

## Glacial Landforms & their Management

### Snow avalanches

An avalanche is a rapid flow of snow downslope due to gravity.

Release zone – the point where the avalanche starts.

Slide path – the route the avalanche takes.

Run out – where the avalanche comes to a stop.

### Types of snow avalanche

#### **Slab avalanche**

Slab avalanches are formed where there is a strong cohesive layer of snow known as a slab. These account for 90% of all snow avalanche fatalities.

#### **Loose snow avalanche**

Loose snow avalanches are formed in snow with little internal cohesion. This snow normally produces small avalanches which are usually harmless, but large loose snow avalanches move over 200mph on an air cushion, and can be much more dangerous.

### Causes of avalanches

Avalanches occur when the shear stress on the slope exceeds the shear strength of the snow patch.

**Shear stress** – the force downslope due to gravity. It depends on how steep the slope is and mass of the snow.

**Shear strength** – the strength of the snow.

An increase in shear stress can be caused by:

- Slope angle – most avalanches happen on slopes of 30-50°.
- Vibrations and shockwaves – earthquakes, controlled explosions, helicopters, heavy traffic, skiers, a small fall of snow from a tree etc.
- Loading the slope – heavy snowfall, wind-blown snow etc.

A decrease in the shear strength can be caused by:

- An increase in temperature
- An increase in humidity

## Avalanche management

### Prediction

- Precise prediction of avalanches is impossible.
- Computer software called Neighbour to Neighbour compares the conditions of the current day with a similar day in the past, to predict probability of an avalanche.
- Measurements of snow surface temperature, crystal formation, wind speed and direction.

### Prevention strategy

- Artificial release – controlled explosions to create small avalanches before a big one has a chance to happen. It is used in ski resorts, but doesn't protect skiers off piste.
- Snow fences – these are designed to stop avalanches by encouraging drifting which reduces the slope angle. A more gentle slope angle has a lower shear stress.
- Afforestation

### Protection strategy

- Skiers need to carry the correct equipment – shovel, avalanche beacon, collapsible probe.
- Search and rescue operations
- Avalanche training – skiers should always ski with at least one other person, stay near the surface in an avalanche and make an air space in front of their mouth.
- Avalanche proof buildings – buildings which use reinforced concrete, no windows on the side facing the slope etc.
- Digital avalanche beacons – these are quicker and make it easier to find people by giving their direction and distance.
- Snowsheds – these protect roads and railway lines.
- Breaking mounds – these take the energy out of the avalanche.
- Avalung – directs carbon dioxide away from the face and has a porous membrane to draw in oxygen from the surrounding snow, to prevent trapped skiers from suffocating so quickly.

### Avoidance strategy

- Avalanche warnings – providing information on risk for each day.

### Acceptance strategy

- Accepting that avalanches happen and not every road, railway etc can be protected. In Norway, it would cost billions to protect all the roads, so only main roads are protected.

### Avalanche case studies

#### **1999 in the Alps**

71 deaths in total

Worst incidence was in Galtir – 38 deaths in total. The second worst incident was in Chamonix – 12 deaths in total.

#### **1915-1918 in the Alps**

Austrian and Italian armies fought in the mountains  
60,000 soldiers died in avalanches.

## Impact of glacial processes and landforms on human activity

### Problems/constraints on human activity

1. Mass movement hazards in glacial environments
2. Glacial outburst floods (jokulhlaups)
3. Glacial advance (including glacial surges)
4. Glacial ablation causing sea level rise

### Mass movement hazards in glacial environments

Mass movement is the downslope movement of rock, soil or snow, due to gravity e.g. avalanches, landslides, mudflows, slumps, solifluction, rock falls and earthflows.

Mass movement is caused by changes in shear stress and shear strength. Shear stress is the downslope force due to gravity. It depends on slope steepness and the mass of the soil/rock/snow. Shear strength is the resistance of a slope to shear stress. It depends on frictional forces and the cohesion of the material. Once the shear strength is overcome, mass movement will occur.

### Why is mass movement common in upland glaciated areas?

<b>Factors increasing shear stress</b>	<b>Physical reasons</b>	<b>Human reasons</b>
Steep slopes	<ul style="list-style-type: none"> <li>• Cliffs are common due to glacial erosion e.g. steep sided glacial troughs, back wall of a glacial cirque</li> </ul>	<ul style="list-style-type: none"> <li>• Building platforms can be cut into steep slopes to create an artificial flat area</li> </ul>
Loading a slope	<ul style="list-style-type: none"> <li>• Glaciers can add a huge amount of weight to a slope</li> <li>• Heavy precipitation adds weight</li> </ul>	<ul style="list-style-type: none"> <li>• Buildings can add weight to a slope</li> <li>• Dams also add weight – the wall and water are heavy (millions of tonnes)</li> </ul>

<b>Factors reducing shear strength</b>	<b>Physical reasons</b>	<b>Human reasons</b>
Lack of vegetation	<ul style="list-style-type: none"> <li>• Glacial areas are cold – tundra vegetation have poor root networks binding soil together</li> </ul>	<ul style="list-style-type: none"> <li>• Deforestation, e.g. in the Alps for ski routes</li> <li>• Grazing animals can compact the soil</li> </ul>
Shockwaves	<ul style="list-style-type: none"> <li>• Earthquakes</li> </ul>	<ul style="list-style-type: none"> <li>• Controlled explosions</li> <li>• Heavy traffic</li> <li>• Helicopters</li> <li>• Skiers</li> </ul>

Mass movement events can be triggered by a range of natural and human factors e.g. an earthquake, heavy rain, the weight of a skier etc. Trigger mechanisms are unpredictable, making mass movement events unpredictable.

