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Glaciers: The New Legacy

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GLACIERS: THE NEW LEGACY

Inaugural Lecture

Delivered at the University
on 24 February 1997

by

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Preamble

It is a great pleasure but also a daunting task for me to give this inaugural lecture as a Professor of Physical Geography at Swansea. It is a great personal pleasure because a professorship signifies recognition within the academic community. Not only that, but I am in a department with a great future as our recently awarded high grades for both teaching and research testify.

It is a daunting task, however, because it is different from most lectures I have had to give in the past. It is different for two reasons. First, it is such a mixed audience. On the one hand, I am expected to impress a wide range of colleagues and students with the breadth and depth of research and scholarship: on the other hand, the lecture has to interest, or dare I say entertain, laypersons and friends. Only exceptionally does one find a Jacob Bronowski or a David Bellamy who have perfected the art of disseminating the frontiers of science to a broader audience; and I do not have that talent.

The second reason for this being a particularly daunting task is a rather unique one. This is because it is following closely upon the inaugural lecture of my wife, Professor Rose D'Sa, who is Professor of European Law at the University of Glamorgan. Fortunately, there is only a very small minority of this audience that will have heard us both and therefore will be able to make the inevitable comparison. In recognition of this unique contest, I dedicate this lecture to Rose, in acknowledgement of the tremendous support she has given me during the last 15 years of my career.

GLACIERS: THE NEW LEGACY

1. Introduction

The importance of glaciers to geography, to science and to society has many aspects. First, glaciers are important because they are there. They are a major constituent of the that part of the solid Earth, termed the cryosphere. If we wish to understand planet Earth then we must understand the cryosphere as well as the other parts of the Earth/atmosphere/ocean system, and how they interact. Glaciologists and environmental scientists, including physical geographers, investigate these aspects of the study of glaciers.

Second, glaciers are agents of landscape sculpture, which account for much of the present-day scenery in areas formerly glaciated, including Wales. Glacial processes and their effects constitute the fields of glacial geomorphology and Quaternary geology and are also an important part of physical geography. Third, glaciers are a major resource. For example, the hydroelectric power industry in many mountainous countries is dependent on a summer water supply from melting glaciers; and glaciers are often a major tourist attraction. Although glaciers no longer exist in Britain, the sand and gravel industry is highly dependent on excavating the deposits left by former glaciers and our engineers need to understand the properties of the glacial deposits upon which most of our roads and buildings are constructed. Fourth, glaciers can be a natural hazard. They can advance over settlements and, as recent events in Iceland have shown, they can be a source of catastrophic flooding. In this respect at least, they are of interest to human as well as physical geographers.

Undoubtedly the greatest influence that glaciers have had on the natural environmental sciences has been through the evidence they have left in the landscape for the existence of ice ages and glaciations - that is, times in the past when glaciers and ice sheets were much more extensive and the climate was very different and much colder than today. This is what most people would understand by the term 'glacial legacy'.

It was about 150 years ago that the idea of an Ice Age first broke upon the scientific world. This was largely due to observations made in the European Alps by Louis Agassiz and others, who recognized the traces of former glaciers far removed from present-day glaciers. The greatest scientists of the day, particularly the most prominent geologists and including some eminent Fellows of the Royal Society, at first dismissed the idea. However, today we know that over the last two million years or so, during the Quaternary, there has been a succession of over 20 cold glacial episodes separated by warm interglacials like today (see Imbrie and Imbrie, 1979). This provides the framework for our present understanding of large-scale climatic change, which has driven so many of the other environmental changes that have affected the Earth's landscapes. The other environmental changes to which I refer include sea-level change, shifts in the global distribution of animals and plants, and variations in the geomorphic processes of erosion and deposition that affect the surface of the Earth. Thus, the study of glaciers can be seen to have been the basis of a revolution in the natural environmental sciences that was of comparable significance to such theories as plate tectonics and evolution.

This then is the 'old' legacy of glaciers. What I want to concentrate on this evening is a newer legacy, left by glaciers more recently. To be more specific, I am using 'new' in the sense of what present-day glaciers are leaving us now, and what modern glaciers have left us since the beginning of the present interglacial in which we live.

