# 11

# PERIGLACIAL LANDSCAPES

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Frozen ground without an icy cover bears an assortment of odd landforms. This chapter covers:

- ice in frosty landscapes
- frost, snow, water, and wind action
- pingos, palsas, and other periglacial landforms
- humans in periglacial environments

A window on the periglacial world

In 1928, the airship *Graf Zeppelin* flew over the Arctic to reveal:

> the truly bizarre landscape of the polar world. In some areas there were flat plains stretching from horizon to horizon that were dotted with innumerable and inexplicable lakes. In other regions, linear gashes up to a mile or more long intersected to form giant polygonal networks. This bird's-eye view confirmed what were then only incidental surface impressions that unglaciated polar environments were very unusual.
>
> (Butzer 1976, 336)

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## PERIGLACIAL ENVIRONMENTS

The term 'periglacial' was first used by Polish geomorphologist Walery von Lozinzki in 1909 to describe frost weathering conditions in the Carpathian Mountains of Central Europe. In 1910, the idea of a 'periglacial zone' was established at the Eleventh Geological Congress in Stockholm to describe climatic and geomorphic conditions in areas peripheral to Pleistocene ice sheets and glaciers. This periglacial zone covered tundra regions, extending as far south as the latitudinal tree-line. In modern usage, periglacial refers to a wider range of cold but non-glacial conditions, regardless of their proximity to a glacier. It includes regions at high latitudes and below the altitudinal and latitudinal tree-lines: polar deserts and semi-deserts, the High Arctic and ice-free areas of Antarctica, tundra zones, boreal forest zones, and high alpine periglacial zones, which extend in mid-latitudes and even low latitudes. The largest alpine periglacial zone is the Qinghai–Xizang (Tibet) Plateau of China.

Periglacial environments characteristically experience intense frosts during winter months and snow-free ground during summer months. Four distinct climates produce such conditions – polar lowlands, subpolar lowlands, mid-latitude lowlands, and highlands (Washburn 1979, 7–8):

1. **Polar lowland climates** have a mean temperature of the coldest month less than 3°C. They are associated with zones occupied by ice caps, bare rock surfaces, and tundra vegetation.
2. **Subpolar lowland climates** also have a mean temperature of the coldest month less than 3°C, but the temperature of the warmest month exceeds 10°C. In the Northern Hemisphere, the 10°C isotherm for the warmest month sits roughly at the latitudinal tree-line, and subpolar lowland climates are associated with the northern boreal forests.
3. **Mid-latitude lowland climates** have a mean temperature of the coldest month less than 3°C, but the mean temperature is more than 10°C for at least four months of the year.
4. **Highland climates** are cold owing to high elevation. They vary considerably over short distances owing to aspect. Daily temperature changes tend to be great.

## Permafrost

Continuous and discontinuous zones of permanently frozen ground, which is known as **permafrost**, currently underlie some 25 per cent of the Earth's land surface. Permafrost may be defined as soil or rock that remains frozen for two or more consecutive years. It is not the same as frozen ground, as depressed freezing points allow some materials to stay unfrozen below 0°C and considerable amounts of liquid water may exist in frozen ground. Permafrost underlies large areas of the Northern Hemisphere Arctic and subarctic. It ranges from thin layers that have stayed frozen between two successive winters to frozen ground hundreds of metres thick and thousands of years old. It develops where the depth of winter freezing is greater than the depth of summer thawing, so creating a zone of permanently frozen ground. **Continuous** and **discontinuous permafrost zones** are recognized (Figure 11.1). Some authors have subdivided the zone of discontinuous permafrost into two, three, or four subzones. In North America, a tripartite sequence of widespread permafrost, sporadic permafrost, and isolated patches of permafrost is typical; in Russia, massive island permafrost, islands permafrost, and sporadic permafrost zones are common sequence (Heginbottom 2002). A **suprapermafrost layer**, which is the ground that lies above the **permafrost table,** tops all types of permafrost. It consists of an active layer and an unfrozen layer or talik. The **active layer** is that part of the suprapermafrost that melts during the day (in temperate and tropical regions) or during the spring thaw (in high latitudes) (Figure 11.2). The depth of the active layer varies from about 10 cm to 15 m. In the continuous permafrost zone, the active layer usually sits directly upon the permafrost table. In the discontinuous permafrost zone, the active layer may not reach the permafrost table and the permafrost itself consists of patches of ice. Lying within, below, or sometimes above the permafrost are **taliks**, which are unfrozen areas of irregular shapes. In the discontinuous permafrost, chimney-like taliks may puncture the frozen ground. Closed taliks are completely engulfed by frozen ground, while open taliks are connected with the active layer. Open taliks normally occur near lakes and other bodies of standing water, which provide a source of heat. Closed taliks result from lake drainage, past climates, and other reasons.

As well as occurring in Arctic and Antarctic regions (**polar** or **latitudinal permafrost**), permafrost also occurs in the alpine zone (**mountain permafrost**), on some plateaux (**plateau permafrost**), and under some seas (**marine permafrost**) (Figure 11.1).

