

Glaciated Landscapes

**Royal
Geographical
Society**

with IBG

Advancing geography
and geographical learning

New A Level Subject Content Overview

Authors: Dr Richard Waller and Dr Peter Knight

Dr Peter Knight is Reader at the School of Physical and Geographical Sciences, Keele University and has written textbooks for both undergraduate and A-level students.

Dr Richard Waller is Senior Lecturer at the School of Physical and Geographical Sciences, Keele University and Consultant to the Geographical Association and regularly delivers talks and workshops

1. Introduction: Geography and Glaciated Landscapes

Landscape systems lie at the heart of physical geography, linking landforms to the processes that create them, and linking those processes to the global environmental system that controls them. Glaciated landscapes provide a good example of how landscape systems work, not only because they demonstrate clearly the links between landforms, processes and environmental controls, but also because glaciated landscapes are widely distributed across the British Isles (and beyond), and provide widespread opportunities for local fieldwork.

At the core of this area of study is the notion that the geography of phenomena is controlled by the geography of the processes that create them. For example, the distribution of glacial landforms is controlled by the spatial pattern of glacier processes such as erosion and deposition. That notion is clearly demonstrated in the connections between the global environment, the characteristics of glaciers, the ways in which glaciers impact the Earth's surface, and the different glacial landscapes that are created where different glacial processes are in play. To understand landscapes of erosion and deposition we need to understand the processes of erosion and deposition, and the environmental controls that drive those processes.

The geographical aspect of glaciated landscapes is apparent at all scales. At the smallest scale (with features ranging from a few metres to several hundred metres in size), individual landforms such as drumlins, moraines or roches moutonnées occur in specific locations where specific glacial processes have occurred. At the largest scale, the occurrence and distribution of glacial landscapes is dependent on the geographical and historical pattern of glaciation, which in turn depends on long-term global environmental change. At an intermediate scale, the patterns of

landforms within a landscape, and the differences between landscapes in different locations, show us in detail the geographical connections between the physical environment, earth-surface processes, and the landscapes that those processes create.

Glaciated landscapes are best understood as part of a system, at the heart of which is the transfer of sediment through the glacier (figure 1). Debris is produced by erosion in some locations, entrained and transported by ice and water, and deposited in other locations. The energy driving this system is the energy that drives the motion of the ice and water through the glacier, and is ultimately connected to the global hydrological cycle and to the physical impact of gravity on surface materials. The system can be observed at a range of timescales: processes can be measured in action at scales from seconds to days at existing glaciers. The effects of processes can be observed in the landscape for many thousands of years where glaciers have existed in the past. The landforms of glacial environments can be regarded as the outputs of this system. Therefore, landforms are best considered not individually in isolation but together as landform assemblages or landscapes; it is the combinations and associations of landforms that tell us most clearly the story of the system that created them and put them together.



Figure 1: Active sediment transport within the debris-rich basal ice layer of an outlet glacier on Bylot Island, Canadian Arctic (N 72° 57' 50", W 78° 25' 13"). Note the large erratic boulder entrained within the ice. Figure for scale.

.....

In the context of environmental change the distribution of presently-glaciated landscapes is changing, and so is the geography of glacier-landscape hazards and resources. The study of these landscapes ties us both to the physical environmental system and to peoples' place within it. In currently glaciated areas, glaciers have a major impact on people's lives. For example, landslides, ice-avalanches and floods associated with glacier are a major hazard in mountainous areas such as the European Alps and the South American Andes mountains. Although only a small proportion of the world's population lives close to present-day glaciers, many people live close to glacier-fed rivers, or live in houses built on glacial sediments, and all of us live with an atmosphere, climate, and oceans strongly influenced by the glacial nature of our planet. Glaciers therefore have effects that are wide ranging in both space and time. Glaciated landscapes have many characteristics that affect human activity long after the glaciers that created them are gone. For example, glacial deposits such as till have particular engineering properties that are relevant to building and need to be taken into account for example, when locating landfill sites. Glacial deposits can also be industrial resources. For example, in northern England, unusually pure silica sand deposited by meltwater streams during the ice age is now being extracted for use both in foundries and in the glass-making industry. Not only do glaciers affect human activity: humans affect glaciers too. Some of this effect is unintentional, such as the melting of mountain glaciers in response to human-induced climate change. Other impacts are deliberate. For example, people have attempted engineering solutions to glacial hazards, and recently attempts have been made to counteract the effects of global warming by reserving or rebuilding glaciers.