The substance of my lecture therefore has two parts. First, I will be talking about recently-deglaciated landscapes; that is, glacier foreland landscapes. Second, I will be talking about recent environmental change over the last 10,000 years; that is, Holocene environmental change. These are topics that I have researched for the last 25 years on my Jotunheimen Research Expeditions to southern Norway. I hope to show that this new legacy is a worthy addition to the scientific tradition that began with the initial discovery of Ice Ages.

2. Glacier foreland landscapes

Glacier forelands are the recently-deglaciated zones in front of retreating glaciers. In Norway, the recently-deglaciated zone extends for up to 5 km in front of the largest glaciers but is much narrower at smaller glaciers. The deglaciated zone has formed over the last 250 years or so. The phase of glacier expansion that culminated in the eighteenth century is known as the 'Little Ice Age' and the formation of the glacier foreland is the result of climatic change. Although evidence suggests that the 'Little Ice Age' was a global event, its scale and timing varied in different regions (see, for example, Grove, 1988).

The glacier foreland landscape is relatively barren and has been likened to a waste tip. The most prominent features in this landscape include, moraine ridges created directly by the glacier, glacio-fluvial outwash deposited by meltwater rivers and streams, areas of bedrock exposed and eroded by the glacier, and vegetated areas newly colonized by plants. Less visible are such features as the developing soils and the local climate that includes cold glacier winds that blow off the glacier, particularly in fine weather. The nature of the glacier foreland landscape is also described in the following quotation from a former Professor of Geography at the University of Oslo:

> *"The field work is rather rough. If there is the slightest possibility of bad weather, one is certain to meet it at the end of the glacier ... The storm always comes down the glacier, with rain, sleet, hail, snow and stiff gushes of wind. The landscape is most desolate, naked rocky wastes, boulders 'big as houses', patches of bottomless mire and raging torrents making a deafening noise. But in fine weather, nothing can be better."*
> (W. Werenskiold, 1939)

This will be familiar to those of you who have taken part on my expeditions or have ever approached a glacier elsewhere. Although the quotation is in characteristically flowery Norwegian language, it is just like that, apart from the bottomless mires - they are quite shallow!

What is it then that attracts geographers to such inhospitable places and why are they important? The answer to these questions requires me first briefly to define what I understand geography is about, what geographers should be doing and what is one of the main obstacles to our being able to do it.

Geography to me is the study of the landscape - landscapes from global to local scales, and landscapes at present, in the past and in the future. If one accepts this definition, then the primary task of research in geography is to develop a sound body of reliable knowledge about the landscape to the benefit of the discipline, science in general and society at large. I am a physical geographer and am concerned mainly with the physical landscape, but I believe what I am saying applies also to human geography.

I would go further and say that the primary task of research by a geographer at a university is to explain the landscape, which involves developing a sound theoretical basis for the subject. This theoretical base provides not only the answers to problems of basic (pure) research but also the most effective solutions to applied problems - to the maximum benefit of society *in the long run*. That is why the theoretical base should in my view be given priority despite the government's desire to encourage research with immediate impact on wealth creation and our quality of life.

And what is the main difficulty in our being able to understand the landscape and develop reliable theories? I would suggest to you that the main difficulty is the complexity of real-world landscapes. Most 'normal' landscapes are intrinsically complex, consisting of mineral and biological components, which exhibit intricate spatial variations and complex interactions. They have also been modified by a long history of natural environmental change as well as by human impacts.

This is where glacier forelands have an advantage. They are relatively simple landscapes. They are simpler than 'normal' landscapes in at least five ways:

- They are small scale - as they are only a few square kilometers in area, comprehensive investigation is possible.
- They are simple geoecosystems - in an arctic-alpine environment, both the physical and biological components are relatively simple.
- They have had a short history of existence - having existed for only a few centuries, they have not been affected by long-term environmental changes.
- They have usually suffered little human impact - in most but not all cases, human impacts have been negligible.
- They exhibit chronosequences - that is, they provide spatial representations of temporal change.

The last point is particularly important. New landscapes emerge at the glacier margin and later stages of development are found with increasing distance from the ice. Thus, I consider glacier forelands to be *field laboratories* for physical geography. Just as physicists and chemists use their laboratories to conduct controlled, simplifying experiments, so glacier forelands can be viewed as a vast natural experiment which is unfolding before us. Let me illustrate this aspect of the new legacy with reference to four aspects of my research on recently-deglaciated terrain.