## Ground ice

**Ground ice** is ice in frozen ground. It has a fundamental influence upon periglacial geomorphology, affecting

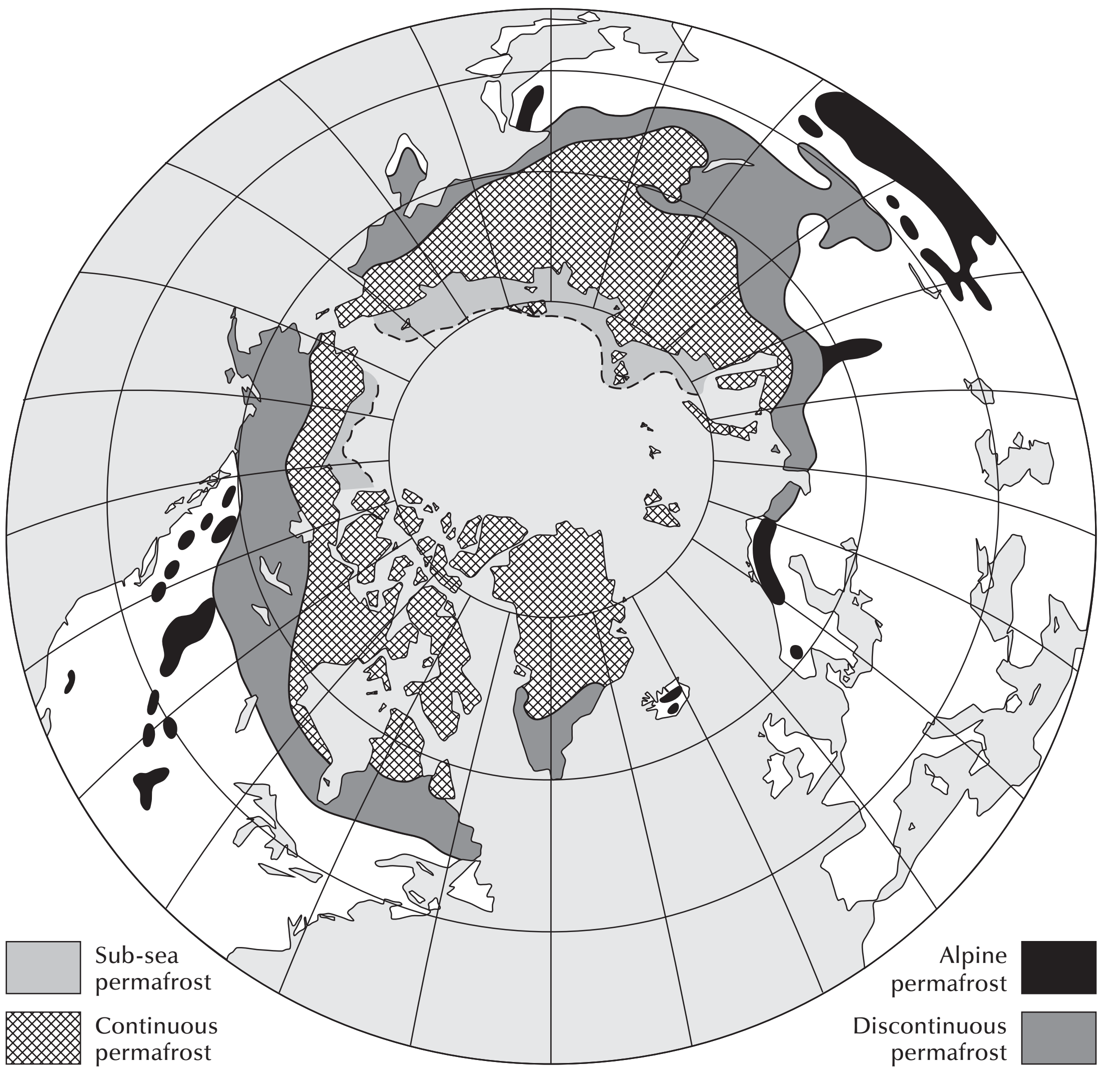

*Figure 11.1* Distribution of permafrost in the Northern Hemisphere. Isolated areas of alpine permafrost, which are not shown, are found in high mountains of Mexico, Hawaii, Japan, and Europe.
*Source:* Adapted from Péwé (1991)

landform initiation and evolution (Thorn 1992). It comes in a variety of forms (Table 11.1): **soil ice** (needle ice, segregated ice, and ice filling pore spaces); **vein ice** (single veins and ice wedges); **intrusive ice** (pingo ice and sheet ice); **extrusive ice**, which is formed subaerially, as on floodplains; **ice from sublimation**, which is formed in cavities by crystallization from water vapour; and **buried ice** (buried icebergs and buried glacier ice) (Embleton and King 1975b, 34). Some ground ice lasts for a day, forming under present climatic conditions, some of it

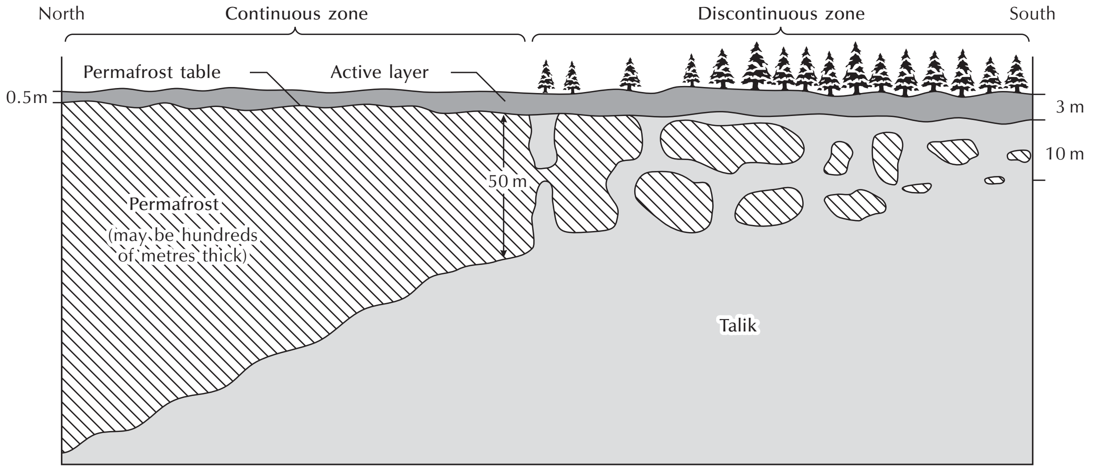

*Figure 11.2* Transect across continuous and discontinuous permafrost zones in Canada.
*Source:* Adapted from Brown (1970, 8)

Table 11.1 Types of ground ice

| *Type* | *Subtype* | *Formative process* |
|---|---|---|
| Epigenetic (formed within pre-existing sediments) | Needle ice (pipkrake) | Forms under stones or patches of earth that cool rapidly as air temperatures fall |
| | Ice wedges | Freezing of water in polygonal cracks |
| | Pore ice | *In situ* freezing of subsurface water in voids |
| | Segregation ice | Migration of water through voids to a freezing surface to form segregation ice layers and lenses |
| | Intrusive ice | Injection of moisture under pressure into sediments |
| | Aggradational ice | Upwards migration of the permafrost table, combining many segregated ice lenses, owing to a change in the environment |
| Syngenetic ice (formed in accumulating sediments) | Buried ice | Burial of snowbanks, stagnant glacial ice, or drift ice by deltaic, alluvial, or other sediments |

for thousands of years, forming under past climates and persisting as a relict feature.

## Periglacial processes

Most geomorphic processes occurring in periglacial zones occur in other climatic zones as well. Fluvial activity in particular is often the dominant process in periglacial landscapes. Some processes, of which those related to the freezing and thawing of water feature prominently, are highly active under periglacial conditions and may produce distinctive landforms.

### Weathering

Geomorphologists have traditionally assumed that chemical weathering is subdued under periglacial climates, owing to the low temperatures, the storage of much water as ice for much of the year, and the low levels of biological activity. However, studies on comparative rates of chemical and mechanical weathering in periglacial environments are few. One study from northern Sweden indicated that material released by chemical weathering and removed in solution by streams accounted for about half of the denudational loss of all material (Rapp 1986). Later studies suggest that, where water is available, chemical weathering can be a major component of the weathering regime in cold environments (e.g. Hall *et al.* 2002). Geomorphic processes characteristic of periglacial conditions include frost action, mass movement, nivation, fluvial activity, and aeolian activity.

