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PAUL WARBURTON

Glaciers as Systems

Geography by its nature is a very broad subject. Like many disciplines there are core elements to Geography; if you were asked to identify these, you would probably mention an emphasis on space and location, and following from that the study of patterns and distributions. In this context, map work has always been central to Geography. But there are also overlaps with other areas of study, including Biology, Chemistry, Physics, Politics, Sociology and History. A systems approach has been widely used in Geography for many years, partly because it has an important integrating role – it brings together many separate strands. Geography could be described as the study of a world-wide ecosystem with people forming the dominant part. Other disciplines also use a systems approach, particularly the sciences. By adapting a systems approach, Geography uses the same language as other disciplines.

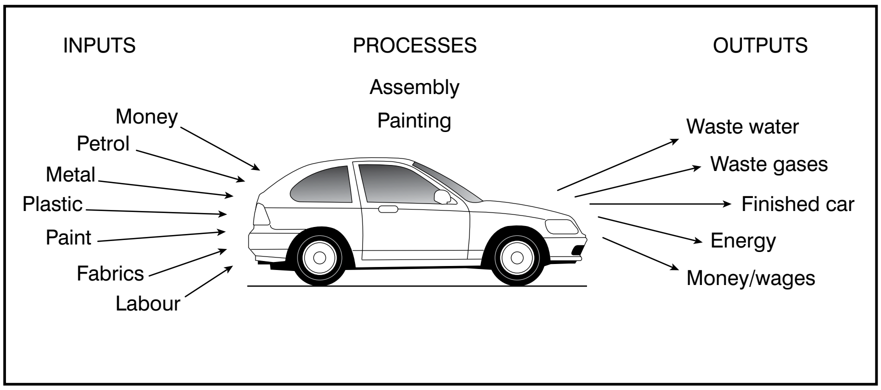
What are systems?

This is a very technical subject but there are some basic ideas and terms that are useful at A level and are relatively easy to understand. They may seem a bit dry, but persevere!

Almost anything can be seen as a system: a car, a house, an animal, a tropical rainforest, a city – or a glacier. All systems have **inputs** and **outputs**. A system also has processes that transform the inputs and lead to outputs. Figure 1 shows how this concept can be applied to the manufacture of a car.

A car is an example of an open system; this is one that has inputs and outputs. An isolated system is one that has no inputs or outputs of either energy or matter. We can ignore this type of system in Geography, as all natural systems are open systems. One example though might be a laboratory experiment carried out in a sealed container to cut off all external influences. A closed system is one that has inputs and outputs of energy but not of matter. The earth as a planet might be a good example, with energy flowing from the sun but matter remaining within the boundaries of the planet and its atmosphere (meteorites and spaceships etc. are the exceptions!).

Figure 1: Making a car as a simple system



We will now see how these ideas can be applied to a glacier.

Glaciers as a system

Glaciers are composed of snow that has been compressed over many years into a mass of ice. Glaciers form when snow remains in one location for long enough without melting or evaporating to turn into ice. Due to their huge mass, glaciers can move along pre-existing valleys like very slow rivers. Some glaciers are about the size of a football pitch while others grow to be over a hundred kilometres long.

At present, glaciers occupy about 10% of the world's land areas, with most located in polar regions like Greenland and Antarctica. They can be thought of as remnants from the last Ice Age which ended about 10,000 years ago, when ice covered nearly 32% of the land and 30% of the oceans.

Inputs

The most obvious input into the glacial system is snow. The fresh snow that gradually starts to become more compact is called **névé**. As the snow become more compact after a year or more, it is called **firn**. This compaction continues for hundreds or even thousands of years, with more layers being added at the surface, increasing the weight. The ice eventually becomes so compact that most of the air is squeezed out, making glacial ice appear blue. Other forms of precipitation can also fall on a glacier, adding to the mass when it freezes. This overall gain in mass is called **accumulation.**

A glacier also has rock fragments on its surface and embedded within and under the ice. This is also part of the mass of a glacier, and is important as it is the tool that carries out erosion and enables glaciers to create huge landforms like glaciated valleys, hanging valleys and truncated spurs. Rock can fall onto the surface of a glacier as a result of avalanches or from weathering processes like frost shattering acting on the valley sides. Rock at the sides of a glacier, or where two glaciers join, can fall down crevasses or move down the sides of the glacier as it advances. The underneath of a glacier, where rock fragments ranging from tiny particles of sand to huge boulders have become embedded in the ice, is like a sheet of sandpaper. This material grinds and gouges the surface over which the glacier passes.