2.1 Dating the landscape

First, the application of dating techniques provides detailed information about landscape age and hence is a basis for all the other investigations. These landscapes can also be used as a testbed for the dating techniques themselves. Because of the limited time available this evening, I can only provide a flavour of the techniques involved, which include the use of historical evidence, lichenometry, rock weathering and radiocarbon dating.

Historical evidence in relation to Norwegian glaciers begins with legal documents entitling farmers to reduced taxes when glaciers advanced over their fields in the eighteenth century. In Krundalen today, the moraine ridge that marks the limit of the 'Little Ice Age' glacier advance is clearly visible as a field boundary. Descriptions and illustrations of glaciers were made by visiting scientists and artists in the nineteenth century, and the earliest photographs of the glaciers were taken in the 1870s. These lines of evidence provide information about the early stages of glacier retreat from the 'Little Ice Age' glacier limit at Nigardsbreen in Jostedalen. Increasingly accurate and frequent measurements of the glacier snout position are available since the beginning of the twentieth century and today, Norsk Hydro, the Norwegian hydroelectric power authority, monitors the behaviour of several glaciers on an annual basis.

The biological dating technique of lichenometry uses lichen size to determine surface age. It is based on the principle that the longer a rock surface has been exposed, the larger the lichens growing on it. Crustose lichens of the yellow-green *Rhizocarpon geographicum* group (the so-called map lichen), which colonizes rock surfaces shortly after exposure by retreating ice, are widely used in this way. If the relationship between lichen size and surface age can be established from the size of the lichens on surfaces of known age, the resulting lichenometric-dating curve can be used to date other surfaces of unknown age (see, for example, Bickerton and Matthews, 1993). Most advances in this technique have been made on glacier forelands by using the moraine ridges as experimental surfaces. The wider applications of lichenometry include the dating of archaeological sites, earthquakes and landslides.

Rock surface weathering provides the basis of another dating technique: in this case depending on the chemical reactions that occur when rock surfaces are exposed to the atmosphere. The thickness of the weathering rinds that develop like a 'skin' on boulders after glacier retreat from the site, and which also affects the rock hardness, are used in much the same way as lichen size for dating.

Radiocarbon dating of organic material buried beneath moraine ridges is the final dating technique I want to mention, partly because we have established the Swansea Radiocarbon Dating Laboratory, run by Dr. Quentin Dresser within the Geography Department. Ours is the only Geography Department in the UK with this type of facility. Radiocarbon dating is based on the principle that the concentration of the radiocarbon (^{14}C) isotope in the air and in living material is more-or-less constant, but the isotope decays slowly at a constant rate once the living organism dies and is buried. By measuring the amount of radiocarbon activity remaining in samples of dead organic matter, it is therefore possible to determine the age of the material and its date of burial.

We have developed a speciality in dating soil, which I will now illustrate (for further details, see Matthews, 1993). Because there is organic material in soil, it is possible to apply radiocarbon dating to soils that were buried beneath moraines as glaciers advanced over them. However, soils are not single organisms that died at one point in time. Soils are composed of the remains of decomposed organic material derived mainly from plants that died at different times. The age of soil is therefore a complicated matter. By examining the radiocarbon age of soils buried beneath moraines known to have formed in the mid-eighteenth century we have made considerable advances in understanding the use of soils for dating.

Undisturbed buried soils have first to be located by excavation. This is a matter partly of judgement and partly of luck. It is a matter of discovering where least damage has been done to the soil during burial. Our most valuable site is found at Haugabreen. Here, our investigations on the age of a podzolic soil buried beneath the mid-eighteenth century moraine have been more intensive than any other studies of soil age anywhere in the world. As the mid-eighteenth century moraine at Haugabreen is relatively small, little damage was done to the soil during burial. Furthermore, as this type of soil has distinct horizons, the fact that the buried soil was largely undisturbed could be easily verified. The radiocarbon age of chemically-fractionated samples from thin slices of this soil (buried about 250 years ago) increases in age from less than 1,000 radiocarbon years near the surface of the buried soil to over 4,000 radiocarbon years at a depth of only 15 cm. The youngest material in the buried soil indicates the *maximum* time elapsed since burial, whereas the oldest material in the soil is a *minimum* estimate of the time since initiation of soil formation at the site.