### Fluvial action

Geomorphologists once deemed fluvial activity a relatively inconsequential process in periglacial environments due to the long period of freezing, during which running water is unavailable, and to the low annual precipitation. However, periglacial landscapes look similar to fluvial landscapes elsewhere and the role of fluvial activity in their creation has been re-evaluated. To be sure, river regimes are highly seasonal with high discharges sustained by the spring thaw. This high spring discharge makes fluvial action in periglacial climates a more potent force than the low precipitation levels might suggest, and even small streams are capable of conveying coarse debris and high sediment loads. In Arctic Canada, the River Mechan is fed by an annual precipitation of 135 mm, half of which falls as snow. Some 80–90 per cent of its annual flow occurs in a 10-day period, during which peak velocities reach up to 4 m/s and the whole river bed may be in motion.

### Aeolian action

Dry periglacial environments are prone to wind erosion, as witnessed by currently arid parts of the periglacial environments and by areas marginal to the Northern Hemisphere ice sheets during the Pleistocene epoch. Strong winds, freeze-dried sediments, low precipitation, low temperatures, and scant vegetation cover promote much aeolian activity. Erosional forms include faceted and grooved bedrock surfaces, deflation hollows in unconsolidated sediments, and ventifacts (p. 301). Wind is also responsible for loess accumulation (p. 296).

## PERIGLACIAL LANDFORMS

Many periglacial landforms originate from the presence of ice in the soil. The chief such landforms are ice and sand wedges, frost mounds of sundry kinds, thermokarst and oriented lakes, patterned ground, periglacial slopes, and cryoplanation terraces and cryopediments.

### Ice and sand wedges

**Ice wedges** are V-shaped masses of ground ice that penetrate the active layer and run down in the permafrost (Figure 11.3). In North America, they are typically 2–3 m wide, 3– 4 m deep, and formed in pre-existing sediments. Some in the Siberian lowlands are more than 5 m wide, 40–50 m long, and formed in aggrading alluvial deposits. In North America, active ice wedges are associated with continuous permafrost; relict wedges are found in the discontinuous permafrost zone. **Sand wedges** are formed where thawing and erosion of an ice wedge produces an empty trough, which becomes filled with loess or sand.

### Frost mounds

The expansion of water during freezing, plus hydrostatic or hydraulic water pressures (or both), creates a host of multifarious landforms collectively called '**frost mounds**' (see French 1996, 101–8). **Hydrolaccoliths** or **cryolaccoliths** are frost mounds with ice cores that resemble a laccolith in cross-section (p. 119). The chief long-lived mounds are pingos, palsas, and peat plateaux, while short-lived mounds include earth hummocks (p. 286), frost blisters, and icing mounds and icing blisters.

#### Pingos

**Pingos** are large, perennial, conical, ice-cored mounds that are common in some low-lying permafrost areas dominated by fine-grained sediments (Box 11.1). Their name is the Inuit word for a hill. Relict or inactive pingos

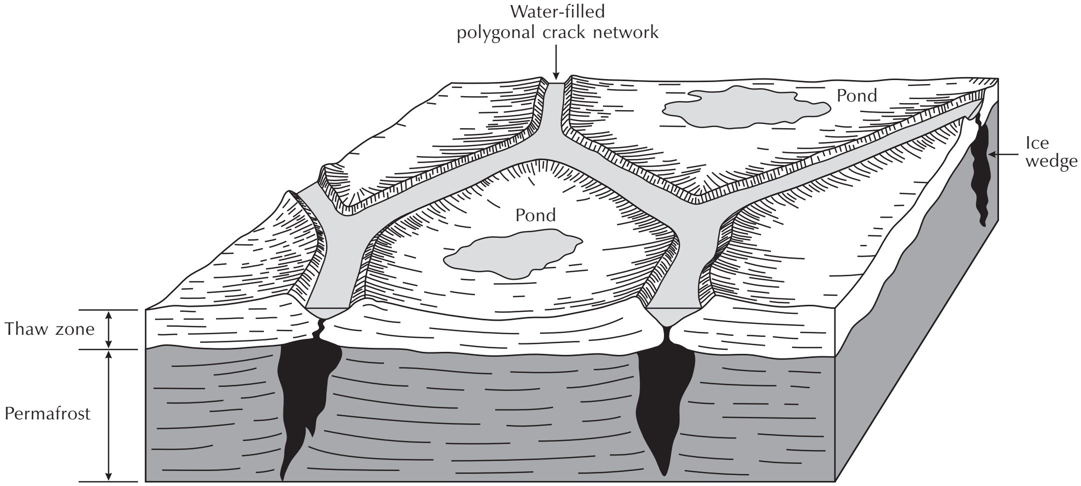

*Figure 11.3* Ice-wedges, ice-wedge polygons, and raised rims.
*Source:* After Butzer (1976, 342)

## Box 11.1

## PINGOS

Pingos are approximately circular to elliptical in plan (Colour Plate 14, inserted between pages 208 and 209). They stand 3 to 70 m high and are 30 to 7,500 m in diameter. The summit commonly bears dilation cracks, caused by the continuing growth of the ice core. Where these cracks open far enough, they may expose the ice core, causing it to thaw. This process creates a collapsed pingo, consisting of a nearly circular depression with a raised rim. Young pingos may grow vertically around 20 cm a year, but older pingos grow far less rapidly, taking thousands of years to evolve. The growth of the ice at the heart of a pingo appears to result from pressure exerted by water being forced upwards. Water may be forced upwards in at least two ways, depending on the absence (closed-system pingos) or presence (open-system pingos) of a continuing source of unfrozen water after the formation of the initial core. First, in **closed-system pingos**, a lake may be in-filled by sediment and vegetation, so reducing the insulation of the underlying, unfrozen ground (Figure 11.4a). Freezing of the lake surface will then cause permafrost to encroach from the lake margins, so trapping a body of water. When the entrapped water freezes, it expands and causes the overlying sediments and vegetation to dome. The same process would occur when a river is diverted or a lake drained. This mechanism for the origin at cryostatic pressure is supported by pingos in the Mackenzie Delta region, North West Territories, in Arctic Canada, where 98 per cent of 1,380 pingos recorded lie in, or near to, lake basins. A second plausible mechanism for forcing water upwards arises in **open-system pingos** (Figure 11.4b). Groundwater flowing under hydrostatic pressure may freeze as it forces its way towards the surface from below a thin permafrost layer. However, unconfined groundwater is unlikely to generate enough hydrostatic force to raise a pingo, and the open-system mechanisms may occur under temporary closed-system conditions as open taliks are frozen in winter.

