BCS 311: Land and Environments of the Circumpolar World I

Module 4: Northern Landscapes

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Overview

Northern landscapes have been shaped over thousands of years by the action of ice in the form of flowing glaciers and ice present within rocks and soil. Glacial erosion has left a legacy of exquisitely sculpted alpine landscapes characterized by sharp-peaked mountains and broad, deep glacial troughs and fjords. The lake-studded landscapes associated with the hard rocks of continental shields are the products of glacial erosion beneath continental-scale ice sheets. The former extent of these great glaciers is recorded by vast expanses of rolling topography associated with the deposition of glacial till forming moraines. Periglacial landscapes are associated with regions characterized by low annual temperatures, intense frost action and the presence of permafrost. The combination of frost action and mass movement processes creates landforms in various shapes including circles, stripes and polygons referred to collectively as patterned ground.

Learning Objectives

Upon completion of this module, you should be able to:

1. Discuss the impact of glaciation on the physical landscape of the North.
2. Distinguish between landscapes produced by alpine glaciation and landscapes produced by continental glaciation on the basis of characteristic landforms.
3. Describe environmental conditions that contribute to the development of permafrost.
4. Correlate various types of ground ice with the periglacial landforms they produce and/or create.
5. Distinguish between upland, hillslope and lowland periglacial landscapes on the basis of characteristic landforms.

Required Readings

AMAP Assessment Report*: Arctic Pollution Issues. 1998.* Chapter 2: Physical/Geographical Characteristics of the Arctic. pp.13-16.

Walsh, J.E. et al. 2005. Cryosphere and Hydrosphere. In *Arctic Climate Impact Assessment*. Cambridge University Press, pp. 201-208 (Glaciers and Ice Sheets) and pp. 209-215 (Permafrost).

Locate a map of the surficial geology of the region where you are presently living.

Locate a hydrological atlas of the circumpolar region.

Key Terms and Concepts

- Ablation
- Abrasion
- Accumulation
- Active Layer
- Englacial Environment
- Mass Balance
- Permafrost
- Permafrost Table
- Plucking
- Proglacial Environment
- Subglacial Environment
- Supraglacial Environment

Learning Material

Introduction

Glaciers serve as active geologic agents capable of eroding, transporting and depositing immense quantities of rock debris in polar and alpine landscapes. Glacial erosion produces classical alpine topography characterized by **cirques**, **arêtes** and **glacial troughs.** Rock debris entrained, transported and deposited in direct contact with glacier ice is known as **glacial till** and creates landforms known as **moraines.** Till is amongst the most common surficial materials represented in present-day and formerly glaciated landscapes. Meltwater generated by melting snow and glacier ice is discharged from glaciers and enters stream channels beyond the ice margin, the **proglacial environment**. Meltwater streams transport rock debris of all sizes from boulders to clay. Deposition of stratified **glaciofluvial** sand and gravel occurs within stream channels while finer silt and clay are deposited as **glaciolacustrine** sediments on the bottom of **proglacial lakes**. These glacial, glaciofluvial and glaciolacustrine deposits constitute the parent materials for many soils throughout the circumpolar North.

In regions where the depth of frost penetration into the ground during the fall and winter is greater than the depth of ground thawing in the summer, a zone of permanently frozen ground known as **permafrost** persists throughout the year. Permafrost refers to a thermal condition observed in soils, peat and rocks in which ground temperatures remain below 0°C for two or more consecutive years. Earth scientists recognize several types of permafrost, i.e., continuous permafrost, discontinuous permafrost and sporadic permafrost. Ground ice refers to all types of ice formed within freezing and frozen ground. Periglacial landscapes are closely linked to regions characterized by low annual temperatures, low annual precipitation, intense frost action and the presence of permafrost. Frost action and permafrost-related processes are important geologic processes in these landscapes. Landforms characterized by a variety of shapes including circles, polygons and stripes are associated with the presence of ground ice in periglacial landscapes. These features are referred to collectively as **patterned ground.**

4.1 Glaciology

A glacier can be defined as a large naturally occurring deposit of perennial ice formed from the accumulation and recrystallization of snow, which is capable of flowing slowly under the pressure of its own weight and the force of gravity. Glaciers cover approximately 10 percent of the present surface of the Earth (Table 4.1). At the Last Glacial Maximum (ca. 30,000 years ago) glaciers covered approximately 30 percent of the Earth's surface. Glaciers presently occupy highlands where winter snowfall is heavy and summer temperatures are not sufficiently warm to completely melt the snow pack. Glaciers serve as active geomorphic agents capable of eroding, transporting and depositing immense quantities of rock debris in polar and alpine landscapes.

Table 4.1: Ice coverage in Arctic regions with extensive glaciations (Dowdeswell and Hagen, 2004).

Arctic Regions	Glacier Area (10^3 km^2)
Greenland Ice Sheet	1640.0
Canadian Arctic (north of 74°N)	108.0
Alaska	75.0
Canadian Arctic (south of 74°N)	43.4
Svalbard	36.6
Novaya Zemlya	23.6
Severnaya Zemlya	18.3
Franz Josef Land	13.7
Iceland	10.9
Norway and Sweden	3.1

Types of Glaciers

Glaciers are generally classified into three types: alpine (valley) glaciers, piedmont glaciers and continental glaciers. **Alpine glaciers** develop in highland regions and are constrained by topography, being confined to mountain valleys (Figure 4.1a, b). **Piedmont glaciers** form when the lower reaches of alpine glaciers coalesce and spread over lowlands at the foot of a mountain range (Figure 4.1c). These two forms of glaciers cover an area ranging from 5 to 10,000 km^2. **Continental glaciers**, on the other hand, cover a vast area exceeding 25,000 km^2. These large glaciers tend to inundate the underlying topography; however, the tallest mountain peaks may protrude through the glaciers as **nunataks** (Figure 4.1a).

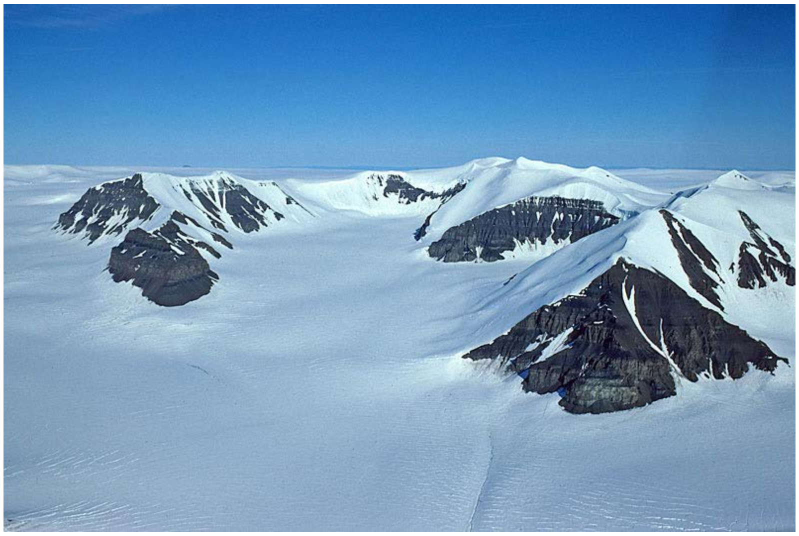

Figure 4.1a. Alpine glaciers, Axel Heiberg Island, Nunavut, Canada. The highest part of Finsterwalder Glacier's accumulation area lies within a cirque (at the centre of the photograph) bordered by nunataks emerging from beneath the ice. The Mueller Ice Cap is in the background (August 8, 1977).
http://www.swisseduc.ch/glaciers/axel_heiberg/finsterwalder_glacier/index-en.html?id=11