What are the conclusions from this work? First, the initial problem mentioned above of the complex age of the soil organic matter can be turned to an advantage. The results not only confirm that burial occurred in the 'Little Ice Age' but also that the soil developed, undisturbed by a larger glacier advance, for at least the previous 4,000 years. Second, if radiocarbon dating of buried soils is to produce reliable estimates elsewhere, the sampling is crucial. Thin, undisturbed samples must be taken from near the surface of the buried soil, or the age/depth relationship must be estimated. For example, previous studies that have relied on bulk samples of soil have given misleading estimates of date of burial, which may be thousands of years too old.

The point I am emphasizing is that the recent, known age of the glacier foreland makes this a valuable natural laboratory for making further advances in the dating techniques themselves. This would not have been possible in a 'normal' landscape due to the additional uncertainties involved. Furthermore, in the case of dating soils, we cannot obtain reliable results from unburied surface soils because they are contaminated by so-called 'bomb' carbon from thermonuclear testing in the atmosphere.

2.2 Reconstructing glacial and climatic variations

This brings me on to the reconstruction of glacier and climatic variations. By using all the dating techniques I have mentioned it is possible to reconstruct the glacial history of the last few centuries in considerable detail.

The general pattern of glacier retreat since the maximum extent of the glaciers in the 'Little Ice Age' is indicated by the pattern and age of the landforms on the glacier forelands. The ages of the moraine ridges are particularly useful because each ridge marks a former position of the glacier snout when a glacier still-stand or minor advance occurred. Dating complex moraine-ridge sequences, such as the sequence at Nigardsbreen, therefore goes some way to reconstructing the glacier history. In Norway generally, the trend has been an accelerating retreat, with glaciers retreating about as much in the twentieth century as they did in the eighteenth and nineteeth centuries combined.

Glaciers advance or retreat depending on the balance between the amount of winter accumulation in the form of snow and the amount of summer ablation or melting, which is determined by summer temperatures. Hence glacier history is a so-called climatic 'proxy' - a source of climatic information that extends back beyond the instrumental record available from meteorological stations.

The predominance of retreat since the mid-eighteenth century indicates decreasing winter snowfall and/or rising summer temperature. Superimposed on this trend, there have been at least eight minor glacier advances. Each involved an advance of up to 150 m, lasting for up to 10 years, and led to the deposition of a distinct moraine ridge. These advances signify intervals of increased snowfall and/or decreased summer temperature. At present, the glaciers are again advancing, which is attributed especially to higher than normal winter snowfall since the 1970s. Annual and cumulative data on the annual glacier-front variations of Briksdalsbreen, for example, show that this glacier has advanced about 500 m since the 1970s and has advanced rapidly at a rate of about 50 m per year during the 1990s (see, for example, Nesje *et al.*, 1995; Winkler, 1996).

There are several reasons why such reconstructions are important. In this instance, however, I want to emphasise the practical value of the work with reference to the current debate about 'global warming'. It is known that the level of so-called 'greenhouse gases', such as carbon dioxide and CFCs, are increasing in the atmosphere due to human activity. Models tell us that the increase in such anthropogenic emissions of the greenhouse gases are sufficient to produce a global rise in mean annual temperature of the order of 1.5 °C within 50 years. There are uncertainties attached to such predictions, which was very clearly indicated on a Christmas card I received last year from colleagues at the Polish Academy of Sciences in Kraców. This depicted the possibility of a rise or fall in temperature within the range ± 4 °C. However, the latest report of the Intergovernmental Panel on Climate Change (IPPC) published last year, is confident in the existence of an enhanced greenhouse effect and attention is increasingly turning to the likely consequences for society.

Because the amount of anthropogenic global warming has so far been small in relation to the climatic changes that occur naturally anyway, I would suggest that the recent trends in the behaviour of glaciers is extremely relevant. If the general retreat due to natural warming since the 'Little Ice Age' continues, then this will act in the same direction as the anthropogenic effect to produce higher temperatures in the next century than we would otherwise experience. If, however, there is a natural temperature fall this could negate the anthropogenic effect and produce a continuation of present temperatures or even the global cooling shown as a possibility on my Christmas card.