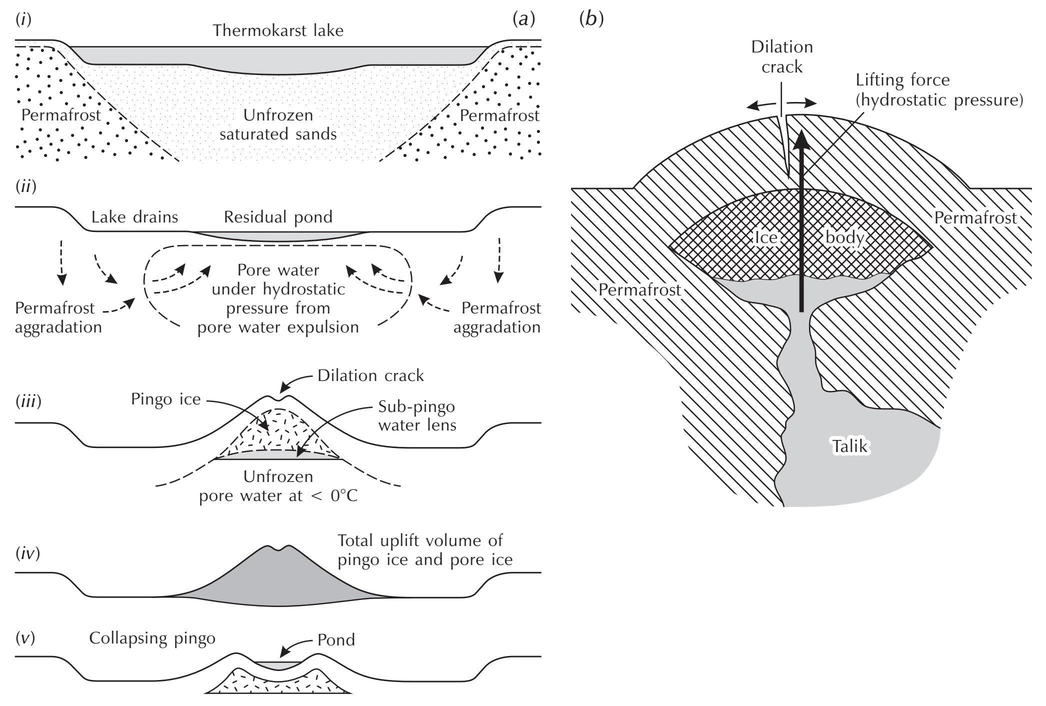

*Figure 11.4* Pingo formation. (a) Closed-system pingo produced after the infilling of a lake. (b) Open-system pingo.
*Sources:* (a) Adapted from Mackay (1998, 8); (b) Adapted from Müller (1968, 846)

occur in central Alaska, the Alaskan coastal plain, and the floor of the Beaufort Sea, in the Canadian Arctic. Active pingos occur in central Alaska and coastal Greenland, and the north of Siberia, particularly in deltas, estuaries, and alluvial areas.

## Bugors

Bugors and bugor-like forms are small and short-lived mounds that occur in the active layer. In Siberia, Russia, **bugors** (the Russian word for knolls) are gently rising oval mounds or hydrolaccoliths that occur in scattered groups. They are 5–10 m high, 50–80 m wide, and 100–5,000 m long. Similar, though slightly smaller, hydrolaccoliths occur in the North American Arctic. These bugor-like forms are seldom higher than 2 m and between 15 and 50 m in diameter. They are used as owl perches and stand out as fairly dry sites. Their origin is unclear as they bear no apparent relationship to topography. Even smaller hydrolaccoliths, which are never more than 1 m high or about 4 m in diameter, occur in parts of the North American Arctic, including Southampton Island, in North West Territories, Canada, and Alaska, USA. These features seem to result from the segregation of ice.

## Palsas, peat plateaux, and string bogs

A **palsa** is a low peat hill, commonly conical or dome-shaped, standing some 1–10 m high and having a diameter of 10–50 m. Palsas have a core of frozen peat or silt (or both), small ice crystals, and a multitude of thin ice lenses and partings. They often form islands within bogs. **Peat plateaux** are larger landforms formed by the coalescence of palsas.

**String bogs**, also called **patterned fens**, occur in muskeg. They are alternations of thin, string-like strips or ridges of peat, mainly *Sphagnum* moss, which may contain ice for at least part of the year and may include true palsas, and vegetation with shallow, linear depressions and ponds. The ridges stand some 1.5 m high, are 1–3 m wide, and are tens of metres long. The linear features often lie at right-angles to the regional slope. It is not certain how string bogs form. Possible formative processes include gelifluction, frost thrusting of ridges from adjacent ponds, differential frost heaving, ice-lens growth, and differential thawing of permafrost, and may involve hydrological and botanical factors.

### Frost blisters

Smaller mounds than palsas contain ice cores or ice lenses. Seasonal frost blisters, common in Arctic and subarctic regions, may grow a few metres high and a few to around 70 m long during winter freeze-back, when spring water under high pressure freezes and uplifts soil and organic sediments. They are similar to palsas but form in a different way, grow at a faster rate, and tend to occur in groups as opposed to singly.

### Icing mounds and icing blisters

**Icings** or **ice mounds** are sheet-like masses of ice formed during winter by the freezing of successive flows of water seeping from the ground, flowing from springs, or emerging through fractures in river ice. They may grow up to 13 m thick. They store water above ground until it is released in spring and summer, when they boost runoff enormously. Icings in stream valleys block spring runoff, promoting lateral erosion by the re-routed flow. By so widening the main channel, they encourage braiding. **Icing blisters** are ice mounds created by groundwater injected at high pressure between icing layers.

## Thermokarst and oriented lakes

**Thermokarst** is irregular terrain characterized by topographic depressions with hummocks between them. It results mainly from the thawing of ground ice, material collapsing into the spaces formerly occupied by ice. Thermokarst features may also be fashioned by flowing water released as the ice thaws. The thawed water is relatively warm and causes thermal and mechanical erosion of ice masses exposed along cliffs or in stream banks. The term thermokarst reflects the resulting landform's likeness to a karst landscape in limestone regions. Thermokarst features may result from climatic warming, but they are often part of the natural variability in the periglacial environment. Any modification of surface conditions can give rise to them, including vegetation disturbance, cliff retreat, and river-course changes.

**Thaw lakes** are prevalent in thermokarst landscapes (Plate 11.1). Many thaw lakes are elliptical in plan, with their long axes pointing in the same direction, at right-angles to the prevailing wind during periods of open water. The alignment may relate to zones of maximum current, littoral drift, and erosion, but its causes are far from fully studied. **Oriented thaw lakes** are common in permafrost regions, but oriented lakes occur in other environments, too.

## Patterned ground

In the periglacial zone, the ground surface commonly bears a variety of cells, mounds, and ridges that create a regular geometric pattern. Such ground patterning occurs in other environments, but it is especially common in periglacial regions, where the patterns tend to be more prominent. The main forms are circles, polygons, nets, steps, and stripes (Washburn 1979, 122–56). All these may occur in sorted or non-sorted forms. In sorted forms, coarser material is separated from finer material, whereas in non-sorted forms there is no segregation of particles by size and the patterns are disclosed by microtopography or vegetation or both. The various forms usually connect, with a transition from polygons, circles, and nets on flattish surfaces grading into steps and then stripes as slopes become steeper and mass movements become important (Box 11.2).