2. Key Geographical Concepts & Concerns

Glaciated landscapes at A-level are studied as part of the "Landscape Systems" theme. The term **landscape** reveals an explicit focus on geomorphology, which is the study of landforms, landscapes and the processes that create them. In glaciated landscapes, these include landforms such as moraines, roche moutonnées, drumlins, cirques and eskers. These landforms, individually or as sets of connected features, can be attributed to the operation of geomorphic processes such as erosion, transport and deposition. The term **systems** draw attention to the way that landforms, processes and materials in any environment are interconnected. The "systems approach" to geography was adopted enthusiastically by geographers following the quantitative revolution of the 1950s (which moved the subject on from a descriptive approach to establishing empirical laws, or patterns), and emphasises the fluxes of energy and material associated with earth-surface processes. A systems approach subdivides a complex system into a series of interrelated component parts that are linked via transfers of mass and/or energy. A change in any part of the system, for example in the operation of a particular process, can lead to changes in the whole system. Sometimes these are accelerated or enhanced as the system reacts (positive feedback),

.....

and sometimes they are slowed down or counteracted by the system (negative feedback). Glaciers provide an ideal illustration of the systems approach: they are part of a broader environmental system and are associated with clear inputs (e.g. the accumulation of snowfall, or the entrainment of debris) and outputs (e.g. production of meltwater or the deposition of sediment). The difference between these inputs and outputs determines how the glacier behaves. For example, the balance between addition and removal of ice (mass balance) determines whether a glacier advances or retreats. The balance between erosion, entrainment, transport and deposition of debris determines how glaciers transform the landscape. Changes in the broader environmental system, such as climate change, can induce a change in the state of a glacier by influencing the balances between inputs, throughputs and outputs.

To fully appreciate the workings of the glacial landscape system, or landsystem, and to understand the origins and characteristics of glaciated landscapes, it is necessary to combine knowledge of glacier systems and landscape systems. The glacier system involves the transfer of material (ice, water and debris) across the earth surface, and these transfers drive processes such as erosion, transportation and deposition that are central to the landscape system. It is artificial and unhelpful to divorce the landscape from the processes that create it, or those processes from the glacial environment in which they occur.

Specific geomorphic processes typically create diagnostic landforms that tell us about the process. Physical geographers use a range of techniques in the field and laboratory to identify these links between process and form. These can include the use of high resolution aerial and satellite imagery to map the size, shape and distribution of landforms. Where they have been created by deposition, sedimentological techniques such as particle-size analysis can be used to constrain the processes and environment of deposition. Research in modern-day glacial environments seeks to identify the processes responsible for particular landforms, so that when the same landforms are found in places where glaciers are long gone, we can work out what processes must have been operating when the landform was created. Glacial striations provide a classic example. Despite their small size, the clear link between striations and the process of basal sliding means that they can be used to infer the former presence of a glacier, the direction of ice flow, the mechanism of flow and the thermal regime of the glacier (figure 2).



Figure 2: *Striated bedrock surface in Llyn Llydaw, Snowdonia (N 53° 4' 23", W 4° 2' 32"). Note the cross-cutting nature of the striations which indicates a change in ice-flow direction. Lens cap for scale.*

Recent research in glacial geomorphology has increasingly focused on **glacial landsystems**. This is an explicitly geomorphological application of the systems approach. A landsystem is an area with a common set of features that are distinct from those of the surrounding area, not only in terms of their topographic characteristics, but also in terms of their constituent materials, soils and overlying vegetation types. This inclusion of earth-surface materials is central to the description and interpretation of depositional features such as moraines, where the internal structure and composition can reveal much about their mode of origin.