Glacial history over the last 250 years suggests that there has indeed been a natural warming trend over this time interval to which an enhanced greenhouse effect is now being added. We know this because the glacier retreat from the 'Litle Ice Age' maximum began before the upturn in the emission of greenhouse gases during the Industrial Revolution.

2.3 Glacial and periglacial landforms and processes

Whereas future climate is a rather fashionable topic for study, the third topic on my list - the study of glacial and periglacial landforms and processes - is a

more traditional area for physical geographical investigation. Indeed, geomorphology, at least until recently, has been the dominant branch of physical geography. It is therefore appropriate to demonstrate with reference to a common landform and a common process, how the newly-deglaciated landscape has something to offer in this area. Both projects from which these examples are taken involved two colleagues from this department, namely Dr. Danny McCarroll and Dr. Richard Shakesby, with whom I have shared many pleasant and unpleasant days in Jotunheimen.

Take, for example, that most basic of glacial landforms, the moraine ridge. There are several theories of moraine ridge formation, which can be labelled for convenience by such terms as pushing, dumping and shearing. Much of our knowledge of moraine genesis has been based on inference from much older forms dating from the last glaciation or before.

The advantage of modern forms on glacier forelands is their recency and the possibility of observing their formation. The latter point is particularly pertinent because prior to the current phase of glacier advance, glaciers were retreating extremely rapidly and conditions were not conducive to moraine formation. Not since the previous phase of advancing glaciers in the 1920s and early 1930s has there been an opportunity to study the formation of moraine ridges.

It has been possible over the last 20 years to make intermittent observations of moraine formation and to demonstrate a new mode of formation at the glacier Styggedalsbreen in Jotunheimen. During this time, this glacier has exhibited a ratchet-like seasonal advance and retreat of the glacier snout. The glacier retreats each summer and pushes forward each winter. During summer retreat, meltwater streams deposit sorted sediments on the thin wasting tongue of the glacier; during the winter, subglacial sediments are frozen-on to the base of the glacier. During the winter advance, the ice tongue together with the sediments above and below moves forward and, when the ice melts in the following summer, the double layer of sediment is deposited. Over a number of years, the moraine grows by the addition of annual increments of sediment (for further details, see Matthews *et al.*, 1995).

Thus, a new theory has been proposed that is likely to provide a modern analogue for the interpretation of older moraines elsewhere. Insights into many other landforms can be gained by exploiting the actively-forming and fresh forms that are to be found on recently-deglaciated terrain.

My second geomorphological example involves the common process of frost shattering, or the breakup of rocks by freeze-thaw action. It produces the angular rubble that often litters the landscape in periglacial environments - that is in environments with a non-glacial cold climate at high latitudes and in mountain regions. This is a surprisingly controversial topic, with all sorts of theories as to the most important mechanisms and controls. For example, the rate of freezing is thought by some to be critical in producing rock breakdown, whereas others emphasize the number of diurnal freeze-thaw cycles.

Observations made on a glacier foreland have been of major importance in demonstrating the importance of the seasonal freeze-thaw cycle. At Bøverbreen, there is a zone of intensely shattered bedrock about 4 m above the level of a small lake. Investigations have shown that this level marks the shoreline of a former ice-dammed lake. Dating of the shoreline by lichenometry shows that the ice-dammed lake formed as the glacier advanced during the 'Little Ice Age' to block the drainage (see Matthews *et al.*, 1986). The ice-dammed lake existed for about 100 years; then the glacier retreated, which allowed the lake level to fall. The damage done to the bedrock thus represents 100 years of frost weathering. The bedrock is shattered in a narrow zone and massive slabs of rock have been prised loose. This occurs only along this narrow zone and there is negligible frost damage to the rock surfaces above this level, despite their much longer exposure.

The interpretation is as follows. During winter cooling, lake ice forms to a thickness of about 1 m and the freezing front also penetrates the adjacent bedrock. However, unfrozen water exists beneath the lake ice during the whole winter. This unfrozen water is therefore constantly available and allows ice lenses to grow continuously within the adjacent bedrock. Above the lake level, it is too dry for frost shattering; below the level, the water does not freeze. The conclusion must be, therefore, that the seasonal freeze-thaw cycle, which involves deep penetration of the winter cold into the bedrock, is much more effective than shorter-term freeze-thaw cycles. The research also demonstrates the necessity for an adequate moisture supply for effective frost weathering.

