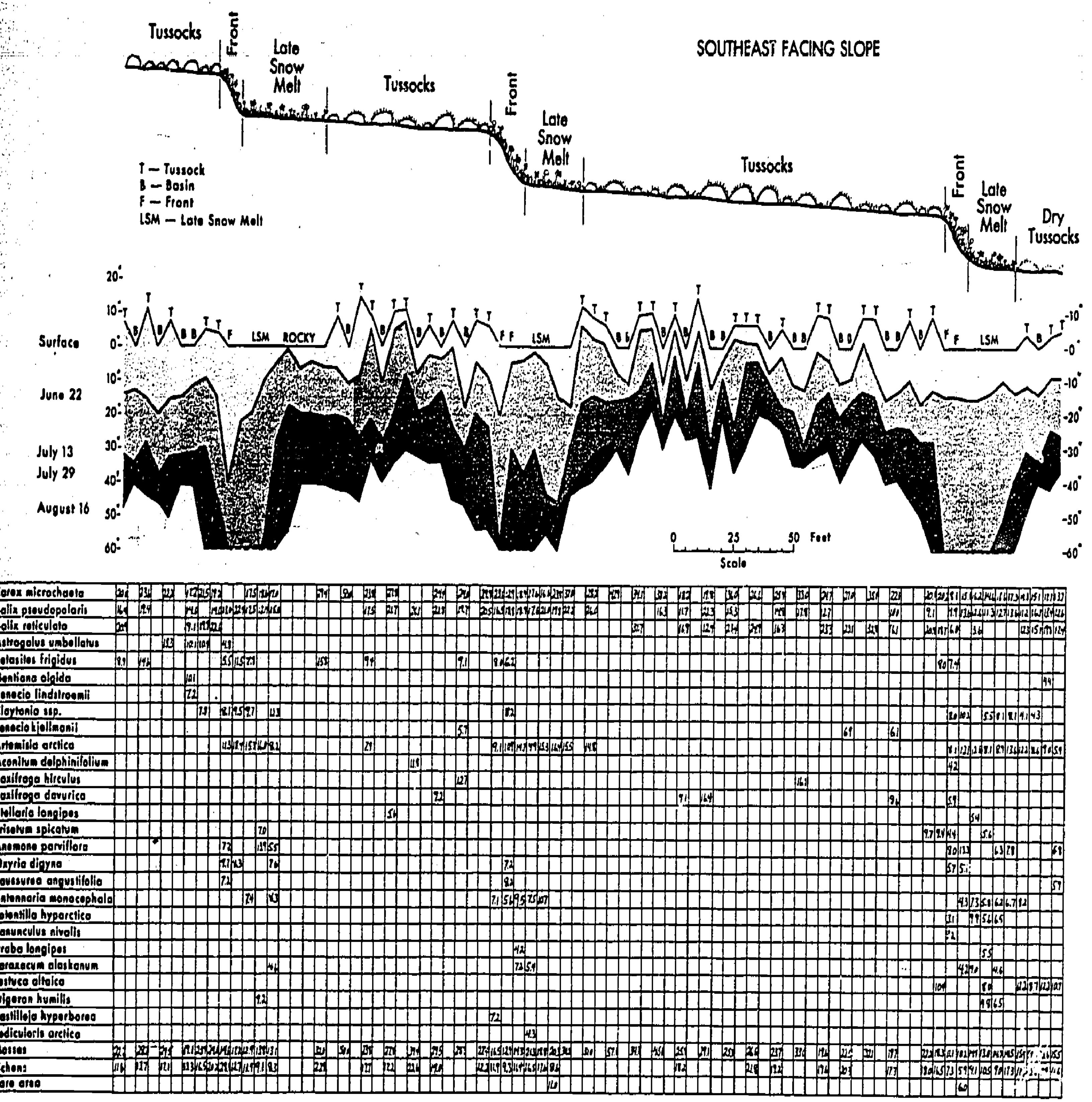

Figure 36. Cross section of solifluction lobes on slope depicted in Figure 31 showing relationship between vegetation and permafrost. The top illustration shows plant communities across the lobes. The middle illustration gives depth of active layer at different times during the season, and the bottom table gives vegetation composition at 1.5 m (5 ft.) intervals across slope. Note that active layer is deepest at lobe fronts where it is warmer owing to the higher angle of incidence, and tussocks do not occur. The greatest number of species occur immediately below the lobe fronts and are a reflection of the more favcrable microhabitat. (After Price 1971b, Figure 5, p. 641.)

microhabitats as is shown by the greater number of species occurring below the lobe fronts and the repetitive nature of the plant communities across the slope (Figure 36). It is much warmer at the lobe fronts than elsewhere on the slope because the sun's rays strike the fronts at a higher angle. Also snow accumulates in the lee of the lobes and serves as insulation in these sheltered areas during the winter.

An additional observation can be made to point out the close relationship between vegetation and permafrost. One of the most striking things about the middle illustration, showing depths of the active layer, is the existence of three deep areas immediately below the lobe fronts (Figure 36). This is due to higher temperatures at the lobe front, as mentioned, but also to the kind of vegetation that exists. Since it is warmer here, there is deeper thawing and the area immediately below the lobe is better drained. As a result. mosses do not accumulate as they do a few meters downslope in the "Tussock Community." A reciprocal relationship is in effect—mosses accumulate due to poor drainage and mosses provide excellent insulation, so permafrost does not thaw as deeply. The opposite is true for the area immediately below the lobe fronts where mosses are not prevalent (Price 1971b).

Tundra plants possess a number of adaptations that allow them to live in such an extreme environment. Perhaps the most obvious adaptation is their low growth form. The environment is vastly different at the surface than it is at a height of 1 or 2 m (3–7 ft.). Soil has a higher thermal conductivity than the air and in summer the temperatures are substantially higher near the soil surface. In winter the soil surface is also warmer than the air due to snow cover. Another important advantage of low growth form is that it allows the plants to escape the desiccating winter wind. Like temperature, a strong gradient exists with wind so that an average velocity of 20–30 knots at 1.5 m (5 ft.) above the surface would decrease to virtually zero a few centimeters above the surface. Shrubs, for example, are usually limited to depressions or the lee of rocks where snow accumulates, and any twigs that stick above the snow are neatly sheared off by the harsh winter wind.

A high percentage of tundra plants are perennial, a fact that has survival value in extreme environments, since it releases the plant from the risks involved in annual reproduction through seeds. Although most tundra plants let seeds, very little reproduction is brought about in this manner because environmental conditions are adequate for seed production and germination only in some years (Bliss 1962, p. 129). One of the major deterrents of seed germination is the thick cover of *Sphagnum* mosses which prevents the seeds from reaching the soil. This is why a relatively lush crop of flowers often occupies the disturbed site after a bulldozer or other vehicle has destroyed this moss layer. It gives a false sense of productivity, however, because the original tundra may take centuries to return and the disturbed area is susceptible to subsidence and erosion due to the thawing of permafrost. Another advantage of being perennial is that it allows the accumulation and storage of starches and sugars in root biomass (tundra plants characteristically have a high root to shoot ratio), so rapid growth may be made once conditions are right in the spring. This is of fundamental importance since tundra plants must be able to complete their life cycle quickly.

Plant reproduction in the tundra is largely through rhizomes, which are lateral stems that resemble roots but have the ability to send off new shoots. Without this or a similar kind of ability it is doubtful if tundra plants could survive in such an unstable environment. They are continually being stretched, broken, and buried due to frost action and solifluction. The rhizomes often form an almost complete mat on the soil surface going in every direction from the plant, and any of these has the ability to send off new shoots. Many weeds of middle latitudes have rhizomes, e.g., dandelions; this is why they are virtually impossible to kill by simply pulling them out of a lawn. Parenthetically, it is interesting to note that many tundra species are closely related both floristically and ecologically to middle latitude weeds (Griggs 1934b).

From this very brief listing of some of the more important characteristics of tundra vegetation, it can be seen that the primary adaptations of arctic plants are to the extreme physical environment. The factor determining whether a species can occupy any given site is its ability to withstand the environmental rigors of that site—not the competition for the site by other species. This is the opposite of what transpires in the tropics where there is little worry about the environment but there is severe interspecies competition for space and food (Dobzhansky 1950). In the tropics, relationships are very complex and organisms develop highly specialized forms and techniques to compete with other organisms. For example, organisms may have elaborate reproduction systems, e.g., the lip of some orchids are constructed to resemble the female of certain insects so males are induced to alight and attempt copulation, thereby bringing about cross pollination (Kullenberg 1950). Also tropical organisms invariably have well developed defense mechanisms such as thorns, claws, or poisonous sap or venom. Not so in the tundra where interspecies relationships are simple and organisms are not highly specialized. Self pollination is more important than wind or insect pollination since in such an extreme environment this important and timely task cannot be left to chance (Bliss 1962, p. 129). Tundra plants do not have thorns, and poisonous plants are unknown (Porsild 1953, p. 17); bumblebees do not even have stingers!

The entire energy of the tundra ecosystem is focused on survival against the environment; little concern is given to other organisms. The vegetation consists largely of pioneer species which colonize sites but, unlike in low or middle latitudes, these "pioneers" are frequently not replaced by other species as in the normal system of succession. When disturbance occurs, the same species usually reoccupy the site, resulting in a kind of perpetual readjustment rather than succession. Therefore, the species that occupy a site are more a function of the local environment than of time. It is for this reason that the concept of climax in the tundra has been severely questioned (Churchill and Hanson 1958).

Although the tundra exists in a very extreme environment and the growing season is usually less than two months long, the vegetation has a surprisingly high rate of energy conversion. Average rates of biomass productivity in both arctic and alpine tundras are similar, ranging from 0.20 to 0.60 $gr/m^2/day$ based on the entire year. When production rates are calculated just for the length of the growing season, however, the values range from 1 to 3 $gr/m^2/day$, which is comparable with that of middle latitude environments (Bliss 1962, p. 137). The conclusion is that tundra plants are amazingly efficient since they have large reserves of carbohydrates stored in their tremendous root biomass ready for immediate use and they can therefore utilize a large portion of the growing season for growth and development.

Wildlife

Like vegetation, the fauna of the arctic tundra is largely circumpolar and is represented by only a few species although many of these comprise large individual populations, e.g., caribou, lemmings, mosquitoes. It is instructive to compare estimates of species' numbers from several taxonomic groups. Of the approximately 8,600 species of birds in the world, only about 70 breed in the arctic and most of these migrate southward in winter (Dunbar 1968, p. 71). There are 3,200 species of mammals but only 30 occur above arctic treeline (Rausch 1953, p.91). There are no snakes or other reptiles, and there is only one amphibian, the wood frog, in the arctic. Fishes are also poorly represented; of the 30,000 or so known species only about 50 live in arctic waters (Dunbar 1968, p. 71). A similar decrease takes place with the invertebrates. Of the several hundred thousand species of insects in the world, a total of only 300 are found in the arctic. Freeman (1952, p. 175) states that there are 38 species of mosquitoes in the boreal forest but only four in the tundra. As mentioned, however, these species are represented by millions of individuals, as anyone who has visited the arctic can attest.

The reason for the striking decrease in species poleward is still a moot question. On an immediate level it would seem to be due to extreme cold, the lack of nutrients, extreme seasonality, and decreased habitat diversity. On a grander scale, however, it must be conceded that the tundra has suffered great instability due to glaciation and climatic change so that evolution has had less time to work. This is greatly contrasted with the tropics, which has been characterized by stability throughout recent geologic time and, of course, has the greatest species diversity of all.

Whatever the ultimate reason for the paucity of species in the polar regions, the most immediate problem for survival is the extreme cold and the seasonality of food supply. As in other extreme environments, animals cope with harsh conditions by three methods: (1) hibernating, (2) migrating, or (3) withstanding. Very few animals hibernate in the arctic tundra owing to the difficulty of maintaining body temperatures above freezing where there is permafrost and winters are so long. Burrowing is common, however, and many small animals spend considerable time underground or under snow. Lemmings, for example, often nestle together in subterranean nests and share body heat between short forays to the surface. Likewise, the ptarmigan roosts in tunnels burrowed in the snow, sometimes for days at a time.

The grizzly and polar bear do not hibernate in the true sense of the word but do den up and go into a torpid state although they may awake occasionally and leave the den for short periods. They also give birth to their young in the middle of the winter. Arctic insects usually pass the winter in the larval or egg stage although they may occasionally overwinter as adults. Many arctic insects can be frozen for months or even years and upon thawing resume activity as if nothing had happened (Kendeigh 1961, p. 320). The only true hibernator is the Arctic ground squirrel (*Citellus parryi*). Their dens are located in well drained rocky or sandy areas and they survive the winter by lowering their body temperature and decreasing their respiration to an almost imperceptible rate (while hibernating they can apparently be handled without awakening them). Although hibernation is an amazing mechanism it is not foolproof in the arctic since the animals must make very careful preparations for it and a few invariably freeze, particularly the young (Mayer 1953, p. 343).

Those species that cannot withstand the extreme cold or lack of food migrate. Birds are the most mobile; perhaps the most spectacular migration of all living things is that of the arctic tern which wings its way every fall 16,000 km (10,000 miles) from the arctic to the tip of South America and parts of Antarctica. Migration of the bird fauna is almost complete, with the exception of the ptarmigan, snowy owl, raven, and some marine birds that live by pools of open water along the coast.

Most land mammals are not mobile enough to migrate, but the caribou does trek southward to the boreal forest annually, although this is probably not so much to escape the cold as to find food in the lichen-rich woodland. Most of the large sea mammals migrate, but once again it may not be the cold they are fleeing so much as the ice forming over their heads and the paucity of food. The jar seal and the bearded seal are able to maintain breathing holes through the ice so they stay through the winter as do some walrus where tidal action and rip currents maintain open water (Baird 1964, p. 118).

The species which do not hibernate or migrate are of perhaps greatest interest here since they withstand the full brunt of the long dark arctic winter and their approach to circumventing the cold is most elucidating. It was observed over a century ago that there is a general tendency for body size of similar species to increase with latitude (Bergmann's Rule) (Bergmann 1847). The physiological basis for this is that heat production in warm blooded animals is proportional to the mass. Heat loss, however, occurs at the surface and the larger an animal is, the smaller its surface area in relation to its mass (volume and mass increase as the cube of linear dimensions while the surface increases as the square). It can be seen, therefore, that larger animals would have an advantage over smaller ones because of their smaller surface/mass ratio. Although Bergmann's Rule is simply an empirical observation, many species obey it (see Hesse, Allee, and Schmidt 1951, pp. 462–466), but many do not, e.g., caribou, raccoons, otters, and some burrowing animals and migratory birds.