Solar energy is also an input into the system. Ice and snow have very high albedos (a measure of the reflectivity of a surface), but the sun's energy still leads to melting and evaporation and the loss of mass.

Outputs

A glacier will also lose mass through melting and evaporation. Sublimation occurs when ice is converted to water vapour without melting. This can take place when it is cold and the atmospheric conditions are dry. If you have seen the fog from dry ice (dry carbon dioxide) then you have witnessed sublimation. Most of this loss is very seasonal, occurring during the summer. The collective term for this output is **ablation**. Rock fragments and finer particles are left in the landscape as a glacier melts and retreats. Material can also be transported away in meltwater streams. These are often a brown or grey colour, reflecting their high load. Less obvious are the milky blue streams flowing from glaciers; they have this coloration due to the high content of very finely ground rock material called **rock flour**. As energy is an input, it will also be an output. Energy is lost through reflection from snow and ice and also radiation.

Glacier movement

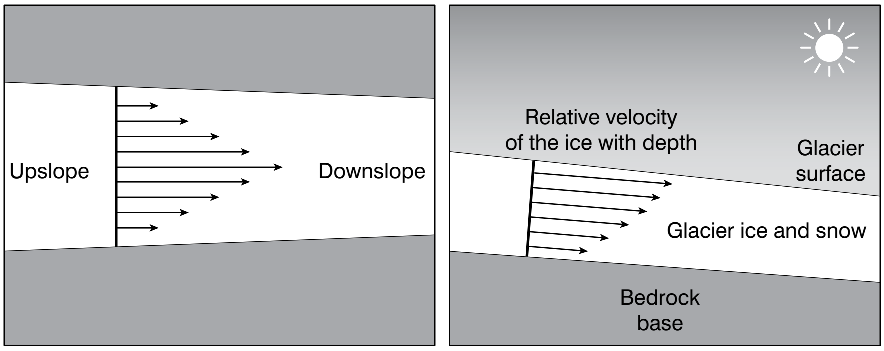
Glaciers move at very different speeds; some have speeds so slow that trees establish themselves among the deposits. In other cases they can move as fast as several metres per day, as is the case of Byrd Glacier, an overflowing glacier in Antarctica which moves 750–800m per year (some 2m per day), according to studies using satellites. Smaller glaciers tend to move faster than larger glaciers and speed of movement is obviously also affected by gradient.

Many glaciers have periods of very rapid advancement, called surges. These glaciers exhibit normal movement until suddenly they accelerate, then return to their previous state. During these surges, the glacier may reach velocities up to 1000 times greater than normal. Alternatively, glaciers may surge, racing forward several metres per day for weeks or even months. In 1986, the Hubbard Glacier in Alaska began to surge at the rate of 10 metres per day across the mouth of Russell Fiord. In only two months, the glacier had dammed water in the fjord and created a lake. This illustrates how quickly a surging glacier can change its surroundings.

Most glaciers move because they are on a slope and are pulled by gravity. The speed at which a glacier moves is largely determined by friction. Rather like a river, movement is greater at the surface and towards the middle, where there is less friction with the valley slides and floor. This was confirmed by experiments in the 19th century, in which stakes were planted in a line across an alpine glacier; as time passed, those in the centre moved faster than those at the sides, and the stakes also started to lean forwards (Figure 2).