This example shows not only the value of the fresh landforms but also the value of a known timescale, which provides information on the rate at which the process is operating. Thus, the glacier-foreland laboratory can be seen to offer insights into relatively long-term changes that would be difficult to obtain from normal, complex landscapes.

2.4 Vegetation succession and soil development

The fourth of my research topics on glacier forelands is the development of ecosystems on the newly-created substrates - that is, primary succession. This takes advantage of the chronosequence of vegetation and soils that exists on ground of increasing age. Glacier forelands provide one of the rare, classical sites where primary succession and soil development can be investigated. Other types of site where new land is being created include sand dunes and volcanoes.

After a few years herbaceous perennials, such as grasses and saxifrages colonize the new ground to form pioneer communities. These pioneers first cover the ground and are then gradually replaced, after 100 years or so, by the later colonizing species that make up the shrubby heath found on the older terrain. After about 250 years, there is a well-developed heath community, with similar dominant species to the mature tundra landscape outside the glacier-foreland. Thus, based on a large sample of sites, it is possible to map the pattern and timing of plant colonization, different species arriving and leaving the succession at different times. It is also possible to analyse the nature of the plant communities as the vegetation cover develops and as each community is replaced by the next until a relatively stable vegetation cover is produced. Finally, the causal factors that initiate change can be investigated. This is currently involving manipulative experiments with colleagues at the University of Oxford and Manchester Metropolitan University, which include the use of soil transplantation, and the addition of fertilizers and seeds.

Much of our understanding of primary succession has been derived from glacier foreland chronosequences. The theory of succession is of major importance in the context of ecology and biogeography. Indeed, a survey of members of the British Ecological Society voted succession as the most important concept of ecology apart from the ecosystem concept itself (Cherrett, 1989). However, although successional change is occurring almost everywhere around us - for example, after forest clearance or following the abandonment of agricultural land, or after the protection of a nature reserve - the changes are difficult to investigate because they are slow. I would like, therefore, to use succession to illustrate how recently-deglaciated terrain has been used to test one important aspect of succession theory.

Succession theory states that as the vegetation landscape develops from an early stage towards a relatively stable, mature landscape, which some would term a 'climax' state, there is a change from a varied vegetation pattern towards uniformity. Although the extreme view of convergence to identity in a monoclimax is no longer held, it is almost uniformly held that at least partial convergence occurs during succession. Thus, two plots would be expected to end up eventually with rather similar plant communities, even if the initial environmental conditions at the two plots differed.

This idea was tested on the Storbreen glacier foreland by measuring the similarity between vegetation communities on terrain of different ages. Three different statistical techniques (principal components analysis, multiple discriminant analysis and non-metric multidimensional scaling) were used to measure the similarities between four communities defined by numerical classification (see Matthews, 1979).

If convergence is occurring, then the 'older' communities should be more similar to each other than the 'younger' communities are. All three techniques showed that the mature communities are less similar to each other than the pioneer and early-successional communities. Hence it is concluded, at least at Storbreen, that successional convergence is not universal and that divergence exists. In other words, the idea of successional convergence has been refuted and existing theory needs to be modified to accommodate these results.

This knowledge also has importance from the viewpoint of applications to the reclamation of colliery spoil and other types of degraded land. The principle is that the way vegetation establishes itself in the inhospitable conditions of the glacier foreland has relevance to the development of a stable vegetation cover on the spoil tip. As many of you must be aware, just such an approach was adopted sometime ago in the reclamation of the Lower Swansea Valley and is in common use. The crucial point I am making here is that a reliable, theoretical knowledge base is necessary not only for the good of the academic discipline but also for successful applications in the real world. And an apparently irrelevant context (such as the glacier foreland) may be necessary in order to develop that reliable theoretical base. In the broader context, this is why university research must not be geared entirely towards forseeable benefits in terms of *short-term* wealth creation or quality of life.

I do not have enough time to spend more on vegetation succession, which was the subject of my Ph.D.. For those who have a particular interest in this topic, I would recommend my book on this subject, '*The Ecology of Recently-Deglaciated Terrain*' (Matthews, 1992), a copy of which is in the Natural Sciences Library.