## **Types of mass movement**

There are many types of mass movement, but all are the result of 5 movement mechanisms: slides, flows, heaves, falls and avalanches.

### **Slides**

Mass movements due to the slide mechanism include landslides and slumps. Large blocks of material (rocks or soil) sliding along a well-defined surface (failure plane). The material will not suffer much internal deformation as it moves as a slide.

Landslides (translational slide or rock slide) have a fairly straight failure plane, and are more common in rock than soil. If a hard layer of rock is resting on top of a weaker rock, the risk of a landslide is high.

Slumps (rotational slide) have a curving failure plane, often tilting the top of the slump backwards. They are common in loose, unconsolidated material e.g. clay.

Landslides are moderate to fast, and some water must be present.

### **Flows**

Mass movements due to flow include solifluction, earthflow and mudflow. Flows involve the movement of material (usually soil) as a viscous fluid. The material will experience internal deformation because it is moving as a flow.

Solifluction is a slow soil flow (about 5-100cm per year).

Earthflow (debris flow) is a moderate/fast flow (a few metres per minute).

With more water, solifluction and earthflow grade into mudflows, which are fast (a few metres per second). These have a very high water content. The most likely causes are high intensity rainfall or a volcanic eruption leading to rapid melting of snow or ice.

### **Heaves**

Mass movements due to heave include soil creep and frost creep.

### **Falls**

Mass movement due to the fall mechanism is known as a rock fall. Rock falls can be very rapid, depending on the height fallen. Rock falls are also dry.

Movement occurs mainly by freefall through the air (i.e. no contact with the slope), but also by bouncing and rolling. Rock falls only occur on steep slopes or cliffs, and are not common unless the slope angle is at least 70°. Rocks normally loosen on the cliff face by freeze-thaw weathering. Over time the fallen rocks at the base of the cliff form scree (talus). Scree slopes consist of sharp, jagged and angular rocks sorted according to size with the largest near the bottom.

### **Avalanches**

Mass movements due to the avalanche mechanism include snow and rock/debris avalanches. Avalanches are very fast and water content is low in rock avalanches.

## Case study: rock avalanche at Randa, Switzerland 1991

### **Impacts of the avalanche:**

- The railway and road were buried and blocked
- The River Matter became blocked, causing flooding in parts of Randa
- Local residents and tourists were trapped
- Power lines broke so Zermatt lost power

### **Strategies used to help the situation:**

- They pumped water out of the lake formed by the flooding river to slow the rate at which the lake was growing
- They dug a new river channel through the debris to drain the lake
- They built the new railway line on the other side of the valley which was less likely to experience a rock avalanche

## **Jökullhlaups (glacial outburst floods)**

Jökullhlaups are sudden fluvio-glacial floods. They normally occur when a large volume of water is released due to the failure of a glacial lake. There are three types of glacial lake involved:

1. **Ice-dammed proglacial lake** (proglacial = a lake which is in contact with the ice). As a glacier moves down a valley, tributary rivers inside valleys may become blocked by the side of the glacier. These usually fail at the end of the summer after melting may have weakened the ice damming the lake.
2. **Moraine-dammed proglacial lake**. When the ice retreats away from the terminal moraine, water can fill the gap between the terminal moraine and the glacier snout. Iceberg calving can raise the water level and cause a tsunami wave which breaks the terminal moraine bank. Landslides into the lake also have the same effect.
3. **Subglacial lakes** (lakes underneath the ice). These can be dangerous because they are often hidden by the ice and therefore not known about.

### Jökullhlaup case studies

#### **Lake Dig jökullhlaup, Himalayas, Nepal, 1985**

This was caused by an ice avalanche, creating a tsunami wave which destroyed the moraine bank that was damming it.

Human lives were lost, as well as 14 bridges and a hydroelectric power station.

#### **Vatnajökull ice cap jökullhlaup, Iceland, 1996**

This occurred when the Grimsvotn volcano underneath the ice cap erupted and melted some of the ice, and formed a glacial lake. Eventually, the lake failed and the water came rushing out, with a discharge of 50,000m<sup>3</sup>/s.

The flood crossed over a sandur (outwash plain), and destroyed the main road (Route 1), and two bridges. This cut off the Eastern part of Iceland, and the bridge needed to be rebuilt.

There were no deaths as Route 1 was closed off before the flood happened.