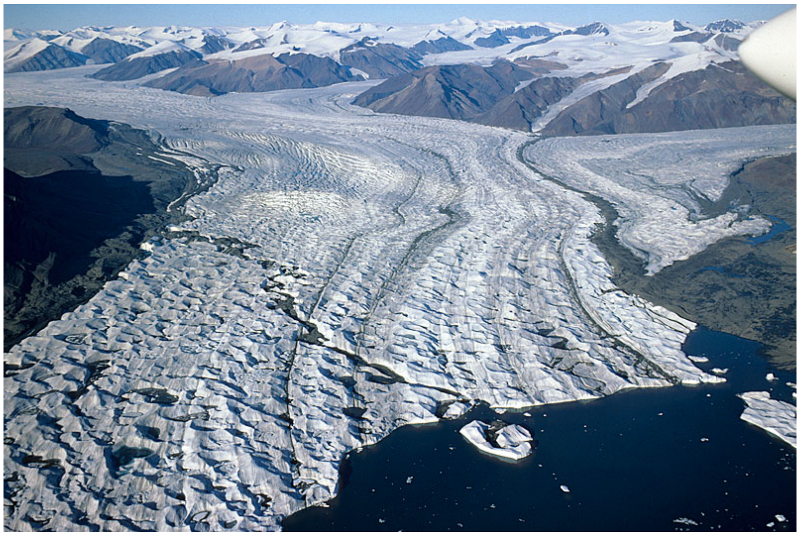

Figure 4.1b. Alpine glaciers, Axel Heiberg Island, Nunavut, Canada. The tidewater terminus of Iceberg Glacier (Aug. 24th, 1977) illustrating ablation via calving of icebergs in the lower right corner of the photograph.
http://www.swisseduc.ch/glaciers/axel_heiberg/iceberg_glacier/index-en.html?id=2

Figure 4.1c. Spectacular piedmont glaciers northwest of Surprise Fjord, Axel Heiberg Island, Nunavut, Canada. (August 24th, 1977). http://www.swisseduc.ch/glaciers/axel_heiberg/axel_south_aerial/index-en.html?id=0.

Origins of Glacier Ice

Glacier ice originates primarily as snow deposited on the glacier surface. Over time snow is gradually transformed into **firn** via the combined action of compaction and melting. Firn is eventually converted into glacier ice. The transformation of fresh snow into glacier ice involves the progressive compression of air bubbles and a reduction in porosity resulting in an increase in the density of the material (Table 4.2).

Table 4.2. Density of snow, firn and glacier ice.

Type of Ice	Density (kg/m^3)
Fresh Snow	50 – 100
Firn	400 – 800
Glacier Ice	830 – 910

Glacier Mass Balance

Glacier mass balance refers to the annual variations in the mass and volume of glaciers that result from the interaction of accumulation and ablation processes. Stated simply ***Mass balance = accumulation – ablation****.*

Accumulation processes include direct precipitation as snow, the refreezing of meltwater and sublimation (i.e., the physical transformation of water vapour into ice). These processes jointly serve to increase the mass and volume of glaciers. **Ablation** processes include the melting of snow and ice via insolation (i.e. solar radiation), friction associated with internal deformation of the glacier, the flow of geothermal heat (i.e., heat supplied from the interior of the Earth), sublimation (i.e., the physical transformation of glacier ice into water vapour), and the calving of icebergs (Figure 4.1b). These processes jointly serve to reduce the mass and volume of glaciers.

The surface of a glacier can be divided into a zone of accumulation (i.e., positive mass balance) at higher elevations and a zone of ablation (i.e., negative mass balance) at lower elevations separated by the equilibrium line (i.e., accumulation equals ablation; Figure 4.2). The movement of a glacier, its ability to serve as a geologic agent, is influenced by the interaction of accumulation and ablation processes. When the volume of snow and ice that accumulates on a glacier exceeds the volume of snow and ice removed by ablation, the glacier is said to exhibit a positive mass balance. The glacier thickens and develops a steep surface slope, the glacier flows more rapidly and the glacier margin advances. Conversely, when the volume of snow and ice that accumulates on a glacier is less than the volume of snow and ice removed by ablation, the glacier is said to exhibit a negative mass balance. The glacier thins and develops a gentle surface gradient, glacier flow decelerates and the glacier margin retreats.

Long-term records of glacier mass balance are distributed sparsely throughout the circumpolar North. The available data indicate that North American (Alaska, Canadian Arctic) and Russian Arctic glaciers have experienced persistent negative mass balances since the 1960s driven largely in response to the trend towards warmer summer temperatures. On the other hand, Scandinavian (Norway, Sweden, Svalbard, Iceland) glaciers have exhibited positive mass balances over the same period driven largely by increased winter precipitation associated with the predominantly positive phase of the North Atlantic Oscillation (see Module 8).

Learning Activity 1

Examine Figure 6.6, p. 203, in the 2005 ACIA Report and determine the present mass balance situation for glaciers in the region where you live. What environmental information would you collect to determine if these glaciers are advancing or retreating?

Glacier Ice Movement

Glaciers serve as a transportation system moving snow, ice and rock debris from the zone of accumulation and disposing of these materials in the zone of ablation. The processes of internal deformation and basal sliding contribute to the motion of glacier ice. Internal deformation involves the slippage of ice crystals past one another within the glacier. Basal sliding involves the glacier ice sliding along the underlying bedrock surface on a thin layer of meltwater. In **warm-based** or **subpolar** glaciers, ice temperatures near the bed are near the melting point of ice. Warm ice deforms easily resulting in a higher rate of internal deformation. Warm ice also permits meltwater generated at the surface or within the glacier to move through the glacier to lubricate the bed thus facilitating basal sliding. **Cold-based** or **polar** glaciers, on the other hand, exhibit basal ice temperatures well below the melting point of ice and these glaciers are frozen to their beds. Motion of these glaciers is via internal deformation only. Average ice velocities range from 10 to 200 m annually, but can exceed 1000 m annually in exceptional circumstances such as glacial surges. For example, Jakobshavn Isbræ, a large outlet glacier that discharges ice from the Greenland Ice Cap near the community of Ilulissat, Greenland (69°10'N, 49°50'W) currently flows at 14 km per year.