A-level curricula in the past have focused on specific landforms in isolation, but the landsystems approach emphasises the importance of examining landforms in their broader geographical context. This broader approach is commonly seen in text books in the form of the “glaciated valley landsystem” associated with a distinctive combination of features including U-shaped valleys, arêtes, hanging valleys, ribbon lakes etc. (figure 3). In fact there is a diverse range of glacial landsystems that vary according to the type of glacier involved, the topographic setting and the

climatic regime. One of the distinct advantages of the landsystems approach is the ability to reconstruct the operation of processes and the characteristics of the parent ice mass far more accurately and in far more detail. In this respect distinctive spatial arrangements of geographies of landforms are invariably far more informative than analysis of any individual landform – the whole is greater than the sum of its parts. One example of this relates glaciers surges, which are rapid advances that are not related to climate. With glacier fluctuations commonly being used to reconstruct past climate change, the ability to distinguish between climate-related and non-climate related advances is of crucial importance. Whilst attempts to identify an individual landform indicative of surges have been largely unsuccessful, ongoing research suggests that they are typically associated with distinctive landform assemblages comprising large push moraines, subglacial lineations and crevasse fill ridges. It is the combination of these landforms that tells the story of how the landscape was created; no one individual landform could tell that story.



Figure 3: *Steindalsbreen, northern Norway (N 69° 23' 29", E 19° 56' 54"). Topographically-constrained valley glacier occupying a classic U-shaped valley. Note the prominent end moraines relating to ice advance during the Little Ice Age in the late 19th Century and the erratic boulder in the foreground.*

.....

An additional level of landscape complexity is revealed by the dynamic nature of glacial environments and the rapid changes that can occur over short periods. Glacial landscapes frequently contain evidence of the changing extent of glaciers in the form of distinct landforms such as recessional moraines, trimlines and meltwater channels; as well as the distribution of glacial deposits and erratics (figure 3). This sort of landscape evidence was used by the Natural Scientist Louis Agassiz in the mid-19th Century to identify the former occurrence of “Ice Ages” and major changes in the past. Efforts to clarify the links between landscape, process and external controls such as climate remain a key endeavour glaciological research. In some situations, different generations of glacial landforms that overlap or overprint each other can demonstrate past environmental change. For example, at some locations different orientations of striations or drumlins can be identified that indicate changing patterns of ice flow over time (figure 2).

3. Subject content

This section examines the key knowledge and understanding and associated skills documented within the “glaciated landscapes” component of the new A-level specification within the broader core theme of “landscape systems” and considers how these might be addressed within taught sessions and related resources.

A. Knowledge and understanding of glaciated landscapes

An obvious precursor to any consideration of glaciated landscapes is the need to address fundamental basics such as: the nature and key characteristics of glaciers; the different types of glaciers including valley glaciers (topographically constrained) and ice sheets (topographically unconstrained), and; the location and extent of glaciers both in the modern world and during the “Ice Ages” of the Quaternary Period (last 2.6 million years) when ice sheets were much more extensive. This information will serve to provide a broader conceptual and geographical context.

A key component of the specification relating more specifically to the landscape element is the need to be aware of the key glacial landforms commonly found within glaciated and formerly-glaciated landscapes. There is a specific requirement to include reference to landscapes beyond the U.K. An obvious way to do this would be to use a range of overseas examples (e.g. Iceland or the European Alps) as examples of currently glaciated landscapes that are actively being created before considering specific U.K. localities as examples formerly-glaciated landscapes. This will enable students to visualise the nature and landscape impacts of modern-day glaciers and thereby establish links between process and form. This can then be used to aid the recognition and interpretation of relict glacial landforms and to use these to reconstruct the extent and character of

the glaciers that are no longer present. The use of Google Earth imagery is ideally suited to both activities (see section C).

There is also a requirement to consider the landscapes characteristic of both valley glaciers that are topographically constrained within valleys (figure 3) and those of ice sheets where the influence of the ice is less topographically constrained (figure 4).