## How glaciers operate as a system

### Inputs and outputs

The material input into the glacier system is mostly snow, and this can be input through direct precipitation onto the glacier, but also through avalanches from the surrounding slopes and by being blown onto the glacier by the wind. Other forms of precipitation such as sleet, hail and rain also add ice to the glacier, causing it to grow. The increase in the mass of ice caused by the addition of snow is referred to as **accumulation**.

Ice mass is lost from a glacier mainly through melting, and this can be supraglacial (melting on the surface of the glacier), and basal melting (melting at the base or bottom of the glacier). Glaciers can also lose ice mass through direct evaporation from the ice surface (known as sublimation), or the calving of ice bergs, where chunks of ice break off from the glacier. The loss of mass from a glacier is referred to as **ablation**.

In addition to inputs and outputs of ice, glaciers also have inputs and outputs of rock debris. Rock debris is input into the glacier by the weathering and erosion of the slopes around the glacier, and also from the erosive action of the glacier itself as it moves along.

The mass balance of a glacier is controlled by changes in the rates of accumulation and ablation.

## Glacial erosion and weathering processes

**Weathering** refers to the physical disintegration and the chemical decomposition of rock in situ.

**Erosion** refers to the removal of soil and rock and their transport by the agents of erosion: wind, glaciers, rivers and the sea.

### Types of glacial erosion processes

#### 1. Abrasion

This is when rock debris embedded in the ice at the base of a glacier is dragged across the bedrock, grinding and polishing the rock surface with a sandpaper-like effect.

Abrasion is responsible for:

- Rock flour
- Smooth surfaces on glacial landforms
- Creating microscale landforms (less than 1m) e.g. striations and chattermarks

#### 2. Plucking

This is a two-stage process, a combination of fracture and entrainment, where rocks are picked up and moved by the ice.

1) **Fracture** – this involves freeze-thaw weathering and pressure release weathering.

**Freeze-thaw weathering** is where water enters cracks in the rock and freezes, expanding by 9% of its volume, shattering the rock and breaking it apart. Repeated freeze-thaw cycles cause rocks to disintegrate into small, angular pieces. Freeze-thaw weathering is most effective where the climate fluctuates a lot, and where the rocks are naturally jointed, e.g. limestone and granite.

**Pressure release weathering** is where the glacier erodes and removes overlying rock material, releasing the pressure and causing the rock below to expand and fracture parallel to the ground surface.

## 2) **Entrainment**

Entrainment is where the ice freezes to the loose rock, and pulls the rock along as the glacier moves.

## 3. **Subglacial meltwater erosion**

This erosion is caused by the rivers which flow inside glaciers. They move at high speeds and carry rock and lumps of ice, eroding the valley sides and bed when they come into contact with them.

### Factors determining the effectiveness of glacial erosion

#### 1. Climatic factors

- Frequent fluctuations in climate allow freeze thaw weathering to attack the rock each time the glacier retreats. When the glacier advances it can erode the loose rock by plucking.
- Climate determines whether the glacier is warm based or cold based. Warm based glaciers move quickly due to water underneath the ice (basal sliding), and therefore the rate of erosion is higher. Cold based glaciers are frozen to their beds, and move very slowly through internal deformation, so little erosion occurs.

#### 2. Geological factors

- Jointed rocks such as granite, sandstone and limestone are more vulnerable to freeze-thaw weathering and plucking than non-jointed rocks
- Fault lines can be exploited by glaciers, such as the Great Glen Fault in Scotland

#### 3. Slope gradient and relief

- Steep slopes e.g. in mountain areas, lead to an increase in ice velocity due to extending flow, therefore the amount of erosion also increases.
- Gentle slopes e.g. in lowland areas lead to a decrease in ice velocity and therefore less erosion takes place.

#### 4. Ice thickness

- Thick glaciers will do more erosion than thinner glaciers.

## Glacial erosional landforms

### Glacial troughs

#### Description

Glacial troughs, also known as U-shaped valleys, are upland features, found in mountainous areas. They are macro-scale landforms, larger than 1km in size. An example of a glacial trough is the Arve Valley in the French Alps.

Glacial troughs have steep valley sides, called **truncated spurs**, and wide, flat bottoms often containing a **misfit river** or stream (a river which is too small to have created the valley). They are relatively straight, and often have **scree slopes** at the bottom of the slopes. **Tributary valleys** often come into glacial troughs, and form **hanging valleys** which lie above the main valley. Many hanging valleys create a waterfall which flows into the main glacial trough.

#### Explanation

Glacial troughs are formed because glaciers do more erosion than rivers as they are in contact with more rock. The main erosion process by which a glacier will remove the interlocking spurs and create the truncated spurs is **plucking**. However, **abrasion** will also be involved, smoothing and polishing the valley sides and bottom. In a warm based glacier, **subglacial meltwater** erosion will also be involved.

### Cirques

#### Description

Cirques are upland features found in mountainous areas, often more than 1km in size (macro-scale landforms).

Cirques are massive, amphitheatre shaped hollows in the mountainside with a steep backwall and smooth cirque lip, usually with striations (scratches). 2 cirques back-to-back create a knife-edge ridge of rock called an **arête**, and 3 or more cirques back-to-back form a jagged mountain known as a **pyramidal peak**, e.g. Aiguille du Midi, French Alps.