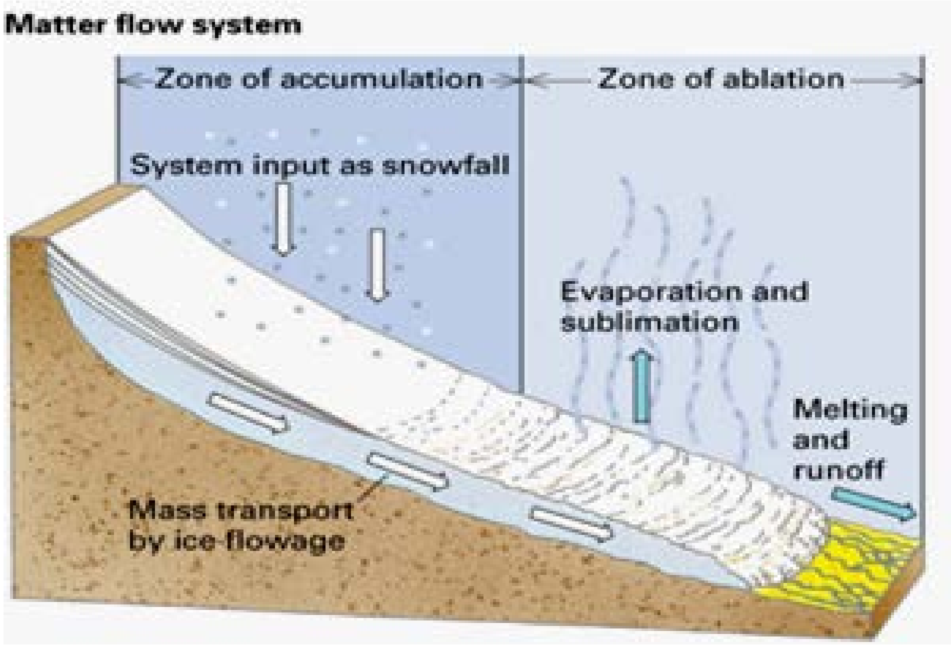

Figure 4.2. Glacier movement serves to transfer matter in the form of snow, ice and rock debris downslope from the zone of accumulation towards the zone of ablation. Source: Strahler and Archibold, 2011, Figure 18.2, p. 434.

4.2 Glacial Processes and Landscapes

Glacier Erosion

Erosion of bedrock by glacier ice involves two processes, **abrasion** and **plucking**. Abrasion is a mechanical weathering process. Glaciers use rock clasts at their base as abrasive cutting tools. The rate of abrasion is influenced by variations in ice pressure and velocity, the concentration of rock clasts near the base of the glacier and the hardness of the rock clasts relative to the bedrock substrate. Thick, fast-flowing ice armed with hard (e.g., igneous and metamorphic rocks) rock clasts promotes rapid and deep abrasion of the bedrock substrate. Plucking is a mechanical weathering process that involves the removal of large blocks of rock from the glacier bed. Plucking occurs where a glacier is forced to flow over bedrock obstacles on the bed of the glacier. In this situation, ice pressure exerted on bedrock obstacles is greater on the upstream side of the obstacle than on the downstream side causing the rock to fracture on the downstream side of the obstacle. Higher ice pressure on the upstream side of the obstacle promotes melting of basal ice and the generation of meltwater. Meltwater lubricates the glacier bed allowing the glacier to slide over the obstacle. On the downstream side of the obstacle the meltwater refreezes, a process known as **regelation**, and loosened blocks of rock are removed by freezing to the base of the sliding glacier.

Meltwater Erosion

Glacier meltwater also contributes to mechanical weathering of bedrock substrates. Beneath warm-based glaciers turbulent, fast-flowing water carrying large sediment loads derived from the melting of debris-rich basal ice can actively abrade bedrock surfaces. High rates of erosion via abrasion are most likely to occur during periods of high meltwater discharge in the summer (Figure 4.3).

Figure 4.3. Summer meltwater discharge in a proglacial stream channel, Alexandra Fiord, Ellesmere Island, Nunavut, Canada. Source: Northern Portal, University of Saskatchewan (Photo Number MG172_2001-072_BX03_Slides_Alexandra_04-01.tif).

Glacier Transport

Rock debris is entrained and transported by moving glacier ice. In the **supraglacial environment** (i.e., on the surface of the glacier) rock debris is delivered via mass wasting (i.e., avalanches, rockfalls, etc.) and aeolian (i.e., wind) processes onto the surface of the glacier. In the accumulation zone of the glacier this supraglacial debris moves towards the glacier bed. This transport of rock debris through the glacier occurs within the **englacial environment**. Englacial transport of rock debris serves to provide a continuous supply of new cutting tools to the base of the glacier thus facilitating abrasion of the bedrock substrate. In the ablation zone, rock debris delivered to the glacier surface is transported at the surface towards the glacier margin.

In the **subglacial environment** (i.e., at the base of the glacier) rock debris is entrained via a drag force and/or regelation. Deformation of moving glacier ice applies a drag force to rock clasts on the bed. If this force is sufficient to overcome friction between the clast and the bed, the particle will be transported by being dragged across the bed of the glacier. The alternate thawing and freezing of basal ice as the glacier moves over obstacles on the bed allows for debris to be entrained via regelation. Beneath the ablation zone of a glacier, basal debris-rich ice moves towards the surface of the glacier. The englacial transport of subglacial debris away from the bed coupled with the melting of glacier ice via solar radiation serves to increase the quantity of supraglacial debris present in the ablation zone.

Glacier Deposition

Rock debris being transported by glaciers will eventually be deposited beneath and adjacent to the glaciers via one of two processes, **ablation** or **lodgement**. Ablation (i.e., melt-out) involves the melting of glacier ice that serves to release supraglacial and subglacial rock debris in transport. The energy required to melt glacier ice is derived from solar radiation, internal friction and geothermal heat. Lodgement occurs when the drag force cannot overcome friction between a rock clast and the underlying bedrock surface beneath thick ice and the clast comes to rest on the glacier bed. Sediment deposited directly from glacier ice via melt out or lodgement is referred to as **glacial till** or **diamicton** (Figure 4.4) and the landforms consisting of these deposits are known as **moraines**.

Figure 4.4.Glacial till consists of a heterogeneous mixture of stones, sand and mud.
Source: http://en.wikipedia.org/wiki/Till.

Erosional Landforms

A variety of landforms develop in response to abrasion and plucking operating beneath glaciers. In mountainous terrain, glacial erosion modifies pre-existing river valleys to produce classical alpine topography characterized by **cirques, arêtes, horns** and **glacial troughs**. Glacial erosion in lowland landscapes creates features such as **roches moutonnées** and **rock basins** in the hard crystalline rocks of continental shields.

Roches moutonnées are asymmetric, streamlined bedrock forms produced by the combined action of abrasion and plucking (Figure 4.5). The gently sloping upstream side of these features is the product of intense abrasion. The steeply sloping downstream side bears evidence of plucking in the form of fractured rock and rugged topography. These features are oriented parallel to the direction of ice flow and provide a sense of ice motion across the landscape.

Figure 4.5a. A roche moutonnée, Melville Peninsula, Nunavut, Canada. The bedrock outcrop in the foreground has been shaped by abrasion. Glacier ice has plucked rock from the end of the outcrop. The three crescentic fracture marks on the upper surface of the rock were produced by the pressure of boulders in the base of the moving ice sheet being forced against the rock. Ice motion was from lower left to upper right in this photograph.

Latitude: 69.290°N Longitude: 85.099°W GSC Photo Number: 2002-499 © Lynda Dredge. Natural Resources Canada (www.nrcan.gc.ca). This photo is a copy of an official work that is published by the Government of Canada and has not been produced in affiliation with or with the endorsement of the Government of Canada.