Another long established maxim in zoogeography with a similar empirical basis is Allen's Rule (Allen 1877) which states that in colder environments appendages such as ears, limbs, tail, and nose tend to become shorter and more compact. The physiological basis of this is that surfaces are decreased so less heat is radiated and less energy is required to maintain body temperature. Examples of animals that adhere to Allen's Rule include the rabbits, wolves, foxes, many rodents, and to a certain extent, man, but there are also many exceptions. For example, the polar bear has the longest neck, head, and nose of all the bears (Dunbar 1968, p. 26).

Scholander (1955) has strongly criticized Bergmann's and Allen's Rules, pointing out numerous exceptions and maintaining that on a physiological basis surface area is of little importance in the conservation of heat as compared with insulation. "The hopeless inadequacy of cold adaptation via Bergmann's rule may be seen by the following consideration. Take a body-to-air gradient in the tropics of 7° and in the arctic of 70°, i.e., a tenfold increase. A tenfold greater cooling in the arctic animal is prevented by covering the surface with fur a few centimeters thick. A relative surface reduction of ten times would require a weight increase of the animal of one thousand times" (Scholander 1955, p. 22). Although these venerable principles of animal ecology may be controversial, and debate will doubtless continue, there is no question that there are more efficient ways to reduce heat loss than the surface/mass ratio. Perhaps the classic work on adaptation to cold in arctic mammals was carried out by Scholander and his associates (1950).

It has long been known that the body temperature of warm blooded arctic animals is similar to that of temperate and tropical animals. This means when temperatures drop to −40° to −60° C (−40° to −76° F) in the arctic, a temperature gradient of as much as 100° C (180° F) may exist between the interior of the body and the environment. Internal body heat must, of course, be maintained within narrow limits and this is usually accomplished by two methods: (1) lowering the heat loss through increasing the insulation, and (2) increasing the heat production by raising the metabolism (Scholander, Walters, Hock, and Irving 1950, p. 225).

Experiments were run on a number of skins from arctic and tropical mammals and, as expected, the fur of the arctic animals had much greater insulating qualities. The arctic fox, for example, can sleep out on the snow comfortably at subzero temperatures and does not have to increase his metabolism until a temperature of −40° C (−40° F) is reached (Scholander, Hock, Walters, Johnson, and Irving 1950, p. 251). Arctic mammals also have well developed subcutaneous fat layers and are more completely covered with fur. The musk ox has a woolen undercoat covered by long guard hairs 60–80 cm (2–2.8 ft.) in length which trail almost to the ground and hide its feet. The snowy owl and ptarmigan have feathers on the bottom of their feet, and the arctic fox, hare, and polar bear have fur on the soles of their feet (Hesse, Allee, and Schmidt 1951, p. 614). There are some arctic species with bare appendages such as the legs of the gull, snow bunting, and raven, but these have the ability to lower the temperature of the extremities to just above freezing which greatly decreases the energy required to keep them warm (Scholander, Walters, Hock, and Irving 1950, p. 233).

Some small arctic mammals, however, such as weasels and lemmings have relatively poor insulation and overlap with many tropical forms. These animals obviously cannot withstand the extreme cold continuously and they escape, at least for their resting periods, into the snow or insulated nests. While above ground, they must maintain a sufficient level of metabolism to substitute for their insufficient insulation. The heat regulation and temperature sensitivity of several arctic and tropical animals are shown in Figure 37. As can be seen, man is a tropical animal with a critical

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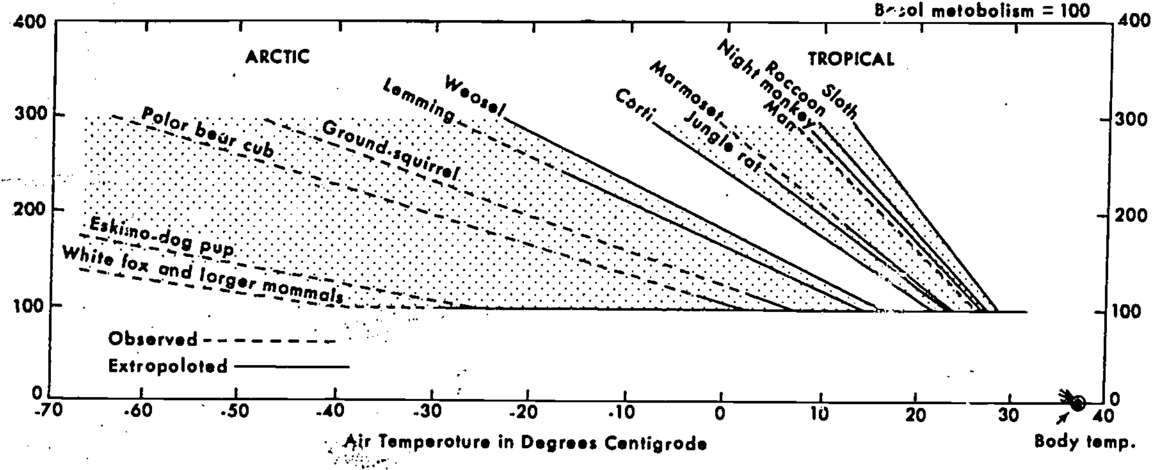

Figure 37. Heat regulation and temperature sensitivity of arctic and tropical mammals. The internal body temperature of all the animals is similar, but as can be seen by the steepness of the gradients, the tropical animals increase their metabolism rapidly when ambient temperatures decrease. On the other hand, the insulation of the arctic fox makes it unnecessary for him to increase his metabolism until a temperature of −40° C (−40° F) is reached and then he has to increase it only slightly. (After Scholander, Hock, Walters, Johnson and Irving 1950, Figure 10, p. 254.)

temperature of 25–27° C (77–81° F) and is able to survive in cold climates only by increasing his insulation, i.e., by wearing warm clothing, or the equivalent of burrowing, constructing a shelter. Most animals that live in the arctic are admirably prepared for the cold. In fact, they frequently have more difficulty in losing heat than in keeping warm. An extreme example is the Alaska fur seal, which becomes overheated only a few degrees above 0° C (32° F); many die from heat prostration during the commercial seal drives on the Pribilof Islands (Bartholomew and Wilke 1956).

Another characteristic of animal life in the polar areas is decrease in bright coloration and patterns. One need only think of the zebra, cheetah, or leopard compared to the moose, caribou, or wolf. Brightness of color and distinctiveness of pattern also frequently decrease poleward within the same species as reflected in butterflies and moths (Downes 1964, pp. 295–299). This is apparently a result of the lower level of competition and selective pressure.

An associated phenomenon is the white coloration of many arctic mammals in winter. Many species undergo this color transformation, including the arctic hare, colored lemming, gray wolf, arctic fox, polar bear, ermine, caribou, ptarmigan, and snowy owl. There are several exceptions to this rule but perhaps the most striking is the raven. Turning white in winter and brown in summer has long been considered an adaptive mechanism because of camouflage value during both seasons. Ptarmigan, for example, stick close to the remaining snow patches in the spring until they lose their white winter plumage. White coloration has also been suggested as giving special protection against heat loss since radiation would be less from a white surface, but this has recently been experimentally disproven (Hammel 1956; Svihla 1956). There may, nevertheless, be something to the assertion that the relative absence of pigmentation during winter would allow more air space in the hair or feathers and thereby increase the insulation.

Our discussion of arctic wildlife would be incomplete without mention of the cyclic fluctuations in populations of certain animals. This is particularly true of the lemming which increases in number for 3–4 years and then suddenly and violently crashes, resulting in a mass exodus and occasionally a "suicidal march to sea." There are two well documented cycles with periodicities of 3–4 and 9–10 years. The 3–4 year cycle is perhaps best developed in the lemming (Figure 38), but it also occurs in the arctic fox, snowy owl, ptarmigan, and mice and voles. The 9–10 year cycle is best developed in the subarctic with the snowshoe rabbit, ruffled grouse, and Canada lynx (Kendeigh 1961, p. 237).

The lemming cycle will be discussed here since it is best documented (Pitelka 1967), but similar cycles occur in the arctic fox and snowy owl since the lemming is a major component of their diet. In the good years they increase their numbers correspondingly, but when the lemmings decrease they must either migrate southward (snowy owl) or die of starvation (arctic fox). The lemming is also essential to the Eskimo since trapping the arctic fox is an important part of their economy and fluctuations in the lemming population would cause fluctuations in their economy.

The reasons for the buildup and subsequent collapse of

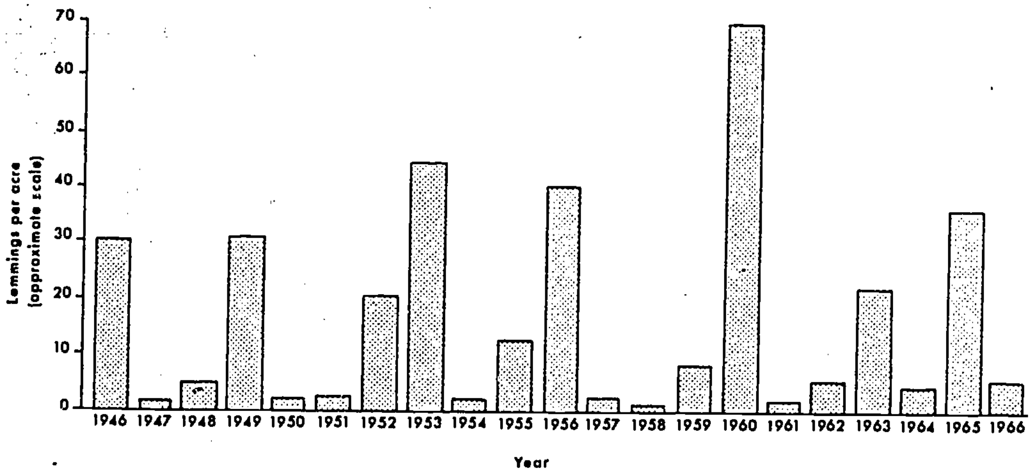

Figure 38. Lemming population fluctuations (cycles) at Point Barrow, Alaska from 1946 to 1966. Note the regular spacing of the peaks of population and how the numbers build up to a peak and then collapse. (After Schultz 1969, Figure 5, p. 37.)

lemming populations are not well understood (Figure 38). There are two basic viewpoints. One is that external factors such as food supply, predator pressure, or disease are responsible; the other is based on animals having an internal mechanism caused by increased psychological stress (as from high population density) which results in exhaustion of the adrenopituitary system (Christian 1950). The problem is that there is no consistency of findings with regard to these theories. Most researchers tend to favor the food supply aspect because heavy lemming pressure in an area can completely denude the vegetation. Lemmings are also highly susceptible to a disease called *toxoplasma*, a protozoan infection of the brain, and some cycles appear to be related to this disease (Elton 1942). The internal mechanism theory is very difficult to prove, but if a crash occurred while there was still ample food available, this would be evidence in favor of the theory; unfortunately too little information exists on this point.

Periglacial Significance

Biological evidence can be very important to reconstructing and interpreting former periglacial environments. The three major factors discussed in this chapter—soil, vegetation, and wildlife—may all provide evidence which, in conjunction with geomorphic evidence, may help reconstruct the former environment. Frequently they reinforce or bridge the information provided from other sources. For example, a glacial geomorphologist may be able to tell a great deal about advance and retreat of the ice on the basis of studying the glacial features, but he can only make inferences about the climatic conditions. By studying the fossil remains of plants and animals in periglacial areas, however, it is possible to reconstruct the former environments and climatic conditions with considerable accuracy. Of course, the sophistication of the interpretations are no better than knowledge of the ecology of plants and animals found as fossils. It is fortuitous in this regard that most Quaternary fossils are closely related or identical to present species so the present ecological requirements of a species are usually similar to those in the past. This is particularly important to man since the Quaternary is the most recent geologic time period (the last one million years) and one that has been characterized by great climatic fluctuations.

Soil

A soil that developed on a former landscape is called a *paleosol*. These are usually buried and preserved beneath younger material and as such may provide important information in the Pleistocene stratigraphy of an area (Ruhe 1965). In addition, since soils may retain their original characteristics long after burial, they reveal something of the former topography, vegetation, and climate. Buried paleosols are seldom continuous, however, frequently being limited to depressions and protected areas so it may be necessary to infer the nature of the upland soils. The key diagnostic aspects of soil profile are its depth and development, especially as reflected in the surface organic layer, color, particle size, and depth of leaching. A tundra soil, for example, would probably have a surface layer of poorly decomposed organic material several centimeters thick with a sharp transition to the underlying mineral soil. The soil particles would be angular and silt-sized or larger owing to the predominance of mechanical weathering. Geomorphic evidence of cold conditions such as ice-wedge casts or particle sorting may also be present. Although the soil profile itself can tell a great deal, it is even more helpful when plant remains are present.

Vegetation

Plant remains are usually divided into two groups—the macrofossils (wood fragments, leaves, seeds) and microfossils (pollen). Both types are commonly found in bogs or other swampy areas where they have been preserved due to anaerobic conditions. The macrofossils are usually assumed to represent species that grew locally unless there is evidence of their being transported in. After identification, the ecology of the area is reconstructed on the basis of the relative abundance of different species. In addition, the macrofossils may provide enough organic material for radiocarbon dating, so it may be possible to establish the time when the different communities and environmental conditions existed, as well as what the succession of changes in these factors has been to the present.

Perhaps the greatest amount of work on plant remains has dealt with the microfossils and pollen analysis (palynology). This consists of identifying and counting pollen from samples collected at different depths through a bog or lake bottom. The percentages of each kind of pollen are assumed to represent the percentages of different species that grew in the region at the time of deposition. This is not so straightforward as it sounds, however, since pollen grains are windblown and can be transported for long distances; also some species may produce a large amount of pollen while others produce only small amounts (Davis 1963). Nevertheless, recent comparisons between macrofossils and pollen from the same bog indicate very close agreement (Watts and Winter 1966) and pollen diagrams are widely assumed to give an acceptable record of the vegetative history of an area (Heusser 1960).

Wildlife

Animal fossils include those of vertebrates, mollusks, insects, and various microscopic animals. Faunal remains have generally not been as useful in reconstructing past environments as have plant remains. The most abundant type of animal fossil is that of mollusks (shellfish). Non-marine mollusks are plentiful in glacial till and loess around the margins of the continental ice sheets, but many of these are now extinct and their ecology is poorly understood. Those still existing, however, do provide general information on the former environmental conditions, although there are many problems in their interpretation (Taylor 1965).