*Plate 11.1* Thermokarst thaw lakes, Mackenzie Delta, Northwest Territories, Canada.
(*Photograph by Tony Waltham Geophotos*)

The origin of patterned ground is not fully clear. Three sets of processes seem important – sorting processes, slope processes, and patterning processes (Figure 11.5). The main patterning processes are cracking, either by thermal contraction (frost cracking), drying (desiccation cracking), or heaving (dilation cracking), of which only frost cracking is confined to periglacial environments. Patterning may also result from frost heaving and mass displacement. Frost heaving is also an important source of sorting, helping to segregate the large stones by shifting them upwards and outwards leaving a fine-grained centre. As many forms of patterned ground are so regular, some geomorphologists have suggested that convective cells form in the active layer. The cells would develop because water is at its densest at 4°C. Water at the thawing front is therefore less dense than the overlying, slightly warmer water and rises. Relatively warm descending limbs of the convective cells would cause undulations in the interface between frozen and unfrozen soil that might be echoed in the ground surface topography. How the echoing takes place is uncertain, but frost heaving is one of several possible mechanisms. Stripe forms would, by this argument, result from a downslope distortion of the convective cells. Another possibility is that convective cells develop in the soil itself, and evidence for a cell-like soil circulation has been found. But the processes involved in patterned ground formation are complex, and all the more so because similar kinds of patterned ground appear to be created by different processes (an example of equifinality – see p. 25), and the same processes can produce different kinds of patterned ground. For instance, patterned ground occurs in deserts.

## Periglacial slopes

Periglacial slopes are much like slopes formed in other climatic regimes, but some differences arise owing to frost action, a lack of vegetation, and the presence of frozen ground. Frost-creep and gelifluction are important periglacial processes and form sheets, lobes, and terraces. Gelifluction sheets, which occur mainly in the High Arctic, where vegetation is absent, tend to produce smooth terrain with low slope gradients (1° to 3°). Tongue-like lobes are more common in the tundra and forest tundra, where some vegetation patches occur (Plate 11.6). **Solifluction lobes** tend to form below snow patches. **Terraces** are common on lower slopes of valleys (Colour Plate 15, inserted between pages 208 and 209). **Ploughing boulders** or **ploughing blocks** move down

**Box 11.2**

## TYPES OF PATTERNED GROUND

### Circles

Circles occur individually or in sets. They are usually 0.5 to 3 m in diameter. **Sorted circles** have fine material at the centre and a rim of stones, the stones being large in larger circles (Plate 11.2). The debris island is a particular type of sorted stone circle in which a core of fine material is girded by blocks and boulders on steep, debris-covered slopes. **Non-sorted circles** are dome-shaped, lack stony borders, and are fringed by vegetation. Circles are not restricted to areas of permafrost, and unsorted sorts are recorded from non-periglacial environments.

### Polygons

Polygons occur in sets. **Non-sorted polygons** range in size from about a metre across to large tundra or ice-wedge polygons that may be a hundred metres or more across. **Sorted polygons** are at most 10 m across and the borders of the polygons are formed of stones with finer material between them (Plate 11.3a). They are usually associated with flat land, while non-sorted polygons may occur on fairly steep slopes. Furrows or cracks edge non-sorted polygons (Figure 11.3). The best-developed polygons occur in regions with frosty climates, but polygons are known from hot deserts. **Ice-wedge polygons** are exclusively found in permafrost zones, the ice-wedges often occurring at the edges of large, non-sorted polygons. Two kinds of ice-wedge polygons are recognized. The first is a saucer-shaped polygon with a low centre, which may hold standing water in summer, and marginal ridges on either side of the ice-wedge trough. The second has a high centre hemmed by ice-wedge troughs.

### Nets

Nets are a transitional form between circles and polygons. They are typically small with a diameter of less than a couple of metres. **Earth hummocks** (also called **thúfur** and **pounus**) consist of a domed core of mineral soil crowned by vegetation and are a common type of unsorted net. They are about 0.5 m high and 1–2 m in diameter and form mainly in fine-grained material in cold environments where ample moisture and seasonal frost penetration permanently displace

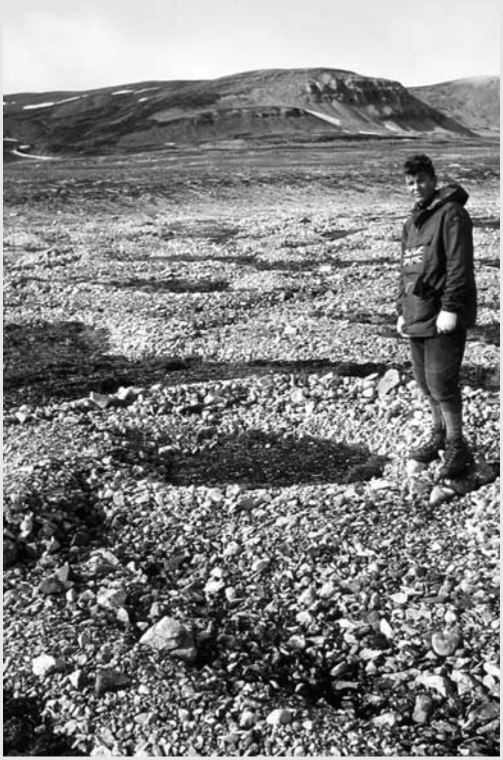

*Plate 11.2* Stone circles, Kongsfjord, Spitsbergen. (*Photograph by Wilfred H. Theakstone*)