3. Glaciers and Holocene environmental change

In the second part of my lecture, I turn to the legacy left by glaciers over the extended timescale of the Holocene - that is, the last 10,000 years of Earth's history. Just as glacier variations over the 'Little Ice Age' interval of the last few hundred years yield information about climatic change, so too it is possible to reconstruct a longer history of glacier and climatic variations for the Holocene. This topic is taking up an increasing amount of my research time and that of my post-doctoral research assistant, Dr. Mark Berrisford.

A major problem here is the large extent of the glaciers in the 'Little Ice Age'. The buried soils and other evidence already discussed indicate that glaciers were smaller than in the 'Little Ice Age' for most, if not all of the Holocene. Most earlier evidence that might have existed in the landscape would therefore have been destroyed by the 'Little Ice Age' glacier advance. Thus, different approaches are required to reconstruct Holocene glacier and climatic variations; and this brings me on to a major current research project of mine, which is being funded by the Natural Environment Research Council and involves collaboration with colleagues at the University of Bergen.

Two kinds of site yield a record of Holocene glaciers. The first of these are glacial lakes, which receive glacial meltwater downstream from the glaciers. When glaciers expand and contract, there is a variable input of sediment into the downstream lakes. The beauty of the lacustrine record is that it is uninterrupted because sedimentation in such lakes has been continuous throughout the Holocene.

How are the sediments sampled? When the lakes are frozen in the winter it is possible to land a helicopter on the lake ice (or in some cases to use snowcat overland transport by courtesy of the Norwegian Army). Then a hole is drilled through the lake ice, and a coring apparatus is lowered down to the lake bottom on wires. Next, a plastic tube is hammered into the sediments at the bottom of the lake, and the resulting sediment core is pulled up back through the hole in the ice. Commonly, the sediment core is 3-4 m long. Back in the laboratory the sediments are dated by radiocarbon dating. Glacier variations are recorded by variations in the nature of the sediments.

In principle, when glaciers are large, the mineral content of the lake sediments is high; this mineral material consists mainly of fine particles, particularly silt-sized particles, eroded at the bed of the glacier. It is these fine, suspended particles - so-called 'rock flour' - that gives the glacial meltwater streams their cloudy appearance and the glacial lakes their brilliant emerald blue-green colour in summer. When glaciers are very small, or if they melt away in periods of warm climate, the silt supply is reduced and the lake sediments are mostly organic in composition. Other sediment characteristics, such as magnetic properties and grain-size characteristics, likewise vary down core and indicate the state of the glaciers in the lake catchment through time.

The other kind of site that can yield a record of Holocene glaciers is the peat bogs on the banks of meltwater streams. These sites are excavated in the summer months, when the bogs are no longer frozen. Grey silt layers again indicate periods when glaciers are active in the catchment. Under these conditions, when the bog is flooded, the rock-flour silt particles are deposited on the bog surface. During periods when glaciers melt away, the orange or dark brown peat accumulates, uninterrupted by silt deposition because the floodwater is then clear.

The pattern of Holocene glacier variations indicated so far is as follows. After deglaciation, at about 9,000 radiocarbon years ago, most glaciers appear to have melted away. There is considerable evidence for the 'rebirth' of glaciers later in the Holocene, an event or series of events known as 'neoglaciation'. The late Holocene is characterized by a history of fluctuating glaciers culminating in the 'Little Ice Age' glacier expansion.

An unexpected outcome of the results was the discovery that the various glaciers do not appear to have behaved entirely synchronously. Whereas all of the sites indicate the absence of glaciers in parts of the early Holocene and relatively large glaciers in the 'Little Ice Age', Gjuvvatnet exhibits five 'Neoglacial' events, Midtivatnet three, and Storevatnet only one. At first sight, this suggested the possibility of errors. For example, parts of the signal may be missing or there may be dating errors. However, the apparently non-synchronous formation and disappearance of the glaciers has proved a key to reconstructing the climatic variations that underlie the glacier variations.

This requires the variations of the different glaciers to be viewed on a comparable, climate-sensitive basis and utilizes variations in the Equilibrium Line Altitude (ELA) of each glacier. The ELA is the altitude at which summer melting equals winter accumulation: a glacier will melt away if the ELA is too high and will only form if the ELA is sufficiently low. As we know the ELA of present-day glaciers from glaciological observation, we can calculate the change in ELA (ΔELA) required for glacier formation and/or disappearance at any site. We also know, from the lake sediments, the times at which the specific glaciers formed and disappeared. It is therefore a relatively simple matter to reconstruct the pattern of ELA variations through time in the form of a graph which incorporates all the evidence from several cores (Matthews and Karlén, 1992).