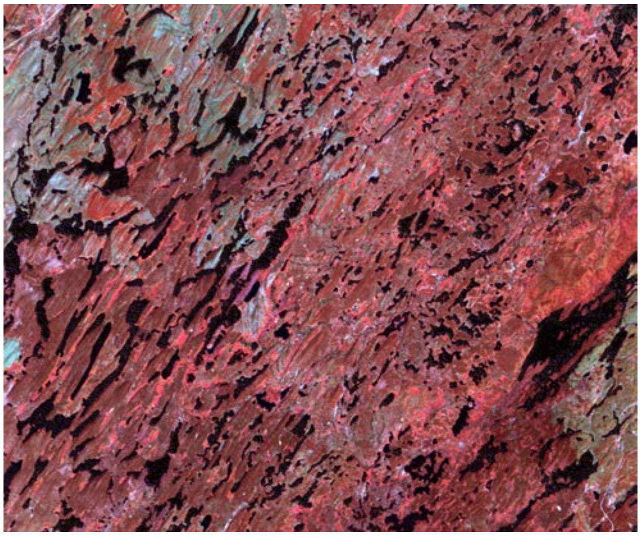

Figure 4.5b. Erosion beneath the former Laurentide Ice Sheet created landscapes characterized by the presence of roches moutonnées (appear as red-coloured hills in this false-coloured satellite image) and rock basins (these water-filled basins appear black in this false-coloured satellite image) over extensive areas of the Canadian Shield. Note that the lake basins are not linked to one another by stream channels: a drainage pattern known as **deranged drainage** that is typical of glaciated landscapes. Source: Atlas of Saskatchewan.

Cirques are amphitheater-shaped depressions excavated in bedrock through the combined action of glacial abrasion and plucking, and the frost shattering of rock (Figure 4.6). Meltwater generated in late spring and summer will flow through glacier ice and into the underlying bedrock. Here the meltwater freezes and expands contributing to the frost shattering of rock. Erosion of cirque floors occurs largely by glacial abrasion. Supraglacial debris and frost shattered rock entrained by the drag force at the base of glaciers provides the cutting tools required to abrade the bedrock surface. The motion of cirque glaciers serves to actively abrade the bedrock substrate and deepen the cirque floor. Cirque growth may progress over time to the point where narrow ridges of rock known as **arêtes** separate adjacent cirques (Figure 4.6). Where cirque glaciers extend into adjacent alpine valleys, glacier erosion will widen and deepen the valleys to create **glacial troughs** (Figure 4.6). Along mountainous coastlines glacial troughs may be eroded several hundreds of metres below sea level. Deglaciation of the coastline allows the sea to flood into and partially drown the glacial troughs to create **fjords** (see Figure 3.2b in Module 3).

Figure 4.6. Alpine glacial topography consisting of amphitheatre-shaped cirques separated by rock ridges (arêtes). Cirque glaciers supply ice to alpine valley glaciers that occupy and flow within broad glacial troughs north of Good Friday Bay, southern Axel Heiberg Island, Nunavut, Canada. The Steacy Ice Cap is in the background (July 1, 2008). http://www.swisseduc.ch/glaciers/axel_heiberg/axel_south_aerial/index-en.html?id=12

Depositional Landforms

Glacial tills are among the most common surficial materials represented in present-day and formerly glaciated landscapes. Moraines are depositional landforms composed of glacial till.

Lateral moraines are composed largely of coarse, angular rock debris delivered to the glacier margin or surface via mass wasting (Figure 4.7a). Till is deposited largely by ablation of the glacier surface to form ridges along each side of a glacier. If adjacent alpine glaciers coalesce, their lateral moraines join to form a **medial moraine**. Rock debris transported supraglacially and englacially and deposited via melt-out in distinct ridges at the margin of glaciers forms **end moraines** (Figure 4.7b). End moraines mark the maximum extent of glaciers in present-day and formerly glaciated landscapes. In contrast to the till that composes lateral moraines, rock clasts present in the till that composes end moraines exhibit a greater degree of roundness (cf. Figure 4.4). The greater degree of rounding is the product of abrasion in a subglacial environment.

Figure 4.7a. Turnweather Glacier, Auyuittuq National Park, Baffin Island, Nunavut, Canada.

Coarse, angular rock debris produced by frost shattering on the valley walls and transported by mass wasting accumulates against the margin of the glacier to form a lateral moraine (right foreground). The ‘stripes’ of rock debris on the glacier surface are medial moraines (left foreground).

Turnweather Glacier is a classic alpine valley glacier, one of many flowing from cirques near Turnweather Peak, east of Akshayuk Pass in Auyuittuq National Park. The mountains here rise to about 2000 metres above sea level close to the coast. The metamorphic bedrock, sculpted by alpine glaciers during the last few million years, is extremely hard making the area a world-class rock-climbing venue.

Latitude: 66.383^{o}N Longitude: 65.517^{o}W GSC Photo Number: 2002-249 © Art Dyke. Natural Resources Canada (www.nrcan.gc.ca). This photo is a copy of an official work that is published by the Government of Canada and has not been produced in affiliation with or with the endorsement of the Government of Canada.

Figure 4.7b. Moraines of an alpine valley glacier, Bylot Island, Nunavut, Canada.

This glacier has constructed massive sharp-crested lateral moraines that are joined by the more rounded end moraine at the glacier terminus. The end moraine is draped over with fine narrow ridges of rock debris. These are the medial moraines, which originated by the coalescence of tributary glaciers upstream.

Latitude: 72.9°N Longitude: 78.35°W GSC Photo Number: 2002-232 © Ron DiLabio. Natural Resources Canada (www.nrcan.gc.ca). This photo is a copy of an official work that is published by the Government of Canada and has not been produced in affiliation with or with the endorsement of the Government of Canada.

Hummocky moraine develops where supraglacial debris is deposited over stagnant ice at the glacier margin. Stagnant ice refers to glacier ice that has become so thin via ablation that it is no longer capable of flowing. Slow and uneven melt out of the buried stagnant ice creates a landscape characterized by rolling topography associated with till ridges interspersed with shallow, water-filled basins known as kettle lakes (Figure 4.8).

Figure 4.8. Hummocky moraine topography associated with ridges of glacial till and glaciofluvial sand and gravel and numerous kettle lakes. The small valley glacier is Midre Lovénbreen located on Brøggerhalvøya in northwestern Spitsbergen.

Source: http://www.swisseduc.ch/glaciers/svalbard/midtre_lovenbreen/index-en.html

Ground moraine is composed of poorly sorted glacial till deposited beneath a glacier by a combination of lodgement and basal melting of the glacier. The till is deposited in layers of variable thickness over broad areas of present-day and formerly glaciated landscapes (Figure 4.9).

Figure 4.9. Ground moraine near Grinnell Lake, northern Melville Peninsula, Nunavut, Canada.

The geologist is working on the stony till surface. Glaciers deposited boulders of local granite (pink and grey), sandstone (brown), and limestone (buff). The rounded edges of some of these boulders attest to the process of glacial abrasion during transport beneath a glacier.

Latitude: 69.739°N. Longitude: 84.406°W. GSC Photo Number: 2002-569 © L. Dredge. Natural Resources Canada (www.nrcan.gc.ca). This photo is a copy of an official work that is published by the Government of Canada and has not been produced in affiliation with or with the endorsement of the Government of Canada.

Learning Activity 2

Examine a map of the surficial geology of the region where you live. What are the most common glacial landforms present? What types of land use, if any, are associated with these landforms?