Insect fossils, particularly beetles, provide very good evidence of past environments since they frequently have a fairly narrow ecological range and may demonstrate the existence of certain plant communities. Very few fossil forms are extinct, so generalizations can be made on the basis of their present ecology and they are apparently excellent climatic indicators. "The response of insects to change in climate is extremely prompt, because they have a rapid dispersal rate and do not have to wait upon the development of particular soil conditions" (Coope 1967, p. 359).

Fossil remains of vertebrates are less common than other animal remains, with the exception of those in caves where carnivores have accumulated animal bones. Scattered bones are occasionally found in glacial till but are not adequate for interpretation of former ecologic conditions (Potzger 1951). If an animal if found *in situ*, however, it may tell a great deal about former environmental conditions. The major vertebrate fossils discovered in former periglacial areas that are now found in the north include the musk ox, reindeer, caribou, lemming, and certain rodents (Hibbard 1949, 1958). Most of the large Pleistocene mammals, such as the wooly mammoths and mastodons, are now completely extinct and the cause for their sudden demise remains an enigma (Martin and Wright 1967).

There is not time here to review all of the ecological implications of fossil soil, plant, and animal investigations, but on the basis of this information it has been fairly well established that successive zones of tundra, boreal forest, and broadleaf deciduous forest or grasslands, respectively, existed around the margins of the continental ice sheets in Europe (Deevey 1949; Wright 1961). The reconstruction of periglacial vegetation zones in North America is not so well established. Some investigations have maintained that similar vegetation zones existed, but the tundra zone, if present, was much narrower (Deevey 1949; Dillon 1956; Martin 1958). Others have maintained that boreal forest dominated the area next to the glacier (Braun 1951; Goldthwait 1958; Wright 1964). Questions such as these will doubtless be resolved as more information becomes available and our techniques of analysis improve. It can be seen, however, that the investigation of fossil organic remains can be a very fruitful endeavor and one that can tell us a great deal about past environments. It is also a field that is only beginning to be tapped, with great opportunities for the biogeographer.

VI. IMPLICATIONS TO MAN

General

The relatively blank areas on world population maps are the tropical rainforests, the deserts, and the polar areas. A question frequently asked on geography graduate student exams is: If you had one million people to settle in one of these broad regions, which would you choose and why? This is a good question because it requires an understanding of the limitations and potentials of these environments. It is also a question of considerable practical importance since these regions are being increasingly encroached upon by man. Although an encompassing answer is beyond the present scope, all of these regions pose major problems for human settlement, and insight into the general question may be gained as the prospects of the polar regions are explored in the following pages.

One of the major problems of the polar regions (environmental considerations aside) is their isolation. They are truly "on the margins of the good earth." The significance of this has been greatly reduced with technology so that even the remotest location is only a few hours away by aircraft. Nevertheless, in terms of man's activities they are largely removed from the mainstream of life. On the other hand, their locations are vitally central, especially the north polar area since about 90% of the people in the world live in the northern hemisphere. The Arctic Ocean is essentially a Mediterranean sea surrounded on every side by major land masses—Europe, U.S.S.R., Canada, and the United States (a thesis first proposed by the famous arctic explorer, Vilhjalmur Stefansson in 1922). The arctic is the hub, centrally located between all of these major world powers. The shortest route from Portland, Oregon to Tokyo is not across the Pacific but across Alaska. If you were to travel from Portland to Moscow by conventional land and sea transportation you would cover about 24100km (15,000 miles), but if you flew over the arctic it would be only 8050 km (5,000 miles) (Gould 1958, p. 7). Most Americans tend to have an east-west orientation to their thinking and don't realize the placement of the continents about the pole. This is probably because of transportation networks and the Mercator projection, which displays the world as a rectangle elongated east-west. Our thinking has apparently not caught up with the air age because no longer is the arctic ice and snow an obstacle to travel as it was in the days of sailing ships. No longer are the polar regions simply areas where meridians project into infinity like pickets on a fence; they are instead the crossroads of modern air transportation.

It was not until World War II that the United States and Canada began to consider seriously the strategic location of the arctic. The Alcan (*Alaska-Canada*) Highway (now generally called the Alaska Highway) was rushed to completion. Major military bases were constructed from Anchorage to Thule, Greenland. In the late 1950's the DEW (Distant Early Warning) line was constructed from Point Barrow to Baffin Island, and it is certain that at the present time the arctic has its share of missile sites.

In addition to its strategic location, however, the far north has considerable resources both renewable and nonrenewable that can be tapped. Some of these have been exploited in the past, but most have been only short term projects where man has taken the riches and left. In fact, this is still largely the pattern of exploitation in the north although there are signs that this is changing. Recent large scale interests in mineral resources, e.g., oil, iron, uranium, and other precious ores, have resulted in permanent settlements in the subarctic and arctic. Most of these projects are still tenuous due to their distance from world markets and the increased cost of operation in this extreme environment. Vast resources such as the oil on the arctic slope of Alaska or the iron ore deposits in central Labrador are certainly solidly based, however, and exploitation of other resources becomes more likely every day. With these developments will come people and increased pressure on the land. In the following pages some of the environmental problems and prospects of this increased activity in the north will be discussed. These are listed under three broad headings—engineering, land-use, and ecology.

Engineering

The problems associated with construction in the north stem mainly from the presence of permafrost. When the ground is frozen it has great bearing strength, but when it is thawed it may turn to a jelly-like substance with no strength. The fundamental factor is the presence of water (ice) which is usually a function of grain size. Bedrock, sand, or gravel give little problem but fine grained material has the ability to hold large amounts of water owing to its pore space. Moreover, when freezing takes place additional water may be drawn to the freezing plane from the surrounding area by capillarity, creating pure ice accumulations (ground ice). Upon thawing the space occupied by ground ice is filled with material from above and settling occurs (Figure 39). The excess water transforms the soil into a slurry, and since the water cannot escape downward due to the impermeability of the underlying permafrost it is available for excessive heaving when refreezing takes place in the fall. These are the sites that cause the greatest engineering problems.

There are four basic approaches to dealing with permafrost depending upon local situations (Brown 1970, p. 40): (1) disregard, (2) eliminate, (3) preserve, (4) design structure to withstand increased stress.

Permafrost can usually be disregarded and middle latitude construction methods can be used when dealing with bedrock or coarse sand and gravel. There is usually good drainage with very little water (ice) present and no marked settlement or frost heaving will occur once the thermal regime is disrupted. Unfortunately, such conditions are usually lacking at the construction site.

In the discontinuous permafrost zone (Figures 8 and 9) where the depth and extent of frozen ground are limited, it may be feasible to thaw the permafrost. This is usually done by removing the insulating vegetation and letting it thaw naturally. It is often advantageous to remove the peat and other frost susceptible material, replacing it with well-drained sand or gravel. This must be done quickly to prevent thawing and slumping of the sides.

In the continuous permafrost zone (Figures 8 and 9), frozen ground extends to a depth of several hundred meters and it is not feasible to remove it. The approach in these areas is to keep it from thawing. This is usually done by either ventilating or insulating. The ventilating technique is used with heated buildings. Piles are inserted by drilling steaming holes into the permafrost and the building placed above ground on the pile foundation so the air can circulate between the building and the ground surface (Figures 40 and 42). The piles will be susceptible to frost heaving in the active layer but if imbedded deep enough in permafrost, frost heaving can be prevented. A general rule of thumb is that the pile should extend into permafrost twice the thickness of the active layer. One novel approach to preventing the frost heaving of piles is to grease the segment in the active layer and wrap it loosely with tarpaper so the frozen ground can slide up and down the pole without lifting the pile itself (Brown 1970, p. 58).

The ventilating technique is not feasible for many structures such as roads or air fields; instead a gravel blanket 0.6–1.5 m (2–5 ft.) thick is spread on the existing tundra vegetation in order to insulate the permafrost. It is very important not to disturb the vegetation, and this is often best achieved by bringing in the equipment during winter or early spring when the surface is frozen and there is good mobility. If timber must be cleared, it is hand cut

Figure 39. A collapsed section of a road used for oil explorations in the Mackenzie River Delta area, N.W.T. The organic surface material was partially removed and this particular spot was underlain by an ice wedge which subsequently melted. (Photo by Lawrence C. Bliss, University of Alberta.)

Figure 40. School house built on permafrost in Glenallen, Alaska in 1953. Air vents in foundation are opened in winter to allow cold air circulation between floor and ground and are closed in summer when school is not heated. The jacks allow correction if any heaving or settling occurs. (Photo No. 915, by Troy L. Péwé, Arizona State University.)

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and the gravel placed directly on the frozen vegetation surface.

Drainage poses a real problem since even the coldest water can thaw permafrost. This is particularly acute when the road runs transverse to the natural drainage. Roads are usually not ditched in the continuous zone; instead culverts are placed on the surface and diversion ditches dug at a safe distance from the road to help drain the area. In the discontinuous zone where permafrost has been thawed, drainage ditches along the road are common; here the problem is to prevent deep penetration of winter frost in the ditches which would cause frost heaving. This is often accomplished by filling the ditches with snow in winter. Roads that run east-west in permafrost are susceptible to greater thawing on the south side due to the sun's rays striking the embankment at a higher angle. This may be counteracted by placing insulating material (such as peat moss) along the south side in summer but removing it in winter (Brown 1970, p. 109).

No matter how much care is taken, there will always be some settling and heaving for the first year or two as the permafrost adjusts to the new circumstances, so all structures should be designed to withstand the increased stress. If properly constructed and maintained, however, structures in permafrost should eventually stabilize and be relatively trouble free. Discussion of the various structures in permafrost areas will illustrate many of the specific problems involved.

Transportation

There were few roads penetrating the North American arctic and subarctic before World War II. The Hudson Bay Railroad, completed in 1929 from Winnepeg to Churchill, was the first to be built in a permafrost area. It was constructed to provide a shipping route to Europe for the wheat from the Prairie Provinces. The narrow-gauge White Pass Railroad from Whitehorse to Skagway was built much earlier in response to the Klondike gold rush, but very little permafrost was encountered. Before World War II, then, North America had very little experience with construction in permafrost. With the onslaught of the war, however, our vulnerability from the north was suddenly realized and three northern projects were initiated and forced to conclusion with little provision for the existence of permafrost. These were: (1) the Northwest Staging Route, consisting of a number of airfields from Edmonton, Alberta to Fairbanks, Alaska for rapid air transportation to the north (its most important use was actually ferrying short range aircraft from the United States to Russia); (2) the Alaska Highway, constructed in 1942–43 from Dawson Creek, B.C. to Fairbanks, Alaska along the Northwest Staging Route, an initial distance of 2897 km (1,800 miles); and (3) the Canol Project, a 998-km (620-mile) pipeline from Norman Wells, N.W.T. to the refinery in Whitehorse. The purpose of the Canol Project was to supply petroleum to the Alaska theater of operations, but insufficient demand and excessive costs closed the project in mid 1945 (Sutherland 1966, p. 260).

Since that time, transportation facilities have expanded considerably, including the construction or improvement of a series of branch roads off the Alaska Highway such as the Circle Highway running north of Fairbanks to the Yukon River, the Richardson Highway south to Anchorage, and the Denali Highway completed in 1956 to McKinley National Park. The Alaska Railroad from Seward to Fairbanks should also be mentioned. In Canada, the Mackenzie Highway was built in the late 1940's through northern Alberta to Hay River, N.W.T. and a 451-km (280-mile) stretch was completed to Yellowknife on the north side of Great Slave Lake in 1960. A companion railway 692 km (430 miles) in length was built in the early 1960's closely paralleling the Mackenzie Highway to transport zinc ore southward from the mines at Pine Point. In addition, a major rail line was completed in 1954 to Schefferville in central Labrador to serve the iron mines there. There are many other smaller roads and railroads connecting mines or towns with the major highways, but the sum total of the transportation network in the north is still very small compared to the vastness of the area.

The problems of road construction in permafrost areas are many, and more will probably be discovered as development continues. The Alaska Highway provides examples of most of these problems since it passes through a wide range of topography and was built in great haste. The construction of this highway by the U. S. Army Corps of Engineers should go down in the annals of great engineering feats. The initial "pioneer road" running from Dawson Creek, B. C. to Fairbanks, Alaska was 2897 km (1,800 miles) long and was completed from March to November in the summer of 1942. Seven army regiments worked on the project 12 hours a day, 7 days a week, under the most primitive conditions. Construction began from the north as well as from the south and eventually met in the middle. A number of men lost their lives in various accidents and considerable equipment was lost, some of it becoming hopelessly mired in muskeg. A series of articles written by Richardson (1942a and b, 1943, 1944a) at the time of construction include many photographs and make fascinating reading.

After the army had completed the initial roadway which was little more than a truck trail, civilian contractors took over and improved the road. By the fall of 1943, 20% had been relocated reducing the length to 2443 km (1,518 miles) (Richardson 1944a, p. 95). It should be mentioned that there was much controversy at the time over the best route for the highway. A Senate subcommittee favored a route running northward between the Coast Ranges and the Rockies through Prince George, B. C. and Whitehorse, Y. T. The highway was eventually built along the so-called prairie route east of the Rockies, owing to the location of the Northwest Staging Route completed the year earlier. An important function of the road was to supply fuel to these airfields although subsequently they were little used.

The first known permafrost on the Alaska Highway occurs in a peat bog 151 km (94 miles) north of Dawson Creek (Brown 1970, p. 115). This is the beginning of the discontinuous permafrost zone and its occurrence is patchy from here northward, although it is usually present in low lying and poorly drained muskeg areas. Beyond Whitehorse about 28% of the road is built on permafrost (Denny 1952, in Brown 1970, p. 116). When the Army first began construction they scraped these areas free of vegetation, as would be done in middle latitudes, but this practice was quickly abandoned as they turned into impassable mires. It was found that hand cutting the trees and piling brush 1–1.5 m (3–5 ft.) deep on the surface without disturbing the peat moss was the best procedure. A layer of gravel 1–1.5 m (3–5 ft.) thick was then placed on top of the brush layer. Gravel for the most part was plentiful, with the average hauling distance being 4.8 km (3 miles) and the longest distance being 29 km (18 miles) (Richardson 1943, p. 135). The Army also ditched along the road as standard procedure and this allowed rapid thawing so that the road sank 2–4 m (7–13 ft.) in some places!

The worst stretch of the entire highway was a 145-km (90-mile) segment near the Yukon-Alaska border where more than half of the road went out and closed the highway to through traffic during the entire summer of 1943. (Materials were transshipped by rail from Whitehorse to Skagway, then by boat through the Bering Sea and down the Yukon River to Circle, and finally southward by road to Fairbanks.) This stretch of road was reached by construction crews late in 1942 after it had already refrozen making it difficult to remove the peat. In addition, there was insufficient unfrozen fill material to follow the established practice of filling over a timber and brush mat. Under the circumstances the roadway was simply cleared and a shallow layer of fill placed on top. By early June of the following year it had turned into an impossible morass. Construction crews worked frantically that entire summer to make the road passable, eventually rerouting much of it to nearby undisturbed sites (Richardson 1944a, pp. 99–100).