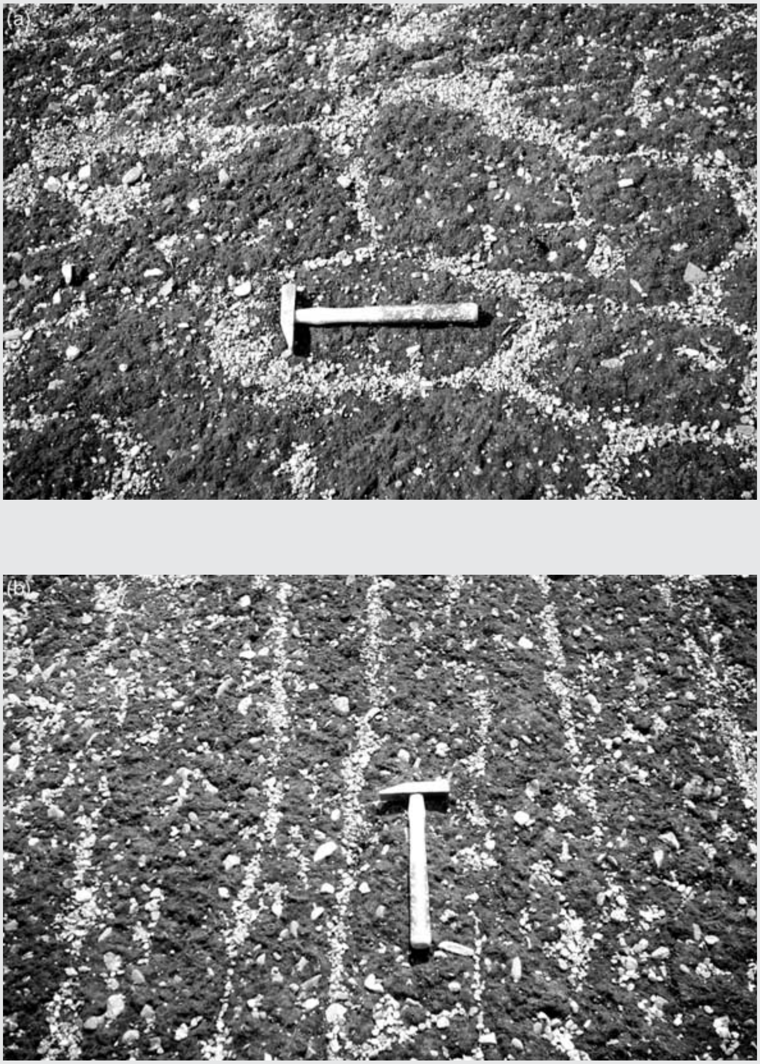

*Plate 11.3* (a) Sorted polygons and (b) sorted stone stripes, Svartisen, northern Norway. The polygons and the stripes are found at the same site, the polygons on a very gently sloping area and the stripes on the steeper slope below. (*Photographs by Wilfred H. Theakstone*)

*Plate 11.4* Earth hummocks, Drakensberg, Lesotho. (*Photograph by Stefan Grab*)

surface materials. Earth hummocks occur mainly in polar and subpolar regions, but examples are known from alpine environments. They are present and periodically active in the alpine Mohlesi Valley of Lesotho, southern Africa (Grab 1994, 2005) (Plate 11.4).

### Steps

Steps are terrace-like landforms that occur on fairly steep slopes. They develop from circles, polygons, and nets, and run either parallel to hillside contours or become elongated downslope to create lobate forms. In **unsorted steps**, the rise of the step is well vegetated and the tread is bare. In **sorted steps**, the step is edged with larger stones. The lobate varieties are called **stone garlands**. No step forms are limited to permafrost environments.

### Stripes

Stripes, which are not confined to periglacial environments, tend to develop on steeper slopes than steps. **Sorted stripes** are composed of alternating stripes of coarse and fine material downslope (Plate 11.3b). Sorted stripes at High Pike in the northern English Lake District occur at 658 m on a scree with an aspect of 275° and a slope angle of 17–18° (Warburton and Caine 1999). These stripes are formed at a relatively low altitude, possibly because the scree has a large proportion of fine material susceptible to frost action and is free of vegetation. The sorted stripes are still active. **Non-sorted stripes** are marked by lines of vegetation lying in slight troughs with bare soil on the intervening slight ridges (Plate 11.5).

*Plate 11.5* Non-sorted striped ground (elongate earth hummocks), Rock and Pillar Range, New Zealand. (*Photograph by Stefan Grab*)

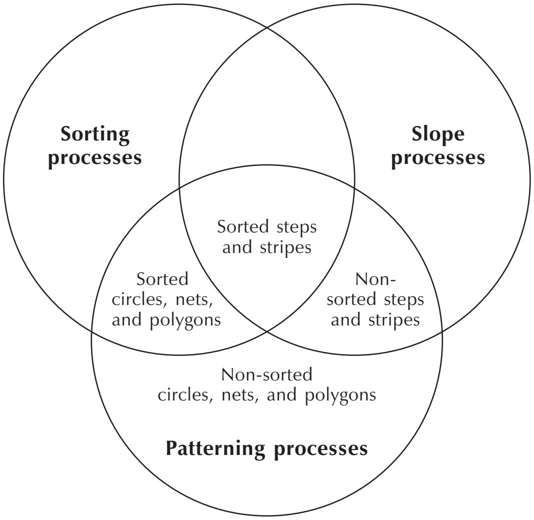

*Figure 11.5* Relationships between patterned ground and sorting processes, slope processes, and patterning processes. *Source:* Adapted from Washburn (1979, 160)

slopes through the surrounding soil, leaving a vegetated furrow in their wake and building a lobe in their van (Plate 11.7).

**Rock glaciers** are lobes or tongues of frozen, angular rock and fine debris mixed with interstitial ice and ice lenses (Plate 11.8). They occur in high mountains of polar, subpolar, mid-latitude, and low-latitude regions. Active forms tend to be found in continental and semi-arid climates, where ice glaciers do not fill all suitable sites. They range from several hundred metres to more than a kilometre long and up to 50 m thick.

Slope profiles in periglacial regions seem to come in five forms (French 1996, 170–80). Type 1, which is the best-known slope form from periglacial regions, consists of a steep cliff above a concave debris (talus) slope, and gentler slope below the talus (Figure 11.6a). Type 2 are rectilinear debris-mantled slopes, sometimes called **Richter slopes**, in which debris supply and debris removal are roughly balanced (Figure 11.6b). They occur in arid and ice-free valleys in parts of

*Plate 11.6* Solifluction lobes, Drakensberg, South Africa. (*Photograph by Stefan Grab*)

Antarctica and in the unglaciated northern Yukon, Canada. Type 3 comprises frost-shattered and gelifluction debris with moderately smooth, **concavo-convex profiles** (Figure 11.6c). Residual hillside tors may project through the debris on the upper valley sides. Such profiles are often identified as relict periglacial forms dating from the Pleistocene, but they are not widely reported from present-day periglacial regions. Type 4 profiles are formed of gently sloping **cryoplanation terraces** (also called 'goletz' terraces, altiplanation terraces, nivation terraces, and equiplanation terraces) in the middle and upper portions of some slopes that are cut into bedrock on hill summits or upper hillslopes (Figure 11.6d). Cryoplanation terraces range from 10 m to 2 km across and up to 10 km in length. The risers between the terraces may be 70 m high and slope at angles of 30° or more where covered with debris or perpendicularly where cut into bedrock. Cryoplanation terraces occur chiefly in unglaciated northern Yukon and Alaska, and in Siberia. They are attributed to nivation and scarp recession through gelifluction (e.g. Nelson 1998), but substantive field research into their formation is very limited (see Thorn and Hall 2002). Type 5 profiles are rectilinear **cryopediments**, which are very gently concave erosional surfaces that are usually cut into the base of valley-side or mountain slopes, and are common in very dry periglacial regions (Figure 11.6e). Unless they cut across geological structures, they are difficult to distinguish from structural benches. Lithological and structural controls are important in their development, which occurs in much the same way as cryoplanation terraces except that slope wash, rather than gelifluction, is more active in aiding scarp recession. The processes involved in their formation appear to be bedrock weathering by frost action combined with gravity-controlled cliff retreat and slope replacement from below. In profile types 3 and 4, residual hilltop or summit tors surrounded by gentler slopes are common on the interfluves. Many authorities argue that periglacial slopes evolve to become smoother and flatter, as erosion is concentrated on the higher section and deposition on the lower section.