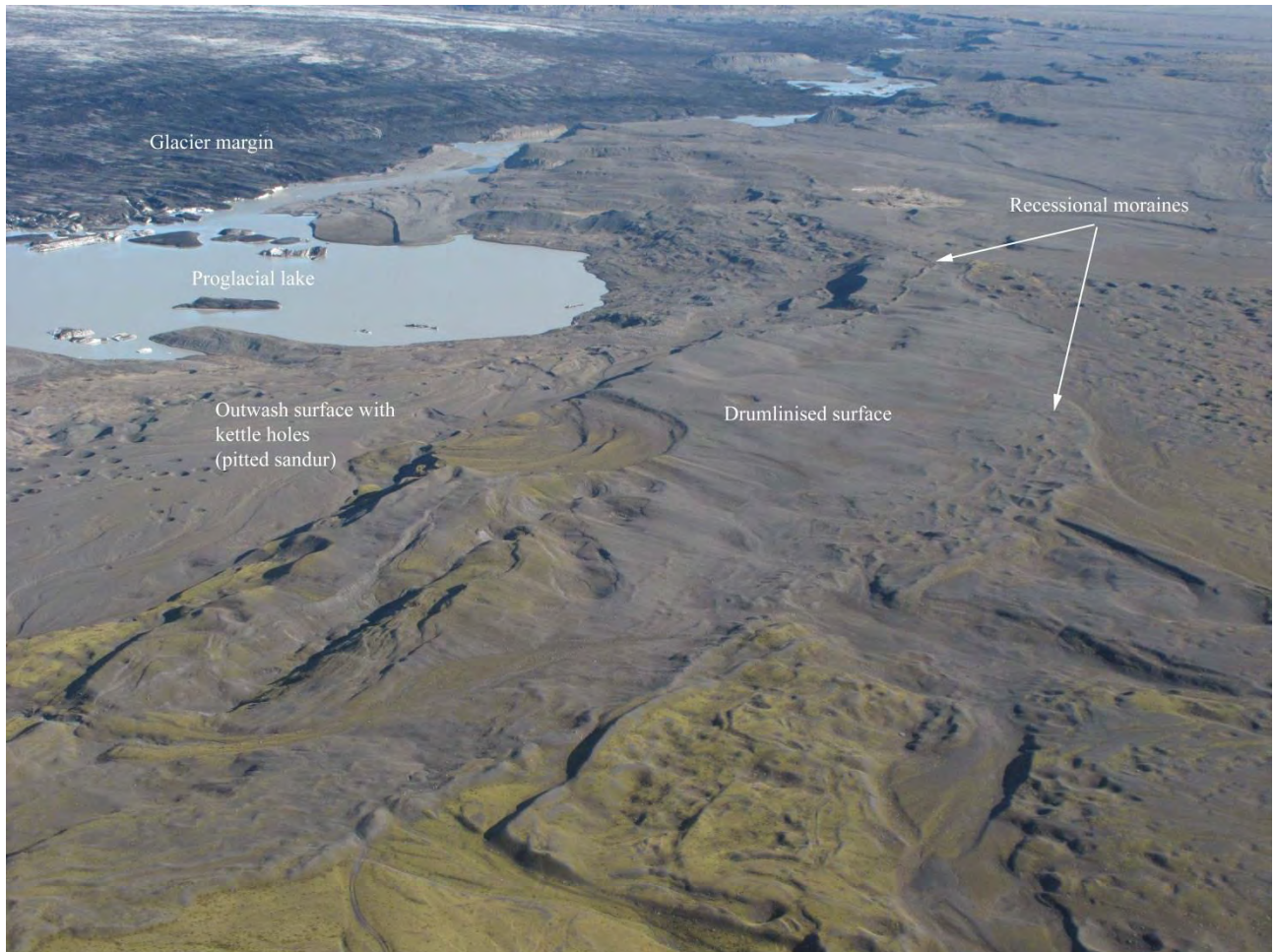


Figure 4: Margin of Skeiðarárjökull (N 68° 53 54, W 17° 10 45), an Icelandic outlet glacier that discharges the Vatnajökull ice cap. This illustrates the diverse assemblages of landforms that can occur at topographically-unconstrained ice margins (see annotations). The “pitted sandur” is of particular note being characteristic of high-magnitude flood events (jökulhlaups).

In considering the glacial processes responsible for the development of specific landforms, there is a need to distinguish between the erosional and depositional impacts of glacier ice. There is also a need to consider the role played by meltwater and “glaciofluvial” processes as well as the glacial processes associated with the direct action of the ice, even though this distinction is not explicitly mentioned within the specification. Table 1 provides an indication of the ways in which these

distinctions can be used to categorise the key features and to help establish the processes responsible for their formation.

Process	Process environment	Key features
Erosion	Glacial	Striations, chattermarks, whalebacks, roche moutonnées, cirques, U-shaped valleys.
	Glaciofluvial	Meltwater channels.
	Glaciolacustrine	Relict shorelines
	Glaciomarine	Submarine iceberg scours, relict shorelines.
Deposition	Glacial	Moraines, drumlins. Deposits: Glacial tills.
	Glaciofluvial	Eskers, kames, kame terraces, outwash plains (sandur). Deposits: Outwash sediments (sand and gravel).
	Glaciolacustrine	Infilled lake basins, relict shorelines (strandlines). Deposits: varved sediments.
	Glaciomarine	Grounding line moraines. Deposits: Ice-rafted debris.