We will see again later that most accumulation occurs at the upper end of a glacier, and most ablation at the lower end. This additional weight at the upper end gradually pushes the glacier downhill – it can even push a

Figure 2: Variations in velocity in a glacier



Source: www.eoearth.org

Figure 3: The contribution of basal slippage and internal flow to total glacier movement (measurements taken from boreholes and tunnels)

Glacier	Country	Basal slippage (%)	Internal flow (%)	Ice thickness (m)
Aletsch	Switzerland	50	50	137
Tuyuk Su	Kazakhstan	65	35	52
Salmon	Canada	45	55	495
Athabasca	Canada	75	25	322
Athabasca	Canada	10	90	209
Blue	USA	9	91	26
Skautbre	Norway	9	91	50
Meserve	Antarctica	0	100	80

Source: W.S.B. Paterson (1969) *The Physics of Glaciers*, Butterworth/Heinemann (Elsevier)

glacier uphill for short distances. This movement and bending of the ice over obstacles or uneven relief can lead to fractures in the ice, called crevasses.

But how exactly does a glacier move? Gravity obviously pulls a glacier downhill, and ice often slips over the surface – this is called basal slip. It is helped by meltwater, which acts as a lubricant. A glacier is solid and fractures as it moves; large masses or blocks can slide against each other. This is the larger picture, there are though many other processes operating with the ice. These processes vary, depending on the location of a glacier (Figure 3).

Cold base glaciers
These glaciers tend to form in high latitudes such as Antarctica. Temperatures at the base are below the pressure melting point, so meltwater is not present beneath the glacier. These glaciers move by internal processes rather than by basal slippage. Such glaciers are frozen to the bedrock and they consequently move only very slowly and there is little erosion.

Warm base glaciers
Warm base glaciers tend to form in lower latitudes and areas of high altitude and steep relief like the Swiss and French Alps. They tend to have a layer of meltwater lubricating the ice/surface contact that facilitates slippage in addition to internal flow causing basal movement. These are faster-moving glaciers (although many at the moment are in retreat).

It follows that there are broadly two groups of processes:

Internal processes (important in cold base glaciers)

- **Plastic flow**. Laboratory experiments have shown that when ice is under pressure it can deform and mould itself like plastic.
- **Intergranular movement**. Ice crystals can slip against each other and movement can occur within crystals along lines of weakness called cleavage planes (rather like cards in a pack sliding over each other).

Basal slippage and related processes (important in warm base glaciers)

- **Basal slippage** occurs when there is a layer of meltwater that acts as a lubricant helping the ice to slide over bedrock.
- **Regelation**. As ice moves it can be forced against an obstacle. Pressure on the upstream side leads to melting, this liberated water can