#### Explanation

##### **Stage 1**

Cirques start off as **snowbanks**, commonly on the **NE facing side** of a mountain where it is more sheltered from the wind and sun, in hollows. The hollows erode and enlarge through a process called **nivation**, which happens underneath the snow in the hollow. Nivation is a combination of **freeze-thaw weathering** and **sheetwash**. Freeze-thaw weathering is the process where water enters cracks in the rock and expands by 9% of its volume when it freezes. When the water melts, it can flow deeper into the rock via the enlarged crack and the process repeats itself. Sheetwash is the process whereby the pieces of fragmented rock created by freeze-thaw weathering are washed away by water flowing over the ground surface via overland flow or surface run-off.

##### **Stage 2**

The snow in the snowbank gets compressed by later snowfalls. The density of the snow increases and the snow turns to **neve** or **firn** ("last year's snow") after one year. After ten years, the snow turns to glacial ice, and forms a **niche glacier**. Over time, the **shear stress** – the downslope force due to gravity – is overcome by friction, and the glacier begins to rotate inside the hollow, causing further erosion due to **abrasion**. Abrasion is the process by which pieces of rock trapped inside the ice are dragged over the bedrock and erode it through a sandpaper-like effect.

##### **Stage 3**

Eventually, the **cirque glacier** is formed.

### Roche Moutonnees

Roche moutonnees occur in upland areas and are meso-scale landforms. One example of an area where roche moutonnees can be found is on the slopes of Mont Blanc in the French Alps.

### Glacial cols

Glacial cols are upland features and macro-scale landforms. Cols are gaps in the mountains, often used as transport routes. Glacial cols are created when glacial erosion lowers an existing col.

### Crag and tail

A crag and tail is a macro-scale landform found in both upland and lowland areas.

They are formed when a 'crag', a section of hard, resistant bedrock e.g. volcanic rock, protects a section of softer, unconsolidated material, the 'tail'. As the ice sheet advances, it is forced to go around the resistant rock, and is therefore unable to erode the softer material directly behind it.

### Knock and lochan landscapes

Knock and lochan landscapes are found in lowland areas, and are macro-scale landforms. An example of a knock and lochan landscape is the Isle of Harris, Outer Hebrides, Scotland.

Knock and lochan landscapes consist of knocks, small rounded hills with no vegetation, and lochs, small lakes. These features are created by intense erosion of an area by an ice sheet. The lochs are formed by overdeepening and the knocks are more resistant bedrock.

## **Glacial deposition**

Drift is the term for all glacial sediment. Drift can be split into two types, sediment deposited by glacial ice, and sediment deposited by meltwater rivers.

### **Till deposits**

**Till** is sediment deposited by glacial ice. Characteristics of till include:

- It is a mixture of clasts and clay
- The long axis of each clast has a shared orientation (point the same way) in the direction the ice moved
- Clasts have a sub-angular shape
- Poorly sorted
- Contains erratics (stones which are foreign to the drainage basin)

### **Fluvio-glacial deposits**

**Fluvio-glacial deposits** are deposited by meltwater rivers. Characteristics of fluvio-glacial deposits include:

- Preferentially transported – when there is a flood, the river has a lot of energy, and all material will be moved regardless of size. As the flood subsides, the river has less energy, and the material is deposited in order of size, with the largest particles being deposited first.
- No shared orientation of long axis
- Clasts have a rounded shape
- Well sorted – the sediment is divided into layers according to size
- Contains erratics

## **Glacial depositional processes**

Till can exist in 3 different environments (supraglacial – on top of the ice, englacial – within the ice, and subglacial – below the ice), and 2 types of ice (active ice which is moving, and stagnant ice which is not moving).

There are 2 main methods by which glaciers deposit till, and 2 main types of till:

1. **Ablation till** – ablation till is deposited when the ice melts. This till is loose and unconsolidated, and found at the snout of the glacier.
2. **Lodgement till** – lodgement till is sediment which has been forced into cracks underneath the glacier as it moves. This till is compacted and always formed in subglacial environments.

## **Glacial depositional landforms (moraines)**

A **moraine** is a landform made of till.

### Ice-marginal moraines

#### Lateral moraine

Lateral moraine is moraine which is always located on the valley sides. Lateral moraine is made of ablation till and has steep former ice contact sides and a flat topped terrace. It is rarely found after glaciation due to destruction by mass movement (collapsing).

Lateral moraine is formed in an ice-marginal environment at the side of the glacier. It is made of ablation till which is dumped as the sides of the glacier melt. An example of lateral moraine is along the south side of the former Wye Piedmont Glacier between Shenmore and Bredwardine.

#### Medial moraine

Medial moraine is a ridge of ablation till running the length of the glacial trough. It is rarely found intact after the ice has melted due to erosion by meltwater rivers and mass movement.