Glaciofluvial Processes and Sediments

Meltwater is discharged across and beneath glaciers and enters stream channels in the **proglacial environment** beyond the ice margin. During periods of high meltwater production in the late spring and summer subglacial and proglacial stream discharge increases. The capacity of streams to erode and transport sediments increases contributing to channel erosion in both the subglacial and proglacial environments and increases in **stream load**. Stream load refers to the quantity of sediment that a stream is capable of transporting at a given discharge. Rock debris of all sizes from boulders to rock flour is entrained and transported by streams during these periods of high discharge.

During periods of low meltwater production, subglacial and proglacial stream discharge decreases. The capacity of streams to transport sediment decreases contributing to the deposition of glaciofluvial sediments in both subglacial and proglacial environments.

Deposition of sand and gravel within channels at the base of the glacier forms **eskers** (Figure 4.10). Beyond the glacier terminus deposition of sand and gravel within proglacial stream channels creates bars that split the stream into numerous small channels to produce an intricate channel pattern known as a **braided stream** (Figure 4.11). The finer silt and clay transported by meltwater streams are eventually deposited as **glaciolacustrine** sediments on the bottom of proglacial lakes. These glacial, glaciofluvial and glaciolacustrine deposits constitute the parent materials for many soils throughout the circumpolar North (see Module 6).

Figure 4.10. An esker near Cowles Lake, Nunavut, Canada.

This photograph shows a large, sinuous esker ridge composed of sand and gravel that stands 10 - 20 m above the surrounding till plain. It formed at a site where meltwater, flowing at the base of a glacier, probably near the terminus, deposited its load of sediment. Parts of the esker have sharp, single-ridged crests, but those segments in the foreground are multi-crested. The multi-crested segments developed where the position of the glacial meltwater tunnel changed while sediments were being deposited.

Latitude: 65.953°N Longitude: 113.074°W GSC Photo Number: 2001-176 © L. Dredge. Natural Resources Canada (www.nrcan.gc.ca). This photo is a copy of an official work that is published by the Government of Canada and has not been produced in affiliation with or with the endorsement of the Government of Canada.

Figure 4.11. Braided stream, Kluane Lake National Park, Yukon Territory, Canada.

This stream is fed by meltwater from a alpine valley glacier. During spring, the entire riverbed is flooded by melting snow and ice, which is channeled through the valley. When the spring run-off ends, the water level drops, because the river is fed mainly by the slow melting of the glacier upstream. The reduced water levels flow through sediments deposited by the river when the velocity of the current becomes too slow to carry the stream load any further.

Latitude: 60.816°N Longitude: 138.466°W GSC Photo Number: 2002-683 © R. Bélanger. Natural Resources Canada (www.nrcan.gc.ca). This photo is a copy of an official work that is published by the Government of Canada and has not been produced in affiliation with or with the endorsement of the Government of Canada.

4.3 Permafrost and Periglacial Landscapes

A zone of permanently frozen ground known as **permafrost** persists throughout the year in regions where the depth of frost penetration into the ground during the fall and winter is greater than the depth of ground thawing in the summer. Permafrost refers to a thermal condition observed in soils, peat and rocks in which ground temperatures remain below 0°C for two or more consecutive years. The upper surface of the permanently frozen ground is known as the **permafrost table** (Figure 4.12). The ground above the permafrost table is referred to as the **active layer**, which thaws in the summer (Figure 4.12). Seasonal variations in ground temperatures decrease with depth towards the **level of zero annual amplitude** that defines the permafrost table (Figure 4.12).

Ground temperatures do not fluctuate at greater depths, but they gradually increase with depth, i.e., 1°C per 50 metres, in response to the flow of geothermal heat towards the ground surface reaching the freezing point at the base of the permafrost layer. **Taliks** are areas of unfrozen ground that are situated within and/or below the base of the permafrost layer. The presence of taliks allows for the movement of groundwater through permafrost to lakes and stream channels (Figure 4.13).

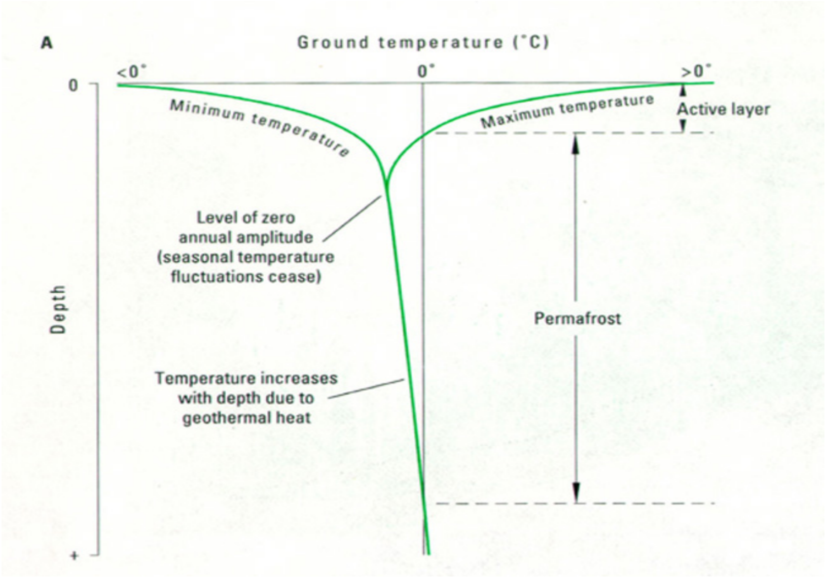

Figure 4.12. Variations in ground temperatures with depth in permafrost.

The Y-shaped figure is a geotherm, illustrating how temperature changes with depth. The geotherm divides at the Level of Zero Annual Amplitude (LZAA). The maximum temperature **geotherm** records warming of the ground surface in summer. The active layer thaws in summer in response to the input and absorption of solar radiation (see ground heat flux, Q_S, in Module 2). The minimum temperature geotherm records cooling of the ground surface in winter (ground heat flux, Q_S). Below the LZAA, ground temperature is unaffected by seasonal temperature changes at the ground surface. At the bottom of the diagram, permanently unfrozen ground, a talik, exists where the geotherm crosses to the right of 0^oC. Source: Briggs *et al*. (1993).

Earth scientists distinguish several types of permafrost:

- Continuous permafrost refers to an environment where more than 80 percent of the ground surface is underlain by permafrost. The southern limit of continuous permafrost corresponds closely to the $–8^oC$ mean annual isotherm derived from air temperatures.
- Discontinuous permafrost refers to an environment where 30 to 80 percent of the ground surface is underlain by permafrost. The southern limit of discontinuous permafrost corresponds closely to the $–1^oC$ mean annual isotherm derived from air temperatures.
- Sporadic permafrost refers to an environment where less than 30 percent of the ground surface is underlain by permafrost.