Figure 4: Crevasses and extending and compressing flow

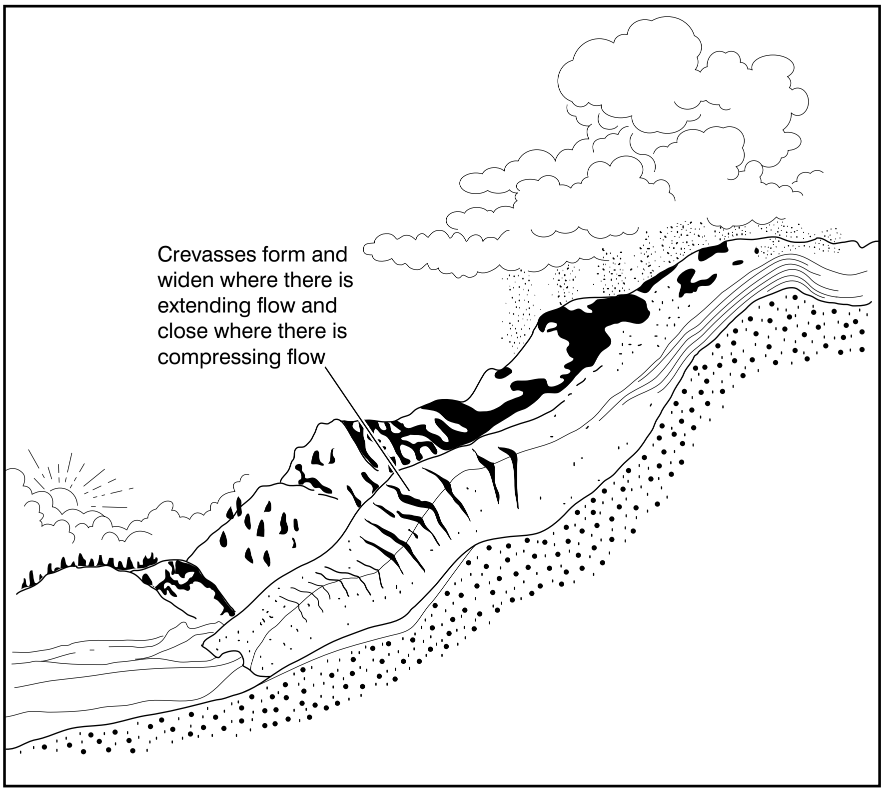
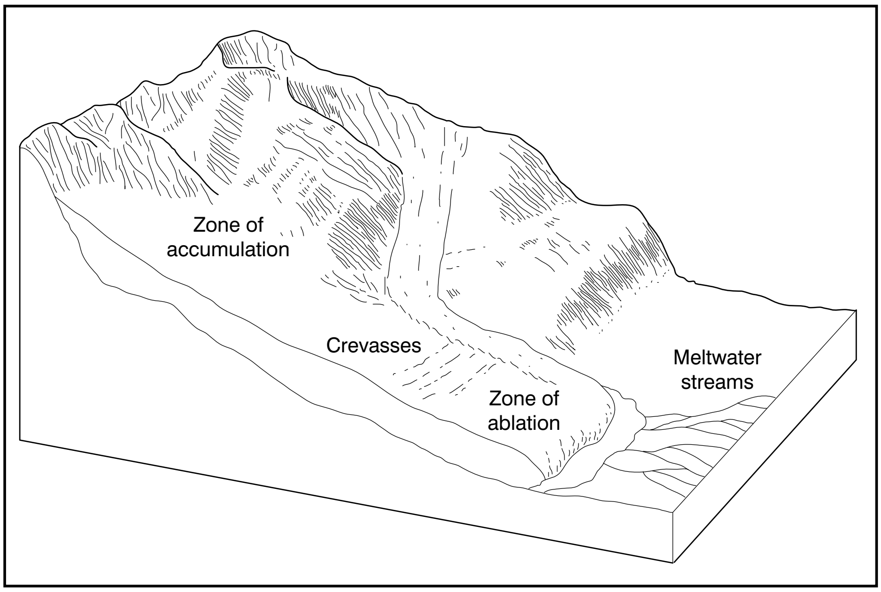


Figure 5: Glacial budget



Source: redrawn from an original by Lydia Warburton

then move to the downstream side where refreezing occurs. In this way movement can occur within a glacier, with the meltwater aiding basal slip.

- **Extending and compressing flow.** The rates of flow of a glacier can be controlled by the gradient of the underlying bedrock. Where there is an increase in the gradient, the ice accelerates and becomes thinner (**extending flow**) – crevasses develop as the ice acts in a brittle way due to the quicker movement (Figure 4). Where the gradient becomes more gentle, the ice decelerates and the ice becomes thicker **(compressing flow)**.
- **Laminar flow.** This is the movement of individual layers within the glacier, for example layers of annual accumulation.

It is worthwhile to briefly consider the movement of ice sheets. Ice sheets are the most extensive areas of ice on earth and includes the continent of Antarctica. Whole mountain ranges are completely buried by the ice sheet at the South Pole, which is greater than 3,000 metres thick. Glaciers can flow within and from ice sheets. Ice sheets move downslope in a number of directions from central areas of high altitude and, unlike a glacier, they are not restricted to a channel or valley. An ice sheet must expand because of the constant accumulation of ice and snow. Ice sheets move more slowly than alpine glaciers, because there is less slope and more mass involved. Ice sheets move mostly by plastic flow.

Glacial budget

In a glacier there is a balance between accumulation (the gain of snow and ice) and ablation (the loss of snow and ice by melting and evaporation). Glaciers also appear to **advance** and **retreat**; this is not technically the same as plastic flow or basal slip. These are apparent motions that are more easily seen over long periods of time. The apparent advance and retreat is the result of the actual motions, coupled with the gain and loss of ice in a glacier. This balance is called **glacial budget** (Figure 5).