Maintenance problems are many on the Alaska Highway, including heaving and creation of a "washboard" surface, sinking of certain sections, bridges destroyed by spring floods, and slumping and landslides occasionally burying the road, but perhaps the worst maintenance problem of all is "icings." Icings are caused by water coming to the surface in the winter and freezing, sometimes covering large areas to considerable depths. This phenomenon is unimportant in middle latitudes but is of major importance in permafrost areas. The most common occurrence is where a cut is made into a hillside intercepting a spring or seepage. The water is frequently under hydrostatic pressure and may flow through much of the winter causing ice to build up on the road.

Another important kind of icing occurs in streams and rivers. Freezing occurs from the surface downward and the stream may freeze completely to the bottom in shallow areas. This often has the effect of damming up the water, creating enough pressure to force the water laterally so it overflows its banks. Sometimes the water simply comes to the surface along cracks and builds vertically. In either case it can be devastating to bridges. Thomson (1966, p. 527) gives an extreme example along the Alaska Highway where a snow covered stream was crossed by a man on snowshoes about 60 m (200 ft.) upstream from the road. This had the effect of decreasing the insulating value of the snow and within a week the stream had frozen to the bottom. Icings 2 m (7 ft.) deep encroached upon the road and created a maintenance problem for the rest of the winter.

Icings are dealt with in different ways. The preventive methods are, of course, the best. This means routing the road to avoid obvious seeps and providing good drainage. In general, it is always best not to cut into a hillside unless absolutely necessary. Unfortunately this was not realized on the Alaska Highway until it was too late. In 1945 there were 126 major and 95 minor icings on the highway, and in 1955 these were still costing over $50,000 a year for maintenance (Brown 1970, p. 119).

The different methods of dealing with icings include thawing by using firepots or steam pressure, blasting, and bulldozing. Another approach is to use a piece of sack cloth 3–5 m (10–16 ft.) long tied between two poles across the seepage site. The cloth becomes saturated, freezes, and dams up the flow (Thomson 1966, p. 528). Another approach to preventing icings on the road when there is seepage upslope is by creating a "freezing belt." In this method an area below the seep is cleared of its insulating cover so frost will penetrate it more quickly in winter and intercept the seepage, forcing the icing to develop away from the road. Seeps may also be dammed to form a pond, the grade of the road can be raised or moved, and larger culverts can be installed. On roads such as the Alaska Highway, icings are not so critical because they can be leveled and driven over, but on railroads, icings become very critical since the rails must obviously be kept clear. Severe icings take place along some sections of the Alaska Railroad and have been creating problems for years.

Buildings

The most prevalent building type in the far north is the simple log cabin. The foundation usually consists of logs, and little concern is given to permafrost. If the building settles it is jacked level in the summer and blocked up with pieces of wood or rock. This is an annual maintenance chore much like changing window screens in middle latitudes. Larger buildings associated with villages or towns have experienced various kinds of disturbance and these have been more difficult to correct (Figure 41). An excellent review of the damage suffered by various buildings in Canadian villages is given in R. J. E. Brown's book, *Permafrost in Canada* (1970, pp. 55–81).

In the last two decades a new era of building has begun in the north. Large and expensive buildings are being built which cannot stand substantial heaving and settling so an increased knowledge of foundation construction in permafrost has been necessary. As mentioned earlier, buildings pose different problems from roads or airfields since they are usually heated. The basic approach is to build above ground on pilings of some sort so the cold winter air can circulate between the building and the ground. This, of course, calls for a very well insulated floor to keep the building warm (Figure 40).

The most important aspect in constructing buildings, as with other structures in permafrost, is to build on coarse and well drained material if possible. One of the problems of many towns in the far north is that they are located at river mouths, river junctions, or islands, where the soil is composed largely of silt (Pritchard 1966, p. 516). This may be satisfactory as long as the town consists of scattered log cabins, but if economic activities increase for some reason and additional facilities are needed, it may be advisable to relocate to a more favorable site rather than try to work with the adverse permafrost conditions. This has happened in the case of Aklavik on the Mackenzie River.

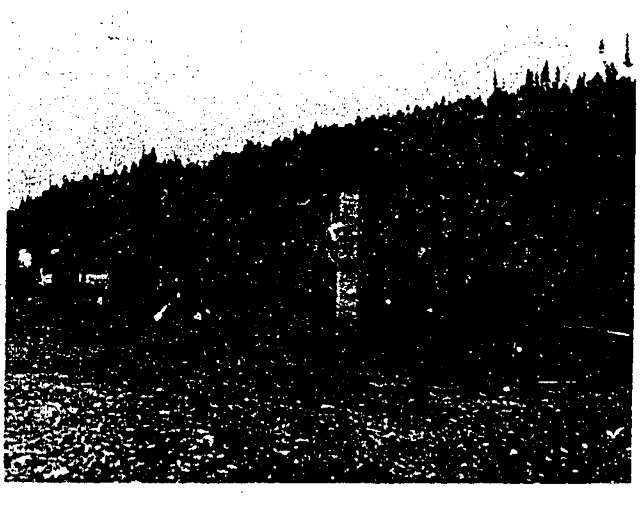

Figure 41. A lodge along the Richardson Highway between Fairbanks and Anchorage, Alaska. Heated portion of building has subsided into thawed ice rich permafrost; front porch was unheated. (Photo No. 2072 by Troy L. Péwé, Arizona State University.)

Aklavik, located at 68° North on the Mackenzie River Delta, was a large fur trading post established in 1912 by the Hudson Bay Company. In 1954 it had a population of 400 but swelled to about 1,500 when the surrounding population came in for the summer. Being the largest town around, Aklavik became the administrative center for the Canadian Government in the western arctic, and with the decision to build the DEW line across the north, more facilities were needed (Robertson 1955, pp. 196–197). Several things were undesirable about Aklavik's site, however. It was located on fine-grained deltaic deposits with a high ice content and the area was poorly drained. Several structures, including the Anglican bishop's residence, the electric generator powerhouse, and the quarters of the Royal Canadian Mounted Police, had all been damaged by settling and frost heave. The town site was restricted to a small space between the river and swampy areas, and the nearest gravel was several kilometers away. In addition, there was the possibility of flooding from the river every spring.

Because of these factors the Canadian Government decided, after an extensive search, to relocate the town to a new site 56 km (35 miles) east called Inuvik (an Eskimo word meaning "a place of man"). The new site is on high ground overlooking the East Channel of the Mackenzie River Delta and is composed largely of sand and silt with extensive gravel deposits nearby for fill and road building. Permafrost is over 100 m (330 ft.) deep and the active layer is less than 1 m (3 ft.) deep. Construction at Inuvik began in 1954 and was completed in 1961. Great care was used in its construction. The natural moss became inviolable, cutting for roads was forbidden, and all roads were built up with layers of gravel over the natural cover. No ditching was permitted and culverts were installed in gravel fill to handle surface runoff. Utilities such as water, sewerage, and power were placed above ground in utilidors and supported by piles (Pritchard 1962, pp. 146–147). All major buildings were placed on piles with air spaces of at least 1 m (3 ft.) (Figure 42). It was learned while driving the piles that permafrost at Inuvik was completely unpredictable and that subsoil conditions varied at any given point. No set rules could be followed in the various operations; they were

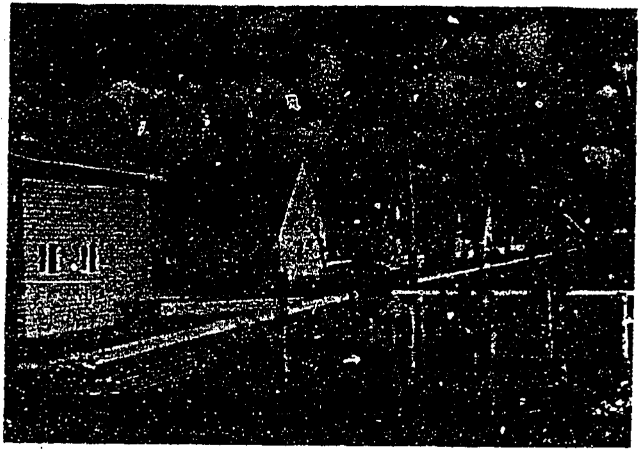

Figure 42. Utilidor system in newly constructed town of Inuvik, N.W.T. Utilidor encloses water, sewerage, and steam heat pipes for central heating. Note the pilings in foreground ready for house to be constructed; also under building at left. (Photo by Roger J. E. Brown, Division of Building Research, National Research Council, Canada.)

simply adapted to fit the conditions. For example, it was found that piles driven in early spring became frozen in much more quickly than those driven in October, the time of maximum thawing. They also learned that most piles were frozen in place within four to six weeks and it was unnecessary to wait the entire winter for freezing to take place so this speeded up construction considerably (Pritchard 1962, p. 149).

In addition to the structures in the town itself, over 32 km (20 miles) of road were constructed and a good sized airstrip was built 13 km (8 miles) from the town. The major problem in the total project was supply of materials from the south and having to train a local labor force to do new jobs. Careful planning and a knowledge of permafrost resulted in very few major problems. Construction costs were obviously higher than if permafrost had not existed, but the cost of expanding Aklavik to the present size of Inuvik with the same large buildings would have been considerably greater (Brown 1970, pp. 73–75).

A fitting epilogue to this story is that in 1961 an ice jam in the middle channel of the Mackenzie River caused the worst local flood conditions in 20 years. The former town of Aklavik was inundated with 1 m (3 ft.) of water in the main street and was cut off from communications with the outside world, while the new town of Inuvik was high and dry (Pritchard 1962, p. 149).

Utilities

The provision of services to northern settlements, particularly water and sewerage, is greatly complicated by the presence of permafrost and deep winter freezing. In summer there is no major problem with either of these amenities because water is available almost everywhere on the surface and sewerage can simply be dumped into a lake or river. In winter, however, surface sources of water are transformed to ice and the landscape becomes a frozen desert. Most small northern settlements handle this problem by cutting chunks of ice and melting them for water; sewerage is hauled by bucket or wagon and dumped on the river ice to be carried away with the spring breakup. In addition to being very laborious, this approach can and does lead to severe sanitation problems. For the larger settlements, then, neither of these methods is satisfactory, especially if highly skilled personnel from the south who are accustomed to the amenities of modern living are to be attracted. The following quotation from a white teacher spending his first winter in the Eskimo village of Savoonga, Alaska on St. Lawrence Island illustrates one person's reaction to the problem of water supply:

> The water situation is lamentable. Like the Ancient Mariner, who bewailed the maddening presence "Water, water, everywhere" we are not provoked by any scarcity of this common commodity; for, except for only seven or eight months of the year when everything liquid and not ninety-nine percent alcohol becomes solid, we have billions and billions of gallons of the stuff all around us. People from south of 60° North have come to take water for granted. Folks who aren't even dirty bathe in overflowing tubs of it. Other ways, countless thousands of gallons are used slightly (and only once!) before it is heedlessly washed down the drain. They wallow in the luxury of it blissfully unaware that here every precious drop must be manufactured! Therein lies our problem. Producing a useable product from the raw materials at hand is a tedious and bothersome thing . . . The summer source of supply is a small creek . . . It is fed by melting tundra; and the water is well filtered (without any beneficial purification, I'm afraid) through the manure of dogs tied thick along its banks and through heaps of rotting meat and stinking bones on which dogs are fed. From there, if fate smiles and Noah's pump works, it can be drawn through pipes into a tank in the utility room. Otherwise, it is packed in sloshing pails, one toilsome, backbreaking trip at a time; and I have yet to see a really opportune moment for replenishing an exhausted supply. Though the Eskimos operate in this manner at all times, and never get to enjoy the thrill of triumph that comes from mastering gravity with the crotchety old pump, they like to no more than I. So, naturally then, it becomes women's work. Winter's water supply comes from ice on the same creek or a small pond a mile away. It is only slightly less unsanitary but infinitely harder to get. In either case, winter or summer, the situation doesn't end with merely getting the water or ice into the house, for due to the prevalence of tuberculosis and the hydatid scare every

drop of water must be boiled for a long fifteen minutes. (Quoted in Alter 1967, p. 228.)

Water. Unfrozen water may exist above, within, or below the permafrost. This is known as suprapermafrost, intrapermafrost, and subpermafrost water, respectively. Suprapermafrost water stands on the surface in the summer and gives a false impression of abundance. It cannot be depended upon for year round supply, however, since much of it freezes during the winter. Lakes or rivers seldom freeze to depths greater than 2–2.5 m (7–8 ft.) but the storage capacity of the lake below this level is greatly reduced so the amount is limited. If the lake is spring-fed the water may be replenished, but if it is simply an accumulation basin for summer surface melt it will not be replenished until the next summer. An additional problem with relatively shallow lakes is that the freezing process tends to concentrate the mineral and organic material in the unfrozen water below the ice, often making it turbid and undesirable for use. This is due to the unique characteristic of water whereby it is most dense at 4° C (39° F) rather than 0° C (32° F). Consequently, as the water cools from the surface downward it continually sinks, concentrating the solids and solutes at the bottom of the lake. In general, only the very large northern lakes provide adequate storage for a community of more than a few people (Brown 1970, p. 83).

Intrapermafrost water occurs in unfrozen zones (taliks) within the permafrost and is most common in the discontinuous zone. This water may be tapped by shallow wells or it may come to the surface under hydrostatic pressure and form springs where icings take place through the winter. This type of water does not provide a stable supply since its occurrence is sporadic.

Subpermafrost water exists below permafrost and is the most dependable source, although problems arise in its procurement. It is initially more expensive since deep wells must be drilled (some will doubtless turn out dry) and steps must be taken to keep the well casing from freezing where it passes through permafrost, e.g., heating the pipe or constant pumping. Subpermafrost water is generally fresh, particularly in the discontinuous permafrost zone where it is recharged from the surface and circulation occurs. In the extreme north, however, deep water retrieved from under continuous permafrost is often brackish and/or highly mineralized (Williams 1970, p. 25).

A typical example of the summer water supply of most small northern settlements is a gasoline pump used to fill 55-gallon barrels from a lake or river. The inhabitants carry the water to their homes in buckets. The water supply in winter is provided by cutting blocks of ice about 0.3 m (1 ft.) thick from a lake or pond in the fall with a power saw and storing them for later use. The ice is melted in a large central tank or by individual families in pots on the stove. In either case, chlorine tablets are usually added.