Table 1: Simple genetic classification scheme for glacial features. Please note this is not meant to be exhaustive. See text for further discussion.

There are some important issues to note when considering any such classification scheme:

1. Key features relating to deposition are not exclusively geomorphological in nature and include the deposition of distinctive sedimentary facies or deposits.
2. The creation of some classic landforms such as drumlins remains the subject of ongoing debate and drumlins for example are likely to be polygenetic in origin. In other words, they can be created by a range of different processes potentially involving both erosion and deposition.
3. Glacial environments are more diverse than commonly reported in A level textbooks and can include glaciolacustrine environments (glacial lakes) and glaciomarine environments whereby “tidewater” glaciers terminate in coastal environments classically producing icebergs.

Once these key building blocks have been identified, there is an implicit requirement to consider of the ways in which these individual features can occur in combination to develop characteristic glaciated landscapes. The specification makes explicit reference of a need to examine landscapes created by both valley glaciers and ice sheets. This is important as these different categories of glacier produce different landscapes. Glaciated valley landscapes are typically dominated by erosional features such as cirques and U-shaped valleys (figure 3), whilst landscapes affected by ice sheets commonly include features such as extensive drumlin fields and outwash plains (figure 4). A consideration of either situation provides the opportunity to consider the specific types and distinctive spatial arrangement of landforms associated with these different types of ice mass.

B. Systems framework – focusing on transfers of energy and movement of materials

As mentioned previously, it is impossible to understand the formation of a glacial landscape without a complementary understanding of the processes responsible for their formation. Specific reference to the flows of energy and material within the specification emphasises the need to consider some key glaciological basics to elaborate on the ways in which physical processes relate to landscape development. Some specific examples are provided below:

- **Glacier formation and mass balance:** Changes in mass balance (inputs vs. outputs) provide the key link between atmospheric processes and glacier extent and help explain how climate change results in a change in extent and the formation of related features such as end moraines. This clearly aligns to the specification's requirement that students understand how landscapes evolve as a result of processes driven by past, present and future climate change.
- **Thermal regime:** Warm-based glaciers where the ice is at a temperature close to its melting point produce large volumes of meltwater that promote the operation of basal processes (see below) and the formation of subglacial landforms (e.g. drumlins) and glaciofluvial features (e.g. eskers). Cold-based glaciers in contrast are commonly thought to be frozen to their beds and associated with limited landscape impacts. Whilst this conceptualisation is reasonable for A-level study, it is worth noting that ongoing research is suggesting that cold-based glaciers can have a subtle yet distinctive geomorphological impact.
- **Mechanisms of glacier flow:** Warm-based glaciers are associated with basal processes such as basal sliding. These promote more rapid ice flow and lead to the development of specific features such as striations (figure 1).

.....

The adoption of a systems framework and a focus on process provides an explicit opportunity to explore their operation at a range of spatial and temporal scales. Basal sliding and associated erosional processes for example, can lead to the creation of small-scale striations (figure 2), intermediate-scale roche moutonnées and large-scale U-shaped valleys (figure 3). Glaciated landscapes can also be viewed as forming over entire glacial cycles that last for tens of thousands of years. However, the occurrence of glacier outburst floods, or jökulhlaups, associated with volcanic eruptions or the catastrophic release of water from ice or moraine-dammed lakes can lead to dramatic landscape changes in the space of a few hours or days (figure 4).

Whilst it is not explicitly mentioned within the specification, it is well worthwhile exploring the links between glacial environments and glaciated landscapes and other types of geomorphic processes. In this way, the interlinkages between different parts of the physical environment in terms of energy and materials can be explored more broadly. One obvious example here is the important link between glaciers, global and local sea level and coastal processes. The landscape impact of glacier recession for example is not restricted to the formation of recessional moraines, but can also be seen in the formation of raised beaches that result from the crustal uplift associated with the removal of thick ice cover and the associated fall in sea level. Glacier recession can also lead to the debuttreassing of slopes and an increase in the incidence of large-scale rock slope failure.

C. Emphasise the use of quantitative approaches

The specification explicitly requires emphasis of the use of quantitative approaches and there are numerous ways in which the study of glaciated landscapes can be used to develop a broad portfolio of geographical skills.