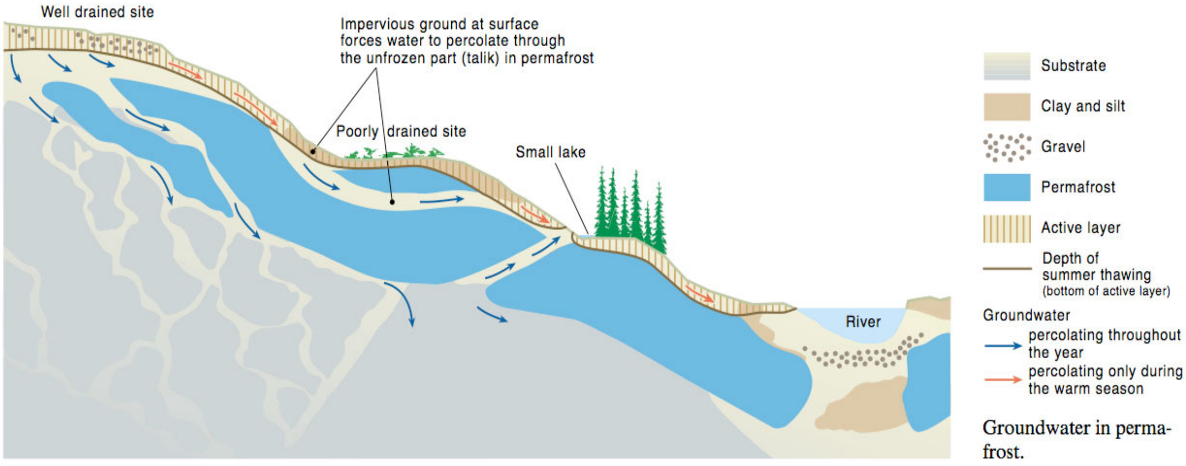

Figure 4.13. Taliks are areas of unfrozen ground that are situated within and/or below the base of the permafrost layer. Taliks facilitate the flow of groundwater through permafrost towards stream channels and lake basins. © Philippe Rekacewicz and Emmanuelle Bournay (GRID-Arendal). Sources: Mackay, D.K. and O.H. Løken, 1974. Arctic hydrology. In: J.D. Ives and R.G. Barry (eds.). Arctic and Alpine Environments, pp. 111-132. Methuen and Co. Ltd., London; Linell, K.A. and J.C.F. Tedrow, 1981. Soil and Permafrost Surveys in the Arctic. Clarendon Press, Oxford, 279 p.

Permafrost occurs extensively within the northern hemisphere. The boundaries of the various permafrost zones in the circumpolar North are illustrated in Figure 4.14. Note the absence of permafrost except in alpine environments throughout the Scandinavian countries.

Learning Activity 3

Review the course materials presented in Module 2.4 Precipitation and the Water Budget. Research data for annual precipitation (P) and surface runoff (R) for a large river watershed in the circumpolar region. Determine the P/R ratio and compare this information with the data presented in Table 2.4. What does your data indicate about the extent of permafrost in the watershed that you examined?

The seasonal cycle of ground freezing and thawing plays an important role in shaping northern landscapes. The rate of spring thawing influences stream flow via the supply of surface runoff and groundwater to stream channels and the rate of fall freeze-up influences the formation of pore ice and frost heaving within soils. Most permafrost is impervious to the percolation of water so there is little or no drainage of water from the active layer. Given this situation the active layer generally consists of materials saturated with water and exhibiting low shear strength.

Figure 4.14. The distribution of terrestrial permafrost in the circumpolar North. The extensive distribution of subsea permafrost beneath the North American and Eurasian continental shelves is not shown on this map. © Philippe Rekacewicz and Emmanuelle Bournay (GRID-Arendal). Source: CAFF, 1996. Proposed Protected Areas in the Circumpolar Arctic 1996. Conservation of Arctic Flora and Fauna, Directorate for Nature Management, Trondheim, Habitat Conservation Report No. 2.

Mass Movement Processes

Mass movement is the downslope movement of rock and soil in response to the force of gravity. Solifluction, the action of slow flowage in water saturated soils, is a ubiquitous process operating on hillslopes in periglacial landscapes. Movement of material occurs via two processes, frost creep and gelifluction (Figure 4.15). Frost creep refers to the downslope movement of particles in response to the expansion and contraction of surficial materials associated with frost heaving of the ground surface. Materials moving in this manner can be displaced downslope several millimetres to several centimetres each year. Gelifluction refers to the flowage of saturated surficial materials within the active layer. The combination of frost creep and gelifluction of surficial materials produces distinct lobate landforms known as solifluction lobes (Figure 4.15).

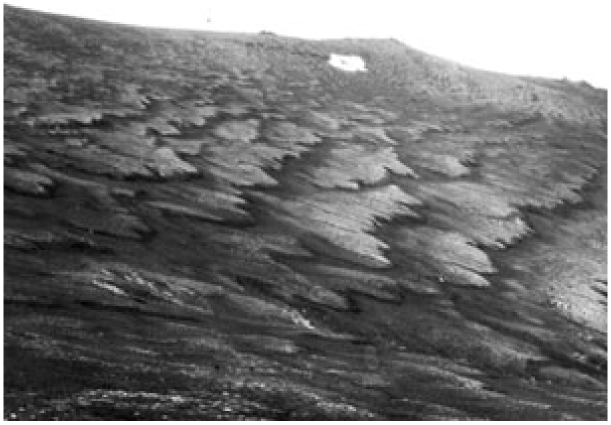

Figure 4.15. Solifluction lobes near Chicken Creek, Alaska. Source: http://permafrosttunnel.crrel.usace.army.mil/permafrost/patterned_ground.html.

Little water can seep into permafrost soil. Thus, water from rain, melting snow, or melting ice in the soil pores is trapped in the active layer of soil. On sloping land, the weight of the water-saturated soil causes the active layer to slowly flow downhill when thawed in summer; this process is known as **gelifluction**. The rate of movement depends on the slope and amount of vegetative cover. Movement occurs slowly at centimeters per year and contributes to the development of landforms known as **solifluction lobes**.

Ground Ice

Ground ice refers to all types of ice formed within freezing and frozen ground. Landforms characterized by a variety of shapes including circles, polygons and stripes are associated with the presence of ground ice in periglacial landscapes. These features are collectively referred to as **patterned ground**.

Stone Circles and Stripes

Common features observed in periglacial landscapes are circular patches of bare, fine-grained soils that are bordered by coarser rock clasts and tundra vegetation known as sorted circles (Figure 4.16). They may occur singly or in groups and commonly vary from 0.5 to 3.0 metres in diameter. These landforms are common on upland surfaces where the soil contains large quantities of coarse sand and gravel in a fine-grained matrix. The origin of these periglacial landforms remains unclear, although numerous theories have been proposed to account for their development.

Freezing of groundwater within pores in soil contributes to the formation of **segregated ice** crystals. The growth of segregated ice within the active layer results in **frost heaving** of the ground surface. Vertical displacements up to 20 cm can be achieved in this manner. Subsequent thawing of segregated ice within the active layer results in subsidence of the ground surface. The mixing of soil that accompanies the seasonal freezing and thawing of the active layer is referred to as **cryoturbation**. This process contributes to the movement and sorting of stones within the active layer. The depth of mixing affects the rooting zone for vegetation and nutrient cycling within soils in periglacial landscapes (see Module 6). Gelifluction can transform stone circles present on upland surfaces into **stripes** on hillslopes as mass movement becomes more important on steeper slopes (Figure 4.17).

Figure 4.16. Sorted stone circles, Canadian Arctic. Source: Northern Portal, University of Saskatchewan

Figure 4.17. Sorted stone stripes, Canadian Arctic. Source: Northern Portal, University of Saskatchewan.