A number of the larger settlements have piped-in water supplies. If a dependable water source is available, the primary problem is to keep the distribution system from freezing; there are two main approaches to this—heating the pipes or continually circulating the water. The former is achieved by either insulating and wrapping the pipes with an electric heating coil or by enclosing the pipes in an utilidor (an insulated and heated conduit or passageway built to carry utilities such as electricity, communication, water, and sewerage lines) (Figure 42). A utilidor may be placed above or below the ground surface depending on soil conditions. Where fine soils and permafrost are present it is usually placed on pilings above the ground. Where the soils are coarse and well drained, it may be satisfactory to put the utilidor below the ground. A utilidor is expensive and most villages cannot afford this approach unless government supported. The utilidor at the newly constructed town of Inuvik, N.W.T. for example cost $224 per 0.3 m (1 ft.); however, it also carries the sewerage collection pipes and hot water for the central heating system (Figure 42). The utilidettes connecting the individual houses with the utilidor cost $134 per 0.3 m (1 ft.). When it is realized that 4575 m (15,000 ft.) of utilidor and 1675 m (5,500 ft.) of utilidettes were constructed, the extremely high cost of living in the arctic becomes apparent (Yates and Stanley 1966, p. 418).

The other way of keeping water pipes from freezing is to keep the water circulating. The heat from the engines that run the pumps is frequently used to heat the water. Fairbanks, Alaska has a recirculation system as does Yellowknife, N.W.T., but being in the discontinuous permafrost zone these places have to use it only in the winter months (Hubbs 1966, p. 428). Another approach is to pump water intermittently during warm spells in the winter, e.g. above –10° C (14° F), to storage tanks located inside different buildings, then to drain the pipes (usually by gravity) and await the next warm spell to refill the storage tanks. Barrow, Alaska has such a system (Hubbs 1966, p. 427).

Still another approach is the system used at Nome, Alaska, which has an excellent water supply from a year-round spring 5.6 km (3.5 miles) from the town. "In summer, water is piped to town from this spring and distributed by above-ground pipes to all paid-up customers. In winter, because of low temperatures and the unprotected nature of pipe, tank truck operations are necessary, and water is sold by container measure, posing severe use limitation" (George 1966, p. 424).

Sewerage. Very few of us ever think about what happens to the effluent that we wash down the drain or flush down the toilet. We are simply glad it is gone. Those who live in the far north, however, are much more familiar with what happens to waste water, because only a few places have what could be called a modern sewerage system. As mentioned earlier, most settlements still handle their sewerage in crude ways. In the discontinuous zone where permafrost is lacking, pit privies, cess pits, and septic tanks are used, but these methods cannot be used in the continuous permafrost zone so some villages simply have individual buckets that are carried and dumped in a designated spot, usually a river or lake. Other places may have chemical toilets and storage tanks with an organized pickup by truck or track vehicle (Yates and Stanley 1966, p. 415).

Some of the larger communities have piped sewerage systems. As with water lines, the principle problem is to keep the pipes from freezing. In the discontinuous permafrost zone the pipes may be insulated, heated, or placed 3–5 m (10–16 ft.) in the ground to protect them from deep freezing. Sewerage comes from buildings at a relatively high temperature so there is not as much difficulty in keeping it from freezing, and during critical periods water can be fed through the pipes to increase the flow. In the continuous permafrost zone very few settlements have sewerage pipes below ground because of the disruption it would cause to the thermal regime of permafrost in both constuction and use. Above ground utilidors are the principle method for protecting sewerage pipes as well as other services in the extreme north (Figure 42). Owing to the combined difficulty of procuring water and disposing of wastes, some arctic settlements, especially military establishments, have experimented with self-contained units in which the waste water from the showers and lavatories is reused as flushing water for toilets. Water use is further reduced by using plumbing fixtures that require only a small quantity of water. A novel approach to the problem of waste disposal tried at one military installation in Alaska is to substitute fuel oil for water. There is no danger of the fuel oil freezing, and by the time the wastes reach the central system, they are sufficiently mixed with the oil so they can be fed directly into the fuel injection system in the central heating plant. This results in an ideal solution where the wastes are disposed of with a minimum of problem and the fuel oil is still usable to produce heat and electrical power for the installation (Alter 1966, p. 408). Coastal communities have used salt water in their sewerage systems. Corrosion is a problem but the lower freezing point of salt water may be adequate protection against freezing.

In addition to the initial removal of sewerage, whether it be hand carried in buckets or by heated pipes in a utilidor, there is the problem of final disposal. This is perhaps the most difficult problem of all (certainly in the long run) because of the low biochemical rates in cold climates. In the humid tropics and temperate latitudes, decomposition of organic matter is more or less rapid, but in the arctic it is incredibly slow. This is one of the primary factors that characterize cold environments and was discussed under the section on soil development. An extreme example of the low rates of decomposition is provided by the still-preserved remains of Pleistocene mammals ranging from 10 to 30 thousand years in age (Figure 10). It should not be difficult, then, to understand that raw sewerage may maintain its identity for many years in the arctic.

Sewerage is dealt with in three main ways in the far north: (1) treatment, (2) no treatment, and (3) sewerage lagoons. Treatment of sewerage is carried out by only a handful of settlements and this is usually only to reduce coliform organisms. No attempt is made to remove biochemical oxygen demand (B.O.D.) or suspended solids (Yates and Stanley 1966, p. 416). By far the most widely used method is simply to dump the raw sewerage into the nearest waterway. For coastal towns this means bays or inlets periodically cleansed by storms; for inland towns it means dumping into river or lakes. This method has worked satisfactorily until now due to the extreme sparseness of settlement, particularly if the water bodies are large. For example, dumping into the ocean or large rivers soon dilutes the bacteria to a harmless level. With increased settlement, however, and indeed as responsible members of the world community, this approach is far from satisfactory.

The sewerage lagoon is a fairly recent development but one that holds great promise. It consists of dumping the sewerage into a large shallow depression and allowing the mixture to decompose anaerobically. The sewerage lagoon appears to work satisfactorily in cold climates although its effectiveness is greatly reduced (especially in winter). For this reason the impoundment should be at least 2 m (7 ft.) deep so some liquid will remain below the ice. The sewerage lagoon is economical and safe and appears to be one of the more acceptable answers to this difficult problem (Brown 1970, p. 88).

Pipelines

The recent discovery of vast amounts of oil near Prudhoe Bay on the Arctic Slope of Alaska has focused attention on the construction of pipelines in permafrost. This comes at a time when world concern over environmental problems is at the highest level ever, and as a result the ecological implications of such an undertaking are of special concern. These aspects will be covered more fully in the last section; here, the engineering problems of such a project, which are considerable, will be discussed.

As a prelude, it might be mentioned that pipelines (and controversies over them) are not new to the north. The Canol pipeline project constructed during World War II involved 2575 km (1,600 miles) of pipeline, all of it in the discontinuous permafrost zone, and it was perhaps the most controversial project of the entire war (Richardson 1944b, p. 78). This project consisted of a 1000-km (620-mile) pipeline from Norman Wells, N.W.T. about 145 km (90 miles) south of the Arctic Circle on the Mackenzie River (essentially the same spot where Alexander Mackenzie discovered oil seeping out in 1789) southwestward across the Mackenzie Mountains (elevation 1520 m–5,000 ft.) to Whitehorse, Y.T. From Whitehorse another 970-km (600-mile) pipeline was constructed to carry gasoline along the Alaska Highway to Fairbanks, and an additional 480 km (300 miles) was run southeast along the highway to Watson Lake, Y.T. Yet another section of pipeline was built from Whitehorse to Skagway, Alaska 180 km (110 miles) away on the inland passage. The basic idea of this project was to pump the crude oil from Norman Wells, refine it to high test gasoline in Whitehorse, and from there pump the gas to the various air fields and to Fairbanks for further distribution. The leg to Skagway allowed the loading of tankers for more distant distribution.

Most of the pipeline was 10 cm (4 inches) in diameter although it ranged from 5–15 cm (2–6 inches). A road and a series of airstrips preceded its construction in all sections except from Whitehorse to Skagway. Pumping stations were eventually built at 80-km (50-mile) intervals along the entire network. Being in the discontinuous permafrost zone, the occurrence of perennially frozen ground was sporadic and unpredictable but where encountered it invariably caused problems. The pipeline along the Alaska Highway was buried and this resulted in frequent miring of equipment during construction and occasional damage to the pipe afterward as the thermal regime of permafrost was further disrupted by heat from the pipeline. These areas were relatively accessible for repairs, however.

The road to Norman Wells was simply an equipment trail with poor accessibility, and the entire route except the southerly section was underlain by permafrost. The pipeline here was simply laid on the ground surface with an effort not to disturb the vegetation except for removing the brush and trees. This was probably the best construction method possible under the primitive conditions and haste with which it was built. The heat from the pipe caused thawing of the permafrost and subsequent settling and some breakage of the pipe, but it worked amazingly well. The only major operational problem was that the pipeline was subjected to very low temperatures since it was above ground. Crude oil has a low pour point (–57° C, –70° F) but considerable pressure was nevertheless required to maintain flow (Richardson 1944b, p. 79).

The following editorial (favorable) from the *Engineering News Record* was published on May 18, 1944 just as the pipeline was going into operation:

> "Canol, the War Department's oil well, pipe line and refinery project in Northwest Canada and Alaska, went into operation early this month. And although this ends the argument over whether it should be completed or abandoned, enough disagreements over fact still remain to assure Canol a place as one of the war's most controversial construction jobs. Yet why it should have generated so much heat is rather puzzling. There are those who claim it should never have been started, but they would seem to have a short memory, forgetting the precarious position of our sea lanes to Alaska in the Spring of 1942. There are others who oppose it because the Army and not some other governmental agency was in charge, but such arguments are rather pointless in wartime. Likewise the charges of waste and excessive cost make little sense; one might as well say that the millions spent in Eritrea or the Caribbean islands for bases that were never used were wasted, instead of recognizing that they actually represented insurance premiums. All in all, the only "open" argument is whether we would have been better off to have abandoned the job when its strategic importance declined, rather than to finish it. Since we did finish it, history will have to supply the verdict."

The pipeline was in operation only 13 months. Its use was discontinued in May 1945 because of the high cost of operation and insufficient demand.

The proposed pipeline to transport the oil from the Arctic Slope of Alaska differs from the Canol project in so many ways that they are hardly comparable. Nevertheless, the Canol project establishes a precedent and gives perspective (although it is only one of several pipelines in the north). The oil reserves in the Prudhoe Bay area are vast, ranking among the largest known petroleum accumulations in the world (Reed 1970, p. 11). In addition, the geologic conditions appear very favorable for large deposits in the shallow Bering Strait and the Mackenzie Delta areas. With such huge resources as these, a way will doubtless be found to tap them, and despite the successful voyage of the Manhattan through the Northwest Passage, the most feasible method of transporting the oil southward appears to be by pipeline. The exact route is still undecided and will in the end probably be a compromise based on political, economic, and ecological rationale. No matter what route is chosen, however, the pipe size will be large (1.2 m - 4 ft. in diameter), the oil pumped through it will be hot, e.g. 70-80° C (156-176° F), and much of the pipeline will be constructed in the continuous permafrost zone. These three factors deserve further comment.

A pipe 1.2 m (4 ft.) in diameter of the type proposed (and in fact already purchased and delivered) weighs about 230 kg (500 lbs.) per linear 30 cm (1 ft.) and the oil will add another 90 kg (200 lbs.) for a total of 320 kg (700 lbs.) per linear 30 cm (1 ft.) or over 910 kg (1 ton) per linear meter (3 ft.) (Harwood 1969, p. 80). This is a heavy burden for even a moist stable substratum, but on a soil with the potential for being transformed into a slurry with little bearing strength, the best that can be hoped for is that the pipe will float.

The possibility of cooling the crude oil as it comes from the ground before pumping it was considered. Oil has a very low pour point, and if it could be cooled to the temperature of the surrounding soil, some of the major problems of permafrost disruption would be solved. This is apparently not possible for the Arctic Slope oil for a number of reasons, not the least of which is the buildup of waxes. Therefore, it will be a hot pipeline and the fundamental problem is to prevent the permafrost from thawing.

Discontinuous and continuous permafrost are different in that the former is patchy and relatively shallow with temperatures just slightly below freezing, while continuous permafrost is deep, continuous, and has temperatures ranging from −12 to −5° C (10 to 23° F) or lower. In the continuous zone permafrost is a constant problem, while in the discontinuous zone it is only an occasional one. In addition, these areas react differently to disturbance. For example, it would take less heat to melt discontinuous permafrost, and it would also reform more slowly, resulting in a lower potential for disruption than continuous permafrost.

There are three basic approaches to building a pipeline in permafrost terrain: (1) bury the pipe in a trench, (2) suspend the pipe above ground on trestles, or (3) build a road along the proposed route with an adequate amount of fill to insure stability and place the pipeline on the edge of the road surface, insulating and covering it with the appropriate amount of fill (Harwood 1969, pp. 81-82).

There are advantages and disadvantages to each of these and the best answer may involve a combination of methods. When a pipe is buried there is initial disturbance of the site and the excavation will be very slow and difficult in frozen ground. The pipe can be insulated by any of several means but at the high temperatures of oil the principal effect of insulating the pipe may be to increase oil temperatures rather than to decrease thawing. Probably the only site where burying the pipe in permafrost would be feasible would be on coarse well-drained soils with very little ground ice. This, of course, involves a careful site investigation of the entire route.

A very detailed theoretical treatise on some of the effects of a heated pipeline in permafrost has recently been published (Lachenbruch 1970) and is highly recommended for the serious student. Some of the more salient findings of this study will be summarized here. First of all, the pipeline will definitely cause thawing of permafrost. A 1.2-m (4-ft.) pipe buried to a depth of 1.8 m (6 ft.) in typical silty soil and heated to 80° C (176° F) would thaw a cylindrical region 6-9 m (20-30 ft.) in diameter within 5 years, and to 10-15 m (35-50 ft.) within 20 years, depending upon whether it was in continuous or discontinuous permafrost (Figure 43). Except under special conditions, equilibrium would not reached and thawing would continue throughout the life of the pipeline, although at a progressively decreasing rate (Lachenbruch 1970, pp. 4-8).

If the soils near the pipeline contain large amounts of ground ice, they may become liquified upon thawing with little cohesive strength, and the entire thawed cylinder may flow downslope like a viscous river. The pipe would settle in the vacuum created by the displaced soil and the process would be self-perpetuating until the pipe was eventually disrupted, spilling large amounts of oil. In addition, the linear depression caused by settling may become a drainage channel altering surface drainage and creating more erosion along the pipeline (Lachenbruch 1970, pp. 10-12).