### Moraines at right-angles to the ice flow

#### Terminal moraine

Terminal moraine is moraine made of ablation till, formed at the end of a glacier at the furthest point the ice reached. Terminal moraine has an asymmetrical cross section, with a steep former ice contact side and a gently sloping front. Terminal moraine banks are usually about 30-40m high but can be more than 100m in height, approximately 1km thick and may be several miles long, with a curving planform reflecting the shape of the glacier snout.

Temporary lakes known as proglacial lakes often form between the terminal moraine bank and the glacier snout, which can sometimes break through and cause a glacial outburst flood, damaging the terminal moraine bank.

#### Formation

Terminal moraine is formed where the glacier has remained stationary long enough for a moraine bank to build up. The ice and any debris within or on it is always moving forward even if the snout is stationary, and as the ice melts at the snout, any debris being carried is 'dumped', forming a moraine bank. Sometimes, when the glacier advances a great distance, perhaps during a surge, the previous terminal moraine bank may be obliterated and another one may form at the new furthest point, if the glacier remains there for long enough.

An example of terminal moraine is the terminal moraine bank stretching 30-40 miles from Clehonger to Kington, marking the furthest point reached by the former Wye Piedmont Glacier.

#### Recessional moraine

Recessional moraine is identical to terminal moraine, however it is not at the furthest point the ice reached.

#### Formation

A period of negative mass balance is required for recessional moraine to form. During the period of negative mass balance, the glacier retreats as there is more melting than accumulation of snow and ice. A period of zero mass balance is then needed to stop the glacier from retreating and keep it stationary, providing time for a bank of recessional moraine to form.

If a glacier retreats then stops many times, a series of recessional moraines can form.

### Push moraine

Push moraine is identical to terminal and recessional moraine; except the till has been slightly compressed and has a steeper angle of dip (i.e. the clasts inside the moraine are tilted).

#### Formation

Push moraine forms where terminal or recessional moraine has been pushed forward a few metres. An example of push moraine is the push moraine at Breinton.

#### Moraines lacking any consistent orientation with the ice flow

### Till plains

Till plains are large areas which have been coated in a thick layer of till. The original relief features have been masked underneath the till.

#### Formation

Till plains are formed due to the deposition of huge amounts of ablation till from an ice sheet or ice cap.

An example of a till plain is the East Anglian Till Plain, formed half a million years ago during the Anglian Glacial Period.

### Erratics

Erratics are rocks that are foreign to the drainage basin. Large erratic boulders are considered to be landforms.

## Fluvio-glacial depositional landforms

### Esker

An esker is a flat topped ridge of outwash. It has a meandering planform and has steep former ice contact sides.

#### Formation

Eskers are formed by subglacial rivers flowing through ice tunnels, depositing outwash. These outwash deposits form the esker. Eskers only form in dead ice (ice which is not moving). An example of an esker is at Shenmore, Herefordshire.

### Kettles

Kettles are holes formed when lumps of ice break off the snout of a retreating glacier. Meltwater rivers running out of the glacier deposit outwash and bury the dead ice. When the ice eventually melts, it leaves behind a hole in the outwash known as a kettle. If the kettle fills with water, it becomes a kettle hole lake.

An example of a kettle lake is the kettle lake at Shobdon, Herefordshire.

### Kame

A kame is a mound of outwash, formed in a number of ways.

- **Crevasse infill** – during the glacial period, supraglacial streams (meltwater streams flowing along the top of the glacier), deposit outwash in crevasses (cracks) in the ice. When the ice melts, the outwash drops onto the ground and forms mounds called kames.
- **Kame deltas** – these form where there is a proglacial lake at the end of a glacier. As the supraglacial streams run off the glacier into the lake, they lose energy and deposit outwash in the lake to form a delta. After the ice melts and the lake drains away, a mound of outwash will be left, forming the kame.

### Kame terrace

Kame terraces are deposits of outwash found at the sides of a valley which have flat tops and steep former ice contact sides. They are formed by meltwater rivers running along the sides of a glacier, depositing outwash. They can be confused with lateral moraine, but the difference is that lateral moraine is made of till, and kame terraces are made of outwash.

### Outwash plain

Outwash plains (sandurs) are plains made of outwash. They are formed by braided rivers (rivers with many channels). The braided rivers deposit vast amounts of sand and gravel, forming outwash plains in front of glaciers.

An example of an outwash plain is the outwash plain on which the City of Hereford is situated.

## Deglaciation

**Deglaciation** is where glacial retreat eventually leads to a complete loss of glaciers in an area.

Landforms and processes which are characteristic of deglaciation:

- Fluvio-glacial erosion and deposition
- Glacial deposition and the creation of moraines, especially recessional
- Periglacial landforms and processes

## **Periglacial environments**

Periglacial environments are areas in which freeze-thaw weathering and permafrost-related processes dominate. **Permafrost** is ground (soil and/or rock) that remains at or below 0°C for at least 2 years.

### **Distribution of Periglacial environments**

About 25% of Earth's land area is currently in a Periglacial environment. Some of it is near modern glaciers, but most is in areas cold enough to have glaciers, however is too dry for glaciers to form. Most areas north of 50° latitude have got permafrost, apart from Europe. This is because the Gulf Stream brings warm water to the UK from the Caribbean.