The resulting composite curve in effect corrects for the fact that glaciers, which differ in altitudinal distribution and size, form and disappear at different times. Assuming the glacier variations are driven by summer temperatures, this pattern implies an early Holocene with summers warmer than today by about 2 °C, and an irregular decline in summer temperatures in the late Holocene, culminating in the 'Little Ice Age' with temperatures some 2 °C colder than today. This ignores any affect of winter precipitation, which can be taken into account by more complicated models (see, for example, Dahl and Nesje, 1996).

Again there are considerable implications for the 'global warming' debate. In particular, the future climatic impact of further emissions of greenhouse gases is highly dependent on the natural background changes that are likely to occur. The glacier record shows that climatic variations of the order of 1-2 °C have been common during in the Holocene. These are of the same magnitude as the likely human impact on the atmosphere over the next few generations. As explained previously, whether there is actually a natural upturn or downturn in global temperature is critical in determining the significance of the human impact.

This implication of the study of Holocene glacier and climatic variations is relevant to society, and is obviously used as a justification for obtaining research grants as it is in line with the government's desire to support research that has a tangible bearing on 'quality of life'. However, I would like to return to my point made earlier, that there is a more fundamental criterion for judging whether a topic is important to science in general and to geography in particular. This is whether or not the topic has the potential to contribute something new to our theoretical base.

Judged by this criterion, the study of Holocene glacier and climatic variations and other aspects of Holocene environmental change is quite fundamental, and explains why this is the focus of one of our research groups here in the Department of Geography at Swansea. Studies of the Holocene present several unique opportunities for theory development, which I have elaborated in the latest issue of our departmental journal, the *Swansea Geographer*, which is edited by our postgraduates (Matthews, 1996). Briefly, these reasons include, first, the opportunity to find more and different examples of environmental phenomena than are to be found in the present landscape. Our understanding of the natural environment will be lacking if it is based only on what can be observed today. Second, detailed Holocene reconstructions of enviromental change, such as the record of Holocene glaciers that I have described, enable us to develop an understanding of the pattern and causes of change on timescales of decades, centuries and millennia. There is relatively little known about these shorter-timescale environmental variations that have occurred throughout Earth's history. The Holocene provides the best opportunity we have to improve our knowledge of short-term environmental change. Third, Holocene environmental change includes the increasing human impact on the landscape, which began to be appreciable from the mid-Holocene onwards. The Holocene can therefore provide a framework for understanding the interrelationships between the human population and nature. This last reason for investigating the Holocene is a particularly opportune one, not only for society, but also for Geography as a discipline. Here is a potential unifying theme for Geography, a subject in which there are major differences in research ethos between the physical and the human branches.

4. Conclusion

In conclusion, my lecture has attempted to demonstrate the importance of the legacy left in the landscape by modern glaciers. This was illustrated with examples from my own work, which I hope you found interesting. This new legacy is different from the more well known and in some respects more thoroughly studied older legacy left in the landscape from previous glaciations.

I outlined first, the legacy left on glacier forelands over the last c. 250 years (since the 'Little Ice Age') and second, the legacy of Holocene glacier variations over the last 10,000 years. Both aspects of the new legacy are important to my subject (Geography), to science in general, and to society. The practical relevance of this research was illustrated with particular reference to climatic change and the possibility of a warmer world in the next century. The glacier variations indicate that the climate of the next century will depend as much on natural factors, which are poorly understood, as on the human impact of further emissions of greenhouse gases.

However, I have also put the case for the importance of basic research on these themes and have sought to demonstrate their importance in developing a sound, well-tested theoretical understanding of the landscape - which I believe to be my main task as an academic geographer in a British University. The underlying reason for this belief is that theory sums up the state of our understanding and as such is the basis of all attempts made to improve the human condition.

Finally, my aim over the coming years is for the Geography Department here at Swansea to become increasingly recognized internationally for fundamental research on Holocene environmental change, of which the new glacial legacy is but a part.

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