Severe problems may also arise when the pipe passes from a strong material to a liquified region since the pipe would be put under considerable stress. Such conditions would be commonplace if a hot pipeline were buried in ice-wedge polygon terrain (which occurs on 5 to 10% of the Arctic Slope) (Figure 13). The pure ice in the vertical ice wedges would thaw quickly, and support for the pipe would be lost over considerable spans, especially when the ice wedges were crossed at low angles (Figure 39). Lachenbruch (1970, pp. 13-15) has calculated that in typical ice-wedge terrain, conditions exceeding the design stress of the pipeline would occur on the average of once every 1.6 km (1 mile).

One of the alternatives to burying the pipeline is to suspend it above ground. This would circumvent thawing of permafrost but it would raise other problems. For example, even though the pipe were insulated it would be subjected to extreme ambient temperatures ranging from −57 to +26° C (−70 to +80° F) resulting in pumping difficulties due to the greater viscosity and wax deposition of the oil. In addition, the suspension system would need to be very carefully engineered to accommodate the large expansion and contraction that would occur. An overhead pipeline would be suspended on pilings installed in permafrost. The pilings should pose no problem because considerable experience has been gained in this field, but the size and tremendous weight of the pipeline will require a dense

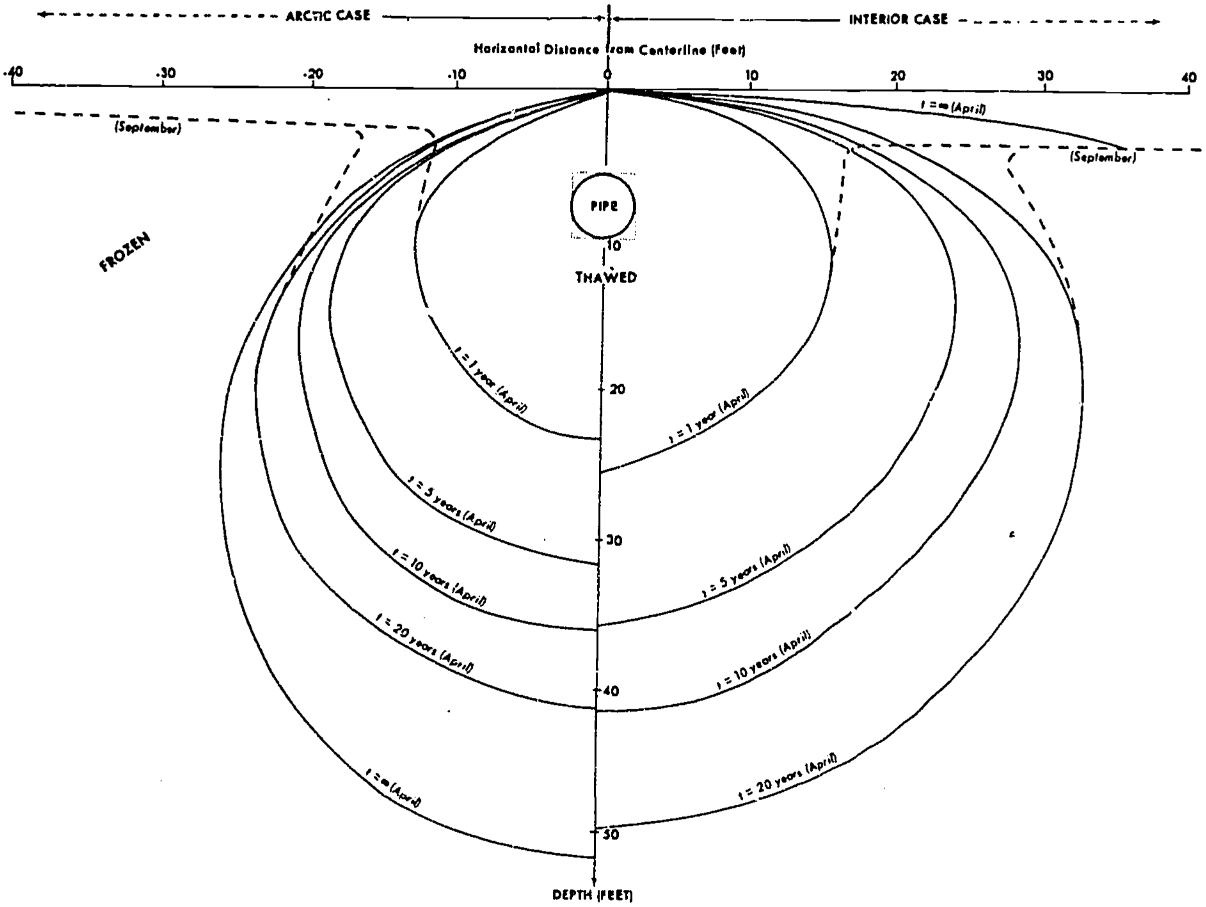

Figure 43. Theoretical growth of thawed cylinder around a 1.2 m (4 ft.) diameter pipe placed with its axis at a depth of 2.4 m (8 ft.) in silty soil and maintained at a temperature of 80° C (176° F). Curves on the left represent conditions near the Arctic Coast; those on the right represent conditions near the southern limit of permafrost. Dashed curves represent conditions at the conclusion of summer thawing (September) for 1 and 20 years. (After Lachenbruch 1970, Figure 2, p. 5.)

piling network which will make the construction of a suspended pipeline unbelievably expensive (especially since it should be high enough to permit free passage of animals, e.g., caribou, under it). Owing to exorbitant cost this method will probably be used only in very critical situations.

The last method suggested, that of building a road and installing the pipe along one side, seems very feasible for large stretches of the route where intermediate conditions occur, i.e., neither coarse and well drained nor poorly drained fine material with large quantities of ground ice. A road will probably eventually be constructed anyway (a winter road already exists and was heavily used in 1969 and 1970 to haul oil equipment to the Arctic Slope) (Polar Record 1970). The problem of heat given off by the pipeline would be critical on the road bed so the thermal conductivity of the fill versus the heat radiated by the pipe would need to be carefully calculated and appropriate thickness of gravel applied (Harwood 1969, p. 81). The major problem will be finding sufficient gravel. This again puts economics and ecology in juxtaposition because there are many places along the northern part of the proposed route where gravel is in short supply (and where it is available, usually along streams, major disruption to salmon spawning may result if it is removed).

The preceding discussion of the implications of permafrost to construction activities sets the stage for what follows. Permafrost poses severe limitations, but with adequate knowledge of its characteristics and with carefully planned and engineered structures, man should be able to work within the framework of permafrost with no excessive difficulty. The question that now arises is: What are the potential uses of the far north?

Land Use

I think it is safe to say that the North American arctic and subarctic will never be heavily populated. The carrying capacity of the land is simply not that great. It is true that the Russian north (and to a certain extent the Scandinavian north) has a relatively high population. The U.S.S.R. has several cities with over 100,000 population located north of 60° N. (the largest in North America is Fairbanks with 20,000), but this has been due mainly to governmental planning where economics was not a prime consideration. As a former professor of mine, Demitri Shimkin, University of Illinois, used to say, the U.S.S.R. developed their north at the expense of great human suffering. It is doubtful if such a development would take place in a capitalistic society. Population nodes may develop at foci of activity, e.g., mining, but these areas will always depend heavily on logistical support from the south.

The idea of development of the north raises an important philosophical question of which there are two main views. One is that the north is simply a potential warehouse of resources that can be exploited. At the opposite end of the spectrum is the view that the north should be actively developed, that part of the profit should be reinvested in the north for roads, dams, utilities, and schools, and that settlement should be encouraged. This latter viewpoint has a considerable following, especially in Canada, and has been embodied recently in the concept of the "Middle North," which calls for active development of the southern fringes of the far north, the zone just beyond the settled areas as reflected by roads, railroads, and cultivated lands (Lloyd 1969). The famous Klondike poet, Robert Service, expresses somewhat similar sentiment in *The Law of the Yukon:* "Dreaming alone of a people, dreaming alone of a day, when men shall not rape my riches, and curse me and go away."

Webster defines exploitation as "selfish or unfair utilization," and this is the proper term for many of our past activities in the north. Dealings with the Eskimo, gold mining, and whaling illustrate this point. To pick just one of these, the landscape of the north has been greatly scarred by placer mining activities of the gold rush and some that have continued since. In the placer mining operations near Fairbanks, Alaska, for example, 15-60 m (50-200 ft.) of surface material is removed so the deeper gold-bearing gravels can be dredged and in the process the material is transposed and the former soil surface buried beneath the excavated material. The result is hundreds of hectares of barren boulderly landscape, which, owing to the slow natural rates of soil formation in the subarctic, will be a legacy for millenia. This is ecologically irresponsible and is similar to the former approach to strip mining in the continental United States. A more responsible approach must be taken in the utilization of resources in the north as man realizes that he no longer operates in a vacuum but in what has suddenly become a very small world. At the same time, the wisdom of actively and forcefully developing the north is also questioned. Just because the land is unpopulated and unused does not mean that it is being wasted and should be purposefully developed. As projects become economically feasible they should be developed, but cautiously, with a sense of responsibility for the total implications of the project. One thing is certain, there will be increasing pressure for development, e.g., oil on the Arctic Slope, and it is up to concerned and knowledgeable people to see that these developments take place within the framework of rational utilization of resources, not exploitation.

The future development of the arctic and subarctic seems to lie within several broad fields—strategic, extractive industries, agriculture, and recreation.

Strategic

The strategic significance of the north polar area was discussed at the beginning of this chapter. It was military considerations that largely brought the north into the 20th century. The indigenous peoples of the north were scarcely touched before World War II, but this event altered their lives to such an extent that they can never return to their native ways and must inevitably become more like the white man. Military bases, radar sites, missile sites, and the personnel to run them have been the mainstay of Alaska. Every third man you meet on the street in Fairbanks or Anchorage is likely to be a government employee of some sort (actually 56% of Alaska's employed labor force is government employed) (Rogers and Cooley 1962, p. 68). This simply illustrates that the economic viability of such areas is largely dependent on support from the south. Be this as it may, their presence is more or less guaranteed in the north because of its fundamental strategic importance, and this will continue to bring in money and to be a major use of the landscape.

Extractive industries

The major extractive industries are fishing, trapping, timber, mining, and oil production, of which the latter two are by far the most important. Commercial fishing is relatively unimportant in the arctic, but in the subarctic where upwelling occurs it is very profitable (Dunbar 1962, pp. 128-131). The bulk of the salmon, halibut, herring, and cod consumed in North America comes from subarctic waters. Many coastal communities have economies largely based on fishing. Recently, however, there has been an increased trend towards pelagic fishing, which contributes little towards the development of the north. Commercial fresh water fishing does not hold much promise owing to the low productivity of northern lakes. The only lake that has an export potential is Great Slave Lake, which apparently has a capacity for sustained production (Rawson 1959, p. 68). Almost any relatively undisturbed northern lake will yield an initially impressive catch of fish, as any ardent fisherman will tell you; but unless the lake is large, the stock will be quickly depleted and it may take years to build up again, even after being left alone. This is due to low temperatures and small quantities of plant nutrients which result in low growth rates (Dunbar 1962, p. 128).

Fur trapping, so important historically to the early development of the far north, is currently relatively unimportant. Trapping is carried on by natives, but it affords nothing more than a subsistence living, particularly since the bottom fell out of the fur market in the early 1950's. Cyclic fluctuations in the number of fur bearing animals, the increased competition from commercial fur farms, and the very erratic fur market which depends upon the whimsies of fashion result in wide variations in annual income from trapping. As a result many natives have turned to other occupations wherever possible (Rawson 1959, p. 68).

The timber industry has been important in the U.S.S.R. where vast areas of the boreal forest have been cut along the major north flowing rivers, but very little of this has been practiced in North America. With the great success of tree farming in southeastern and northwestern United States where a crop of pulpwood can be grown in about 30 years, it is doubtful if the North American boreal forest will ever be used as a major source of timber. This is for the best because the slow growth rates of timber in cold environments make its harvest a very marginal economic use of the land, except for short term gain.

The major extractive industry in the north is mining. This began with the Klondike gold rush in Yukon Territory and Alaska and has continued to the present with mining operations for copper, zinc, lead, asbestos, iron, uranium, gold, silver, and nickel, just to mention a few. Much of the transportation system of the north has been developed in response to mining operations. Although most northern roads are built with governmental help, the ore deposits must, nevertheless, be very rich and extensive to make such a capital investment worthwhile. Even with a road or railroad the cost of operations in the north is exorbitantly high compared to a similar operation farther south. Factors which incur extra expense include: greater distance from market, higher salaries for employees, and problems of the environment such as permafrost, extremely low temperatures, and very little daylight in winter (Brown 1970, pp. 139-179). Inaccessibility itself can affect the economics of an operation in a number of ways, ranging from a longer period for replacement of broken parts to difficulty in maintaining a dependable skilled work force. Nevertheless, the future of mining looks very bright indeed and it will continue to be one of the major economic activities in the north.

Oil production shares many of the same physical and economic problems of the mining industry. Although oil has played a relatively unimportant role in northern development compared to mining, it has the potential for greatly affecting the future, as has become dramatically apparent with the discovery of vast petroleum deposits on the Arctic Slope. The utilization of this oil will almost certainly involve an all-weather road as well as a pipeline. With the road will follow the amenities necessary for travel, i.e., food, lodging, gasoline, and maintenance facilities. There are also excellent possibilities for large deposits of oil on the continental shelf off northern Alaska, in the Bristol Bay area, Alaska (Weeden and Klein 1971), in the Mackenzie River Valley, N.W.T., and in the Arctic Archipelago (Nickle 1961, in Brown 1970, p. 171). The eventual development of any or all of these areas will make man and his paraphernalia an increasingly dominant part of the northern landscape.

Agriculture

Agriculture in the far north is greatly limited by the extreme climate. Nevertheless, gardens, crops, and livestock have been grown successfully in a number of places even beyond the Arctic Circle, and there is considerable potential for further development. One of the most severe limiting factors for plant growth in high latitudes is the short growing season (frost-free period). For example, the major agricultural region of Alaska, the Matanuska Valley near Anchorage, has only a 90-day growing season. This is compared to an average of 150-220 days for middle latitude areas. A great deal of publicity has been given to the idea of "the land of the midnight sun," and it is true that the longer day length farther north partially compensates for the shorter growing season but not entirely, since average summer temperatures are lower and most cultivated plants are not adapted to the long hours of daylight. Even when ambient temperatures are adequate for plant growth, the soil temperatures are frequently not. This is particularly true when the area is underlain with permafrost, which serves as a reservoir of cold and impedes drainage. The latter factor may have as much beneficial as deleterious effect, however, since precipitation is very low in the far north and the higher water table may help compensate for the lack of rainfall. Additional problems result with areas underlain with permafrost when the natural vegetation cover is removed. The increased thawing that results may cause settling as ground ice melts, and slumping may occur if on a slope. If ice wedges are present, thermokarst mounds may develop as they did in some areas of the Tanana Valley near Fairbanks, Alaska when the boreal forest was cleared (Rockie 1942, Péwé 1954) (Figure 16). Thermokarst development creates rough surfaces that are difficult or impossible to negotiate with farm equipment.