- Between 74 and 65°N, there is continuous permafrost, which contains no gaps and extends downwards for hundreds of metres.
- Between 65 and 61°N, there is discontinuous permafrost, which contains small patches of unfrozen ground known as talik.
- Between 65 and 50°N, there is sporadic permafrost, which contains large areas of talik.

**Talik** refers to the layer of unfrozen ground beneath the permafrost, or the areas of unfrozen material within it.

The **active layer** is the layer of soil above the permafrost, usually a metre or so thick. It freezes in the winter but thaws in the summer months.

## **Periglacial processes**

### **1. Freeze-thaw weathering**

This is a physical weathering process which leads to the disintegration of rock into angular rock debris. Freeze-thaw weathering does not require permafrost to occur.

Water seeps into rocks through cracks, then freezes and expands by 9% of its volume, slowly pushing the rock apart. Repeated freeze-thaw cycles gradually break rocks up. It is most effective on rocks which are jointed such as limestone, sandstone and granite.

### **2. Solifluction**

This is a mass movement process that leads to the upper part of the active layer slowly flowing down the hillside. Solifluction only occurs in areas with permafrost.

As water infiltrates into the active layer, the soil becomes saturated as the water is unable to move into the permafrost. The soil then slowly flows down the hillside, forming solifluction terraces made of head deposits.

### **3. Frost heave**

Frost heave refers to the heaving of the ground as the water within it freezes. It is most common in water-rich deposits. The heaving can range from a few centimetres to over 30 metres.

- Normal frost heave – this does not require permafrost. It occurs when there is moisture in the soil. When the water freezes, it expands by 9% and causes the ground to heave (rise) by a few centimetres.
- Ice lens frost heave – this requires permafrost. When water infiltrates into the active layer, it is unable to penetrate into the permafrost as it is an impermeable layer. When the water freezes, ice begins to form in the pore spaces within the soil. Over time, the ice crystals may begin to accumulate in localised areas, forming an ice lenses. In autumn, the active layer begins to

freeze from the surface downwards, forming a more rigid layer. As water expands by 9% when it freezes, the ice lens will begin to heave the active layer upwards.

#### **4. Frost creep**

Frost creep is a mass movement process which moves rocks slowly downslope. It does not require permafrost to occur.

Frost creep happens when tiny columns of ice known as needle ice form underneath small stones. The needle ice lifts the stone into the air by a few millimetres, at right angles to the slope. When the needle ice melts, the stone will fall vertically back onto the ground due to gravity. Repeated lifting and dropping of stones is called frost creep and will slowly move stones downslope over time.

#### **5. Frost sorting**

Frost sorting brings stones which are buried in the soil up to the surface.

- In autumn, the active layer begins to freeze from the surface downwards.
- Frost heave then occurs, with the active layer pushed up by a few centimetres.
- In winter, needle ice forms underneath the stone.
- In spring, sediment is washed under the stone between the needle ice.
- When the needle ice eventually melts, the stone can't sink back to its original position due to the new sediment underneath it.

#### **6. Frost wedging**

Frost wedging causes the ground surface to crack in a polygon pattern. The polygons are typically 10 metres or more in diameter and the cracks themselves can be several metres deep and penetrate into the permafrost. Permafrost is required for frost wedging to occur.

When ice is cooled, it shrinks in volume. If there is water in the soil, at 0°C it will freeze and expand by 9% of its volume. If the temperature gets even colder and falls to -30°C, the ice will contract by 0.5% of its volume. As the ice in the soil contracts, it will cause the ground to crack, forming a polygon shape on the surface. In the summer, water from the active layer drips into the cracks, which then freezes to form an ice wedge.

## **Periglacial landforms**

### **1. Scree slopes (talus)**

Scree slopes are accumulations of loose, angular, rock debris at the base of a cliff. Scree is sorted with large rocks at the base of the cliff and smaller rocks at the top. Scree slopes do not require permafrost to form.

Freeze-thaw weathering breaks up the rock on the cliff face. The rock then falls down the cliff via mass movement and forms a pile called a scree slope.

An example of a scree slope is the scree slopes near Wastwater Lake, Lake District, UK.

### **2. Pro-talus ramparts**

A pro-talus rampart is a bank of scree in front of a cliff. They are different to scree slopes in that they form some distance away from the base of the cliff, instead of right next to it. Permafrost is not required for these to form.

Pro-talus ramparts form when there is a snowbank at the base of the cliff. Freeze-thaw weathering breaks up rock at the top of the cliff face, which then falls down the cliff due to mass movement. The rock debris then slides down the snowbank and lands away from the cliff, forming the pro-talus rampart.

### **3. Solifluction terraces**

A solifluction terrace is a terrace of head deposits at the base of a slope, formed by the process of solifluction.

An example of a solifluction terrace is Edale Valley, Derbyshire, UK.

### **4. Asymmetrical valleys**

An asymmetrical valley is a valley one side which is steeper than the other. Asymmetrical valleys require permafrost to form.