Ice-Wedge Polygons

Ice-wedge polygons are common landforms observed in periglacial landscapes. The conditions favourable for the development of these landforms occur in poorly drained lowlands within the continuous permafrost zone. The sequence of events leading to the development of ice-wedge polygons is initiated by prolonged freezing of ice-rich soil at temperatures below –15°C during winter. In response to this intense freezing the ground contracts and cracks, a process known as **frost cracking**. The cracks outline the borders of polygons visible on the ground surface.

In the following spring and early summer meltwater infills the cracks and freezes creating narrow, wedge-shaped veins of ice that penetrate to depths below the active layer. As the active layer develops over the summer the soil warms and expands. However, soil expansion is constrained by the presence of the ice wedges so that the soil is forced to expand upward forming a slightly raised rim of soil adjacent to the ice-filled frost cracks.

The ice wedges present within the frost cracks exhibit lower strength than surrounding ice-rich soil which form lines of weakness within the ground. In the following winter frost cracking occurs preferentially within the ice wedges and the cycle is repeated year-after-year progressively enlarging the ice wedges so that they become wider and deeper. As the ice wedges enlarge the soil adjacent to the frost cracks continues to be thrust upward to form distinct ridges.

The end result is a polygonal landform characterized by a marginal trough occupied by ice wedges and a raised rim of soil and vegetation surrounding a central depression. This landform is referred to as a **low-centred ice-wedge polygon** (Figure 4.18a). The dimensions of these landforms vary considerably from place to place. The width of the polygons varies from 15 to 40 metres. The width and depth of ice wedges range from 1 to 4 metres and 3 to 10 metres, respectively. The raised rim may stand 0.5 to 1.5 metres above the central depression. Differences in the topography between the marginal rim and central depression cause noticeable differences in drainage and the composition of plant communities that inhabit the surface of these polygons. The central depression is often waterlogged in summer and inhabited by wetland vegetation dominated by mosses and sedges (*Carex* spp.). The rim exhibits better drainage and is inhabited by a variety of plants better suited to drier soils, such as dwarf willow (*Salix* spp.), dwarf birch (*Betula* spp.), crowberry (*Empetrum nigrum*), bearberry (*Arctostaphylos uva-ursi*), bilberry (*Vaccinium uliginosum*), grasses and lichens.

Over time low-centred ice-wedge polygons are transformed into high-centred ice-wedge polygons. Several processes operating simultaneously serve to bring about this transformation. Continued enlargement of ice wedges at the margins of these landforms serves to gradually raise the ground surface in the interior of the polygons. At the same time, the gradual accumulation of plant debris and aeolian sediments serves to raise the ground surface within the central depression above the surrounding terrain. As the ground surface rises drainage improves and the soil becomes progressively drier. Plants inhabiting the rim of the polygon expand and displace the wetland vegetation at the centre of the polygons. Water passing over this landscape is progressively diverted into marginal troughs. The flow of water within the troughs serves to thaw the upper surface of ice wedges and erode the margins of the polygons resulting in the progressive widening and deepening of the troughs. The end result produces a dome-shaped polygon referred to as a **high-centred ice-wedge polygon** (Figure 4.18b).

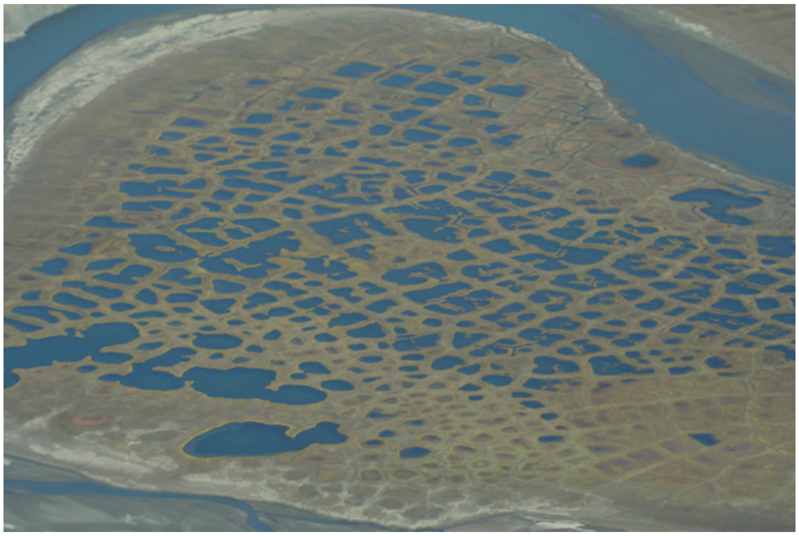

Figure 4.18a. Low-centred ice wedge polygons.
Source:http://permafrost.gi.alaska.edu/photos/image/487#image-load

Figure 4.18b. High-centred ice wedge polygons.
Source: http://sis.agr.gc.ca/cansis/taxa/landscape/ground/nwt.html

Conclusion

The agents of denudation, mass movement, glacier ice, ground ice, running water and wind collectively contributed to the development of modern circumpolar North landscapes over tens of thousands of years. The rugged topography of highland landscapes derived from the juxtaposition of cirques, arêtes, horns, troughs and moraines are the products of alpine glaciation. Continental glaciers operating on a far grander scale have produced extensive areas of scoured bedrock associated with roches moutonnées and rock basins where ice flowed over the hard igneous and metamorphic rocks that compose the continental shields. Deposition of sediment beneath these gargantuan ice sheets mantled the landscape with ground moraine. Wherever the advance of an ice margin was blunted by ablation extensive deposits of glacial till contributed to the development of end moraines and hummocky moraines. Meltwater generated by ablation flows across and beneath glaciers and enters streams in the proglacial environment beyond the ice margin. Deposition of coarse-grained sediments within channels beneath glaciers contributes to the development of eskers, while braided stream channels develop in response to deposition of coarse-grained sediments in proglacial streams. The finest fractions of stream sediment loads are deposited as glaciolacustrine sediments in lake basins situated beyond the margins of glaciers.

Periglacial landscapes are closely linked to regions characterized by low annual temperatures, low annual precipitation, intense frost action and the presence of permafrost. Frost action and permafrost-related processes create a variety of landforms characterized by shapes including circles, polygons and stripes associated with the presence of ground ice in periglacial landscapes. These features are collectively referred to as patterned ground**.**

Discussion Questions

1. Describe the movement of rock debris, sediments and water in glaciated alpine landscapes. Include brief descriptions of characteristic landforms associated with the transfer of sediment and water through these alpine landscapes.
2. Compare and contrast periglacial landform development associated with the formation of segregrated ice and frost heaving versus frost cracking and the formation of ice wedges.

Study Questions and Answers

1. What is glacial till? Compare and contrast the physical properties of subglacial tills (think about ground moraine) and supraglacial tills (think about lateral moraines).

   Glacial till is a term applied to poorly sorted heterogeneous sediments deposited in direct contact with glacier ice. Sediments that compose subglacial tills are generated by plucking and abrasion processes at the base of the glacier. This basal debris is subjected to mechanical weathering (crushing and abrasion) during transport. This results in the progressive rounding of the rock clasts and the generation of fine-grained debris that contributes to the matrix of subglacial tills. Much of the rock debris present in supraglacial tills is derived from the frost shattering of rock on the valley walls above the glacier surface. This coarse, angular rock debris falls and accumulates along the margins of alpine valley glaciers. This debris is transported at the glacier surface and is not subjected to the crushing and abrasion that occurs in subglacial environments. Under these circumstances rock clasts retain their angular shapes and a fine-grained matrix is largely absent in supraglacial tills.