## HUMANS AND PERIGLACIAL ENVIRONMENTS

Attempts to develop periglacial regions face unique and difficult problems associated with building on an icy substrate (Box 11.3). Undeterred, humans have exploited tundra landscapes for 150 years or more, with severe disturbances occurring after the Second World War with the exploration for petroleum and other resource

*Plate 11.7* Ploughing boulder with furrow, levee, and frontal lobe, Rock and Pillar Range, New Zealand.
(*Photograph by Stefan Grab*)

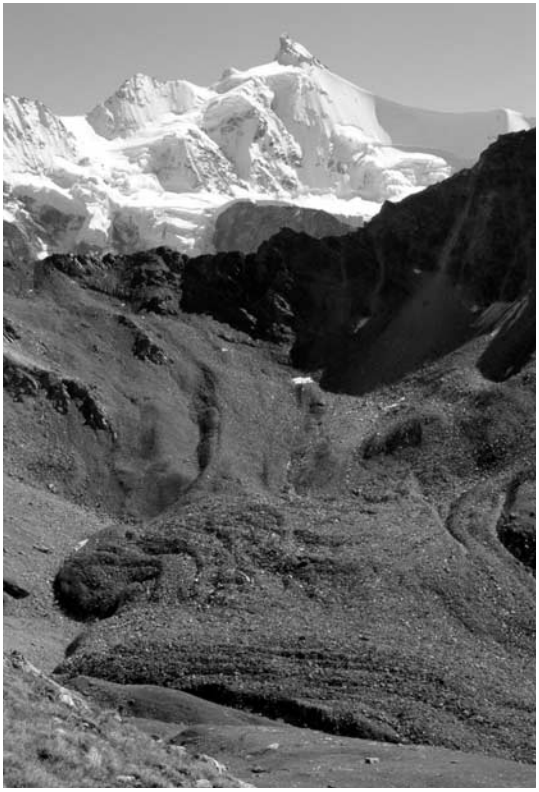

*Plate 11.8* Active rock glacier, Swiss Alps.
(*Photograph by Stefan Grab*)

development (e.g. Bliss 1990). **Permafrost degradation** occurs where the thermal balance of the permafrost is broken, either by climatic changes or by changing conditions at the ground surface.

In the Low Arctic, mineral exploration has led to the melting of permafrost. Under natural conditions, peat, which is a good insulator, tends to prevent permafrost from melting. Where the peat layer is disturbed or removed, as by the use of tracked vehicles along summer roads, permafrost melt is encouraged. Ground-ice melting and subsequent subsidence produce **thermokarst**, which resembles karst landscapes (cf. p. 284). In the Tanana Flats, Alaska, USA, ice-rich permafrost that supports birch forest is thawing rapidly, the forests being converted to minerotrophic floating mat fens (Osterkamp *et al.* 2000). A hundred years ago or more at this site, some 83 per cent of 260,000 ha was underlain by permafrost. About 42 per cent of this permafrost has been affected by thermokarst development within the last 100 to 200 years. The thaw depths are typically 1–2 m, with some values as high as 6 m. On the Yamal Peninsula of north-west Siberia, land-use and climatic changes since the 1960s, when supergiant natural gas fields were discovered, have led to changes in the tundra landscape (Forbes 1999). Extensive exploration meant that large areas were given over to the construction of roads and buildings. Disturbance associated with this development has affected thousands of

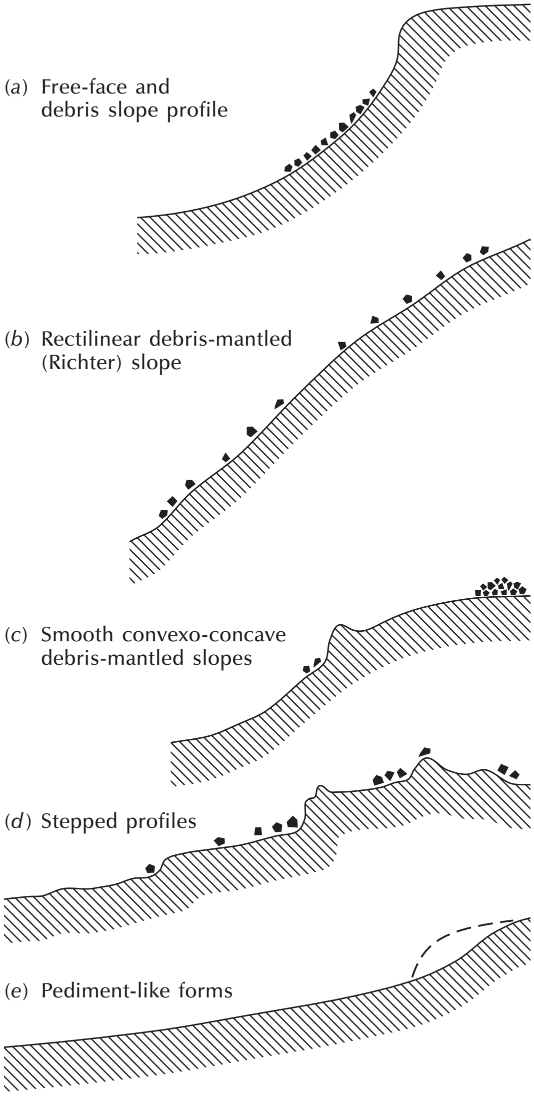

*Figure 11.6* Types of periglacial slopes. (a) Cliff above a debris slope. (b) Rectilinear, debris-mantled or Richter slope. (c) Smooth concavo-convex profile with frost-shattered and solifluction debris.
(d) Stepped profiles: cryoplanation or altiplanation terraces. (e) Pediment-like forms, or cryopediments.
*Source:* Adapted from French (1996, 171)

hectares of land. The increasing amount of land given over to roads and buildings, together with the associated disturbed land, has driven a fairly constant or increasing reindeer population on to progressively smaller patches of pasture. In consequence, the patches have suffered excessive grazing and trampling of lichens, bryophytes, and shrubs. In many areas, sandy soils have been deflated. The human- and reindeer-induced disturbance may easily initiate thermokarst formation and aeolian erosion, which would lead to significant further losses of pasture.