In an asymmetrical valley, the south-facing side is more gentle than the north-facing side. Because the south-facing side receives more solar radiation, which leads to more solifluction taking place, and the formation of a thicker active layer. The north-facing side receives less solar radiation, and is most commonly affected by freeze-thaw weathering and mass movement, producing a steeper gradient.

Examples of asymmetrical valleys are those found within the Chiltern Hills, South East England.

### **5. Tors**

A tor is a jumbled mass of exposed bedrock, normally on a hilltop. Permafrost is required for tors to form.

Tors start off as pieces of resistant bedrock buried in the soil. Then solifluction slowly removes the soil to expose the bedrock. After the bedrock has been exposed, freeze-thaw weathering is able to fracture and erode the bedrock. Wind erosion then erodes the rock further, giving it a smooth texture and eroding it into unusual shapes.

## 6. Pingos

A pingo is a very small rounded hill, about 30m high.

Pingos are created by ice lens frost heave.

An example is the pingos in the Mackenzie Delta, northern Canada.

## 7. Pattern ground

Pattern ground consists of stone circles a few metres in diameter, or of stone stripes. Permafrost is required.

There are 3 processes involved in the formation of pattern ground:

- Frost sorting – brings the stones to the surface
- Frost heave – raises the soil to form bumps
- Frost creep – moves the stones to the base of each bump to create a ring

## 8. Blockfields

Blockfields are fields in which the surface of the ground is at least 50% covered by large boulders.

Two processes are involved in their formation:

- Frost sorting – brings the boulders buried in the soil up to the surface
- Solifluction – removes the soil to leave the boulders exposed

## **Opportunities and limitations for human activity presented by the northward shift of the permafrost limit**

### **Opportunities for human activity**

#### **Oil and gas resources**

There are major hydrocarbon deposits in Alaska, Canada, Norway and Russia, with an estimated 90 billion barrels of oil north of the Arctic Circle (this makes up approximately 13% of the world's oil). Currently, much of these reserves are inaccessible as the hostile environment of the Arctic, with very low temperatures and strong winds, could damage oil and gas rigs both on land and at sea. As the permafrost limit retreats northwards and the sea ice begins to melt, these hydrocarbon deposits are likely to become recoverable.

#### **Mining and metal resources**

Opportunities for mining and mineral extraction may arise as the permafrost limit shifts northwards. Many Arctic countries have large mineral reserves, including copper, iron, coal and diamond deposits in northern Sweden and Russia, which are currently unable to be exploited. As the permafrost thaws, new areas of bedrock will become exposed, presenting new opportunities for the mining and mineral extraction industries in Arctic areas.

#### **Fishing**

The Arctic seas are a major source of food, including both marine and fresh water fish species. Retreating sea ice will result in the growth of populations of certain fish species, and new fishing areas becoming accessible. As temperatures rise and conditions become more favourable, the populations of certain fish species such as herring and cod are able to grow. Additionally, the reduction in sea ice also means that new fishing grounds are able to be accessed, allowing the fishing industry to expand.

#### **Forestry**

Forests are a major source of income in Arctic countries and they generate huge amounts of money in these areas through the timber industry and its products. Currently, Arctic forests account for 38% of all global forests, and this number is likely to grow as global temperatures rise the permafrost limit moves northwards, allowing Arctic forests to expand.

#### **Tourism**

The Arctic is becoming a popular tourist destination, with increasing numbers of tourists visiting to experience its wilderness, wildlife and sporting opportunities. As the permafrost limit shifts northwards, polar and glacial environments become more accessible, allowing the Arctic ecotourism industry to expand, creating jobs and benefitting local economies.

#### **Settlements**

The northward shift of the permafrost limit also means that more land will become available to build on. It is difficult to build on permafrost due to subsidence and other structural damage.

#### **New shipping routes**

A further opportunity for human activity presented by the northward shift of the permafrost limit is that new shipping routes may be able to be identified, and existing shipping routes will become useable as the Arctic sea ice melts. As the sea ice melts in the summer months, new shipping routes can open up, such as the Northeast Passage which follows the northern coasts of Russia and Norway, linking the Atlantic and Pacific Oceans, encouraging trade and allowing the faster transport of goods and resources such as oil and gas.

## Limitations for human activity

### Ground subsidence and structural damage caused by thawing permafrost

Thawing of the permafrost creates **thermokarst** landscapes, with lots of small surface depressions formed by subsidence as the ice in the pores of the soil melts. Building on thermokarst landscapes is difficult due to the damage caused to structures and requires specialist engineering and construction.

Houses and other small buildings are often elevated about 1m above the ground, to increase air flow under the building and stop heat from the building being transferred to the permafrost and causing further subsidence. Larger buildings along with roads, railways and airstrips are built on **aggregate pads**, layers of coarse sand and gravel 1-2m thick to insulate the permafrost and stop heat transfer.

Provision of electricity, water, energy supplies and waste disposal is another challenge faced in permafrost areas. Telephone cables, electricity cables and water pipes cannot be buried underground because they would be broken or damaged by the freezing and thawing in the active layer. Telephone and transmission poles also require constant maintenance due to the damaging effects of frost heave.