2. Describe the environmental factors that influence seasonal variations in meltwater production from glaciers (see radiation and energy balances in Module 2). How do seasonal variations in meltwater production affect erosion, transport and deposition of sediments in glaciofluvial environments?

   Melt water production from glaciers is influenced by the quantity of insolation received at the glacier surface and the albedo of the glacier surface.

   Winter – Insolation is low (low sun angle) and the glacier surface is covered by fresh snow, a highly reflective surface that limits the quantity of energy absorbed and available to promote snowmelt. Glacier motion is dominated by internal deformation.

   Spring – Insolation increases as the sun angle increases. A greater proportion of the snow, a highly reflective surface that limits the quantity of energy absorbed and available to promote snowmelt. Glacier motion is dominated by internal deformation.

   A portion of the insolation absorbed at the glacier surface serves to raise air temperatures facilitating further meltwater production. During this season meltwater is stored temporarily in the snow pack or infiltrates the glacier surface and begins the process of creating an internal network of drainage channels within the glacier. As the season progresses meltwater begins to flow in subglacial channels at the base of the glacier.

   Summer – Insolation at its maximum (high sun angles). Removal of the snow cover and exposure of debris-rich ice, especially in the ablation zone of the glacier, lowers the surface albedo and facilitates the absorption of a greater proportion of the insolation received at the glacier surface. Meltwater generated at the glacier surface moves rapidly across the glacier surface into and through the internal drainage channels to the base of the glacier where it is eventually discharged at the glacier margin to support the flow of proglacial braided stream channels.

   Fall – Insolation decreases as sun angles decreases. Less energy is available to generate meltwater and subglacial and proglacial stream discharge gradually declines.

   The increase in meltwater production through the spring and summer serves to increase the discharge of subglacial and proglacial stream channels providing the power needed to erode and transport large volumes of sediment. As stream discharges decline through the fall streams lose their capacity to erode and transport sediments. Sediment deposition occurs within subglacial channels creating eskers and within braided stream channels creating bars.

3. Discuss the relation between the surface radiation and energy balances (see Module 2) and the seasonal development of the active layer of permafrost.

   See discussion above regarding seasonal changes in the radiation and energy balances.

   An increasingly positive radiation and energy balance develops at the ground surface as spring progresses into summer. Insolation absorbed at the ground surface is used to melt snow, raise air temperatures and as the snow cover is removed, serves to raise ground temperatures facilitating development of the active layer.

An increasingly negative radiation and energy balance develops at the ground surface as fall progresses into winter. Heat stored in the ground is gradually lost to a cooling atmosphere. This cools the ground and contributes to freezing of the active layer.

4. Describe factors that influence the strength of rock and soil in the active layer of permafrost and influence the process of gelifluction.

   Thawing of the ground associated with active layer development is accompanied by the melting of segregated ice. Melting of ground ice saturates the pores present within rocks and soil with water above the permafrost table creating high pore water pressures that reduce the strength of these materials. The saturated rock or soil is drawn slowly down

Glossary of Terms

Arête – A sharp, narrow rock ridge commonly found above the snow line in mountainous areas that have been sculpted by glaciers.

Braided Stream – A river channel that consists of a network of small channels separated by small and often temporary islands called bars.

Cirque – A steep bowl-shaped hollow occurring at the upper end of a mountain valley, especially one forming the head of a glacier.

Cryoturbation – In rock, sediments or soils affected by the presence permafrost, cryoturbation (or frost churning) refers to the mixing of materials due to freezing and thawing.

Eskers – A long, narrow, sinuous ridge of coarse gravel deposited by a stream flowing in or under a decaying glacial ice sheet.

Fjord – A long narrow inlet of the sea between high steep cliffs of a mountainous coast formed by glacial erosion.

Firn – Granular, partially consolidated snow that has passed through one summer melt season but is not yet glacial ice.

Frost Cracking – Contraction of sediments and ice at extremely low ground temperatures; commonly associated with low air temperatures and a lack of snow and vegetation cover.

Frost Creep – The downslope movement of debris, firstly through the growth of needle-like ice which lifts a thin surface layer of particles at right angles to the ground followed by thawing, which allows the loosened debris to slip slowly downslope.

Frost Heaving – The uplift and cracking of a ground surface through the freezing and expansion of water underneath.

Gelifluction – The slow, downhill movement of saturated rock, sediments or soil in areas typically underlain by permafrost.

Geothermal Energy – Energy derived from the heat in the interior of the Earth.

Glacial Till/Diamicton – Glacial till consists of coarse-grained, extremely heterogeneous sediments deposited directly by glaciers.

Glacial Trough – A deep U-shaped valley with steep valley walls that was formed from glacial erosion.

Glaciofluvial – A term pertaining to streams fed by melting glaciers or to the deposits and landforms produced by such streams.

Glaciolacustrine – A term pertaining to lakes fed by melting glaciers or to the deposits and landforms located within them.

Horn – When there are three or more cirque headwalls and arêtes joined together to form a single pyramidal shaped peak with very steep walls called a horn.

Ice-wedge Polygons – A 3- to 6-sided polygon of ice wedges with straight to gently curving sides formed by ice segregation and the freezing and contraction of sediments.

Kettle Lake – A water-filled depression left in a mass of glacial till formed by the melting of an isolated block of glacial ice.

Level of Zero Annual Amplitude – The distance from the ground surface downward to the level beneath which there is practically no annual fluctuation in ground temperature.

Lodgement – Deposition of sediment by plastering of glacial debris from a sliding glacier bed.

Moraine – A mass of glacial till deposited in the form of mounds or long ridges.

Nunatak – An isolated bedrock hill or peak projecting prominently above the surface of a glacier and completely surrounded by glacial ice.

Roche Moutonnée – An elongate mound of bedrock worn smooth and rounded by glacial abrasion. A roche moutonnée has a long axis parallel to the direction of glacial movement, a gently sloping, striated side facing the direction from which the glacier originated and a steeper side facing the direction of glacial movement.

Rock Basin – A depression formed in bedrock by abrasion performed by the sharp-edged boulders that are transported at the bottom of a glacier.

Stone Circles – Stone circles range in size from a few centimeters to several meters in diameter. Circles can consist of both sorted and unsorted material and generally occur with fine sediments in the center surrounded by a circle of larger stones. Unsorted circles are similar, but rather than being surrounded by a circle of larger stones, they are bounded by a circular margin of vegetation.

Stone Stripes – Stripes are lines of stones, vegetation and/or soil that typically form from transitioning steps on slopes at angles between 2° and 7°. Stripes can consist of either sorted or unsorted material. Sorted stripes are lines of larger stones separated by areas of smaller stones, fine sediment or vegetation. Unsorted stripes typically consist of lines of vegetation or soil that are separated by bare ground.

Talik – A Russian term applied to permanently unfrozen ground in regions of permafrost; usually applies to a layer which lies above the permafrost table but below the active layer, that is when the permafrost table is deeper than the depth reached by winter freezing from the surface.

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