Thermokarst is less likely to develop in the High Arctic, owing to the lower permafrost temperatures and the generally lower ice content. Nonetheless, gully erosion can be a serious problem in places lacking a peat cover. For instance, snow piled up when clear areas for airstrips and camps are ploughed melts in the spring. The meltwater runs along minor ruts caused by vehicles. In a few years, these minor ruts may be eroded into sizeable gullies. A trickle of water may become a potent erosive force that transforms the tundra landscape into a slurry of mud and eroding peat. Restoration work is difficult because gravel is in short supply and a loss of soil volume occurs during the summer melt. In any case, gravel roads, although they will prevent permafrost melt and subsidence if they are thick enough, have deleterious side-effects. For instance, culverts designed to take water under the roads may fill with gravel or with ice in the winter. In three sites within the Prudhoe Bay Oil Field, studied from 1968 to 1983, blocked drainage-ways have led to 9 per cent of the mapped area being flooded and 1 per cent of the area being thermokarst (Walker *et al.* 1987). Had not the collecting systems, the camps, and the pipeline corridors been built in an environmentally acceptable manner, the flooding and conversion to thermokarst might have been far greater. Water running parallel to the roads and increased flow from the culverts may lead to combined thermal and hydraulic erosion and the production of thermokarst.

**Global warming** during the twenty-first century is bound to have a large impact on permafrost landscapes, and no effectual countermeasures are available (Lunardini 1996). Much of the discontinuous permafrost in Alaska is now extremely warm, usually within 1–2°C of thawing. Ice at this temperature is highly susceptible to thermal degradation, and any additional warming

**Box 11.3**

## PROBLEMS OF DEVELOPMENT ON PERMAFROST

Buildings, roads, and railways erected on the ground surface in permafrost areas face two problems (e.g. French 1996, 285–91). First, the freezing of the ground causes frost heaving, which disturbs buildings, foundations, and road surfaces. Second, the structures themselves may cause the underlying ice to thaw, bringing about heaving and subsidence, and they may sink into the ground (Plate 11.9). To overcome this difficulty, the use of a pad or some kind of fill (usually gravel) may be placed upon the surface. If the pad or fill is of the appropriate thickness, the thermal regime of the underlying permafrost is unchanged. Structures that convey significant amounts of heat to the permafrost, such as heated buildings and warm oil pipelines, require the taking of additional measures. A common practice is to mount buildings on piles, so allowing an air space below between the building and the ground surface in which cold air may circulate (Colour Plate 14). Even so, in ground subject to seasonal freezing, the pile foundations may move, pushing the piles upwards. In consequence, bridges, buildings, military installations, and pipelines may be damaged or destroyed if the piles are not placed judiciously. Other measures include inserting open-ended culverts into pads and the laying of insulating matting beneath them. In addition, where the cost is justified, refrigeration units may be set around pads or through pilings. Pipes providing municipal services, such as water supply and sewage disposal, cannot be laid underground in permafrost regions. One solution, which was used at Inuvik, in the Canadian North West Territories, is to use utilidors. Utilidors are continuously insulated aluminium boxes that run above ground on supports, linking buildings to a central system.

The Trans-Alaska Pipeline System (TAPS), which was finished in 1977, is a striking achievement of construction under permafrost conditions. The pipeline is 1,285 km long and carries crude oil from Prudhoe Bay on the North Slope to an ice-free port at Valdez on the Pacific Coast. It was originally planned to bury the

*Plate 11.9* Subsidence due to thawing of permafrost, Dawson, Klondike, Alaska, USA.
(*Photograph by Tony Waltham Geophotos*)

pipe in the ground for most of the route, but as the oil is carried at 70–80°C this would have melted the permafrost and the resulting soil flow would have damaged the pipe. In the event, about half of the pipe was mounted on elevated beams held up by 120,000 vertical support members (VSMs) that were frozen firmly into the permafrost using special heat-radiating thermal devices to prevent their moving. This system allows the heat from the pipe to be dissipated into the air, so minimizing its impact on the permafrost.

Few roads and railways have been built in permafrost regions. Most roads are unpaved. Summer thawing, with concomitant loss of load-bearing strength in fine-grained sediments, and winter frost-heaving call for the constant grading of roads to maintain a surface smooth enough for driving. Paved roads tend to become rough very quickly, most of them requiring resurfacing every 3 to 5 years. Railways are difficult to build and expensive to keep up in permafrost regions. The Trans-Siberian Railway, and some Canadian railways in the north of the country (e.g. the Hudson Bay railway), cross areas where the ground ice is thick. At these sites, year-round, costly maintenance programmes are needed to combat the effects of summer thawing and winter frost-heaving and keep the track level. The Hudson Bay railway has been operating for over 60 years. For all that time, it has faced problems of thaw settlement along the railway embankment and the destruction of bridge decks by frost heave. Heat pipes help to minimize thaw subsidence but they are very expensive.

during the current century will result in the formation of new thermokarst (Osterkamp *et al.* 2000). In the Yamal Peninsula, a slight warming of climate, even without the human impacts on the landscape, would produce massive thermokarst erosion (Forbes 1999).

## SUMMARY

Periglacial landscapes experience intense frosts during winter and snow-free ground during the summer. They are underlain by either continuous or patchy permafrost (permanently frozen ground), which at present lies beneath about 22 per cent of the land surface. Several geomorphic processes operate in periglacial environments. Frost action is a key process. It causes weathering, heaving and thrusting, mass displacement, and cracking. Frost creep and gelifluction dominate mass movements. Nivation combines several processes to form hollows under snow patches. Fluvial and aeolian action may also be very effective land-formers in periglacial environments. Periglacial landforms, some of them bizarre, include ice wedges, a range of frost mounds (pingos, palsa, peat plateaux, string bogs, frost blisters, icing mounds and icing blisters), thermokarst and oriented lakes, patterned ground, and distinctive slopes. Patterned ground is a geometrical arrangement of circles, polygons, nets, steps, and stripes. Periglacial slopes include cryoplanation terraces. Human activities in periglacial environments and global warming are leading to permafrost degradation and the formation of thermokarst.

## ESSAY QUESTIONS

1. **How distinctive are periglacial landforms?**
2. **How does patterned ground form?**
3. **Examine the problems of living in periglacial environments.**

## FURTHER READING

Ballantyne, C. K. and Harris, C. (1994) *The Periglaciation of Great Britain*. Cambridge: Cambridge University Press.
A very good book that includes an introduction to the idea of periglaciation.

French, H. M. (1996) *The Periglacial Environment*, 2nd edn. Harlow, Essex: Addison Wesley Longman.
The best recent account of periglacial landforms and processes.

French, H. M. (ed.) (2004) *Periglacial Geomorphology* (Geomorphology: Critical Concepts in Geography, Volume V). London: Routledge.
A valuable collection of essay on various aspects of periglaciation.

Washburn, A. L. (1979) *Geocryology: A Survey of Periglacial Processes and Environments*. London: Edward Arnold.
Another good account of periglacial landscapes.

Williams, P. J. and Smith, M. W. (1989) *The Frozen Earth: Fundamentals of Geocryology*. Cambridge: Cambridge University Press.
Well worth a look.