In a typical glacier in the Alps it is the annual snowfall that adds to the mass. Most of the accumulation occurs at the upper end of a glacier. At higher altitudes where it is much colder, this exceeds losses due to ablation. There is therefore **net accumulation** and this part of a glacier can be called the **zone of accumulation**. At the lower end of a glacier the reverse is the case. Ablation at warmer, lower altitudes exceeds accumulation so there is **net ablation** and this part of a glacier is called the **zone of ablation**.

If the amount of accumulation in a given year (or longer period) is greater than the amount of ablation, the upper end of the glacier gains mass and causes the entire mass to move downhill faster than before. If this pushes the end faster than ice is removed by ablation, the glacier will **advance**, and its end will move further down valley.

If, on the other hand, the amount of ice added at the upper end is lower, the glacier's mass will decline and it will move downhill more slowly. This may allow the lower end to melt faster than it can be replaced, so the glacier will **retreat**. Although it might appear that the ice is moving back uphill this is obviously not the case. The retreat is entirely because the ablation rate is higher than the rate of advance.

Figure 6: Retreat of Muir and Riggs Glaciers in Glacier Bay National Park, Alaska

Source: www.ns.umich.edu (Robert A. Rohde/Global Warming Art/National Snow and Ice Data Center/USGS)

Vertical variations in movement

We have already seen how movement can be dependent on variations in pressure and temperature within a mass of ice. Above a depth of about 50 metres, the weight of the overlying ice is insufficient to cause plastic flow. This more rigid upper zone is sometimes called the zone of fracture. It is carried along piggy-back style on the lower layer. Sometimes the zone of fracture moves faster than the underlying layer moving by plastic flow. If this happens, especially down a steep slope, the surface breaks into a series of deeper fissures called crevasses. Crevasses also result where a valley curves because the ice flows faster on the outside of a bend than the inside. A steep descent may also result in an ice fall; this results in a piled up mass of splintered ice blocks from a series of rapidly formed crevasses.

Conclusions

Global warming has been adding a new dimension to the behaviour of glaciers and ice sheets. Climate change is resulting in disturbance to the budget of many glaciers around the world. As ablation exceeds accumulation, glaciers are retreating every year at a relatively rapid pace. Figure 6 shows two retreating glaciers in Alaska. The Muir Glacier, parts of which were greater than 65 metres thick in 1941, has retreated out of the image in 2004 (towards the upper left). The distance to the visible Riggs glacier in 2004 is about 3 km. During this time, the Muir Glacier retreated more than 20 km.

Glaciers seem to be solid, stationary masses of ice, and in that sense perhaps rather unexciting. Unlike a river, glaciers move very slowly and their immediate effects are less dramatic. They are nevertheless dynamic systems, slowly moving and changing their position every year. There are video clips on YouTube which have speeded up this movement using time lapse photography – the dynamic nature of a glacier then becomes more apparent. As glaciers move, they shape landscape. A visit to major mountain ranges like the Alps, the Andes or the Himalayas will show spectacular landforms that are the result of the work of glaciers.

Useful sources of information

Some useful animations (if any of these do not work, try typing 'glacier movement animations' into a search engine like Google):

http://highered.mcgraw-hill.com/sites/0072402466/student_view0/chapter12/animations_and_movies.html#

http://www.uky.edu/AS/Geology/howell/goodies/elearning/module13swf.swf

There are also many excellent video clips on YouTube – you may need to experiment with what you type into the search box. Here are a few you may find helpful.

Underneath a glacier time lapse:
http://www.youtube.com/watch?v=njTjfJcAsBg&feature=related

Mt Blanc glacier time lapse:
http://www.youtube.com/watch?v=89sOW-FzolI

350 days in the life of a retreating glacier:
http://www.youtube.com/watch?v=6dFbuaz130c&feature=related

Focus Questions

1. Draw a diagram like Figure 1 showing a glacier as a system. You will need to identify the inputs and outputs and summarise some of the key processes.

2. Make up a spider (star) diagram summarising the factors that control the rate of movement of a glacier.

3. Study Figure 6.
(a) Describe the changes in the glaciers between 1941 and 2004.
(b) Explain the variations in the balance between the percentage of movement accounted for by basal slippage and internal flow.