Arctic and subarctic soils were discussed earlier and it was pointed out that they are generally of poor quality. The dominance of low temperatures and frost action result in shallow, poorly developed soil profiles consisting of coarse material with very little clay. The low rates of decomposition hinder organic matter assimilation, and northern soils are usually quite acid with a low nutrient status. They apparently respond well to fertilizers, however. The greatest percentage of arctic and subarctic soils are poorly drained and boggy, and another large portion of the landscape was subjected to glacial erosion which has left a legacy of bare rock surfaces. The best agricultural areas are in the alluvial soils of the river valleys, but there are many other small pockets, such as gentle south facing slopes, where crops can be grown successfully. In general, very little of the far north has class I land as defined by the U. S. Soil Conservation Service (productive, nearly level, and suitable for growing the crops common in the locality). Even in the Matanuska Valley, the best land is class II which is described as having "...some limitations because of soil properties, external features, the climatic environment or for some other reason" (Rockie 1946, p. 24).

It is conservatively estimated that Alaska has about one million acres of arable land (Kellog and Nygard 1951, pp. 123-124) and northern Canada has about the same, mainly in the Mackenzie and Yukon River valleys (Brown 1970, pp. 193-199). Much greater estimates can be made if grazing lands are included, but this is often pointless since the critical factor is the production of winter feed (hay, grain, and silage) and the provision of winter shelter which is often not feasible in these areas. On the subject of agricultural potential in the far north, it should be realized that there is a great deal of difference between what *could* be developed if all economic factors were favorable and what will or *should* be developed. This is particularly so when it is considered that much potential agricultural land still exists in the middle latitudes. In fact, agricultural land use has been declining in the United States in spite of an increasing level of agricultural production! The trend has been towards farm consolidation, with use of the better land under more efficient methods, and as a result the use of marginal lands has actually declined (Francis 1967, p. 500).

The major crops grown in the far north are those that have been successfully grown in continental areas with extreme winters such as Minnesota or southern Canada. These include potatoes, barley, oats, spring wheat, rye, and alfalfa. Livestock may also be raised but shelter during the winter is a major problem. Milk is the major agricultural product of Alaska but winters in the Matanuska Valley, where most of the dairy industry is located, are greatly ameliorated by marine influence. In the interior areas cattle must be continually sheltered. Garden vegetables such as radishes, carrots, onions, turnips, and cabbages may also be grown. The more tender crops such as tomatoes, cucumbers, and lettuce can be successfully grown by "hot house" methods (constructing a crude greenhouse from stretching polyethylene over a pole frame).

Most of the agricultural produce of the far north is grown for local consumption. There are many small garden plots located by settlements, mines, and trading posts, which help supplement produce shipped in from the outside. The yield of these areas is highly variable, depending on local environmental conditions and the skill and care used in them, but they do illustrate that cultivated crops can be successfully grown even in areas of continuous permafrost. Commercial agriculture is largely limited to Alaska although during the Klondike gold rush there was quite an agricultural development near Dawson, Y.T. to supply the over 25,000 people in this town. Most of these farms have since been abandoned (Brown 1970, p. 199). Alaska has three major agricultural areas–Tanana Valley, Matanuska Valley, and the Kenai Penninsula. The products raised here are almost totally for consumption within the state.

Francis (1967) has likened the agriculture of Alaska to "outpost agriculture" since its entire function is to supply what is essentially a remote colony. Agriculture in Alaska has also lost many of its pioneer qualities since the farms now are on high value land, highly mechanized, and strongly commercial. The chief products are milk, vegetables, meat, and eggs in that order, and most of these items are just barely competitive with similar products transported in from the south. In fact the Alaska legislature has had to exert pressure in various ways to protect the local producer from outside competition (Francis 1967, pp. 500-503). For this reason it is doubtful if Alaska will ever be able to compete on world markets except for selected commodities such as hides or wool. Nevertheless, agriculture provides a livelihood for the people associated with it and provides broader economic base for what would otherwise be an even more narrowly based economy.

The important point is that although Alaska and northern Canada have considerable agricultural potential in terms of what could be cultivated, the development of this potential will await the presence of enough local consumers to warrant its production, and then only through an effort of the people to support the locally grown products, rather than purchasing frequently better quality and less expensive imported products. As Karl Francis has said, "It is part of the American mystique to assume that marginal land is awaiting development, that the future will favor such development, and that all that is needed to make marginal land productive is population pressure and the pioneer's persistence and hard work.... A new image is needed" (Francis 1967, p. 504).

Recreation

Recreation has the potential for being one of the more valuable uses of the north in the long run. There are several reasons for this. At the largest scale, population is growing rapidly and there will be more and more pressure on traditional vacation areas. Man is also acquiring substantial leisure time due to technology, and we are becoming an increasingly urbanized society with all the ensuing pressures, from pollution to interpersonal relationships. This means that the relatively unpeopled and wild areas of the country will have an increasing appeal. Activities such as hunting, fishing, boating, hiking, camping, and just plain relaxing are excellent in the boreal forest and tundra. Recreation is an ideal use of the land since it would be largely summer oriented when the temperatures are warm, the days long, the vegetation at its best, the wildlife active (unfortunately including insects), and simply living in this environment can be a refreshing experience. The recreation industry could be very lucrative for the entire range of associated concerns, from the travel agency to the lodge operator to the guide and outfitter. These activities would also have a minimum impact on the landscape if properly handled.

Ecology

The periglacial environment is one of the most fragile environments on earth. In addition to being very easy to disrupt, it may also take an exceptionally long time to reestablish itself after disturbance. This is due to the dominance of low temperatures and the resulting low rates of biochemical activity. This means that man must be very careful with this environment because if he makes mistakes, and he will, it may take decades or centuries for them to be corrected. In the tropics after an area is cleared it may be completely revegetated within a few years, but not so in the arctic. A personal experience will illustrate this. I spent two field seasons in dissertation research in a subarctic alpine tundra environment in southwest Yukon Territory. The first summer, three of us camped in a valley and walked up the slope everyday to the study area. We followed roughly the same path for the two months we were there. The tundra vegetation consisted of sedges and grasses and it was trampled along the path, but I thought it would rebound quickly. The next year we camped in another area, but when we returned to the original site the path was still very obvious, and I suspect that the imprint from that brief encounter will remain for many years to come.

The fragility of the tundra ecosystem is in some ways a paradox, however, because tundra exists in one of the harshest environments and its success in coping with this environment is proof that it can withstand these rigors. As was discussed in the *Biologic Processes* chapter, the tundra ecosystem is well adapted to instability, so it is curious that it should at the same time be so vulnerable to disruption by man. Perhaps this is partially a matter of perception owing to the great length of time it takes for the effects of disturbance to be erased. The tundra ecosystem does have considerable potential and dependability of replacement due to the large populations of comparatively few species. In addition, most tundra species are not highly specialized and can therefore occupy a wide range of habitats. A threshold exists, however, where the damage may be irreparable, and this threshold is frequently lower in the tundra than in other environments. For example, a humid middle latitude or tropical area may be able to assimilate an oil spill within a few years and the damage would be negligible, but in the tundra assimilation may not occur, and even if it does, the length of time necessary would be greatly magnified. Unfortunately very little is known about the threshold of the periglacial environment to different kinds of disturbance, and this will be a fruitful field of investigation in the future. Unfortunately, again, much of this research will probably be carried on after the damage has already been done.

What are the ecological implications of man's use of the subarctic and arctic? One approach to answering this question is to consider some of the major projects that have been proposed for the far north and look at their potential ecological impact on the landscape. Three such proposals that should allow insight into several facets of the problem are: the Alaska pipeline, the Rampart Dam, and damming of the Bering Strait.

Alaska pipeline

The problems involved in the construction and maintenance of a large hot pipeline in permafrost are truly monumental, as discussed earlier. The ecological problems of such a project may be even greater, however. To start with, there will be considerable disturbance to the vegetation and soil in both transporting and installing the pipeline. This could be minimized if all operations took place in the winter when the ground was frozen or if giant helicopters were used in critical areas. In the past, this care has not been taken and as a result many areas of the tundra are more or less permanently marred by the linear scars of tracked vehicles (Figure 44). Some of the scarring was done 10-30 years ago by the caterpillar tractor trains used in seismic exploration by the U. S. Navy near Barrow, Alaska and a great deal more was done during construction of the DEW Line across the North American Arctic (Weeden and Klein 1971, p. 481; Mackay 1970). Such disturbances are not only bad aesthetically but they are also bad ecologically since rapid thawing and the concentration of water often transforms the tracks into stream channels which may alter the drainage pattern (Figure 44). Sometimes they may cause drainage of lakes or even create new lakes due to ponding and caving in of the sides as permafrost thaws. On sloping ground, erosion can carry excessive silt loads into small tundra streams that may be important as spawning and brooding areas for grayling and the arctic char (Weeden and Klein 1971, p. 481). The use of tracked vehicles on thawed tundra was prohibited by Alaska and the Federal Government in 1969 so this should be less of a problem in the future.

Other disturbances during initial construction may result from the large quantities of gravel that will be required for insulating roads, construction camps, airfields, and the pipeline itself, to keep the permafrost from thawing. Away from the coast the major source of gravel is along streams and its removal may increase stream turbidity; in addition,

Figure 44. Aerial view of recent scars left by heavy equipment in oil and gas explorations on Melville Island, N.W.T. (75° N. Lat.). This is a high arctic site with low amounts of soil moisture and ground ice so problems of thermokarst are much less than those encountered in the middle arctic. Nevertheless, the tracks shown are major disturbances and are more or less permanent scars on the tundra surface. One wonders why a separate trail was made for each crossing. (Photo by Lawrence C. Bliss, University of Alberta.)

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by removing or silting over spawning beds, the fisheries may be threatened. Much of the coastal plain of northern Alaska is fairly level and poorly drained. As a result even slightly elevated areas are favored denning sites for foxes, wolves, mink, and many small burrowing animals. Unfortunately, these are the same sites preferred by man since they provide a more stable substratum. A good example of such conflict exists on the sand dunes near Prudhoe Bay, Alaska where oil companies have bulldozed garbage pits and leveled large areas for pipe storage. The foxes that denned in this area are now threatened (as are the dunes themselves since much of the stabilizing vegetation has been destroyed). In addition, the foxes have become a nuisance since they frequently chew on plastic and rubber coated cables for their salt content, so the oil companies have financed an active fox trapping program in this area (Weeden and Klein 1971, p. 482).

Another conflict that arises with animals is due to garbage dumps. Grizzly bear, wolves, and wolverenes scavenge in these areas and are brought into close contact with man; since these animals pose a potential threat, they are often killed. This is not a major transgression, but in an area of low productivity where such animal populations could easily be endangered, it is serious enough for concern. The oil companies usually prohibit guns in work camps and most employees head south on their off time rather than stay on the tundra, so the legal harvest of wild animals on the Arctic Slope has not increased to the extent that Alaskan biologists first feared. On the other hand, the behavorial reaction of wild animals to these new activities is unknown. We have no answers to such questions as the following asked by Weeden and Klein, University of Alaska (1971, p. 483). "Are tundra birds adversely affected by hovercraft, helicopters, and large low-flying aircraft? How do migrating marine and land animals react to the stench of flared natural gas or to burning waste in sumps? Will caribou maintain their usual migration paths with dozens of roads, camps, airfields, and feeder pipelines athwart their lines of movement? Will ungulates, attracted to salt licks formed by the NaCl used in drilling, ingest toxic materials at these sites? Does the harassment of bears and other large animals by aircraft increase their mortality rates?" There is already some evidence of damage. For example in Canada it is feared that continued dispersal of musk-ox herds by helicopters is exposing them to increased predation (since their primary defense is to gather in a tight circle with the calves in the center). Also mountain sheep are known to abandon parts of their range after disturbance and may be very slow to reoccupy abandoned territory.

The foregoing are some of the ecological considerations important primarily during initial construction of the pipeline, but many will be of continuing concern. After the pipeline is completed (assuming it is) there are additional concerns. These have to do with pipeline breakage and oil spillage, thawing and erosion along the pipeline, increased facilities along the maintenance road (if one is constructed) to handle travelers, and the effect of the pipeline and associated structures on the movement and migration of animals.

The proposed route from Prudhoe Bay to Valdez, Alaska crosses several major fault zones, and it will be very difficult to prevent breakage if severe earthquakes such as the 1964 Alaska Earthquake occur. Considerable risk of breakage is also present where thawing and differential settling in permafrost may exceed the stress limits of the pipe. If oil is spilled on the tundra, it will cause devastating short term and possibly long term damage to the vegetation. The underlying permafrost will not allow seepage downward, and although some may be carried away by surface drainage, most of the oil will simply saturate the active layer and transform the affected area into a sodden and sterile blemish. The time necessary for assimilation of such an oil spill on the tundra is unknown, but it is certain that it would take a very long time, probably centuries.

Spillage of oil is also a serious concern in Prince William Sound at Valdez where the oil will be transferred to tankers for shipment southward to refineries. Weeden and Klein (1971, p. 486) cite a source which maintains that an average of one out of every 1,000 units of oil carried is spilled at sea or in port through tanker mishaps. Even if this greatly exceeds what actually will be spilled, the volume of tanker traffic in this area makes occasional massive oil spills a distinct likelihood. Perhaps of even more concern, is the oil that is spilled offshore as ballast disposal from tankers and from discharge of treated ballast at shore facilities. Ships coming to Valdez will normally carry 50-60% of their tanks full of sea water for ballast and before loading they must pump out the water. Although ships will be equipped to clean the ballast water, there will still be 50-100 parts of oil per million parts of effluent. It is now legal to dump this ballast into the bay, but the oil companies have agreed to install shore ballast tanks to unload the water and then release it to the bay with no more than 10 parts per million. These are very rigid standards, but at normal operational levels of about one million barrels of ballast per day, there will still be the equivalent of 12 barrels of oil pumped into Prince William Sound daily (Weeden and Klein 1971, p. 486).