In relatively large settlements of a few thousand people or more, **utilidors** are used to carry the water supply, heating pipes and sewers between buildings. Utilidors are insulated box conduits made of concrete, wood or metal that are elevated above the ground. In smaller settlements where the use of utilidors would be uneconomical, water supply and waste disposal are provided by truck.

## **Opportunities and problems presented by the human use of glacial landscapes**

### **Agriculture**

#### Opportunities

- Glacial till plains are very fertile because they usually have a clay matrix, therefore producing soils with a clay texture. Clay soils retain water and nutrients well, so they are very fertile if on a well-drained gently undulating plain. An example of a till plain is the East Anglian Till Plain.

#### Problems

- Outwash sands and gravels deposited by glacial meltwater rivers have a coarse texture which facilitates rapid percolation of water through the soil, producing an arid soil of little agricultural value.
- Glacial eroded lowland areas are sometimes almost completely devoid of soil cover. The knock and lochan landscape of South Harris in the Outer Hebrides is one of the most inhospitable farming areas in the UK, characterised by numerous bare rock outcrops, peat deposits and small lakes. Most of the land is only able to be used as rough pasture.
- "Dead ice topography" has a complex mixture of hummocky till deposits and kettle hole lakes and produces a chaotic drainage pattern highly undesirable to farmers.

### **Communications**

#### Opportunities

- Abandoned spillways from proglacial lakes and glacial cols provide natural gaps or passes through upland areas. These gaps can be used to allow roads and railways to pass through upland areas, e.g. the Col des Montets enables the main road and railway to go from Chamonix in France to Switzerland.
- Fjords (also known as sea lochs in Scotland) have deep water and are sheltered from the elements, produce natural harbours such as the Royal Navy's nuclear submarine base at Gare Loch on the Clyde.

#### Problems

- Steep sided glacial valleys are vulnerable to mass movement, e.g. the 1991 rock avalanche at Randa in Switzerland blocked the River Matter, as well as the railway line and road to Zermatt.
- Snow avalanches can present problems for roads and railways in the Alps and expensive avalanche shelters often have to be built.

### **Settlements**

#### Opportunities

- Till plains and outwash plains both have advantages to settlements, e.g. till plains can provide fertile soils for farmers, and outwash plains can provide solid foundations for building on. Saxon settlers in the Wye Valley selected a site for the future city of Hereford just outside the extensive till plain on the firmer sand and gravel deposits of the former Wye Glacier outwash plain. This gave them solid foundations to build on, and left them within close reach of the fertile Herefordshire till plain.

## Problems

- Glacial outburst floods can sometimes threaten settlements and cause loss of life. For example, in 1892, 200 people were drowned as a result of a glacial outburst flood from the Tête Rousse Glacier on the slopes of Mont Blanc flooded parts of the small Alpine town of St Gervais.
- Periods of positive mass balance and glacial advance can threaten entire settlements. Sometimes the advancing glacier can destroy settlements directly by demolishing the buildings, such as during the Little Ice Age from 1660-1830 when some of the hamlets in the Arve Valley near Chamonix were destroyed by advancing glaciers. Other times, advancing glaciers can destroy settlements indirectly, such as in 1986 when the Hubbard Glacier in Alaska advanced at a rate of 10m per day, blocking off the Russell Fjord and turning it into a lake. The meltwater from the glacier continued to flow into the lake, causing the water level to rise by a further 25m. If the ice damming the lake had not failed, the lake may have overflowed and flooded the town of Yakutat.

## Industry

### Opportunities

- Sand and gravel deposits are often extracted from former outwash plains for concrete and road bases, e.g. the former sand and gravel pits at Belmont.
- Modern hi-tech industry is comparatively footloose and often attracted to locations with attractive environments. In Western Europe, "skibelt" locations such as Annecy in the French Alps have proved to be major growth centres.

## Energy supplies

### Opportunities

- Waterfalls which flow out of hanging valleys may be harnessed to provide hydroelectric power. Ribbon lakes and tarns provide natural reservoirs to maintain water supplies throughout the year, e.g. the Emosson Dam pump storage scheme in Switzerland.
- Glacial lakes can also provide cooling water for nuclear power stations, e.g. on Lake Geneva.

## Tourism and leisure

### Opportunities

- The jagged mountains, sheer cliffs, deep valleys and numerous lakes of glacial landscapes are very attractive. They attract sightseers, climbers, walkers, skiers and water sport enthusiasts. Glacial landscapes therefore encourage tourism and this in turn can create lots of jobs for ski resorts, hotels etc.
- The Alpine skiing industry attracts 100 million visitors per year to the Alps and generates ¼ million jobs.

## Problems

- There is a high risk of avalanches in glacial areas.
- Glacial environments are fragile environments (steep, unstable slopes, thin soils, harsh climates etc), and are therefore unable to cope with mass tourism.
- Negative mass balance conditions and glacial retreat can threaten the viability of lower ski resorts such as Le Bettex near St Gervais les Bains in the High Savoy Department of the French Alps.