The use of Google Earth imagery provides an ideal tool for the exploration of both contemporary and formerly glaciated landscapes from around the world. Ongoing improvements in the resolution of the imagery mean that in many cases it is possible to resolve intermediate and large-scale landforms. Google Earth imagery can be used to develop observation skills through the simple identification and interpretation of glacial landforms in any chosen locality. It can also be used to develop basic geo-spatial mapping skills, for example mapping the distribution of specific landform types to identify their interrelationships within distinctive landscapes. Finally, the combined use of measuring tools and the historical imagery feature allow the quantification of rates of glacier recession over time in response to ongoing climate change. For those using GIS software (e.g. ArcGIS for schools), there is the opportunity to make use of existing landform databases such as BRITICE (see links below).

There are however no substitutes for fieldwork activities that can allow students to explore and directly experience glaciated landscapes and provide truly transformative learning experiences. With the majority of the UK having been glaciated, there are numerous opportunities to undertake valuable fieldwork activities that can develop data collection and manipulation skills. Within formerly glaciated uplands, the measurement of striations can allow the reconstruction of ice-flow directions that in some instances reveal changes in ice-flow direction over time (figure 2). Coastal locations in formerly glaciated areas can also provide easy access to sequences of glacial deposits where the analysis of clast shape and roundness can be used to identify transport pathways and the measurement of clast orientation can again help identify ice-flow directions.

With Iceland becoming an ever more popular destination for school field excursions, there is a growing opportunity for students to directly experience glacial environments and to see for themselves how they work. In addition to field observation and sketching skills, the mapping of moraine sequences and the analysis of lichen diameters (lichenometry) provides a classic research project that can develop mapping skills and quantitative analysis skills and allow students to directly measure the impact of climate change on glacier recession.

4. Relevant case studies

- *European Alps* – presently glaciated landscape with topographically constrained glaciers including valley glaciers and cirque glaciers. Illustrates both present-day glacial impact on landscape and evidence of formerly more extensive glaciation. Also provides extensive evidence of ongoing glacier recession.
- *Iceland* – presently glaciated landscape with both topographically unconstrained ice caps and topographically constrained outlet glaciers. Illustrates interactions of glaciers with many other aspects of geomorphology including coasts, rivers and volcanoes. Some glacier margins display distinctive features relating to rapid advances (surges – e.g. Eyjabakkajökull) and high-magnitude flood events (jökulhlaups – e.g. Skeiðarárjökull, figure 4).
- *Antarctica* – presently glaciated landscape with topographically unconstrained continental ice sheet. Illustrates global-scale effects of glaciation via continental ice sheets and their impact on landscape, climate and sea level. The rapid break up ice shelves and the recession of tidewater glaciers provides a dramatic illustration of the impacts of climate change on cold environments.

- *English Lake District*– formerly glaciated landscape shaped primarily by topographically constrained glaciers including valley glaciers and cirque glaciers. Features a range of classic landforms characteristics of upland environments. Illustrates complex spatial patterns of overlapping erosional and depositional landforms within a small geographical area.
- *North American Laurentian shield* – formerly glaciated landscape shaped by a continental scale ice sheet. Illustrates long-term survival of continental scale glacial landscapes. Comparison with a formerly-glaciated upland landscapes (e.g. the English Lake District) demonstrates the contrasting landscape impacts of valley glaciers and ice sheets referred to in the specification.
- *Channelled scablands, North America* – spectacular landscape shaped by floods of glacial meltwater at the end of the last ice age, illustrating high magnitude events and rapid landscape change.

5. Useful internet resources

Glaciers online (<http://www.swisseduc.ch/glaciers/>)

Provides extensive imagery from glacial environments around the world and includes a useful photoglossary

AntarcticGlaciers.org (<http://www.antarcticglaciers.org/>)

Focuses on “explaining the science of Antarctic glaciology” and contains a range of detailed but accessible resources relating to the nature and behaviour of Antarctic glaciers, their landscape impacts and the impacts of environmental change.

BGS Observatory at Virkisjokull, Iceland

(<http://www.bgs.ac.uk/research/glacierMonitoring/home.html>)

Provides a range of resources relating to the British Geological Survey’s ongoing monitoring of the recession of an outlet glacier in Iceland. Includes timelapse imagery and access to live cameras on site. Also provides access to a range of datasets that could be used as the basis for research projects and includes timelapse imagery