This area is very rich in wildlife resources including salmon, halibut, herring, crabs, clams, sea otters, sea lions, seals, whales, ducks, geese, and many marine birds. It is estimated that the total potential value of the fishery resources of the area is 9.7 million dollars per year (U.S. Department of Interior 1970, in Weeden and Klein 1971, p.

487). The biological effects of oil pollution in this area are not known but they are certain to be detrimental. Those species that live in the inter-tidal zone, near the surface of the water, and in the quiet bays will be most affected. Oil washed on shore will affect the littoral vegetation, and oil in the upper water levels may affect plankton, a major source of food for many s[illegible]als. Either of these circumstances could have long-term repercussions owing to the importance of their p[illegible] the food chain. The problem of oil spillage on land or at sea is very serious in any environment but its effects are greatly magnified in cold climates since they last much longer. It is therefore of utmost importance that such occurrences be kept to a minimum. This will require both governmental supervision and continuous maintenance of standards by industry.

The probability of thawing and erosion along the pipeline was discussed in the first part of this chapter and illustrated in Figure 43. The primary concern of thawing and erosion, in addition to the possibility of pipeline disruption and oil spillage, is that excessive silting will result in small streams and adversely affect fish spawning. Other implications of the higher soil temperatures in the immediate vicinity of the pipeline include higher root temperatures which would presumably increase growth rates. In addition, the area above the pipeline would probably remain free of snow, and condensation due to localized evaporation may result in ground fogs over the pipeline, particularly after snowfalls (Lachenbruch 1970, p. 18). Although very little snow falls in the tundra, high winds cause constant drifting, and continual melting of this drifting snow along the pipeline would result in increased water content in the thawed cylinder around the pipe (Figure 43). This would contribute to the potential for flow as well as surface erosion along the pipeline.

It is probable that a road will be constructed along most sections of the pipeline for maintenance purposes and it will undoubtedly encourage greater travel. Amenities such as lodging and gas will be needed and man will become an increasingly permanent fixture along this narrow corridor extending northward. Development in the north has historically taken place in this manner, but never before has it penetrated the arctic tundra to such an extent. It must be realized that road construction, like that of the pipeline, carries with it the responsibility to respect the fragility of the environment.

A final ecological concern of the pipeline is that it might disrupt the migration of caribou, particularly if it were not high enough to allow free passage under it or if no ramps were built for passage over it (Weeden and Klein 1971, p. 484). More than 300,000 caribou use the Arctic Slope of Alaska during the summer and migrate southward to the boreal forest in the fall. They calve in the north and traditionally return to their calving sites every year. It is not known what effect such obstacles as the pipeline or roads will have on this migration. The Richardson Highway between Fairbanks and Anchorage transects a major caribou migration route but they have continued to cross the highway twice a year. The Denali Highway, completed in 1956 to McKinley National Park, also has apparently not affected their movements. On the Steese Highway north of Fairbanks, however, they have ceased their traditional migration but it is not known if the highway is to blame (Weeden and Klein 1971, p. 485). In northern Norway a railroad has disrupted normal movements of wild reindeer so that one area of their former range is overgrazed while the area on the other side of the railroad is undergrazed (Klein 1971, pp. 393-394). The answer to the question is therefore unresolved. Though there are only a few roads across their path now, what will happen in a few years when many more roads are built? In general, the disruption of traditional migrations would lead to lighter population pressures in some areas at the expense of others, with resultant overgrazing and eventual population reduction.

The foregoing has established the basis for very real concern for the ecological impact of the pipeline. It is to the credit of concerned individuals that the project has been delayed until adequate safeguards are taken to protect the environment. Although industry is becoming more and more attuned to this fact, it is nevertheless primarily motivated by economic considerations and as a result is often shortsighted and moves forward without sufficient planning. To illustrate, the pipe for the Alaska pipeline was purchased and partially delivered (from Japan) before meaningful consideration of the pipe size was possible. Thus did a 1.2-m (4-ft.) diameter pipe become the only option (Johnson 1970, p. 8). It seems that the government must assume greater responsibility in overseeing such activities because the far north is too great a heritage to be trusted to any individual or groups of individuals with vested interests that may not coincide with the public good.

Rampart Dam

The Rampart Dam was proposed in the early 1960's for a narrow stretch of the Yukon River called the Ramparts, located 160 km (100 miles) northwest of Fairbanks. It would have impounded an area 320 km (200 miles) long by 130 km (80 miles) wide, making it the largest manmade lake in the world (Cooke 1964, p. 277). The dam was seen by its supporters as a way of bolstering the sagging economy of Alaska which was in dire straits at the time (Gruening 1965). It was to have been built by the U. S. Army Corps of Engineers, and its construction alone would have brought in over 1.3 billion dollars to the state. The main purpose, however, was to provide cheap hydroelectric power. It would have had a capacity of over five million kilowatts per hour. Although Alaska's total power requirements are presently only about one million kilowatts, it was envisioned that the cheap power would attract industry to Alaska.

Considerable opposition was mustered against the project (Brooks 1965) and it was eventually rejected by Congress. It may be enlightening, however, to consider some of the potential ecological implications of this project. The area that would have been inundated is a low-lying swampy river flat that contains over 30,000 shallow lakes and ponds and is a major breeding center for wildfowl. The U. S. Fish and Wildlife Service estimates that this habitat contributes about 1,500,000 ducks, 12,500 geese, and 10,000 little brown cranes to the four major flyways of North America. The lake created by a dam would provide no substitute since the shores would be steep and preclude marsh formation (cited in Brooks 1965, p. 57). The area also supports a heavy population of fur-bearing animals, especially muskrat, beaver, mink, otter, and marten. About 40,000 pelts are taken annually by the local Indians, which represents 7% of Alaska's total fur production. It is not known what the fate of these fur bearers would be if a lake were created. Presumably most would migrate, but there would be a net loss in numbers since other habitats would have only a limited carrying capacity.

The Yukon Flats provide an excellent habitat for moose with a carrying capacity of about 12,500, although this would be no great loss according to Senator Gruening of Alaska, since there is already an excess of moose (Gruening 1965, p. 57) A lake would be in the way of caribou migrations with possible repercussions, as discussed in the preceding section. In Norway, hydroelectric projects have proved to be man's most detrimental influence on wild reindeer. These developments usually take place in valley bottoms which are the most productive in terms of grazing. Also migrations take place in the spring and fall just when the ice is most treacherous. If lake level is changed due to drawdown, the shore ice often slants downward to the floating ice and becomes a virtual death trap (Klein 1971, pp. 394-395).

A major damage to the ecology caused by such a project would be its effect on fish spawning. The Yukon River and its tributaries are primary spawning grounds for several species, but of chief concern are the salmon. Over 270,000 salmon pass the dam site annually heading upstream to spawn; some even go into Canada 820 km (510 miles) past the dam site (Brooks 1965, p. 57). The salmon runs would be almost entirely destroyed. Even if a fair proportion of the salmon was safely transported across, it is doubtful that the returning young could navigate successfully in such a large body of still water.

In terms of human occupancy, there are about 2,000 Athabascan Indians living in villages along the river, the largest of which is Fort Yukon. All would have to be relocated. These people and their ancestors have occupied this land for several thousand years. Although Alaska natives have no formally constituted rights to the land they occupy, they do have certain generalized rights to land use according to the terms of the Alaska Purchase Treaty of 1867. The interpretation of these rights is determined by Congress, but the issue was never pressed since the project was rejected (Cooke 1964, p. 279). (It will be interesting in this regard to see how the Eskimos on the Arctic Slope fare as a result of the oil developments.)

A concern voiced by some was the effect a lake would have on the regional climate. There probably would be some effect in a narrow zone surrounding the lake in the form of lake breezes, and the retarding of present temperature patterns in spring and fall. These changes would be negligible, however, to the regional climate. A good comparison can be made with a similarly situated and sized body of water such as Great Slave Lake, N.W.T., which does not offer any significant amelioration in the regional climate.

One of the greatest potential ecological threats of a dam is the reduction of the effect of spring breakup and flooding of the Yukon River. The waters of the Arctic Ocean and the Bering Sea are very cold and are warmed primarily by warm currents from the south. An additional source of heat is the annual breakup of the major rivers which enter into the Arctic Basin. The critical temperature of many of the phyto- and zooplankton is just slightly below the present temperature of the water, and slight cooling may be detrimental to them. The annual heat flux from the Yukon River to the Bering Sea is therefore vitally important to the survival of these small creatures which are the major food source for the large marine mammals such as seals, walrus, and whales. If the phytoplankton are eliminated from the area, the larger mammals will also disappear. The Rampart Dam project is an excellent example of the importance of considering the total implications of our actions when dealing with manipulations of the environment.

Damming of Bering Strait

One of the grandest schemes devised by man in some time is the proposal to dam the Bering Strait between Alaska and Siberia. The purpose is to warm the Arctic Ocean and therefore the climate of the far north. This idea has been discussed in various forms in the U.S.S.R. for several decades but was first given serious consideration in 1959 when the eminent Russian scientist, P. M. Borisov, presented his proposal at a special scientific conference (Problems of the North 1961). The warming of the arctic would be of great advantage to the U.S.S.R. and Canada since much of their territory lies within the periglacial environment. The implications of such a project, however, are very far reaching and the disadvantages far outweigh the advantages.

The Arctic Ocean is essentially a Mediterranean sea and receives its heat from the equatorical regions largely through ocean currents. The Bering Sea is a cold body of water and the flow northward through the Bering Strait is relatively small because of the narrowness of the channel and the deflection of the Japanese Current by the Aleutian Peninsula. Nevertheless, it does contribute some heat. The major amount of heat is contributed by the North Atlantic Drift which flows northward between Greenland and Norway. The proposed dam for the Bering Strait, which is 80 km (50 miles) wide and 50 m (160 ft.) deep, would have an elaborate system of pumps, sluices, and hydroelectric plants to transfer the cold water from the Arctic Ocean to the Bering Sea. In theory this would allow greater inflow of warm water from the North Atlantic Drift and the arctic ice pack would be melted and the climate would be warmed.

Considerable opposition was mustered against the project when it was proposed, by Russian scientists as well as the rest of the scientific community. Many people did not think it would work. Dunbar (1962, p. 133) calculated that pumping the cold arctic layer off the Arctic Ocean at the rate planned would take tens of thousands of years. Stepanov (1963a, pp. 129-130) calculated that even if it were possible to melt the arctic ice, it would probably reappear in the winter due to the absence of solar energy. For this reason Stepanov (1963b, p. 126) suggested that it would make much more sense to deepen the ridges that limit the inflow of the North Atlantic Drift. The major obstacle is Thomson Ridge between Great Britain and the Faeroe Islands, 150 km (90 miles) long by 50 km (30 miles) wide and 400 m (1,300 ft.) deep. It would apparently not be necessary to deepen the Nansen Ridge between Greenland and Spitzbergen because its central part is already about twice as deep as the Thomson Ridge. The increased flow of Atlantic waters into the arctic would thin the polar ice pack in its central part and melt it completely around the land margins, so the entire area would be navigable during the summer. In winter the ice would reform and prevent heat loss to the atmosphere from the ocean. According to this approach the ice would not be completely destroyed, but only thinned and the result would be a warmer arctic spring and summer climate. A major advantage of this proposal is that the arctic would still benefit from the warmer Pacific water through the Bering Strait.

Gargantuan undertakings such as this truly "boggle the mind." Although it would involve considerable time and expense, there is no question that man could build a dam across the Bering Strait if he so desired. The implications, however, are so far reaching they are difficult to conceive. A listing of only a few of these will illustrate the potentialities and liabilities of this project. First of all, the climate of the arctic probably would be warmed, particularly around Greenland and the Arctic Archipelago, and this would cause melting or at least thinning of the polar ice pack. The zone of marine mixing and upwelling would be shifted northward and would greatly increase the fishery resources of these areas (Dunbar 1962, pp. 130-132). Navigation would also be improved, as mentioned, since breakup would occur earlier and freeze up would take place later, and the entire littoral zone would be free of ice (Stepanov 1963a, p. 132). Ports could be established and the shipping of resources out and supplies into the arctic would be greatly facilitated. Warming of the climate would also improve agricultural prospects owing to the higher temperature and longer growing season. Treeline would presumably begin migrating northward and permafrost would begin to retreat although it would take several thousand years to disappear altogether.

Taken alone these are all very desirable improvements of the environment. It is unfortunate therefore that the undesirable ramifications of the project greatly overshadow the good aspects. The partial melting of the polar ice would cause some rise in sea level, but if the climate warmed sufficiently the glaciers of the Arctic Archipelago and the Greenland ice cap might melt also. This added water would raise the level of the oceans 8-10 m (26-33 ft.) above present sea level. Most of the world's large cities are located in coastal areas less than 30 m (100 ft.) above present sea level. A rise of the magnitude mentioned would flood almost all the coastal cities of Europe, as well as Tokyo, New York, and Miami, to mention only a few.

The ecology of the Bering Sea would be greatly affected by the change in flow caused by pumping of the cold arctic water into it. As mentioned, this body of water is already cold owing to poor circulation because of the Aleutian Peninsula. It is probable that much of the phyto- and zooplankton would be destroyed, or at least their distribution would be affected, and this in turn would cause concomitant changes in distribution and numbers of the large marine mammals that subsist on them.

The warming of the arctic would also cause major disalignments in world weather patterns. Cyclonic activity would increase in the higher latitudes with a subsequent decrease in the middle latitudes. This would result in decreased precipitation in the temperate zone, and continental climates would become even more continental, particularly in winter. There is also a distinct possibility that the deserts would encroach farther north (Stepanov 1963a, p. 132). Perhaps the major climate change, however, would be a long term one. Warming of the arctic and melting of the polar sea ice is an integral part of one of the foremost theories to explain the origin of the ice ages (Ewing and Donn 1956, 1958)!

It should be abundantly clear from the three major examples mentioned that the ecology of the periglacial environment is very easy to disrupt. This does not mean that the landscape should remain untouched and preserved in its natural state. It does mean, however, that developments of the far north should proceed cautiously after careful thought has gone into their total implications. It should also be stressed that the projects do not have to be of the scale and flamboyancy of the ones mentioned to be critical. It was small individual farmers who pushed into the marginal lands of the high plains of the U. S. and eventually created the dust bowl; likewise it was poor farming techniques that created the disastrous and irreparable gullying of the southeastern U. S. And in the long run, each of us must share the blame for polluting the environment to its present state. The north does not have the resiliency or the capacity to rebound from such maltreatment. When mistakes are made they will be much more lasting and damaging. This should not be viewed as a deterrent but as a challange, since it is a quality shared by all of the world's marginal landscapes—tundra, desert, and tropical rainforest. As man moves increasingly into these areas, he must understand this challenge, and perhaps more importantly, he must accept the responsibility it carries with it.

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